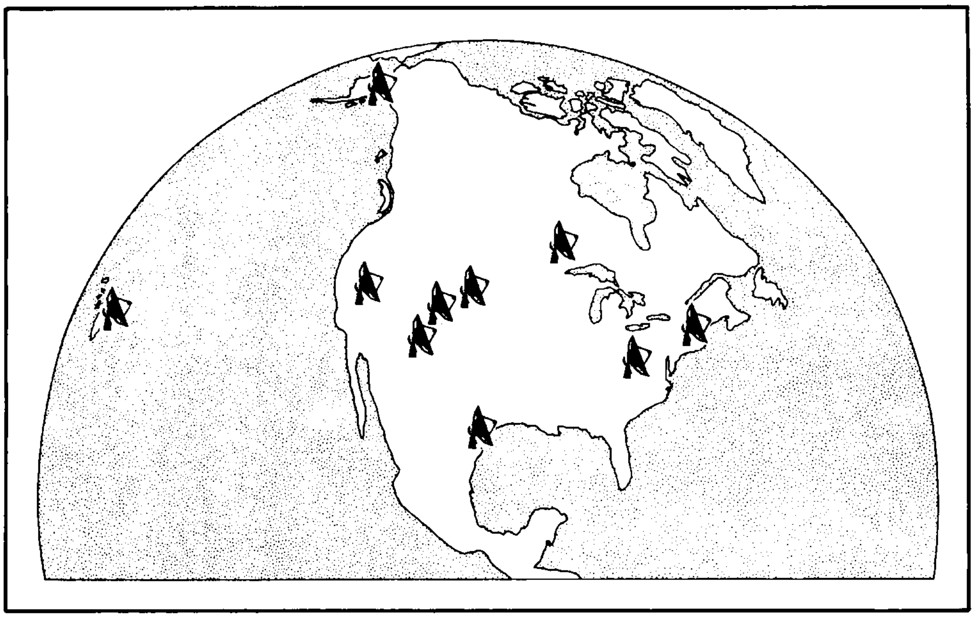
THE VERY LONG BASELINE ARRAY RADIO TELESCOPE



VLBA

Volume II
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NATIONAL RADIO ASTRONOMY OBSERVATORY

T H E

V E R Y   L O N G

B A S E L I N E   A R R A Y

R A D I O   T E L E S C O P E

JUNE 1982

NATIONAL RADIO ASTRONOMY OBSERVATORY

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PREFACE

This document contains technical reports and memoranda which have been prepared as part of the VLB Array design program. They are reproduced here in essentially their original form to provide more detailed technical information than is given in the VLB Array Proposal. Not included is material which has been superseded by more recent reports, or internal memoranda of an organizational or administrative nature.

More extended background material can be found in the 1977 and 1981 NRAO design studies, and the 1980 Caltech design study.

K. I. Kellermann
Green Bank, W. Va.

June, 1982

VLB ARRAY

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I. THE ARRAY CONFIGURATION

VLB ARRAY MEMO No. 97

AN ATLAS OF TRANSFER FUNCTIONS FOR POSSIBLE VLBI ARRAYS

6/23/82

R. C. WALKER
National Radio Astronomy Observatory

Turn back now all ye who despise u-v tracks!

INTRODUCTION

Many possible arrays have been explored during the VLBA configuration studies. Some of these have proven useful and appear in the proposal, in the design studies that preceeded the proposal, or in other documents related to the Array. Others have not proven useful and have not appeared where persons not working actively on configuration studies can find them. Questions often arise about the usefulness of particular stations. The object of this document is to describe some of the considerations that go into the selection of a configuration and to answer some of the questions on the effects of particular sites.

This document is only concerned with u-v tracks for possible configurations. There is no attempt to use more sophisticated and computationally intensive array comparison methods. For details and applications of those methods, refer to the design studies (Cohen 1980, Kellerman 1981), and to VLBA documents by Linfield on the effects of the use of closure parameters in the mapping and by Mutel and Gaume on a u-v plane based quality measure. U-v tracks are the computationally easiest way to compare arrays and give the most insight into the effects of particular stations and therefore are the most useful way of comparing a large number of configurations.

The u-v tracks shown in this document are all plotted in a consistent manner in order to facilitate comparisons. The tracks for each array configuration are computed at 8 declinations, each of which represents the center of a strip of sky containing 10 percent of the total area of the sky. Therefore there should be approximately equal numbers of extragalactic sources to observe at each of the declinations plotted. Galactic sources are concentrated in the galactic plane and tend to have low declinations where the performance of most arrays is relatively poor. There are only three different scales on which most of the tracks are plotted and Array D2, which is the array of the NRAO design study (Kellermann 1981), and is the array used for demonstration purposes in the VLBA proposal, is shown at each of the scales. The largest scale is appropriate for showing global arrays with baselines up to 11,000 km (the scale actually goes to 16,000 km). The next scale is appropriate for arrays confined to U. S. territory and shows a maximum baseline of 10,000 km. A smaller scale, with a maximum baseline of 2000 km, is used to show the short baseline coverage of some arrays. In addition to these three scales, the coverage of the VLA and the VLA plus nearby stations are shown on smaller scales. All u-v tracks are plotted to scales given in km in order to be independent of frequency.

This report begins with a description of the process by which Array D2 was chosen. Many of the factors that should be considered in deriving any configuration are described. The constraints under which the Array configuration should be chosen are summarized in Table 1. The rest of the report is devoted to showing the u-v tracks for many possible arrays. The text related to the u-v tracks is entirely contained in the figure captions. The figures are divided into 6 groups and are listed in Table 2. The names, abbreviations, latitudes, and longitudes of the stations used in the arrays displayed are given in Table 3.

ARRAY D2

Array D2 is the configuration used for demonstration purposes in the VLBA proposal and in the NRAO VLBA design study (Kellermann 1981). It contains antennas at the locations listed in the caption of Figure I-1. Many of the considerations that go into the selection of a configuration can be described nicely by discussing the process by which Array D2 was found.

One of the most important constraints on the configuration is that it provide the highest resolution possible. For east-west baselines, this can be most effectively met with stations near the equator, but a constraint that all antennas should be on U. S. territory has been placed on the initial design studies. The effects of relaxing this constraint will be shown in the figures where the value of foreign stations is shown. Under the U. S. territory constraint, the longest baselines are from either New England or Puerto Rico to either Alaska or Hawaii. Puerto Rico to Hawaii is the longest and Hawaii to New England is a reasonable second. At the time D2 was chosen, there was some fear that there may be complications operating in Puerto Rico (although a major U. S. observatory, Arecibo, is there) and that the high frequency observing conditions might be poor there, so the Hawaii to New England baseline was selected. The effects of choosing Puerto Rico will be shown later and Puerto Rico is prominent in the alternative arrays shown in the figures.

In order to minimize operating problems and expenses, it is desirable to place as many antennas at existing observatories as possible. For this reason, Haystack Observatory in Massachusetts was selected as the New England site, causing a small but acceptable loss in resolution over using a site in Maine. Similarily, the Owens Valley Radio Observatory in California and the National Radio Astronomy Observatory in Green Bank, West Virginia were selected as sites. Several other existing sites, such as North Liberty Radio Observatory in Iowa, the Harvard Radio Astronomy Station in Fort Davis, Texas, and the Hat Creek Radio Observatory in California were also considered but did not work well with Array D2 as it was being formulated. Doubtless other arrays with performance similar to Array D2 could be found in which some other combination of existing sites is used.

There is significant debate as to whether existing sites should be used. The existing site could provide technical support and manpower which helps reduce expenses and reduce the time needed for repairs requiring skilled personel. On the other hand, if an antenna is built at the site of an existing antenna, that existing antenna is no longer useful as a part time addition to the array for experiments requiring the highest possible dynamic range and sensitivity. Also, many of the existing sites do not meet the accessibility requirements that will be placed on new Array elements. For example, there is a six hour drive involved in getting to OVRO and Green Bank in not much better. An attractive alternative is to place the new antennas near the existing observatories in order to obtain local support, but far enough away to provide interesting short baselines for low resolution experiments at the lower frequencies where the existing antennas can operate.

One observatory which should have Array antennas nearby is the VLA near Socorro, New Mexico. The VLA is a very powerful interferrometer with baselines up to 35 km in length and with antennas very similar to those proposed for the VLBA. Scientifically, the ideal VLBA configuration would cover all baselines from 35 km to the nearly 8000 km Hawaii to New England baseline and the short baselines would be near the VLA so that the combined instruments would smoothly cover all possible spacings. This is not possible without increasing the number of antennas and the cost of the VLBA significantly. However, by placing the shortest spacings of the VLBA near the VLA, some of the intermediate spacings can be acquired. For this reason, there is an element of Array D2 at Socorro, somewhat less than 100 km from the VLA, and other elements of Array D2 are placed in New Mexico and adjoining states. The VLBA and the VLA, both of which will be NRAO instruments, can be operated in several modes: as separate instruments, as a sensitive VLBI instrument using the entire VLA in phased array mode as one VLBA element, as a somewhat higher resolution version of the VLA by using a nearby VLBA antenna as a VLA element (meanwhile the VLBA may be using one of the 27 VLA antennas), or as a very powerful combined instrument studying a source over many orders of magnitude in angular scale.

Another important feature of the VLBA will be the ability to observe sources at low declinations. East-west arrays with relatively small numbers of elements can be devised which provide very good coverage over a wide range of baselines for northern sources. This is the type of array proposed by the Canadian Long Baseline Array project because of the very limited north-south extent of accessible territory in Canada. Arrays of this type were also proposed in some early U. S. array studies. Providing good coverage for low declination sources is much more difficult. The antennas must be well distributed in two dimensions, greatly increasing the complexity of the configuration selection process. While optimal one-dimensional geometries, such as minimum redundancy geometries, are known, no optimal two-dimensional geometries have been presented. The VLA logarithmic wye is a very good configuration if the antennas must be moved. However the radial arms concentrate most of the baselines along a small number of radial directions in short observations leading to non-optimum beams. With an array of fixed antennas such as the VLBA, such concentrations of baselines should be avoided.

In order to observe low declination sources, sites well dispersed in the north-south direction are required. The longest available north-south spacings available on U. S. territory are from Hawaii to Alaska and from Puerto Rico to New England. The latter baseline is significantly shorter than the former but has the advantage that sources farther to the south can be seen from New England than from Alaska. For Array D2, Alaska was chosen for the northern station. Next, a baseline with the greatest possible north-south extent within the contiguous 48 states should be chosen so there is not a large gap between the Hawaii-Alaska baseline and the next shorter north-south baseline. Southern Texas and Florida are the southern-most possible sites with Texas prefered because it has a drier climate and because is it closer to the VLA. A southern Texas station should be complemented by a station along the Canadian border. Eastern Washington or Idaho would be preferred for operational and climatic reasons but the baselines to that area and to sites near the VLA from Hawaii or from the Northeast are nearly equal for high declination sources and the uniformity of coverage for such arrays is poor. A rough line of sites running from northeast of the VLA and ending in North Dakota provides much better coverage. Stations at Los Alamos, New Mexico; Denver, Colorado; and Grand Fork, North Dakota were selected to provide the desired coverage. Many other possible sites in the Southwest were tried in a search for good intermediate spacings that interact well with the rest of the array, but those chosen seem to be the best. Sites in the Northwest, rather than North Dakota, do seem to work well in arrays that include Puerto Rico.

Array D2 provides good coverage of the u-v plane and would be acceptable as a final array configuration, assuming the U. S. territory constraint is kept. Other U. S. only arrays can be found that are as good or maybe even slightly better, but there is little chance that a very much better array can be found. However, Array D2 has some operational difficulties that would be nice to avoid and further efforts to find a better configuration will continue. The most obvious problems are that the North Dakota station must be operated in a rather extreme winter environment (worse that the Alaska station) and that the south Texas station and some of the others are not in optimal high-dry sites for observations at the highest frequencies. Also the coverage provided by a station in Puerto Rico on low declination sources and the enhancement of the coverage that Puerto Rico provides when possible new antennas to the south are used is sufficiently good that such a station should probably be included in the final configuration.

TABLE 1

ARRAY CONSTRAINTS SUMMARY

I. All configurations to be studied in the effort to find a final configuration for the VLBA will satisfy the following constraints:

  A. Ten stations.
  B. Most sites on U.S. territory.
  C. Maximum spacing greater than 7500 km.
  D. Minimum spacing less than 200 km.
  E. Two dimensional for low declination coverage.
  F. Short spacings near the VLA.
  G. Sites should be as far south as possible for good low declination coverage.
  H. Inner third provides good coverage.
  I. Sites are near good transportation.
  J. As many high-dry sites as possible.
  K. Sites are near existing technical facilities.
  L. Array interacts well with other observatories.
    1. Europe.
    2. Japan.
    3. Canada.
    4. Possible southern stations to be added later.

II. Arrays satisfying each of the following constraints concerning existing observatories will be studied.

  A. Sites at existing observatories where possible.
  B. Sites near but separated from existing observatories (ones that will survive) for short spacings.

III. Arrays satisfying each of the following geographic constaints will be studied.

  A. All sites on U.S. territory.
  B. One site near Mexico City.
  C. Two or three sites in Canada.
  D. One site in Mexico and some sites in Canada.
  E. No geographic constraint on a few sites.

IV. Sites will be located in the following areas in all configurations that will be studied:

  A. Hawaii (Specific location within Hawaii not important).
  B. Within 100 km of VLA.
  C. Within 200 km of fixed site B.
  (D. Puerto Rico - feasibility must be verified)

TABLE 2.

Summary of Figures

Figure #	Scale max. (km)	Description
Section I:	Array D2 and variations.	
I-1	10,000	Array D2
I-2	16,000	Array D2 - Large scale.
I-3	2,000	Array D2 - Inner portion
I-4	10,000	Array D2 Green Bank --> Jacksonville FL.
I-5	10,000	Array D2 Grand Fork --> Spokane WA.
I-6	10,000	Array D2 Brownsville --> Laredo TX.
I-7	10,000	Array D2 Anchorage --> Arecibo PR.
I-8	10,000	Array D2 OVRO --> Clark Lake, CA.
I-9	10,000	Array D2 Green Bank --> Michigan.
I-10	10,000	Array D2 Hawaii and Anchorage --> Bonn and Arecibo.
I-11	10,000	Array D2 u-v coverage with 10% bandwidth.
Section II:	Other arrays.	
II-1	10,000	Array 13 from Caltech design study (Cohen 1980)
II-2	10,000	Array 13 + Socorro NM and Arecibo PR.
II-3	10,000	A reasonable 8 station array.
II-4	10,000	A 10 station array that has two Hawaii sites.
II-5	2,000	Inner portion of II-4.
II-6	10,000	A strongly centrally condensed array.
II-7	2,000	Inner portion of II-6.
II-8	10,000	A 10 station array with Mexico and Northern Canada.
II-9	10,000	A 10 station array of nested triangles.
II-10	10,000	A 10 station with a N-S line plus other sites.
II-11	10,000	A 10 station wye configuration.
Section III:	Arrays based on existing stations:	
III-1	10,000	5 station U. S. Network experiment.
III-2	10,000	7 existing stations - typical network plus Europe experiment.
III-3	10,000	15 existing stations - maximum, low freq. effort.
III-4	10,000	10 existing US sites + Hawaii and Puerto Rico.
III-5	10,000	The 7 stations of III-4 that would work at 1.3 cm.

TABLE 2 (Cont.)

Figure #	Scale max. (km)	Description
Section IV:		Arrays using South American and Pacific sites.
IV-1	16,000	Array D2 + Galapagos.
IV-2	16,000	Array D2 + Easter Island.
IV-3	16,000	Array D2 + Galapagos and Easter Island.
IV-4	16,000	Mutel Array SG-1: 10 stations with Galapagos.
IV-5	16,000	IV-4 with Quito instead of Galapagos. (SQ-2)
IV-6	16,000	Mutel Array SE-1: 10 stations with Easter Island.
IV-7	16,000	Mutel Array SEG-1: 10 stations with both Galapagos. and Easter Island.
IV-8	16,000	Array D2 + Argentina.
IV-9	16,000	Array D2 + Argentina and Quito.
IV-10	16,000	Array of Fig. II-4 + Argentina and Quito.
IV-11	16,000	Array D2 + Itapatinga, Brazil.
Section V:		Array D2 plus other sites.
V-1	10,000	Mexico City.
V-2	10,000	Acapulco.
V-3	10,000	Edmonton, Alberta.
V-4	10,000	Newfoundland.
V-5	10,000	Yellowknife, Northwest Territories.
V-6	10,000	Penticton, British Columbia.
V-7	10,000	Algonquin Radio Observatory, Ontario.
V-8	10,000	Newfoundland, Algonquin, Yellowknife, and Penticton.
V-9	16,000	Bologna, Italy (Similar to any European station).
V-10	16,000	Bonn, West Germany.
V-11	16,000	Jodrell Bank, England.
V-12	16,000	South Africa.
V-13	16,000	Tokyo, Japan.
V-14	16,000	Tidbinbilla, Australia.
V-15	10,000	The proposed Canadian Long Baseline Array.
V-16	2,000	Center portion V-16.
Section VI:		VLA plus other sites.
VI-1	50	9 elements of VLA — every third element.
VI-2	200	VLA (9 elt) + Socorro
VI-3	2,000	VLA (5 elt) + Array D2

TABLE 3

Station Locations

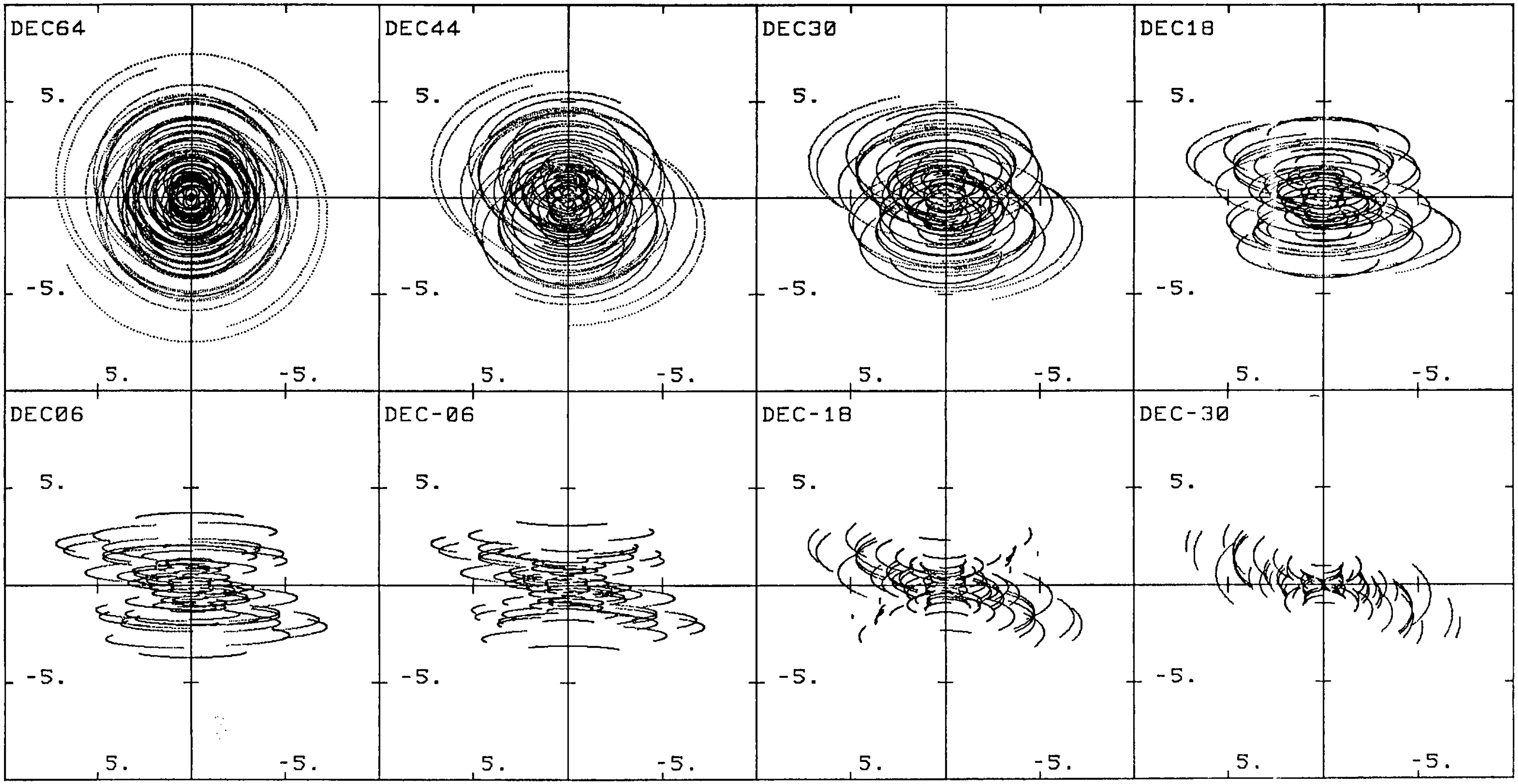
Abbr.	Station	Latitude	Longitude
AE3	VLA station AE3	34.0667	107.5861
AE6	" " AE6	34.0389	107.5167
AE9	" " AE9	34.0000	107.4083
AN3	" " AN3	34.1056	107.6222
AN6	" " AN6	34.1583	107.624
AN9	" " AN9	34.2444	107.633
AW3	" " AW3	34.0639	107.6444
AW6	" " AW6	34.0278	107.7083
AW9	" " AW9	33.9722	107.8083
ACAPUL	Acapulco, Mexico	17.5	100.0
ANCH	Anchorage, Alaska	61.	150.
ARECIBO	Arecibo Observatory, Puerto Rico	18.3435	66.7533
ARGENT	Observatory, Western Argentina	-32.	69.
ARO	* Algonquin Radio Observatory, Ont.	45.95	78.07
ATIK	* Atikokan, Ontario	48.94	91.80
BANGOR	Bangor, Maine	44.8	68.8
BGNA	Bologna, Italy	44.5	-11.3
BISMARCK	Bismark, North Dakota	46.8	100.8
BLDR	Boulder, Colorado	40.0036	105.2617
BOIS	Boise, Idaho	43.6	116.2
BONN	100 m telescope, Bonn, West Germany	50.3360	-6.88444
BRVL2	Brownsville, Texas (slightly inland)	26.2	98.0
CAPECAN	Cape Canaveral, Florida	28.5	80.5
CHURCH	Churchill, Manitoba	58.9	94.0
CLARK	Clark Lake Observatory, California	33.3	116.2
COME	* Come By Chance, Newfoundland	47.36	54.76
DALLAS	Dallas, Texas	32.6	96.6
DSS14	Goldstone DSN Station, California	35.2444	116.8895
DSS43	Tidbinbilla DSN Station, Australia	-35.2210	211.0187
DWINGELOO	Dwingeloo Observatory, Netherlands	52.6276	-6.3967
EASTER	Easter Island, Pacific Ocean (Chile)	-27.	110.
EDMT	Edmonton, Alberta	54.5	114.0
FDVS	Fort Davis, Texas (HRAS)	30.4678	103.9472
GALAPA	Galapagos Islands, Equador	-1.0	92.0
GRFALL	Great Falls, Montana	47.5	111.3
GRFK2	Grand Forks, North Dakota	48.0	97.1
HAWAII	Near Mona Kea, Hawaii	19.8	155.5
HILO	Hilo, Hawaii	19.5	155.0

* Proposed Canadian Long Baseline Array Stations

TABLE 3 (cont)

Abbr.	Station	Latitude	Longitude
HSTK	Haystack Observatory, Massachusetts	42.4317	71.4881
HCRK	Hat Creek Observatory, California	40.6276	121.4733
IOWA	North Liberty Observatory, Iowa	41.5805	91.5745
ITA	Itapatinga Observatory, Brazil	-23.2	46.55
JODRELL	Jodrell Bank, England	53.0516	2.3066
JCKVLE	Jacksonville, Florida	30.0	81.8
KAUAI	Kauai, Hawaii	22.0	159.6
LASL	Los Alamos, New Mexico	35.9	106.4
LETH	* Lethbridge, Alberta	49.23	112.39
LRDO	Laredo, Texas	27.5	99.5
LVGS	Las Vegas, Nevada	36.2	115.2
LVNM	Las Vegas, New Mexico	35.6	105.2
MEXDF	Mexico City, Mexico	19.5	99.0
MICHNEW	Dexter, Mich. (U of Mich Rad Ast Obs)	42.3979	83.9350
NEWF	Newfoundland	48.	57.
MHAT	* Medicine Hat, Alberta	49.21	110.06
NPLAT	North Platte, Nebraska	41.3	101.
NRAO	Green Bank, West Virginia	38.2508	79.8358
NRL	Maryland Point, Maryland	38.3739	77.2333
OKLA	Oklahoma City, Oklahoma	35.2	97.5
OMAHA	Omaha, Nebraska	41.3	96.0
OVRO	Owens Valley Obs., California	37.0465	118.2824
ONSALA	Onsala Observatory, Sweden	57.2184	-11.92
PENT	* Penticton Obs., British Columbia	49.3	119.6
PUEBLO	Pueblo, Colorado	38.3	104.5
QUITO	Quito, Equador	-0.2	77.0
SAFR	Hartebeesthoek, South Africa	-25.7393	-27.4407
SALEM	Salem, Oregon	45.0	123.0
SASK	* Western Saskatchewan	49.20	109.05
SDGO	San Diego, California	33.0	117.0
SOCORRO	Socorro, New Mexico	34.1	106.9
SPKN	Spokane, Washington	47.7	117.4
TOKYO	Tokyo, Japan	36.0	-140.0
TOPEKA	Topeka, Kansas	39.0	95.7
TUSC	Tuscon, Arizona	32.7	111.0
TUSCNE	Near Tuscon, Arizona	32.5	110.5
VLA	VLA Site, New Mexico	34.079	107.618
VLASW	Southwest of VLA, New Mexico	33.4	108.3
WEYB	* Weyburn, Saskatchewan	48.94	91.8
YELKNF	* Yellowknife, Northwest Territories	62.7	114.5

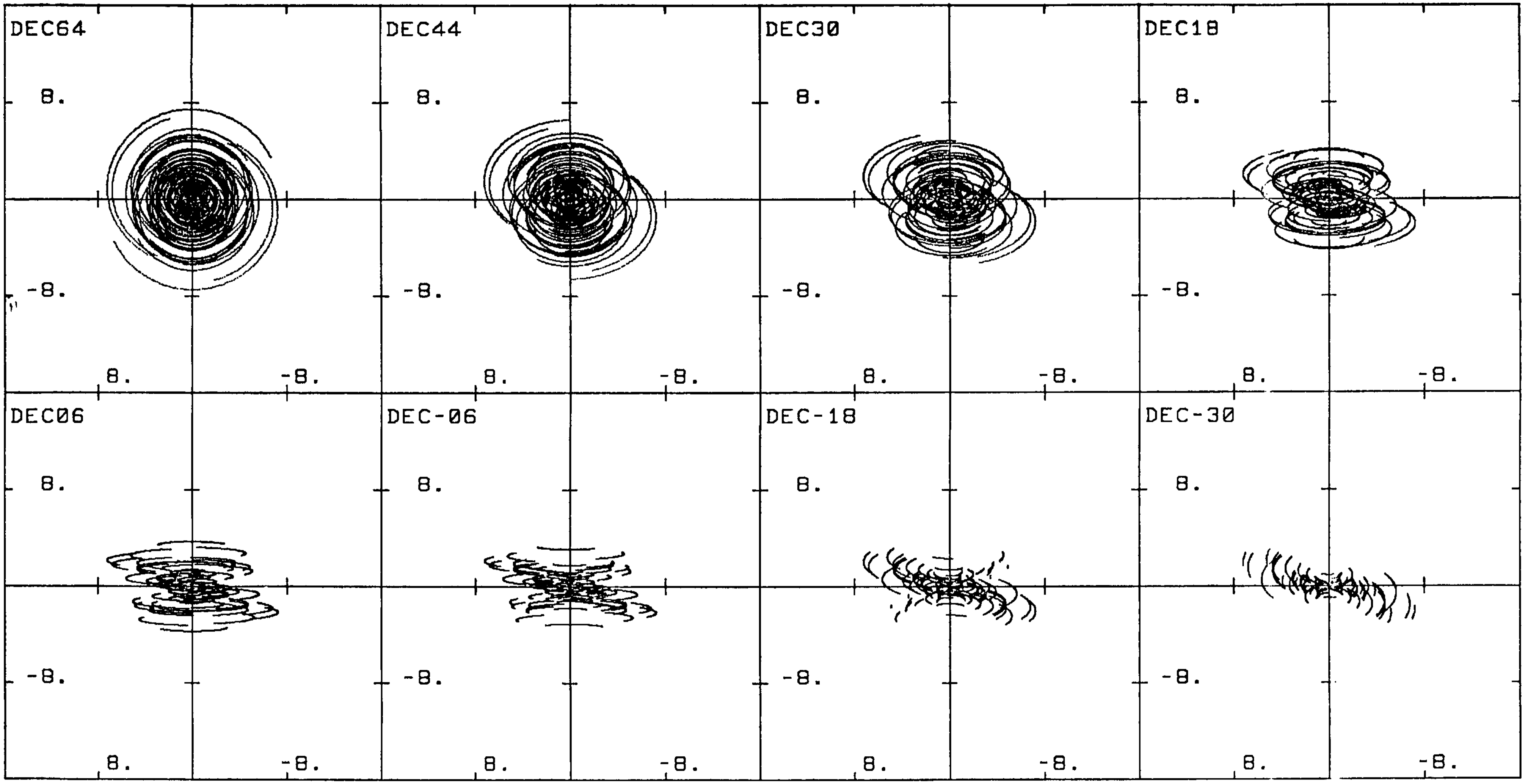
* Proposed Canadian Long Baseline Array Stations



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

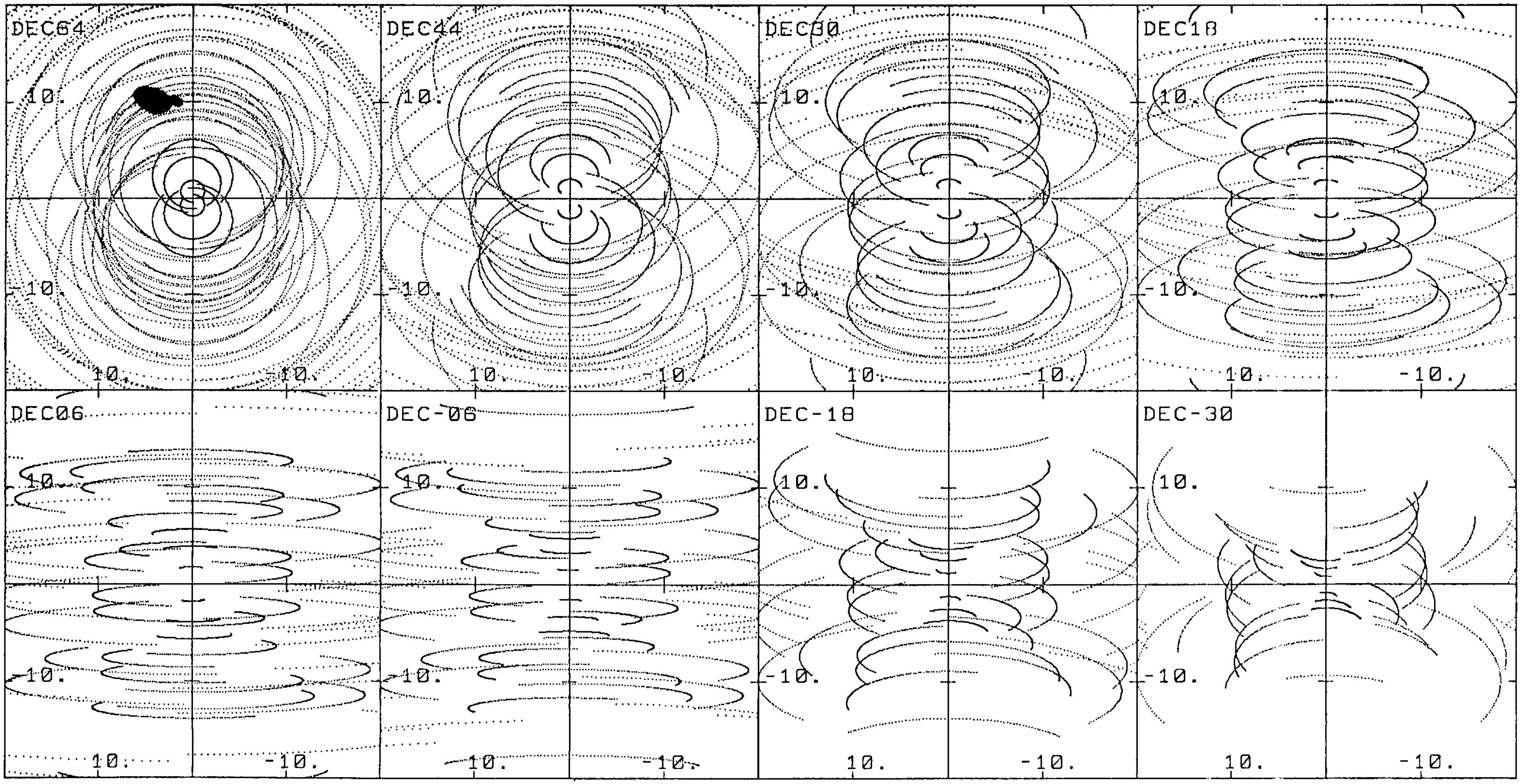
Figure I-1: Array D2 at the scale appropriate for plots of US arrays. The scale maximum is 10,000 km.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

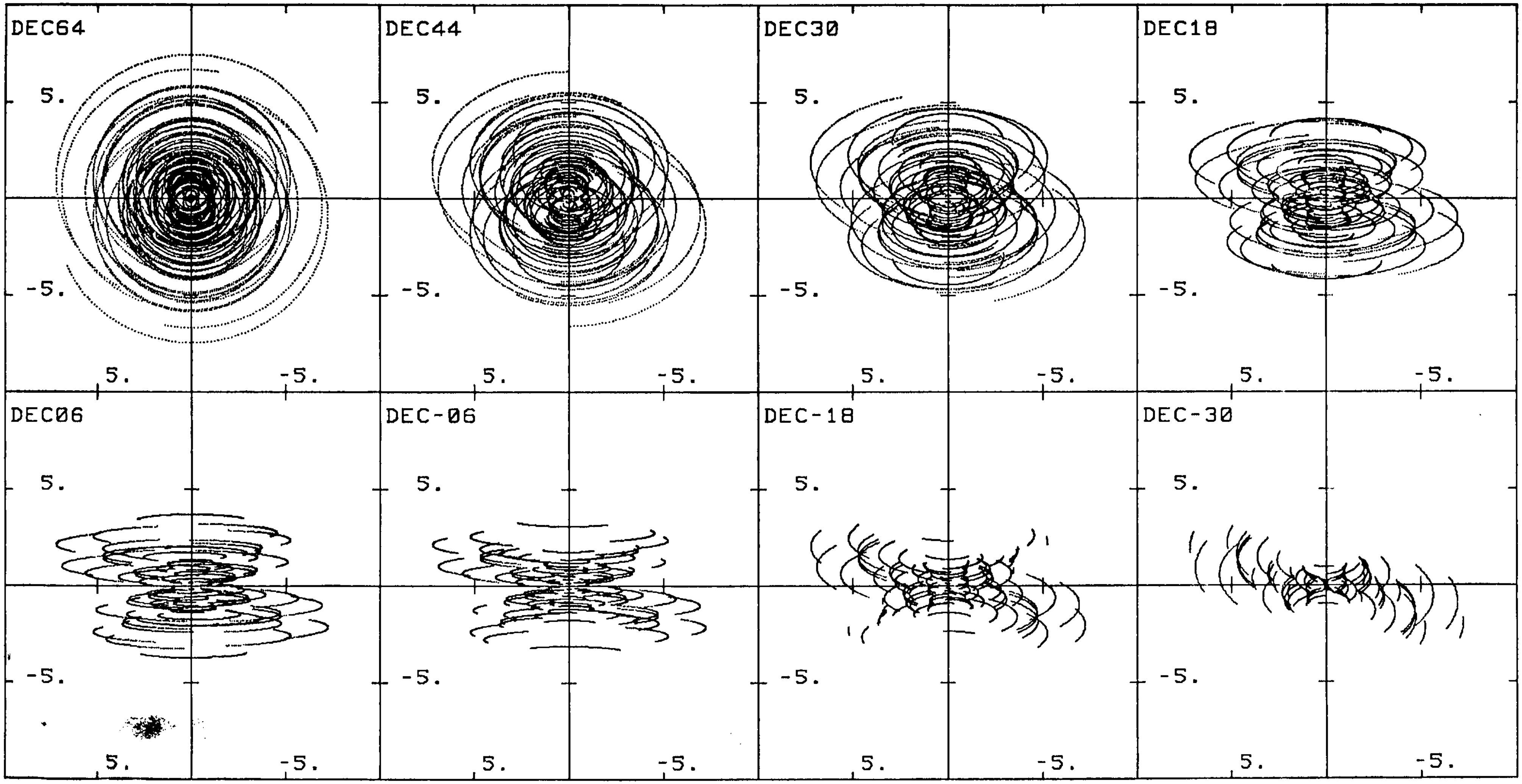
Figure I-2: Array D2 at the scale appropriate for plots of arrays that use the full size of the Earth. The scale maximum is 16,000 km.



Scale Maximum 2,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

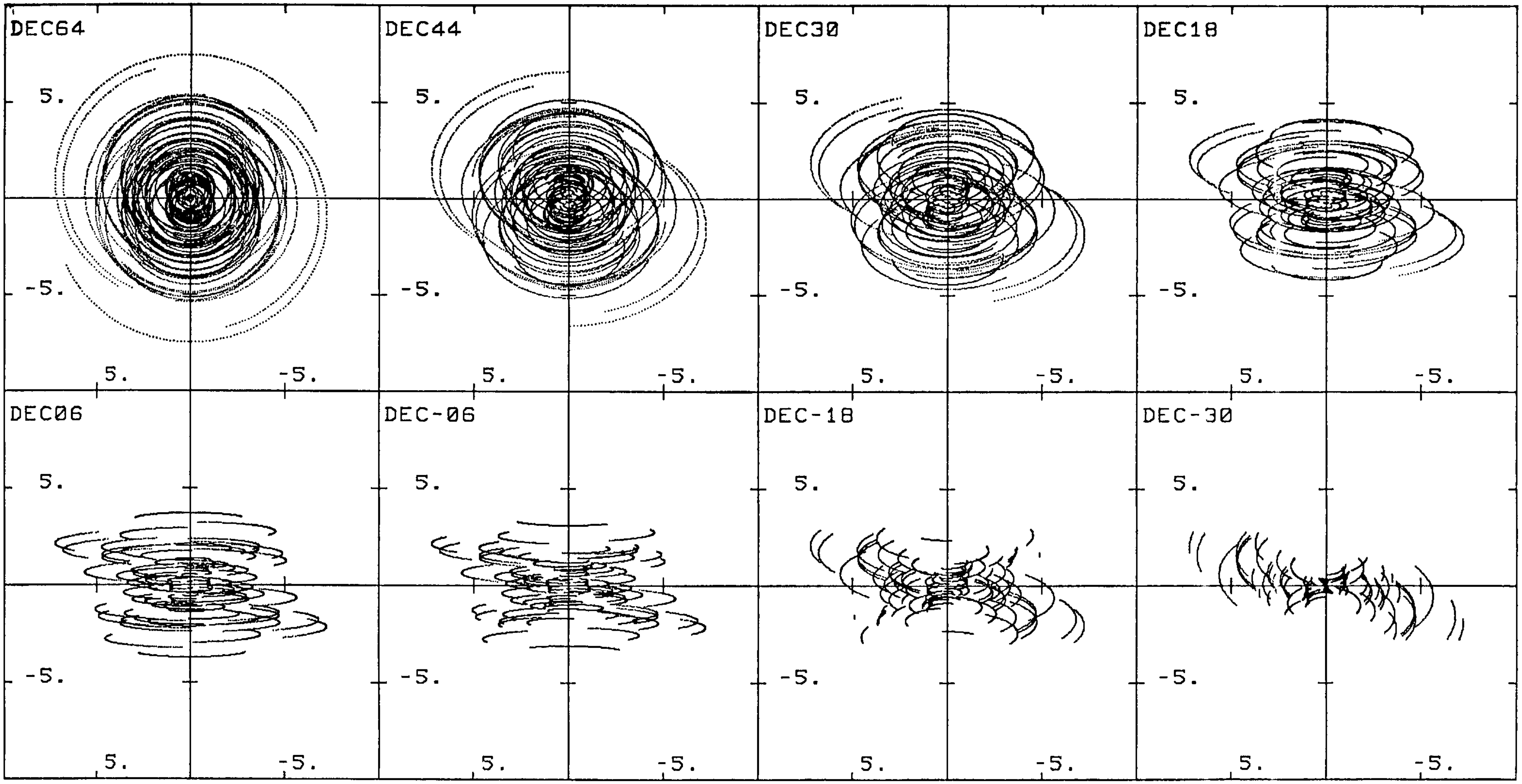
Figure I-3: Array D2 showing the coverage out to a maximum of 2000 km.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 JCKVLE HSTK BRVL2

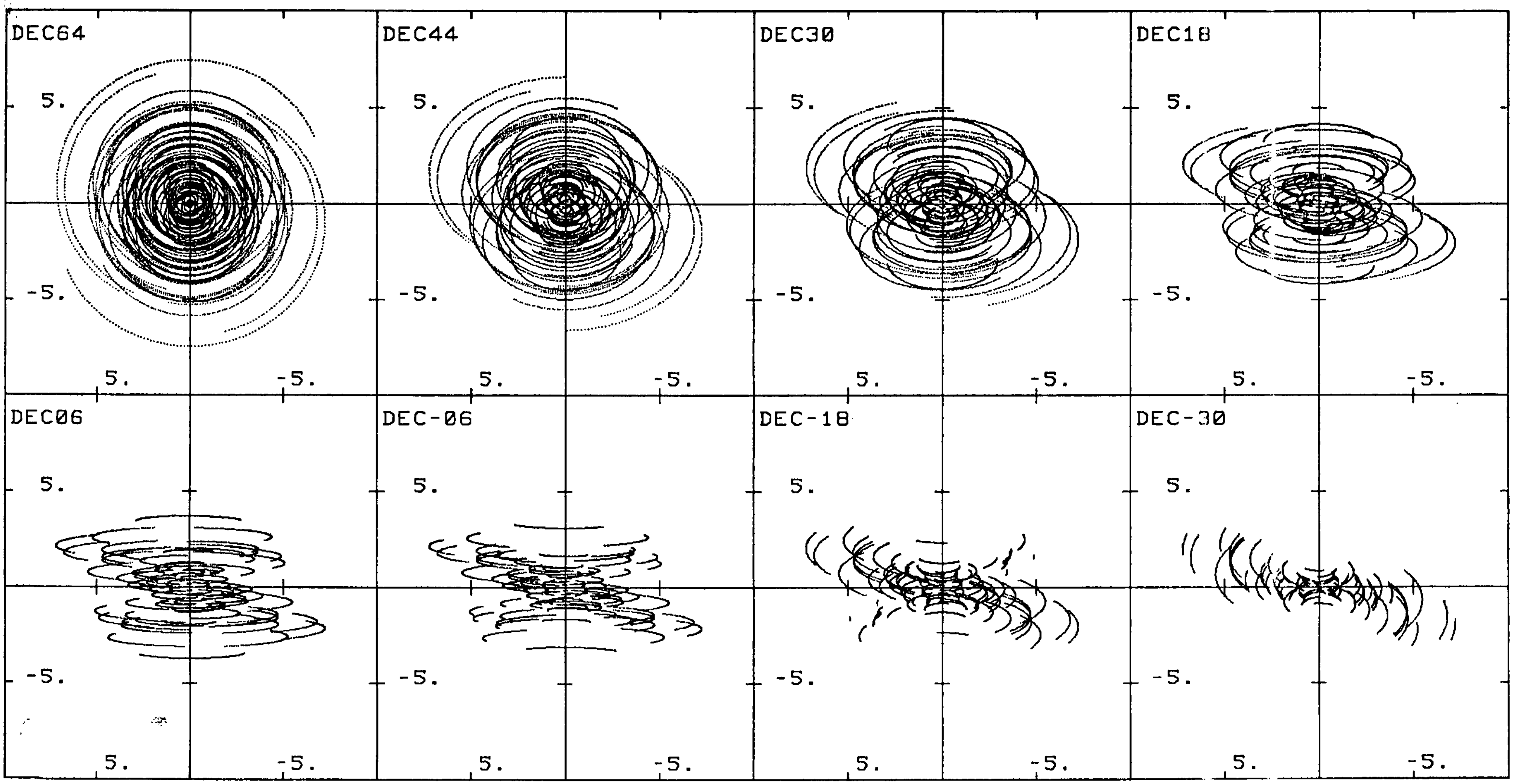
Figure I-4: Array D2 with the Green Bank, WV station moved to Jacksonville FL. This is a good alternative to Green Bank although the technical support available at Green Bank would be lost. However it may be useful not to use the sites of existing observatories so that they can be used as additions to the array.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR SPKN NRAO HSTK BRVL2

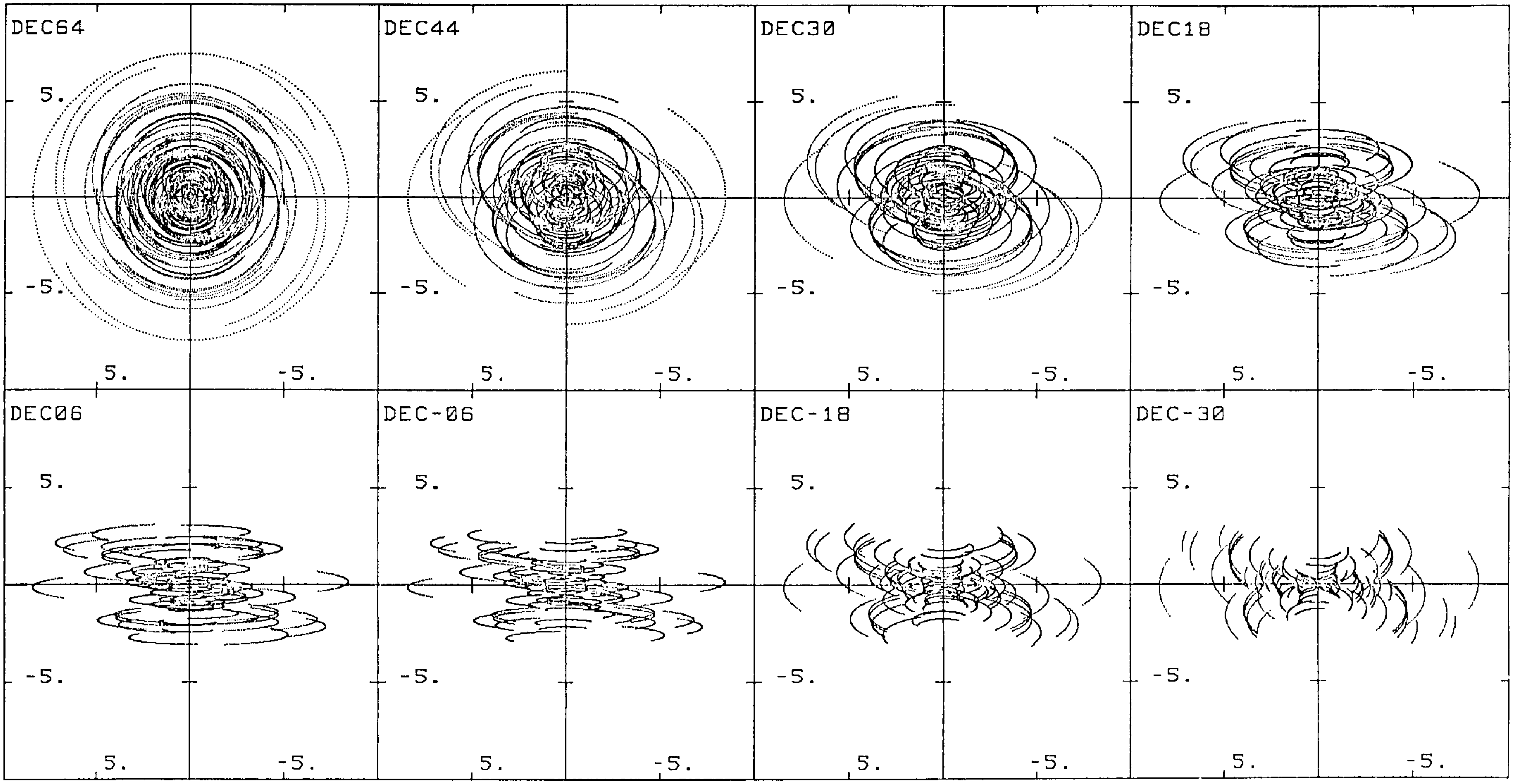
Figure I-5: Array D2 with the North Dakota station moved to Spokane, Washington. This move would be desirable for climatic and operational reasons but it produces holes in the coverage at the higher declinations. A northwest station can be used in arrays that include Puerto Rico as will be seen in later



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK LRDO

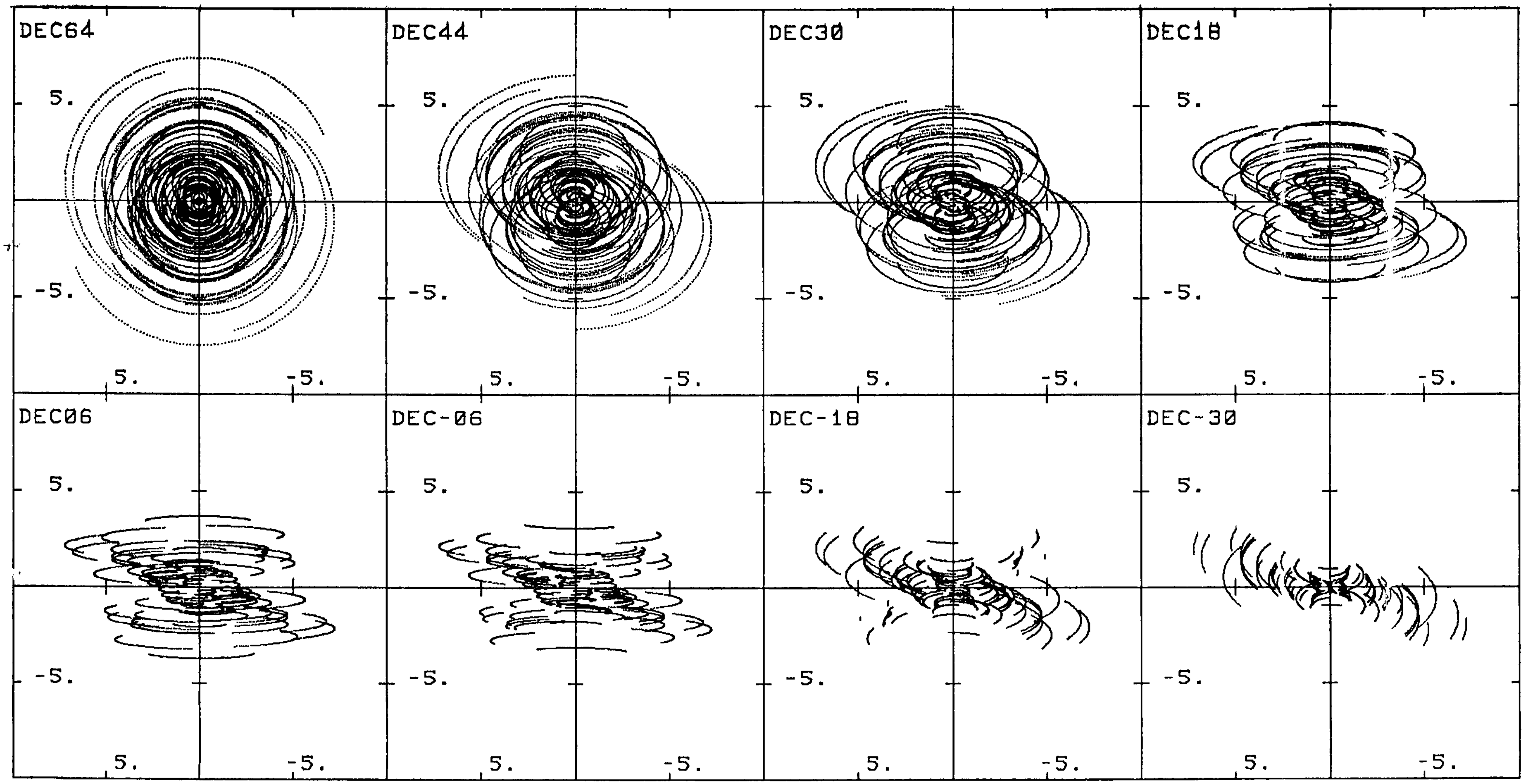
Figure I-6: Array D2 with the Brownsville, Texas station moved inland and north to Laredo, Texas. This causes a small reduction in the maximum north-south baselines at the lowest declinations but may be worthwhile for climatic reasons.



Scale Maximum 10,000 km.

HAWAII ARECIBO OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

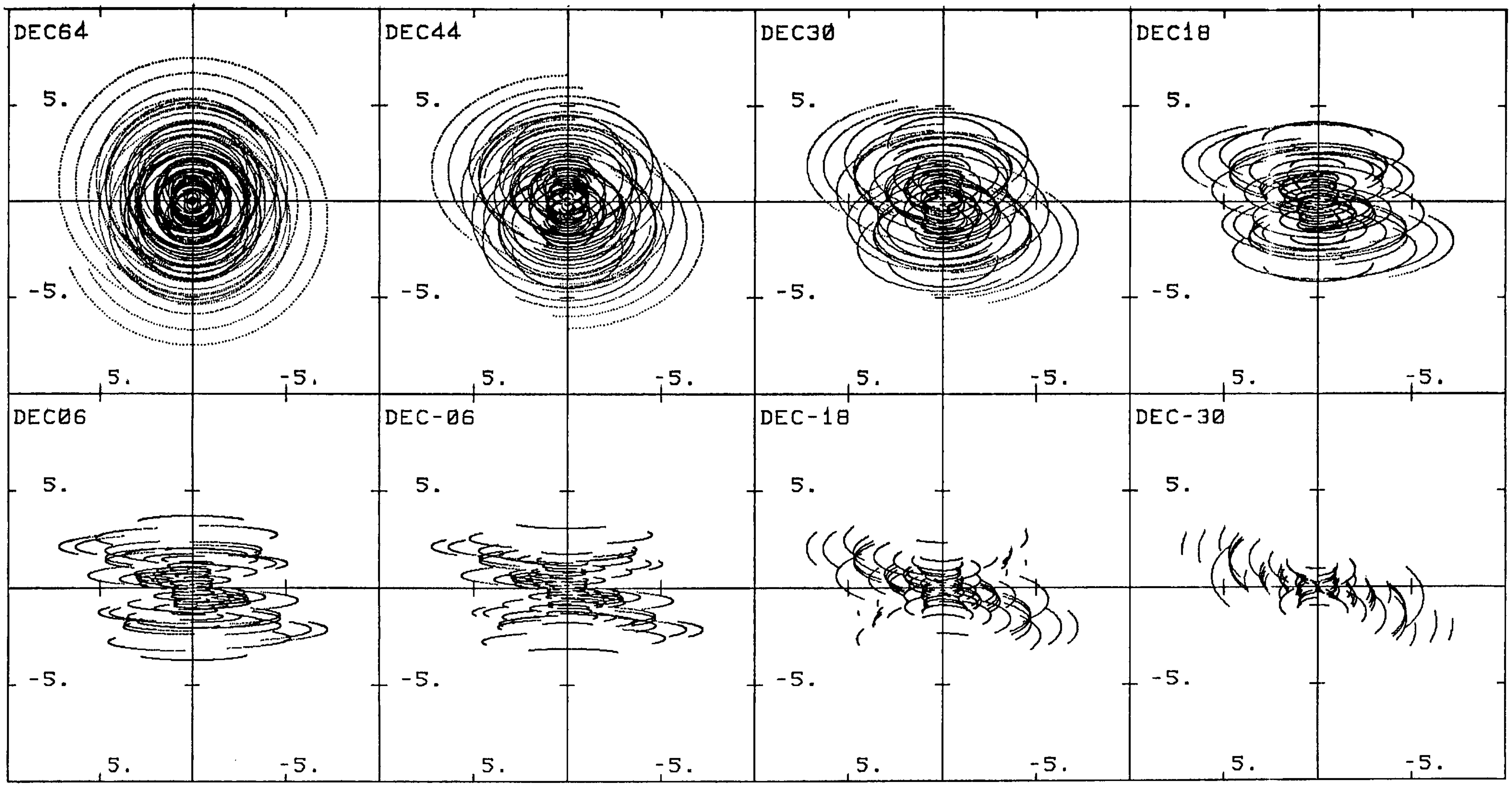
Figure I-7: Array D2 except that the Anchorage station is replaced with Arecibo. The maximum north-south spacing is shorter than with Anchorage but, at the lowest declinations, the effect is reduced because of projection effects. The maximum east-west baseline is a bit longer and Arecibo can see stations far to the south and has a milder climate than Alaska so such an array has advantages and should be considered. As will become apparent later in the discussion of South American stations, an array that includes a site in Puerto Rico is much better than Array D2 when used with stations to the south. The large holes in the coverage shown here show that if a Puerto Rico site is used, several of the other sites must also be moved to obtain good, uniform coverage.



Scale Maximum 10,000 km.

HAWAII ANCH CLARK SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

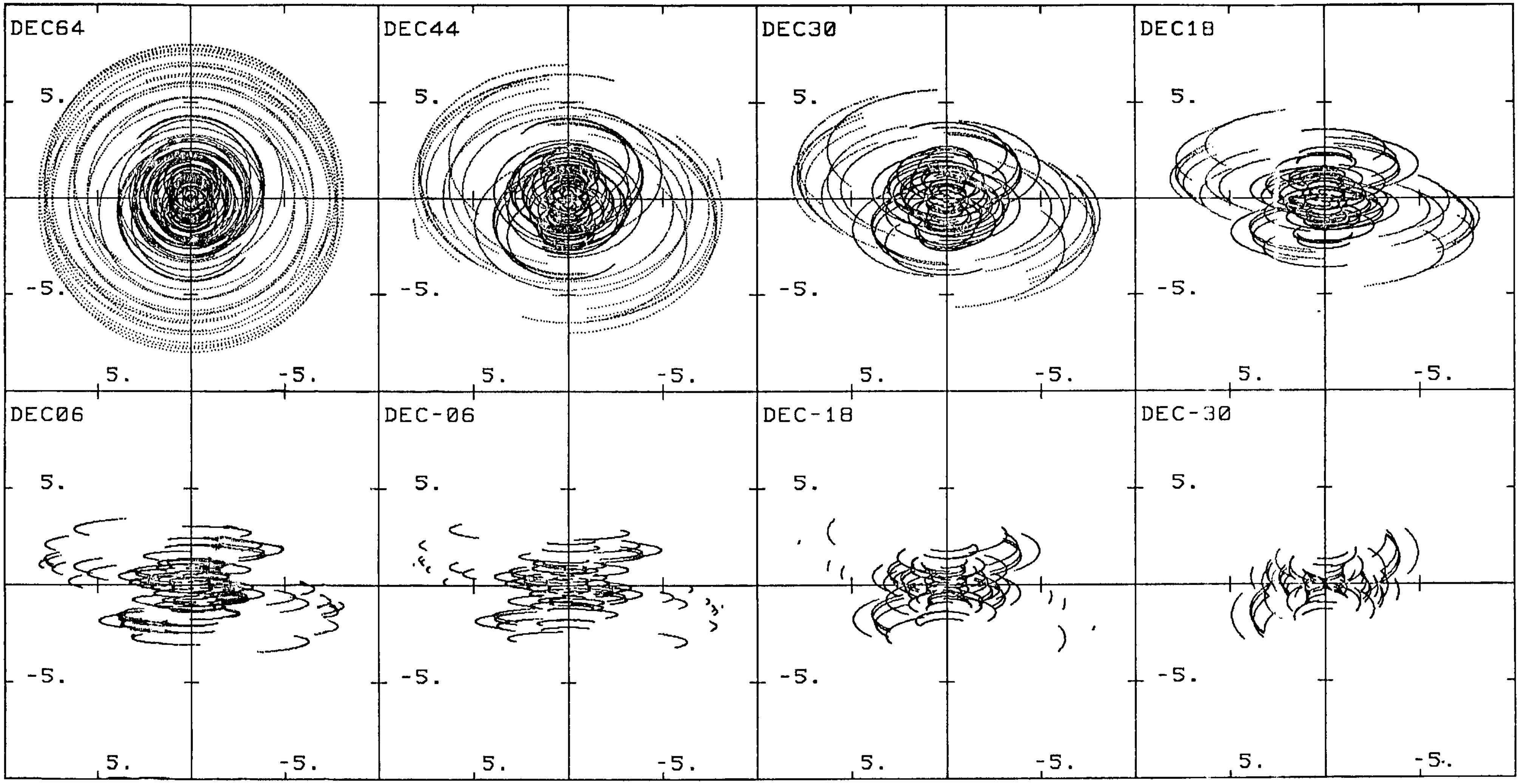
Figure I-8: Array D2 with the OVRO antenna moved to Clark Lake in Southern California. This move opens up some small holes at all declinations. It is likely that if a Southern California site were desired, a good array could be found with one, but more than just the OVRO site must be changed. Clark Lake has existing radio astronomy facilities but is at a very low elevation. Other Southern California sites would probably offer a better environment and greater accessibility.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 MICHNEW HSTK BRVL2

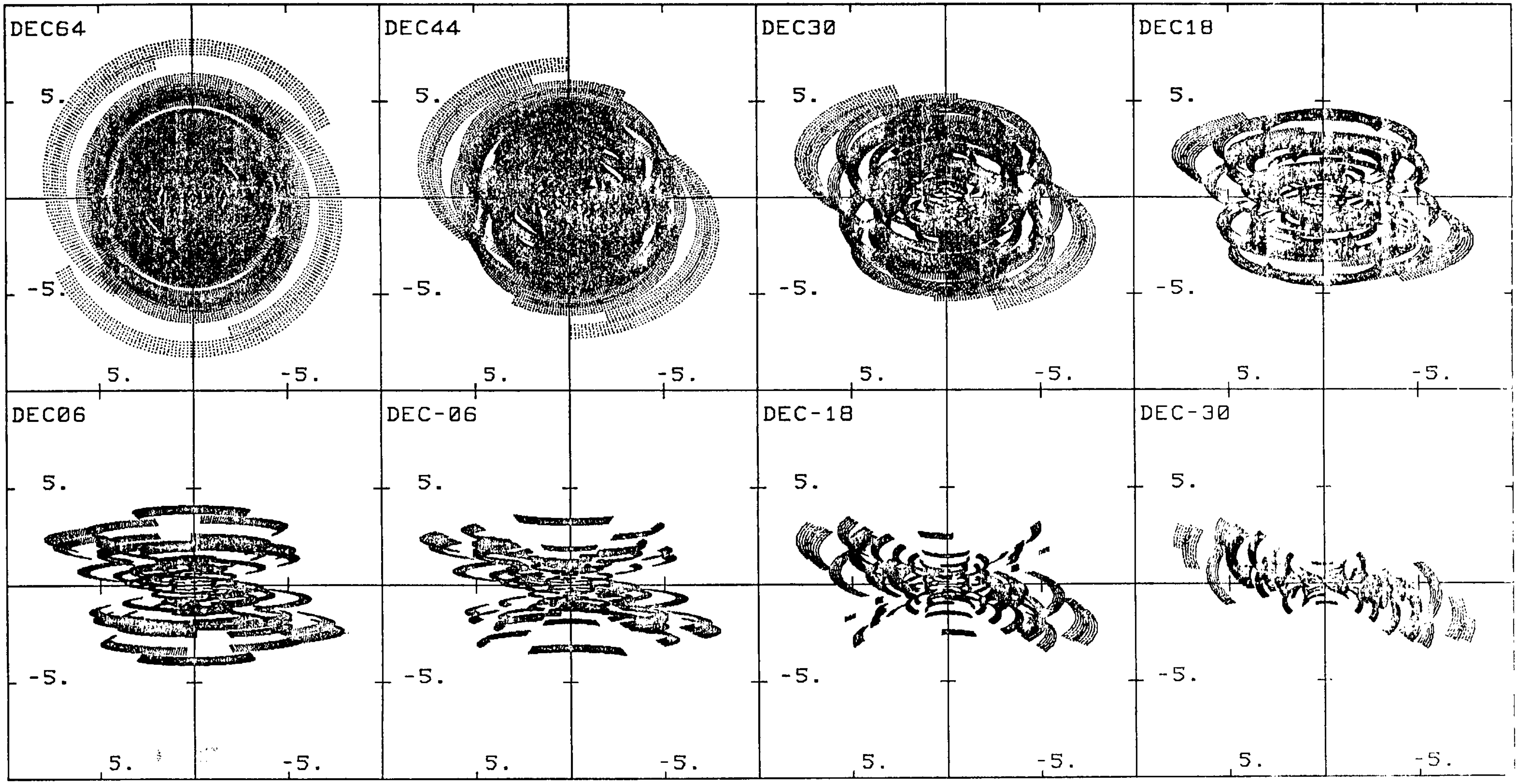
Figure I-9: Array D2 with the Green Bank antenna moved to the University of Michigan Radio Astronomy Obs. site. This move most seriously affects the high declination coverage. As does Figure I-8, this figure demonstrates that if one station of a good array is moved, others must also be moved in order to maintain good coverage.



Scale Maximum 10,000 km.

BONN ARECIBO OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

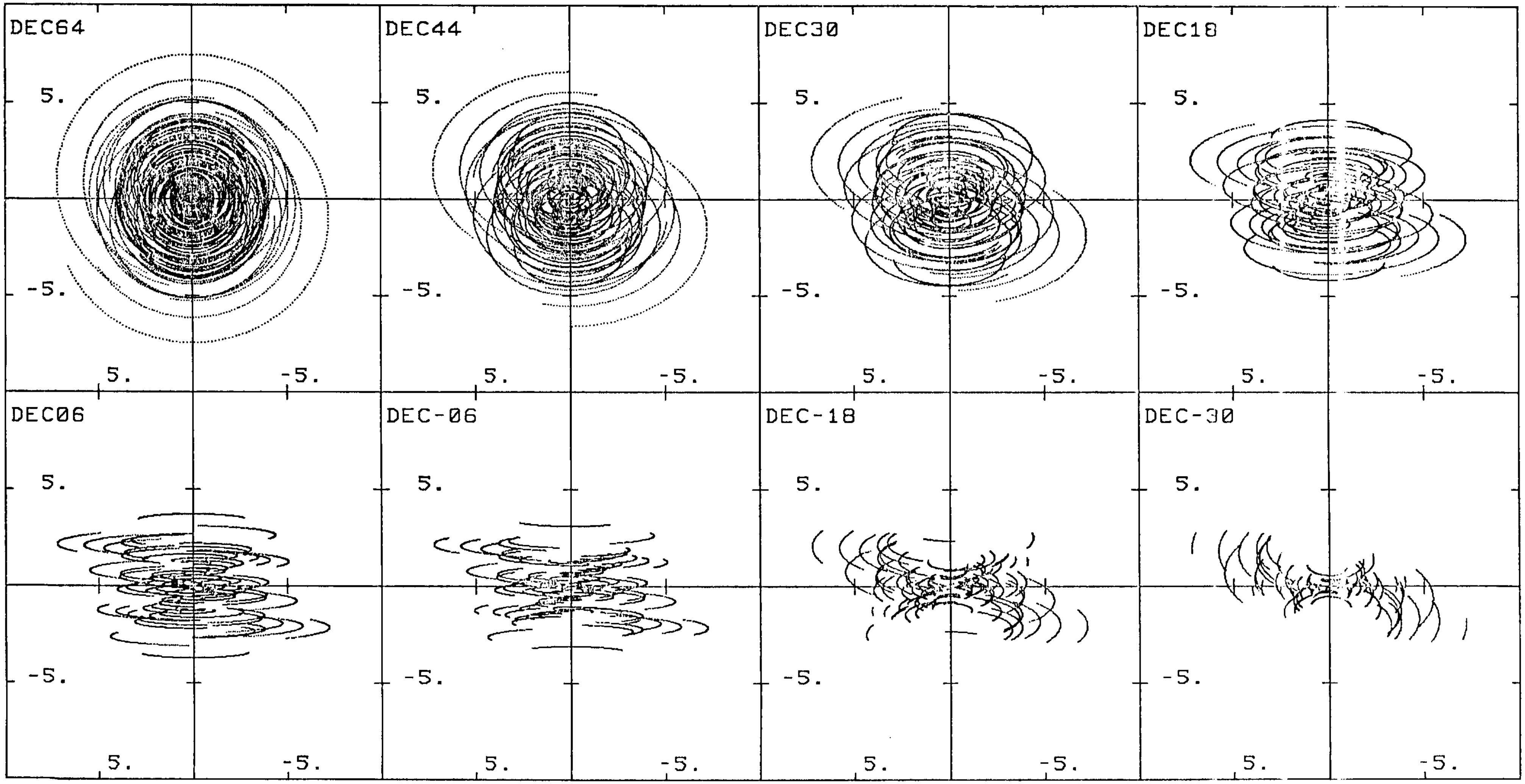
Figure I-10: Array D2 with the long baselines toward the east rather than the west. Hawaii and Anchorage have been replaced by Arecibo and Bonn. Such a configuration has the advantage that there are several active VLBI observatories in Europe so there would be much local support. However there are significant dissadvantages, mostly because of the high latitude of Europe, that make the long baselines to Hawaii much more attractive. The baselines to Europe are similar in length to those to Hawaii so the resolution is similar at high declinations, but the change in longitude is much higher. Therefore, not only does Europe not see nearly as far south as Hawaii, but the time of mutual visibility for low declination sources is much lower. This leads to the very short u-v tracks seen at declinations of 18 degrees and lower. These short tracks are one of the big problems faced in current VLBI work.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

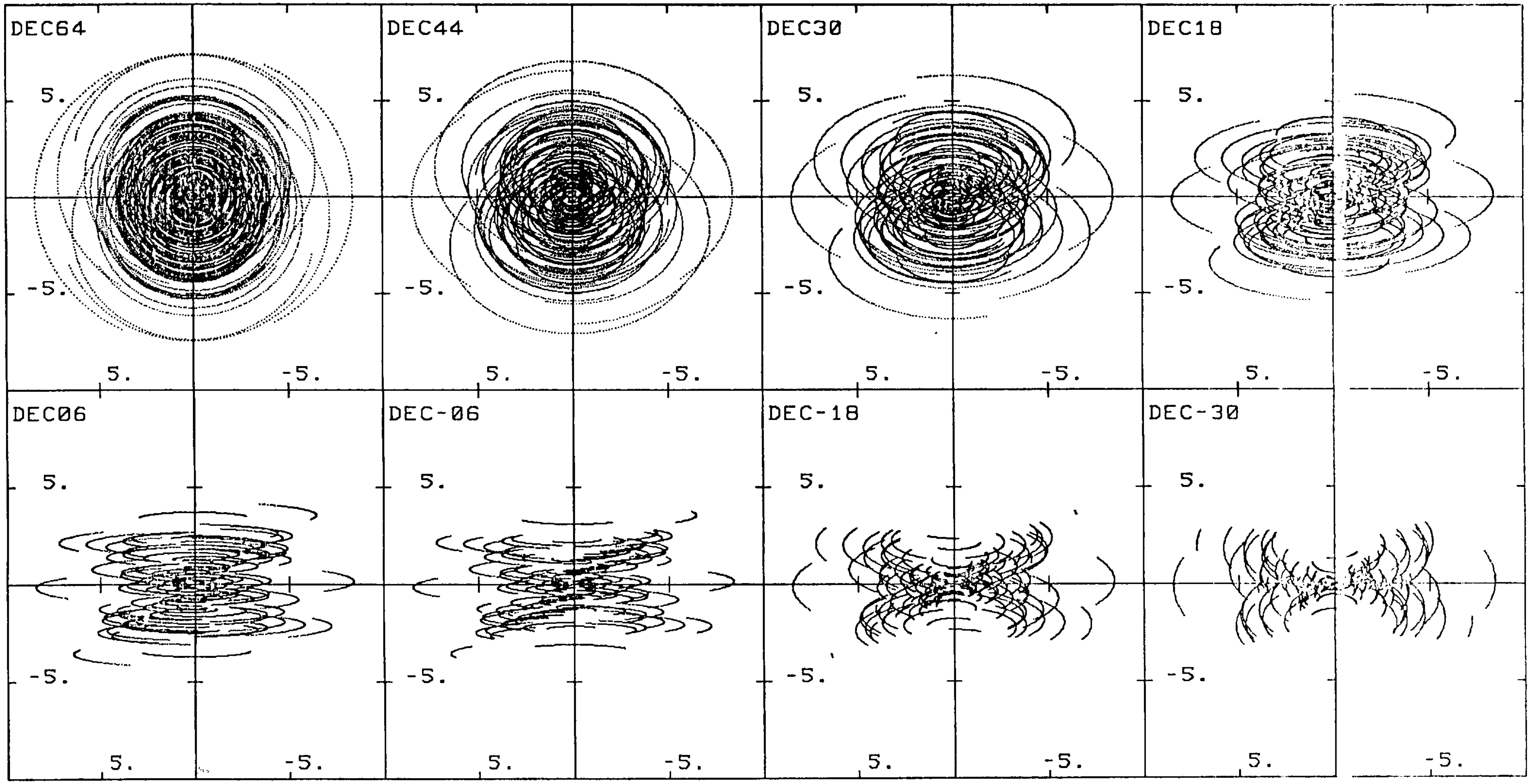
Figure I-11: Array D2 showing the u-v coverage that could be obtained if several frequencies spaced over 10 precent of the observing frequency were used. The increase in u-v coverage is very interesting but there will be serious complications in dealing with sources whose spectral index varies with position. Also the technique cannot be used on spectral line sources.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SALEM BOIS BLDR DSS14 IOWA HSTK LRDO

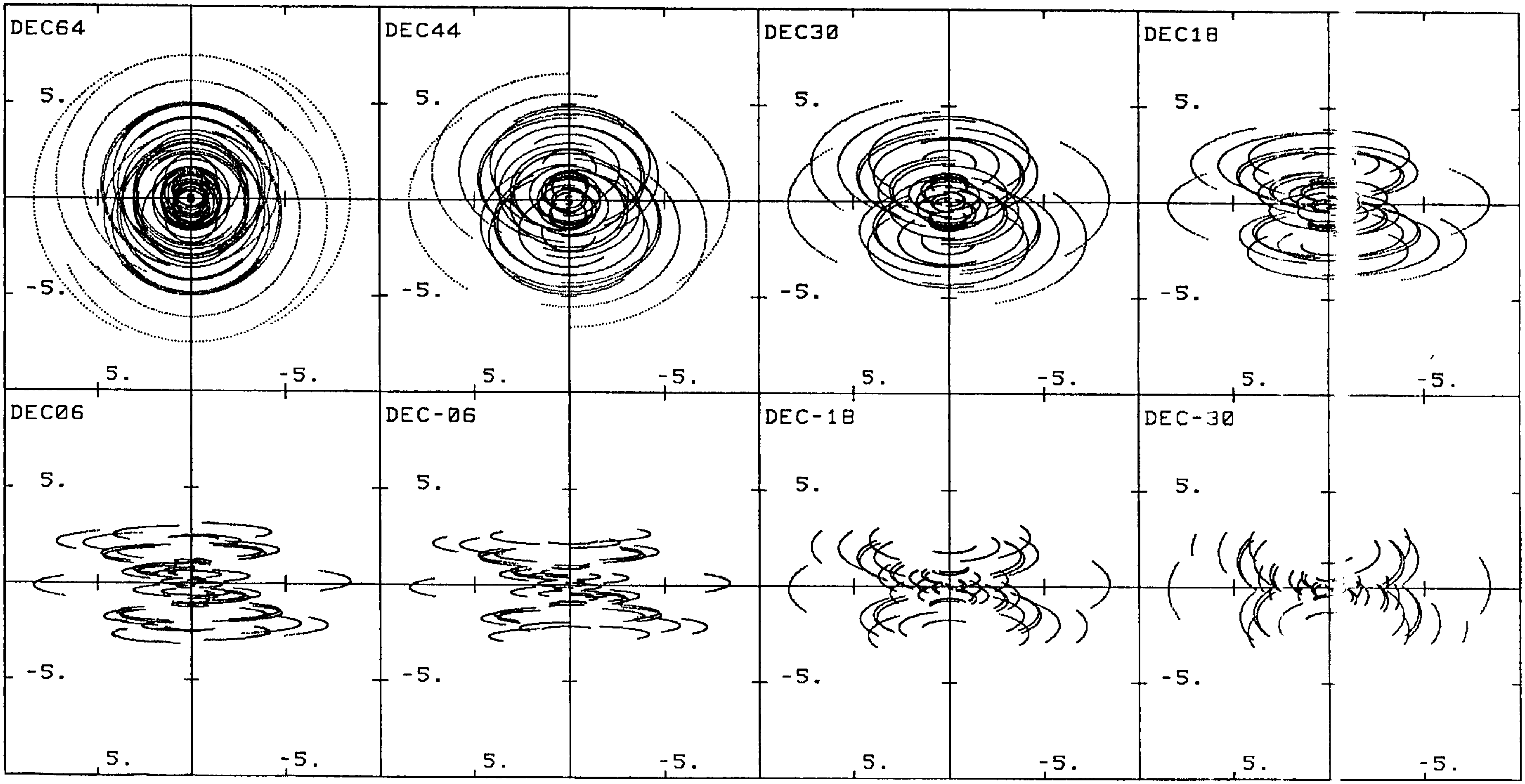
Figure II-1: Array 13 from the Caltech design study (Cohen 1980). This was the best of the arrays found in the early VLBA design effort. It was derived under the constraint that the short baselines are in California rather than near the VLA. In performance, it is similar to Array D2, but it does not interact well with the VLA so it will not be seriously considered.



Scale Maximum 10,000 km.

SOCORRO ARECIBO HAWAII ANCH OVRO SALEM BOIS BLDR DSS14 IOWA HSTK LRDO

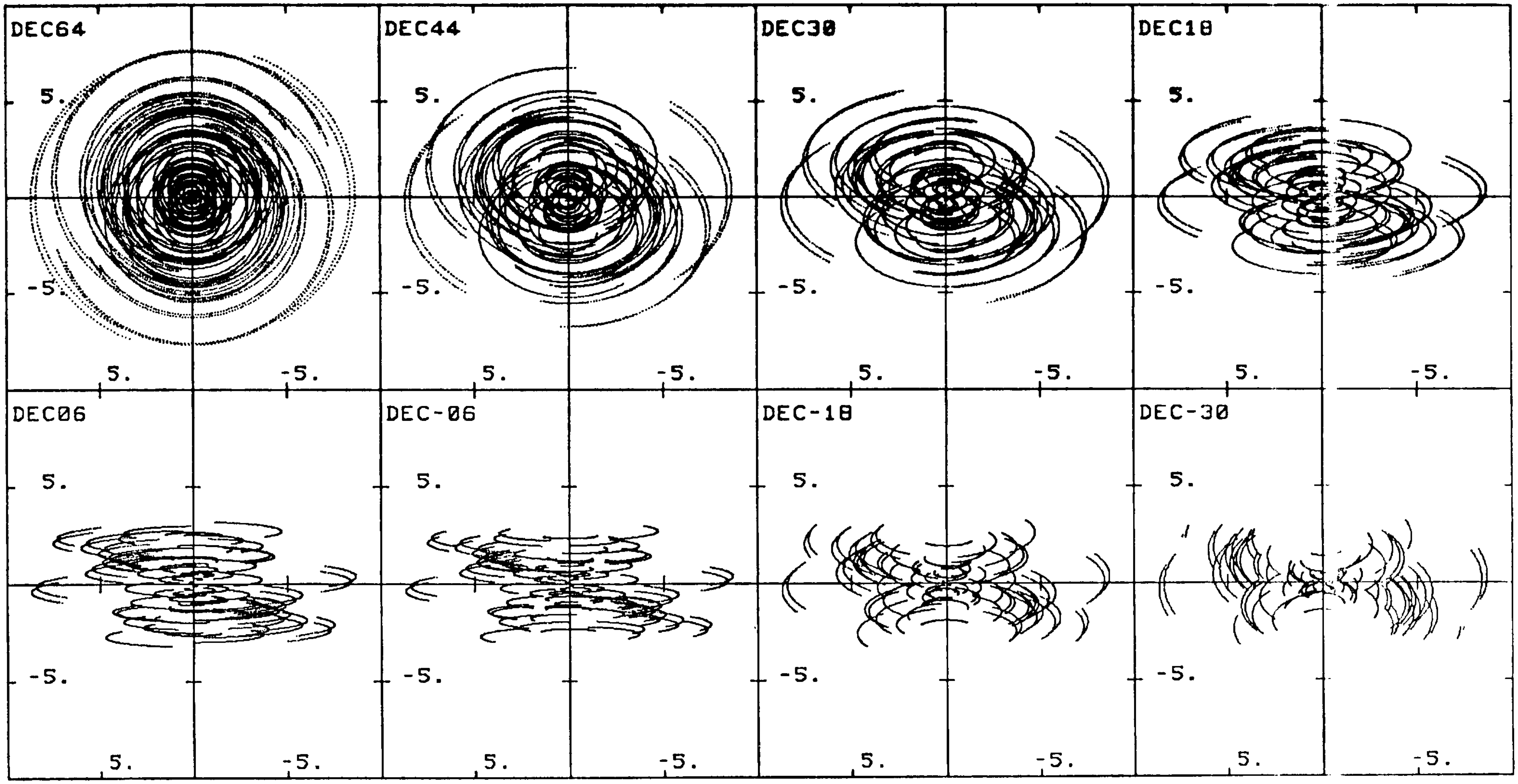
Figure II-2: Array 13 plus Arecibo, Puerto Rico and Socorro, New Mexico. This is a reasonably good 12 array based on Array 13 but with some of the lack of interaction with the VLA corrected by adding a station in Socorro and with improved long spacing coverage obtained with the addition of Arecibo. Comparison with Array 13 shows dramatically the advantage of having Puerto Rico for low declinations.



Scale Maximum 10,000 km.

ARECIBO HAWAII GRFALL HSTK SOCORRO IOWA LVGS LVNM

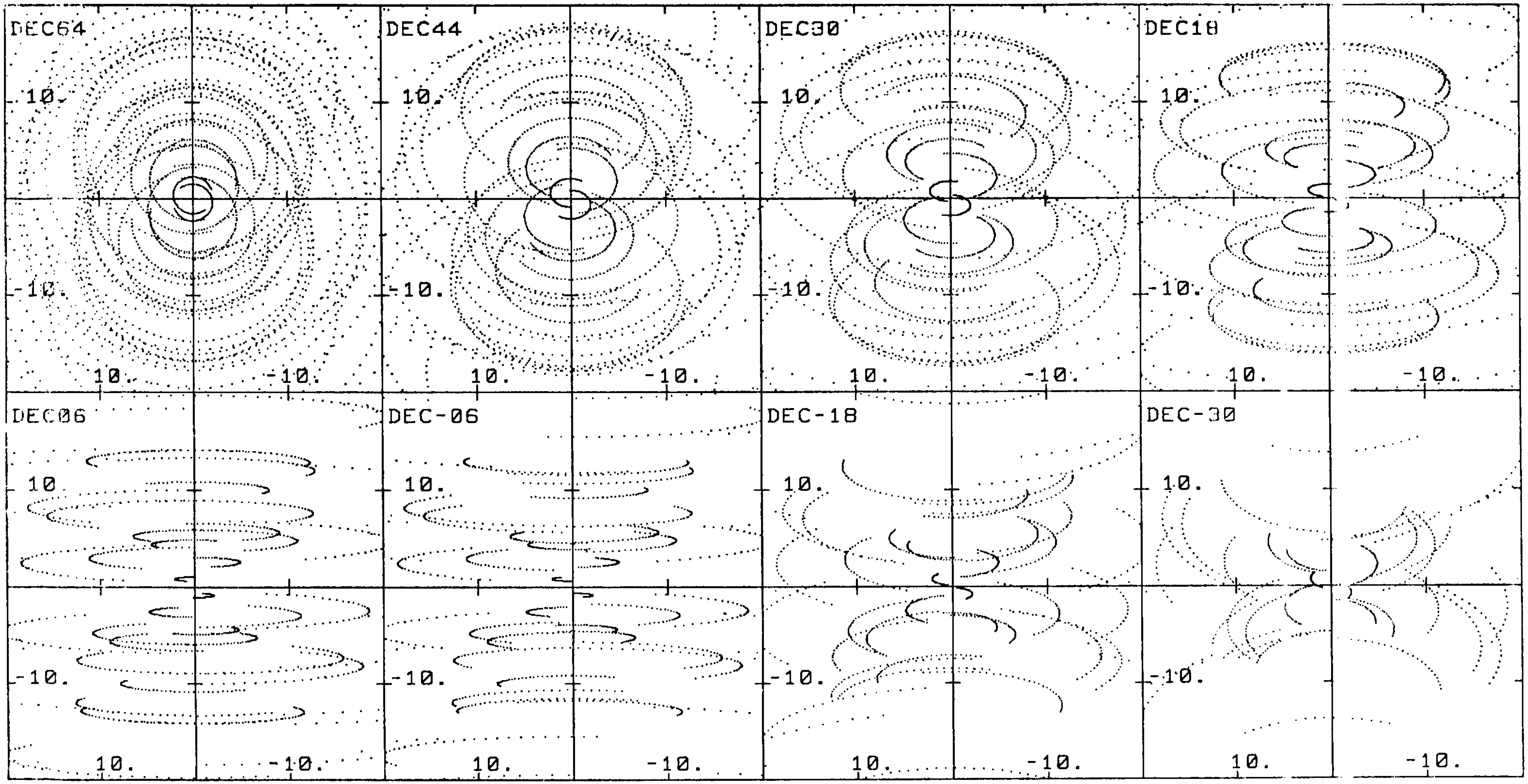
Figure II-3: A good 8 station array derived under the constraints applied to the other arrays. Note the sparse and non-uniform coverage. With the wide range of spacings desired, some stations must be close together so it is not possible to get good uniform coverage with this few sites.



Scale Maximum 10,000 km.

KAUAI HILO SPKN TUSCNE VLASW LRDO IOWA BANGOR ARECIBO PUEBLO

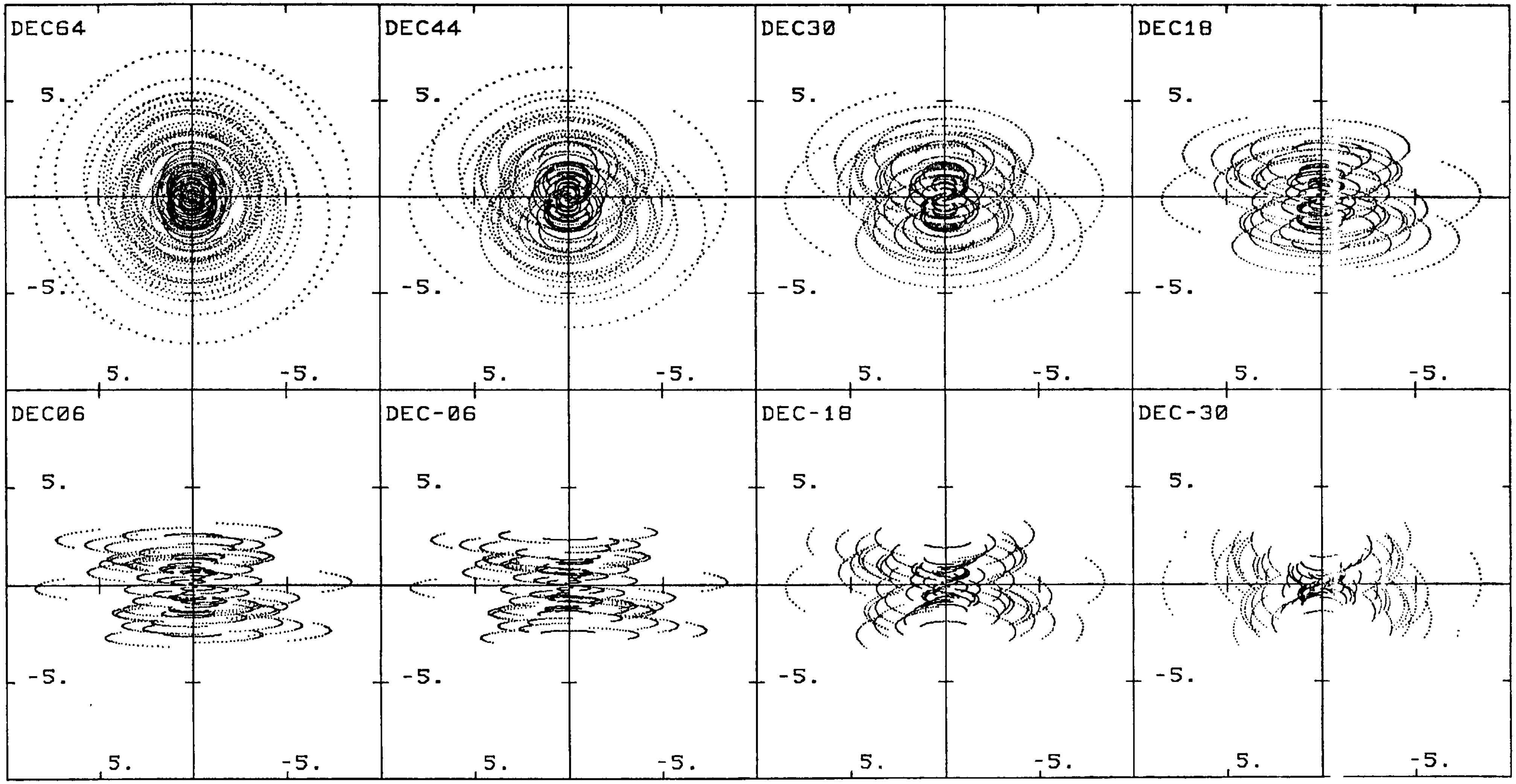
Figure II-4: A ten station array that has two sites in Hawaii. This is a reasonably good 10 station array that is very different from Array D2 and Array 13 but that has similar, although not quite as good, performance. It shows a possible configuration using Puerto Rico and shows what might be done if it were decided that isolated stations (a long way from other stations) are poor for calibration reasons. This is not considered a problem using current techniques.



Scale Maximum 2,000 km.

KAUAI HILO SPKN TUSCNE VLASW LRDO IOWA BANGOR ARECIBO PUEBLO

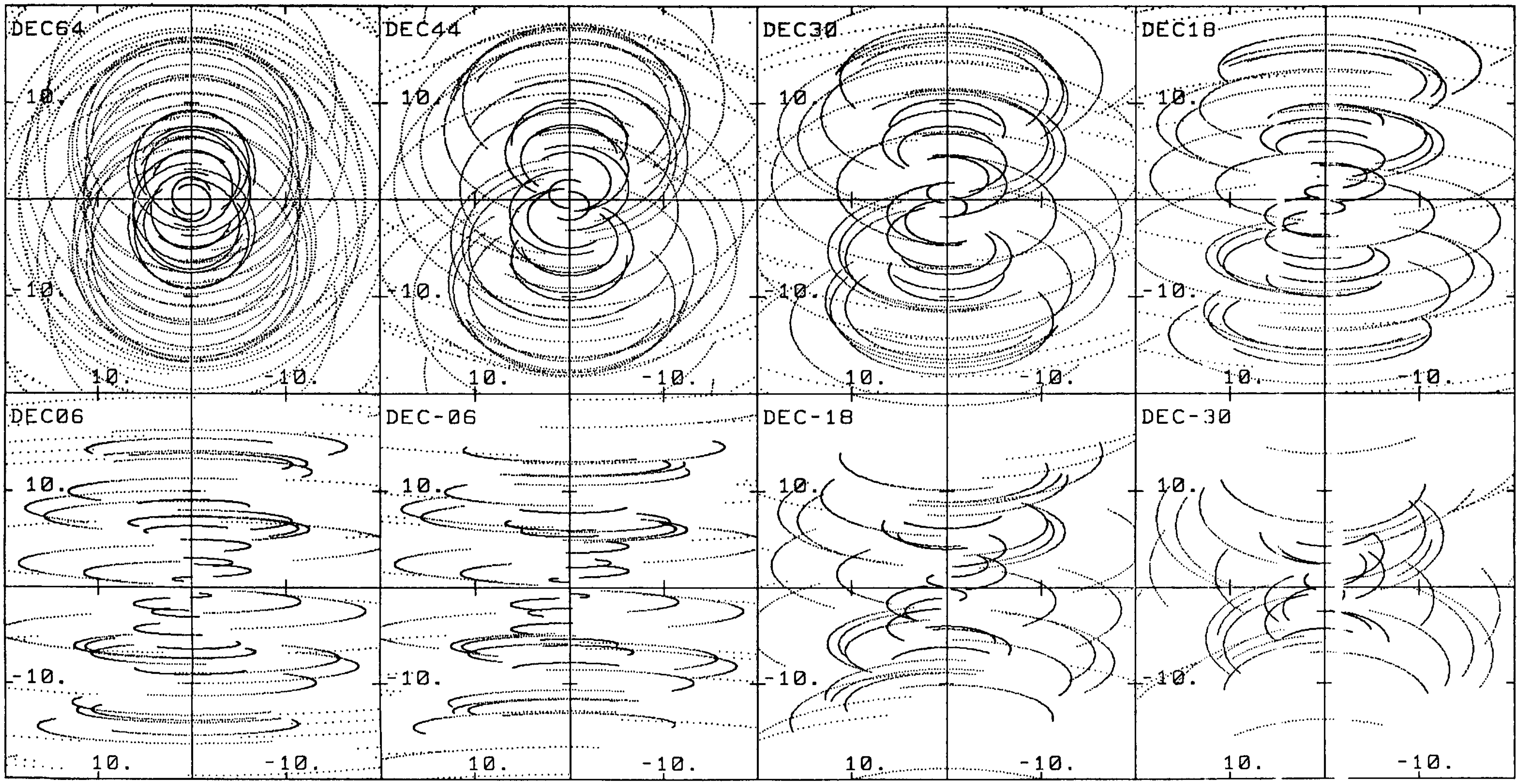
Figure II-5: The inner 2000 km of the array of Figure II-4. With the large scale plots, it is easy to miss poor aspects of the coverage at short spacings. As can be seen here, this array has reasonably uniform coverage at the shorter spacings.



Scale Maximum 10,000 km.

HAWAII ARECIBO SPKN BANGOR BRVL2 VLASW IOWA TUSCNE FDVSNEW BLDR

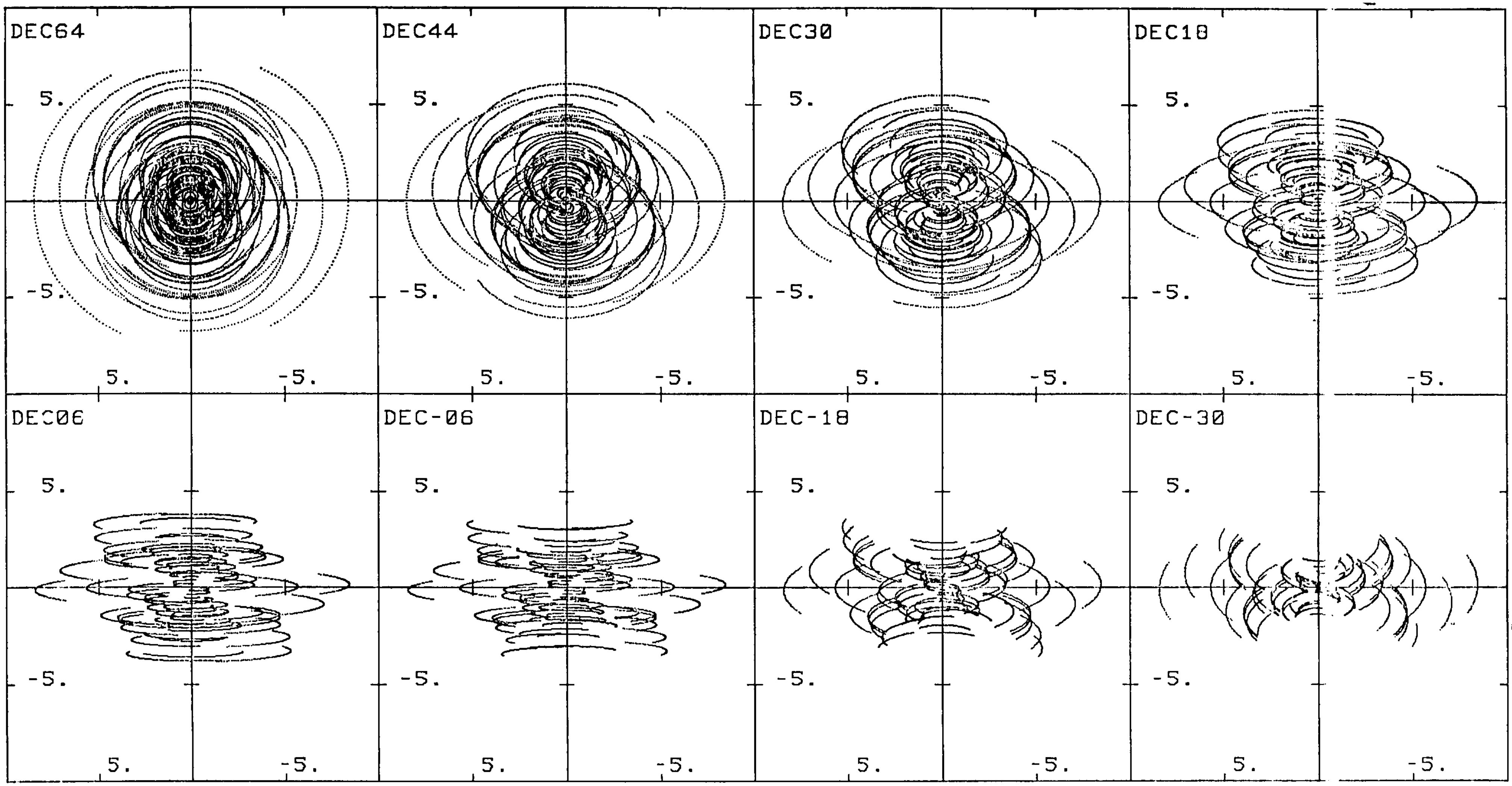
Figure II-6: A strongly centrally condensed ten-station array. This is a configuration that sacrafices some coverage at the longer spacings in order to improve the short spacing performance. This may be desirable in order to map sources over a wide range of scale sizes. This configuration shows what can be done bu it is not highly optimized.



Scale Maximum 2,000 km.

HAWAII ARECIBO SPKN BANGOR BRVL2 VLASW IOWA TUSCNE FDVSNEW BLDR

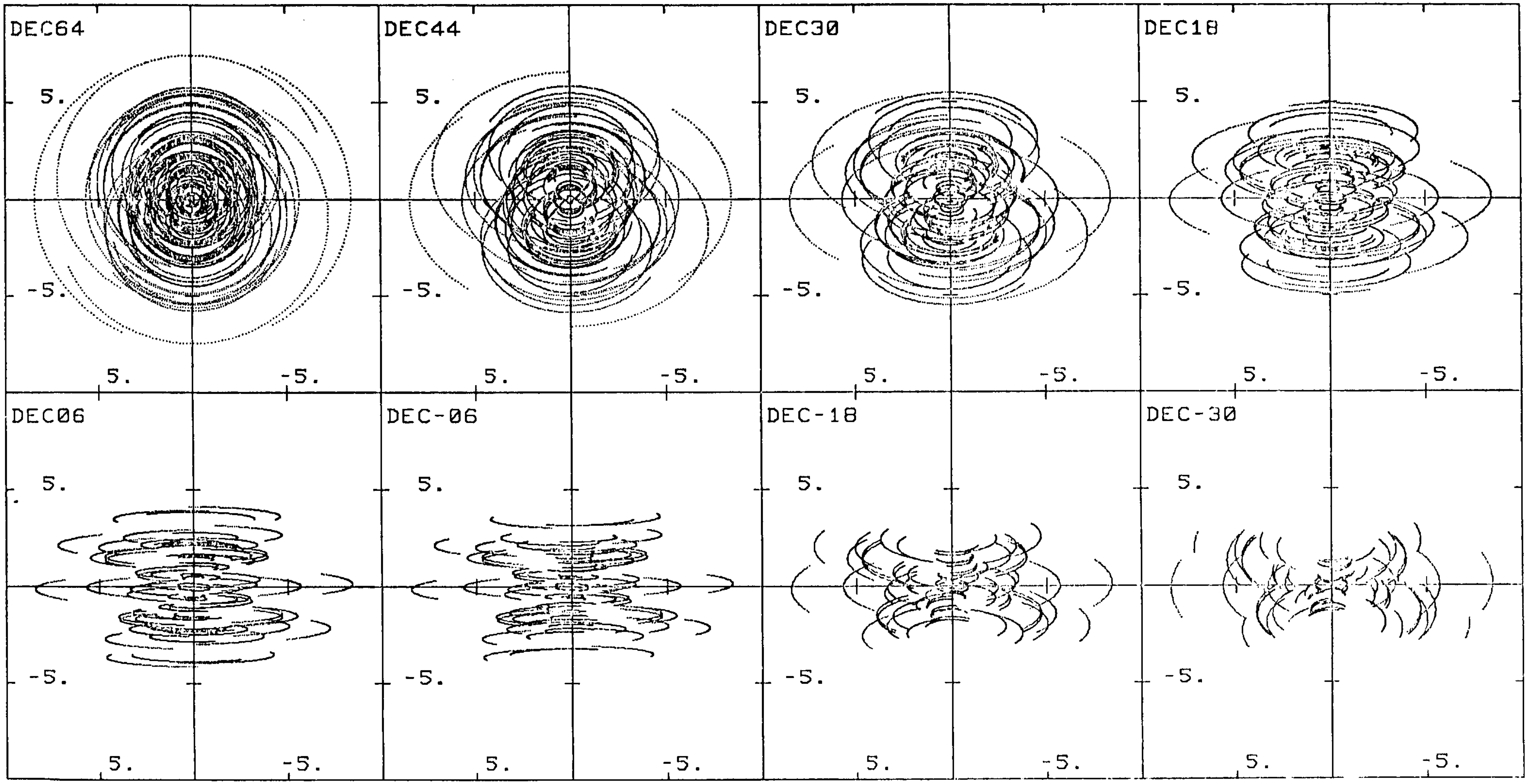
Figure II-7: The inner 2000 km of the centrally condensed array of Figure II-6. This shows the relatively dense coverage in the inner regions.



Scale Maximum 10,000 km.

HAWAII BLDR SDGO SOCORRO LASL CHURCH GRFK2 ARECIBO MEXDF CAPECAN

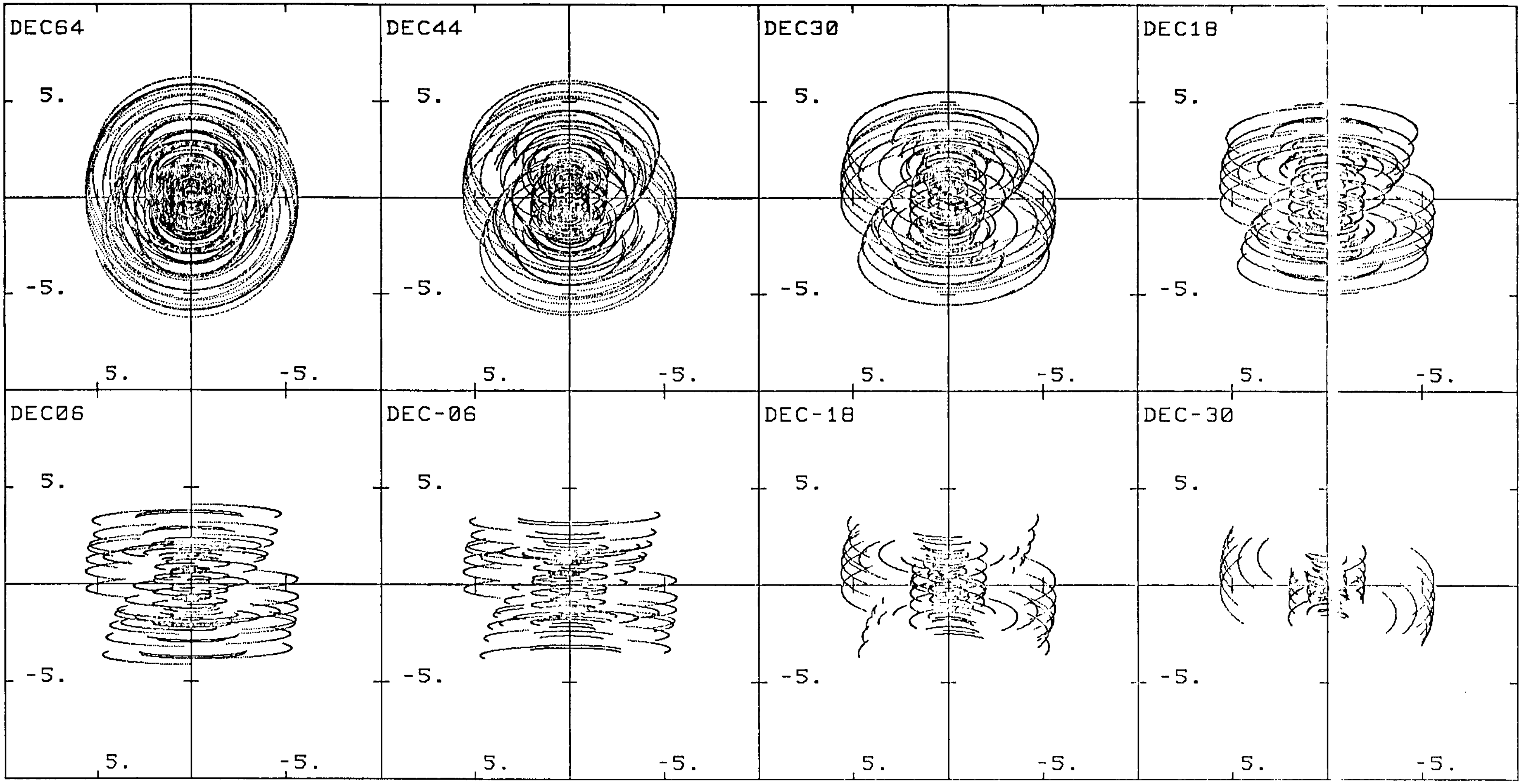
Figure II-8: A 10 station array that includes stations in Mexico and Canada. Note the improved performance near u=0 for low declination sources. Use of Mexico is very desirable because it allows observations of sources further to the south than can be seen from some US sites and because it provides a good high-dry site to replace the southern Texas station needed in all US configurations. Canada also helps improve the north-south coverage for moderately low declination sources although it is too far north to see the lowest declinations. While the latitude of any reasonably accessable site in Canada is no higher than Alaska, it is directly north of the main concentration of sites in the southwestern US, giving better interaction with those stations. There is also strong interest in VLBI in Canada and a Canadian VLBI array may be built.



Scale Maximum 10,000 km.

HAWAII YELKNF ARECIBO HSTK SPKN MEXDF LASL OKLA NPLAT SOCORRO

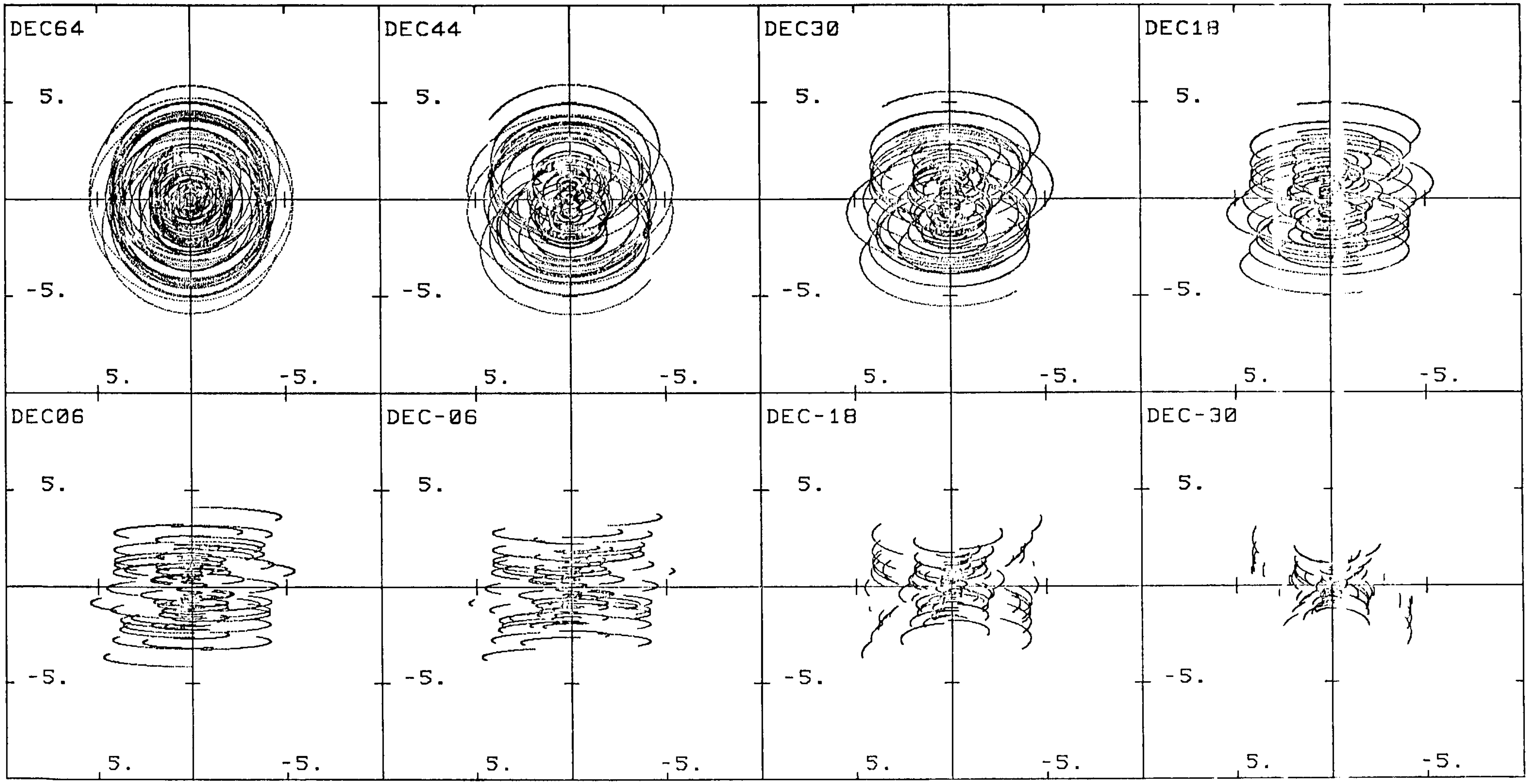
Figure II-9: This is a ten station array formed of nested triangles. It was one of several attempt to explore regular geometries. The outer triangle is Hawaii-Yellowknife-Arecibo. Inside this, but off center, is Haystack-Spokane-Mexico City, a triangle that is inverted relative to the largest one. The inner triangle is Los Alamos-Oklahoma City-North Platt. A tenth station at Socorro provides short baselines and a tie to the VLA. The coverage is not bad but the uniformity would have to be improved to match the better optimized arrays, especially in the short spacings.



Scale Maximum 10,000 km.

CHURCH GRFK2 OMAHA TOPEKA DALLAS BRVL2 ACAPUL HAWAII ANCH OVRO SOCORRO

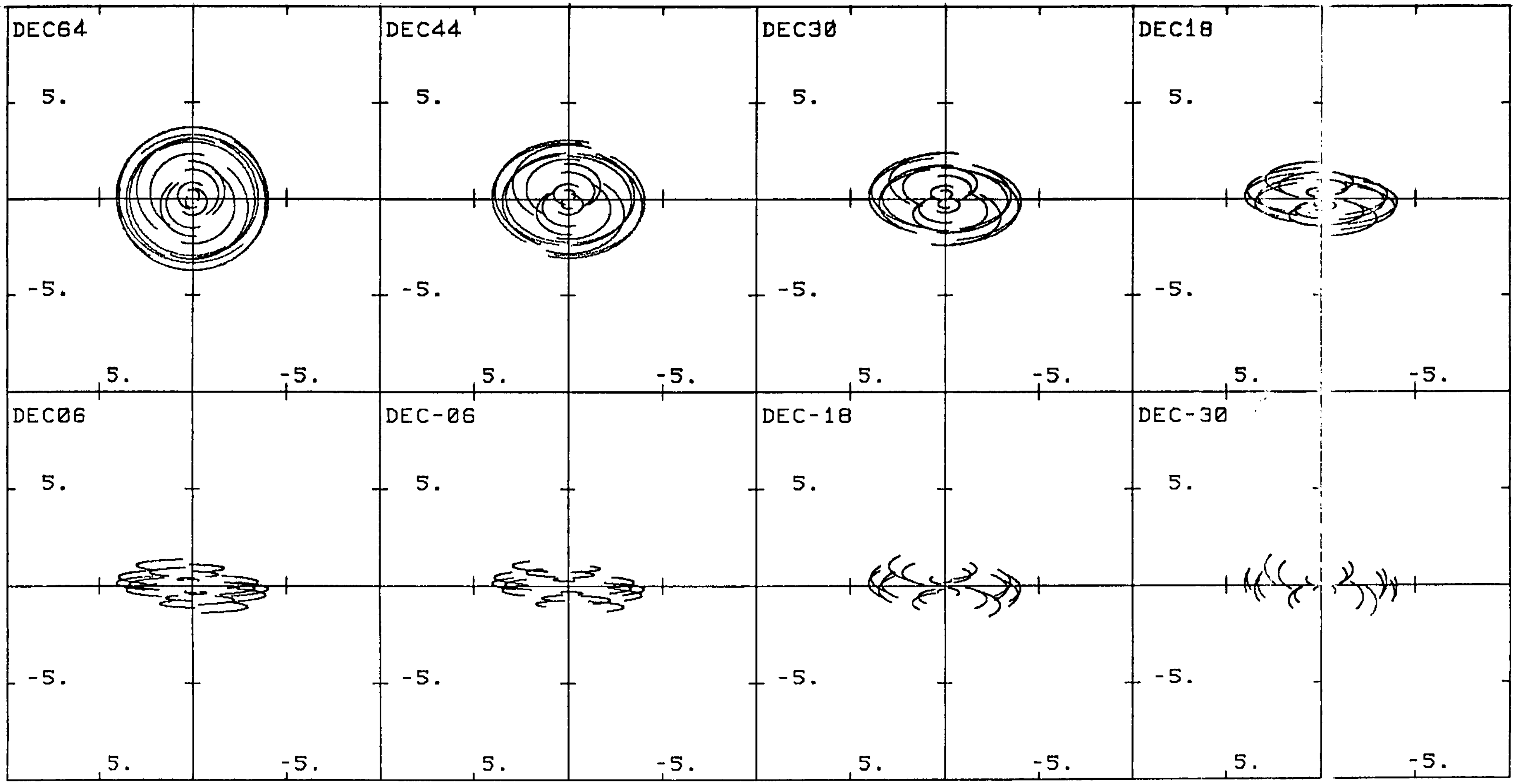
Figure II-1[illegible]: This array consists of a north-south line of sites from Churchill, to Acapulco, Mexico plus 4 stations stretching east-west. The regularity can be seen in the systematic groups of tracks. The coverage is poor - there are too many north-south baselines relative to east-west baselines and there are big gaps. In general, lines of stations are poor because they give a concentration of baselines along the line. This is seen in VLA snap-shots (short observations) where there are 6 radial concentrations of u-v points. The lines of stations are needed at the VLA because the antennas must be moved to change configurations and the lines minimize the amount of track needed. For the VLBA, there is no such constraint so a more distributed pattern of antenna locations is preferred.



Scale Maximum 10,000 km.

STAT 1 STAT 2 STAT 3 STAT 4 STAT 5 STAT 6 STAT 7 STAT 8 STAT 9 STAT10

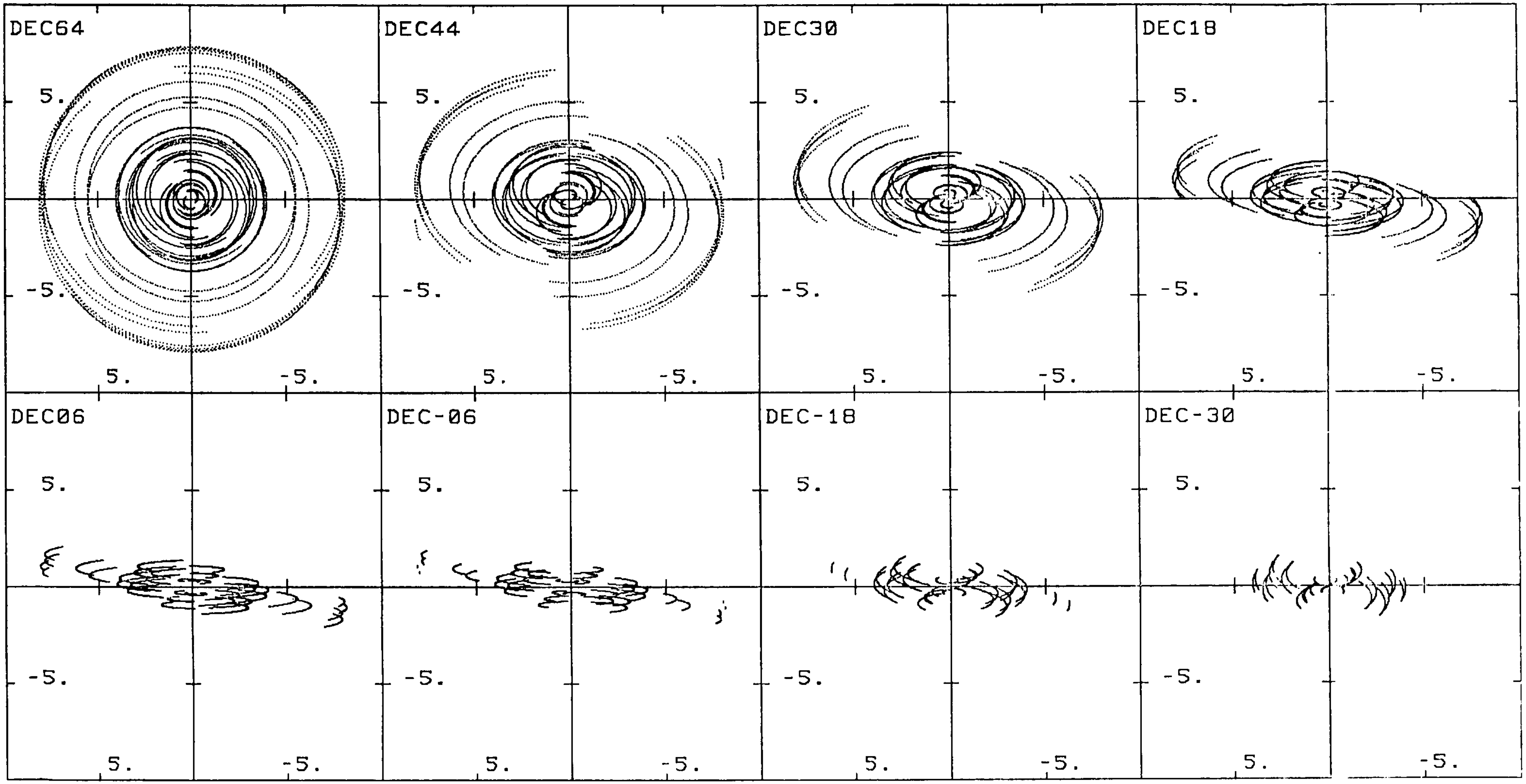
Figure II-11: This array is a 10 station power law wye with the junction of the arms at Socorro and the ends of the arms at Anchorage, Newfoundland, and Acapulco. (The station locations are not listed in the stations list.) As in the last figure, the effects of the regularities are apparent and there are large gaps at the low declinations. Note the contrast between the coverage of this wye which has arms that curve with the Earth, and the coverage of the VLA (Figure VI-1), which has sites that are effectively on a plane.



Scale Maximum 10,000 km.

HCRK OURO FDVS NRAO HSTK

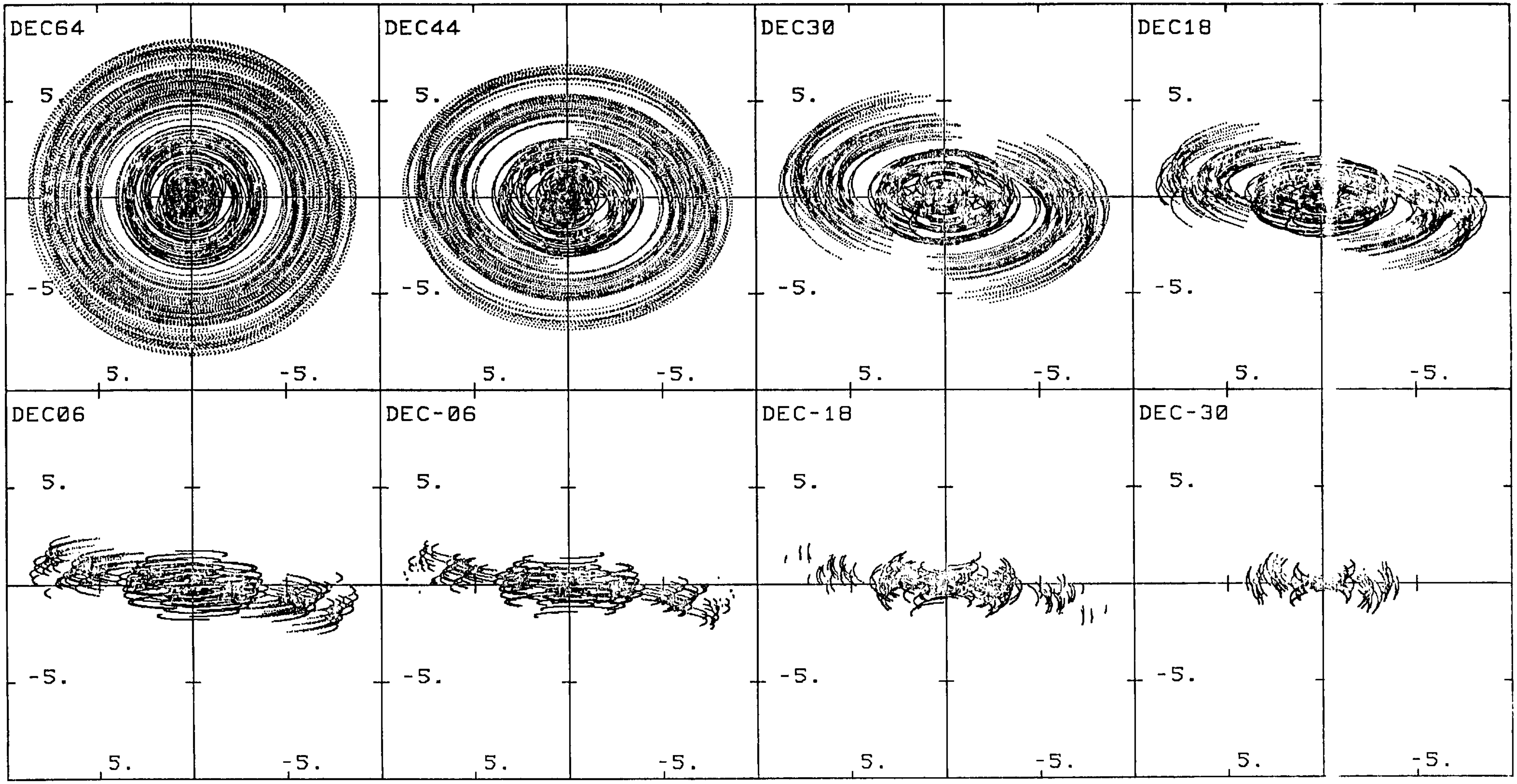
Figure III-1: The coverage of a U. S. VLBI Network experiment that uses the 5 most active stations and does not use a European station. With only 10 baselines the coverage is sparse. The sites of the stations were not chosen with VLBI in mind so the uniformity of the coverage is poor. At high declinations the large holes due to the 'midwest gap' can be seen. Iowa fills these holes but has poor frequency coverage and low sensitivity. Without Europe, the resolution is severely limited by the lack of a Hawaii site.



Scale Maximum 10,000 km.

HCRK OVRO VLA FDVS NRAO HSTK BONN

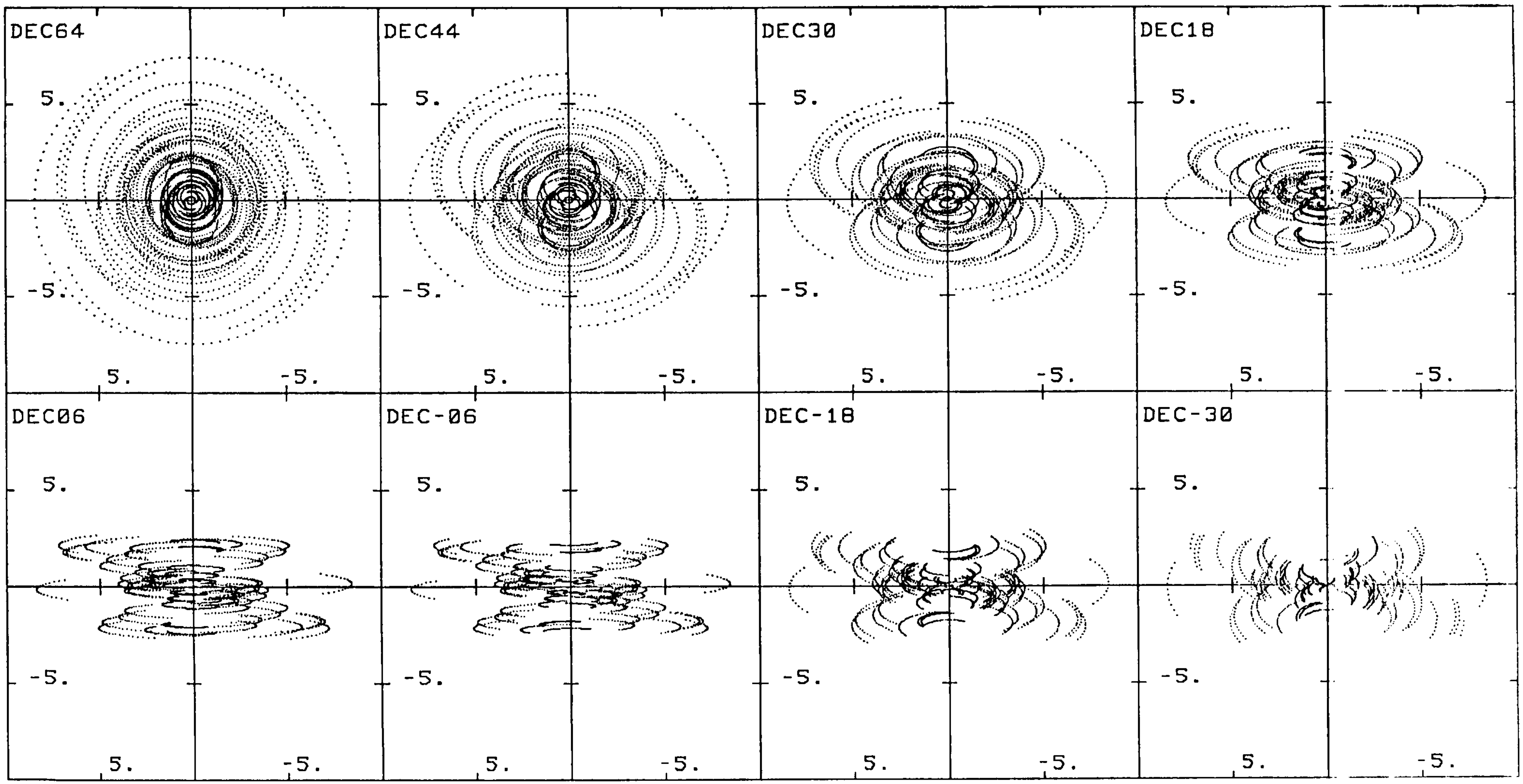
Figure III-2: The u-v coverage of seven existing stations that are commonly used in current VLBI Network observations at frequencies below 10 GHz. The VLA and Bonn have been added to the usual Network stations shown in the last figure because, although they are not full Network stations, they are used in a large fraction of current experiments. Note the large gaps and the poor north-south distribution at low declinations. Also note the loss of long spacings at low declinations that is a result of the high latitude Europe. The performance of some of the antennas is poor at frequencies of 10 GHz and higher.



Scale Maximum 10,000 km.

HCRK OVRO VLA FDVS NRAO HSTK BONN PENT ARO NRL ONSALA JODRELL IOWA DWINGELO BGNA

Figure III-3: The u-v coverage of a very large experiment that might be done with existing observatories at low frequencies (such an experiment has been proposed for a source at 4 degrees declination). Note that there are still gaps corresponding to the midwestern United States and to the Atlantic Ocean. An experiment of this magnitude can only be done at low frequencies (eg 1650 MHz) and only with cooperation from many observatories. With current facilities, such experiments will be rare.



Scale Maximum 10,000 km.

ARECIBO HAWAII OVRO HCRK VLA FDVS IOWA NRAO NRL HSTK

Figure III-4: An array consisting of 8 existing U.S. observatories plus new antennas at Arecibo and Hawaii (Note that the new Arecibo antenna is at an existing observatory - the current antenna has very limited hour angle coverage). The coverage is not as uniform as the coverage obtained with an optimized array but is very much better that what is currently available. Note that the well-known 'midwest gap' is filled by the 60 foot antenna at Iowa which is being upgraded for use at 5 GHz and maybe higher. The coverage shown here could only be obtained at frequencies below 5 GHz (or 10 GHz with poor performance at some sites).

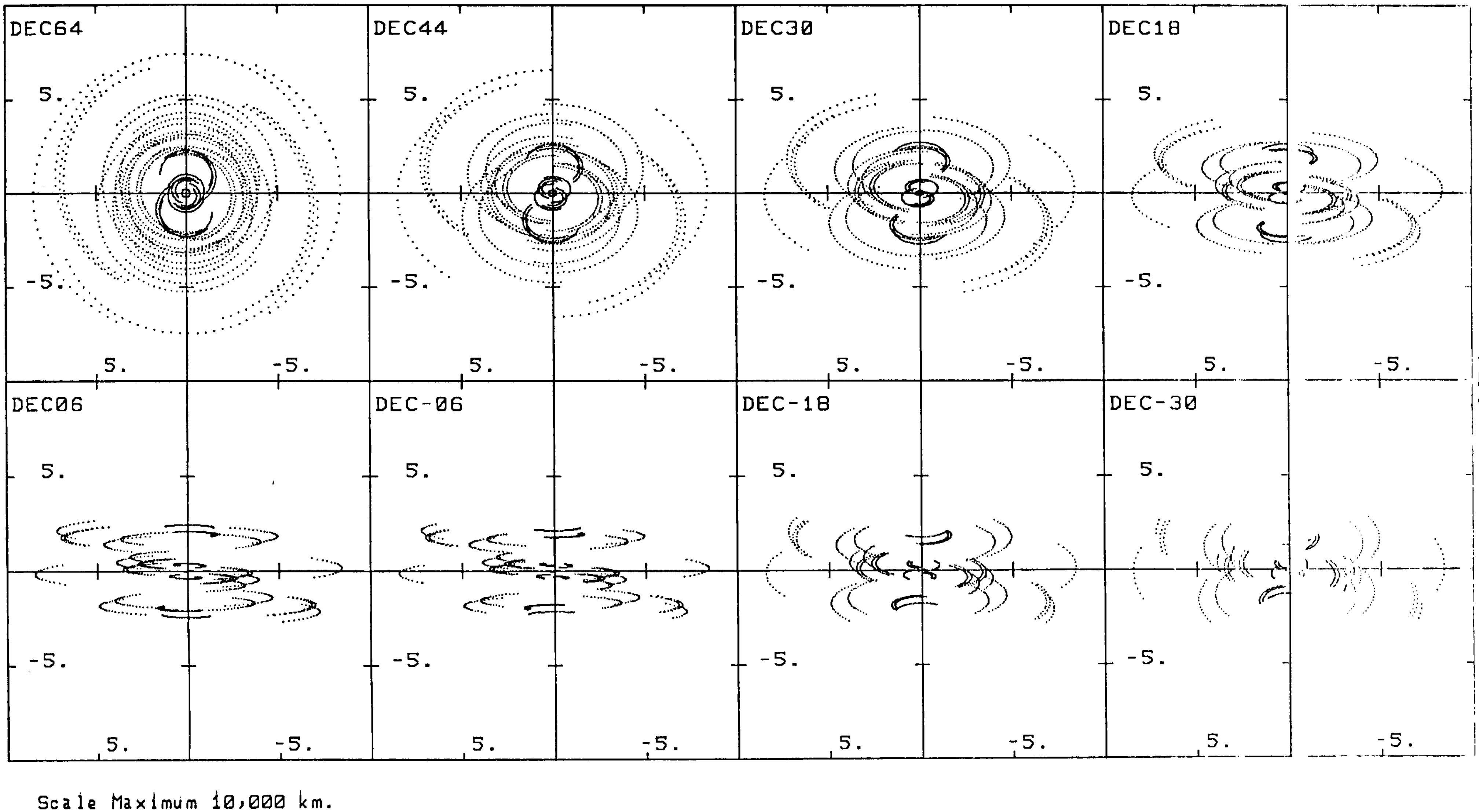
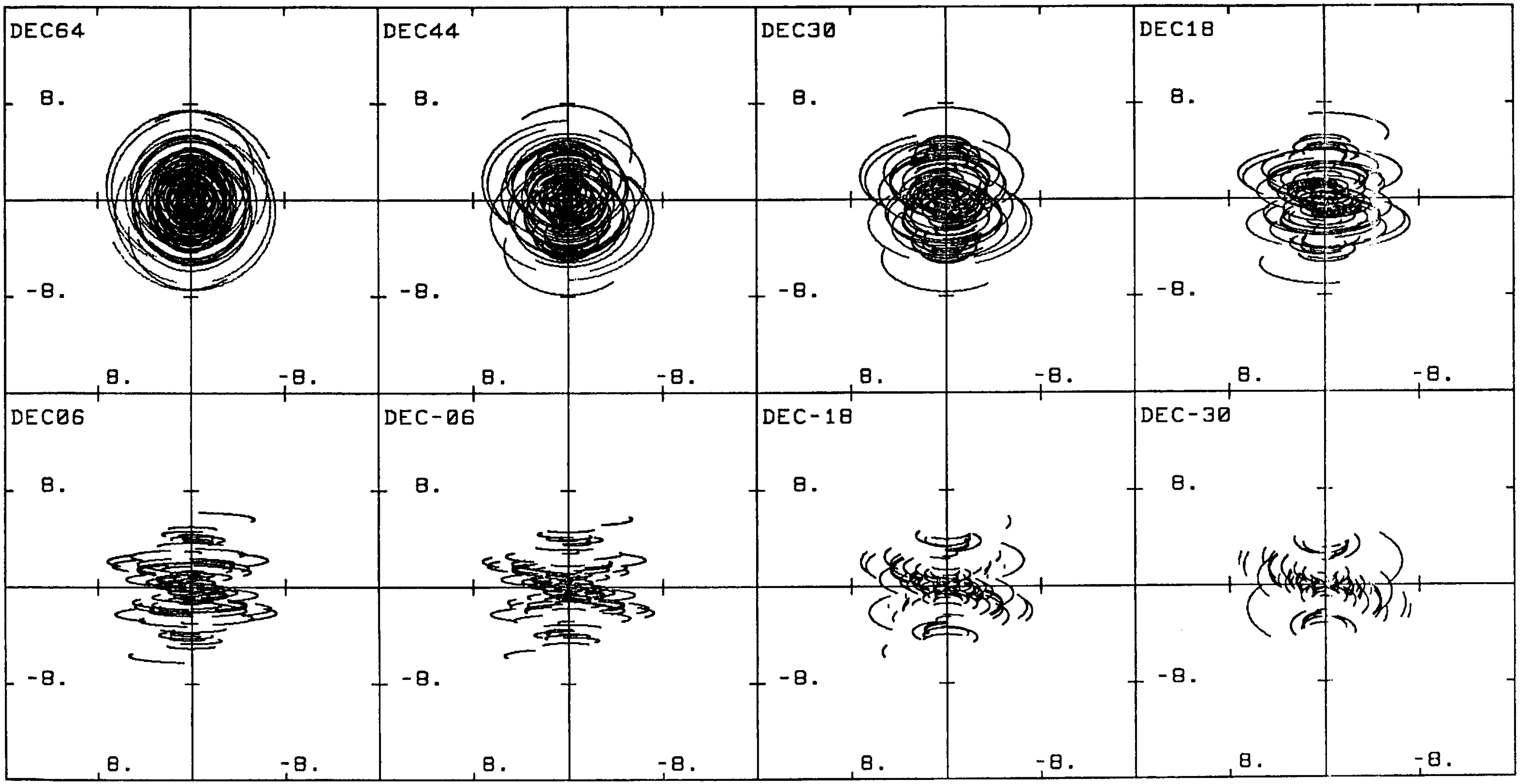


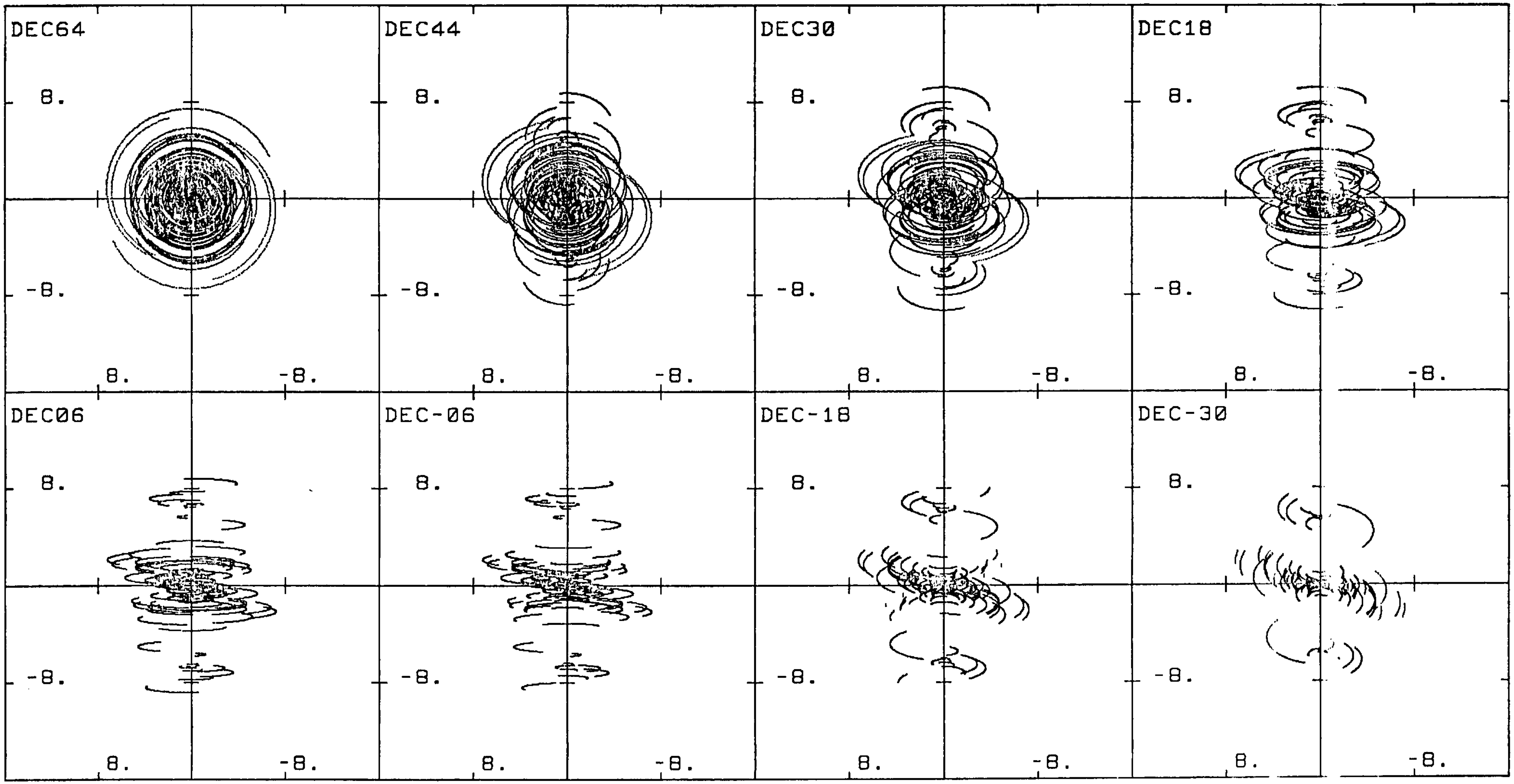
Figure III-5: The coverage of the 7 antennas of the array of Figure III-3 that would give useful performance at 22 GHz (eg the H2O maser frequency). Now the coverage is very poor.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 GALAPA

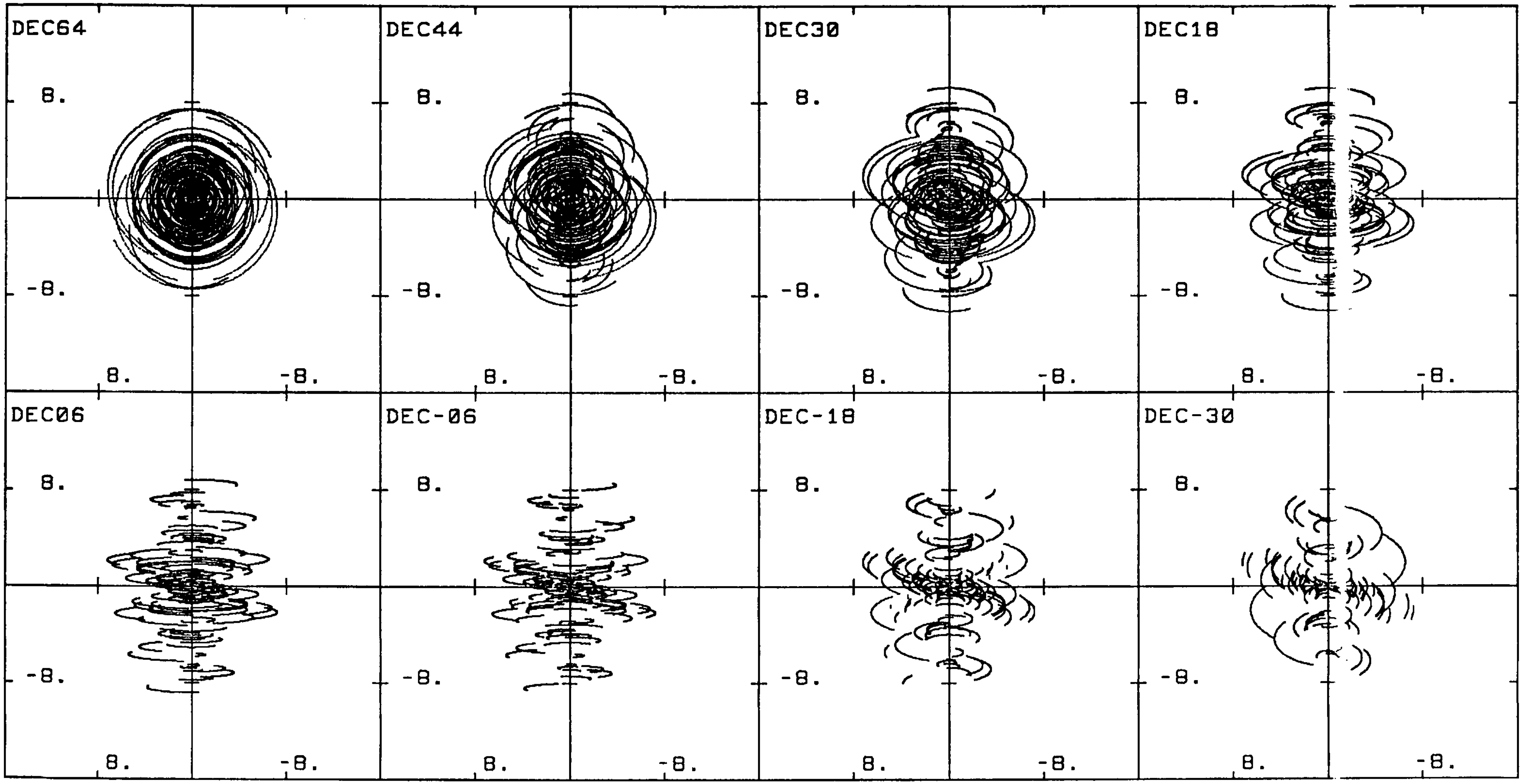
Figure IV-1: This is the first of several figures showing what could be gained by using stations in South America and/or on islands west of South America. This figure shows the u-v coverage of Array D2 plus a station in the Galapagos. The north-south coverage is improved dramatically at low declinations although there is a large gap. That gap can be avoided with a suitable choice of U.S. stations as will be shown in later figures - the inclusion of a Puerto Rico station seems to be the key. The Galapagos are owned by Equador and are serviced by daily flights to Quito.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 EASTER

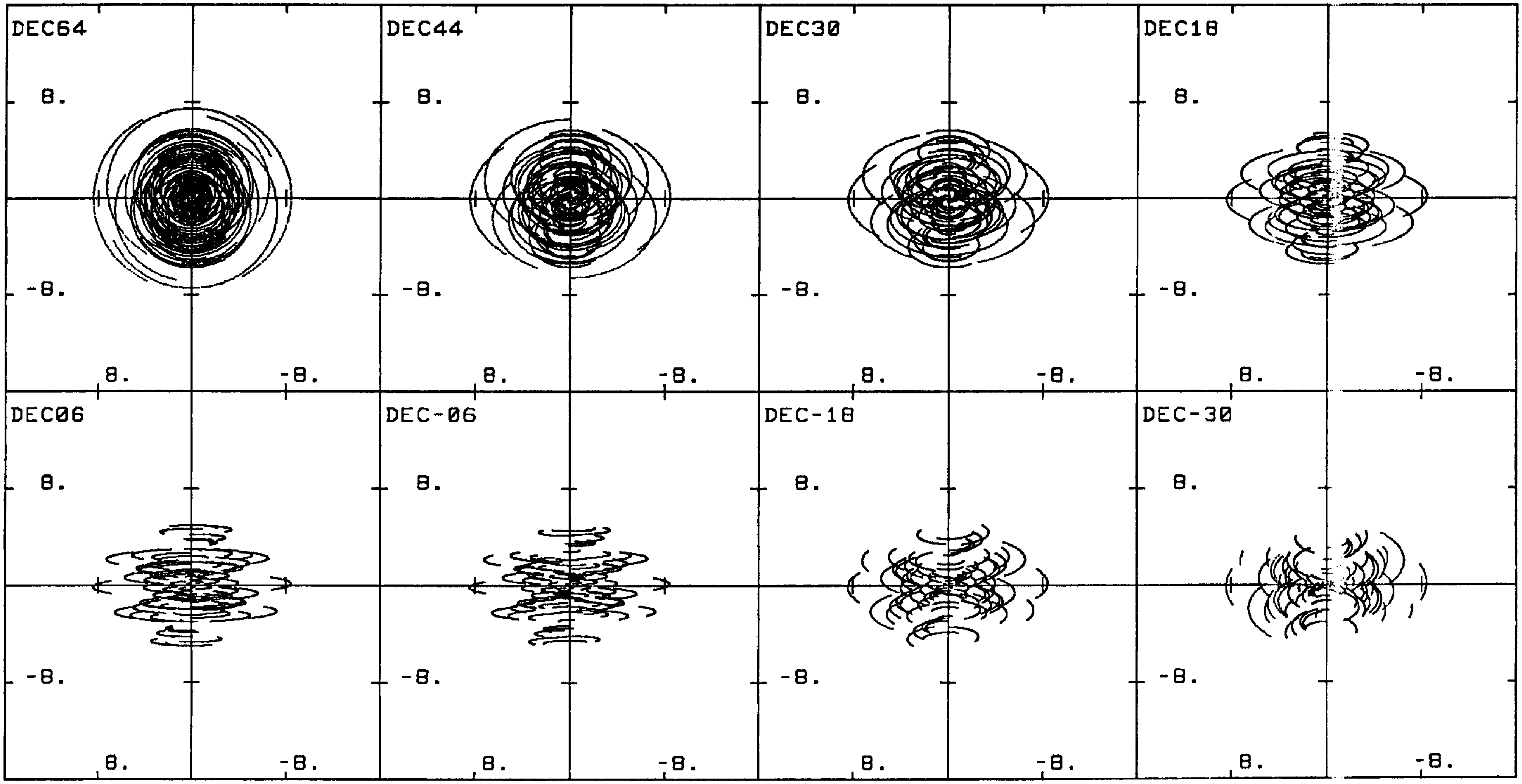
Figure IV-2: Array D2 plus Easter Island. This provides very long north-south baselines but leaves a large gap. Easter Island is owned by Chile and is serviced by several flights a week from Chile.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 GALAPA EASTER

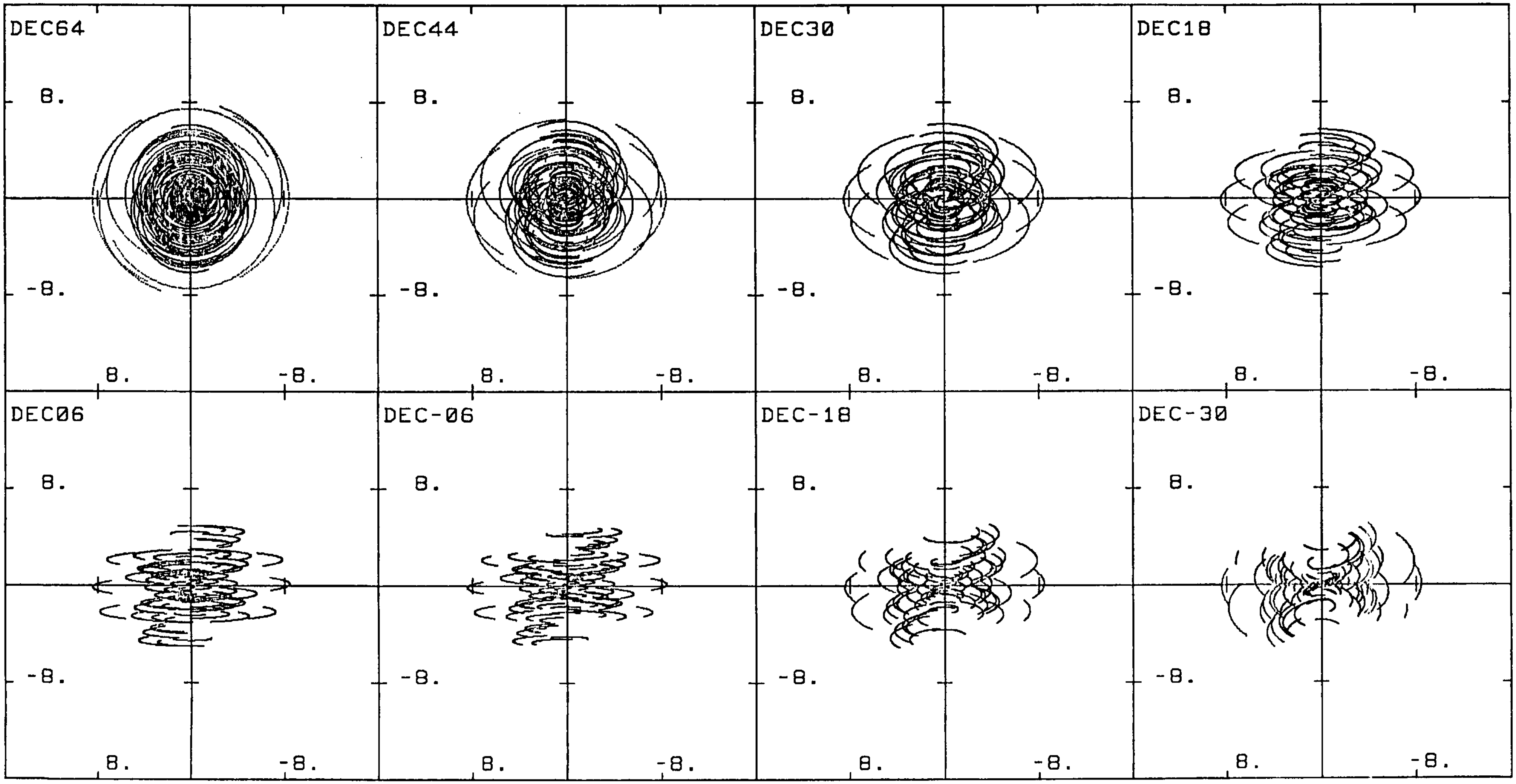
Figure IV-3: This shows the coverage of Array D2 plus antennas in the Galapagos and on Easter Island. The north-south coverage is significantly improved over that of Figure IV-1. Again the gaps can be avoided with a suitable choice of North American sites. More discussion of the use of the Galapagos and Easter Island can be found in Mutel and Gaume (1982). South America is much more to the east of North America than most people realize and stations on the mainland are not as good as station on these islands.



Scale Maximum 16,000 km.

HSTK OVRO SALEM HAWAII VLA TUSC BRVL2 ARECIBO GALAPA BISMARCK

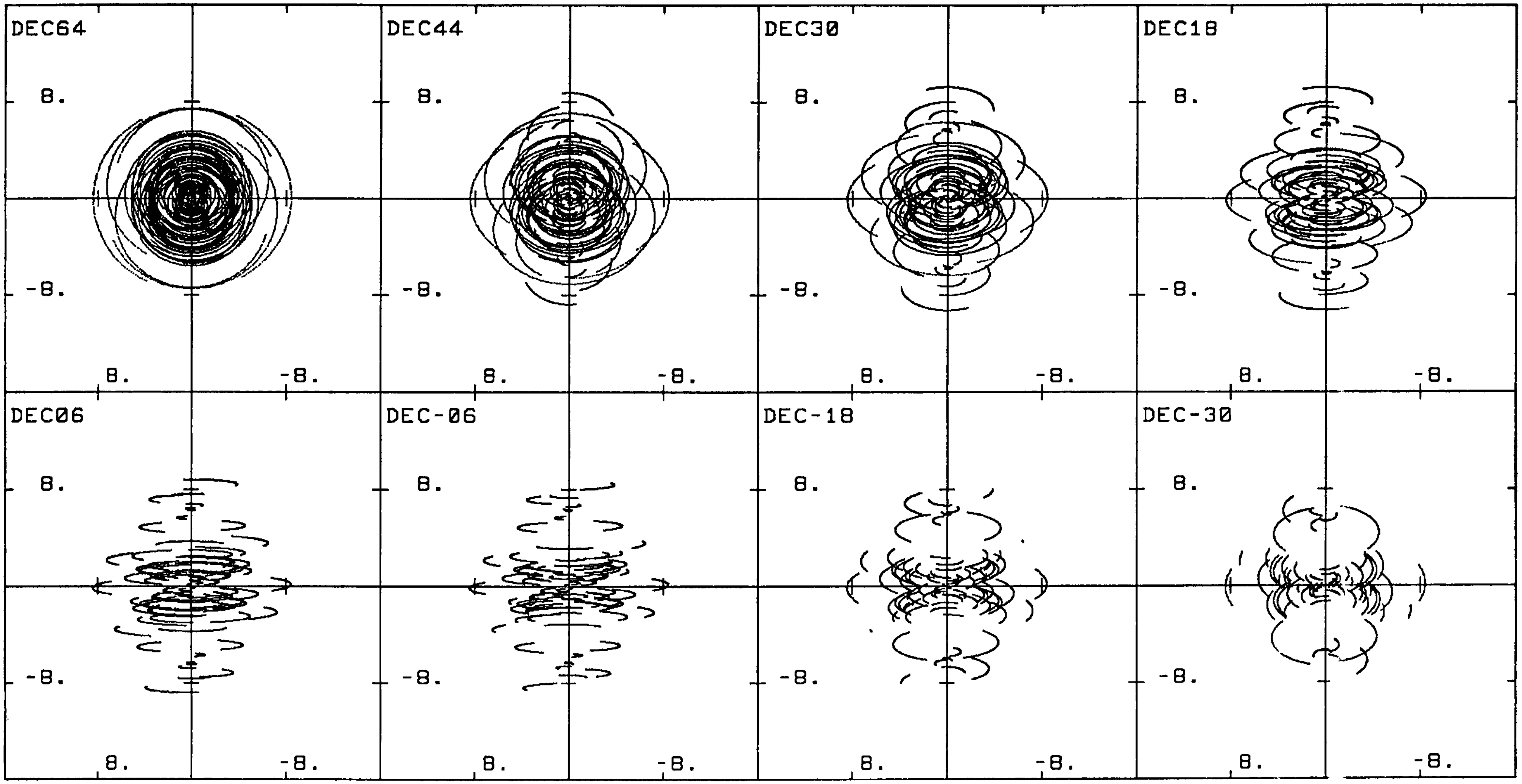
Figure IV-4: Array SG-1 of Mutel and Gaume (1982). This is a 10 station optimized array that uses the Galapagos.



Scale Maximum 16,000 km.

HSTK OVRO SALEM HAWAII VLA TUSC BRVL2 ARECIBO QUITO BISMARCK

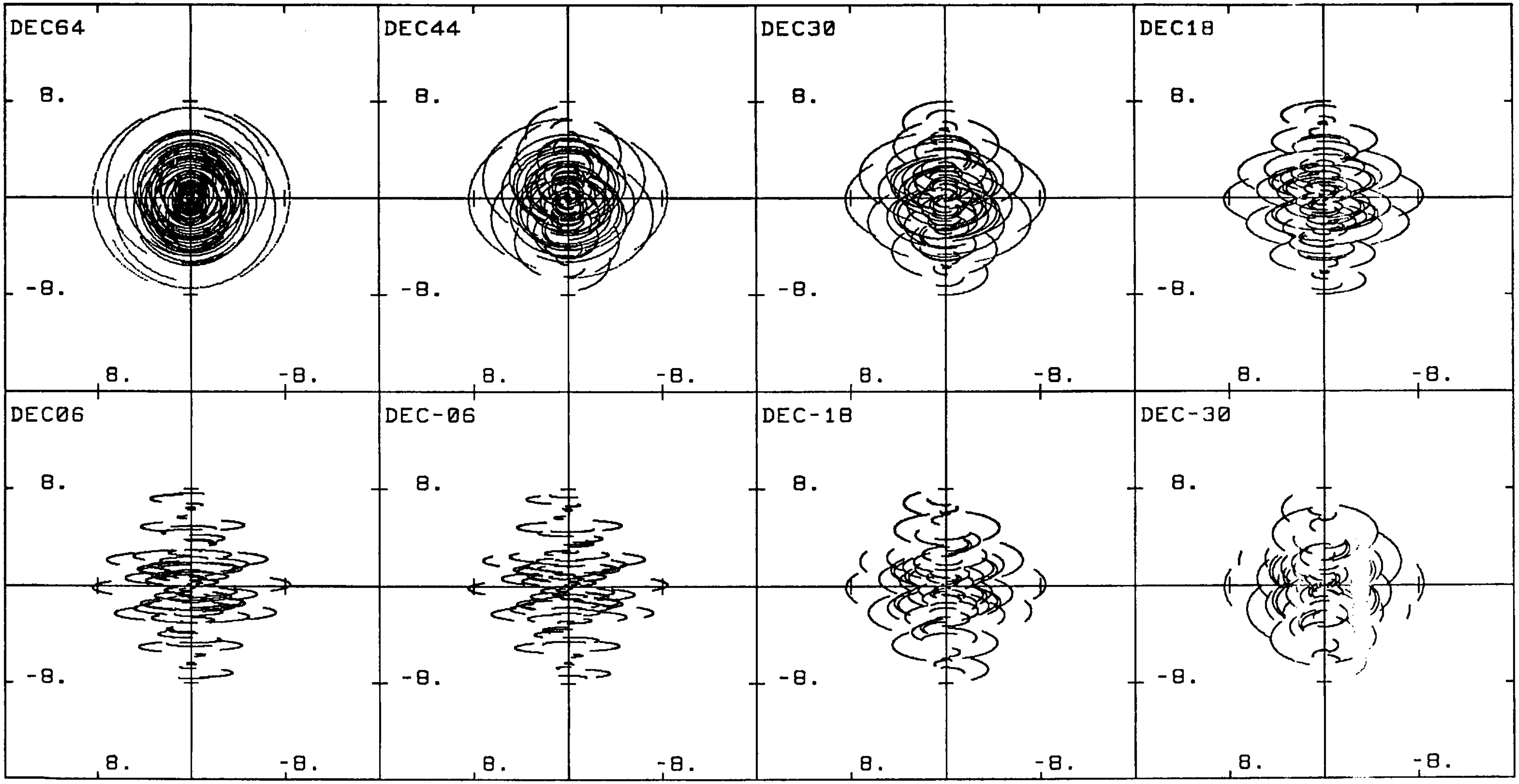
Figure IV-5: Array SG-1 (Figure IV-4) with Quito instead of the Galapagos (SQ-2 of Mutel and Gaume). The coverage is not as good as with the Galapagos because of the more easterly location of Quito but it is good enough that Quito may be preferred for logistical reasons.



Scale Maximum 16,000 km.

HSTK OVRO EASTER HAWAII VLA TUSC BRVL2 ARECIBO ANCH BISMARCK

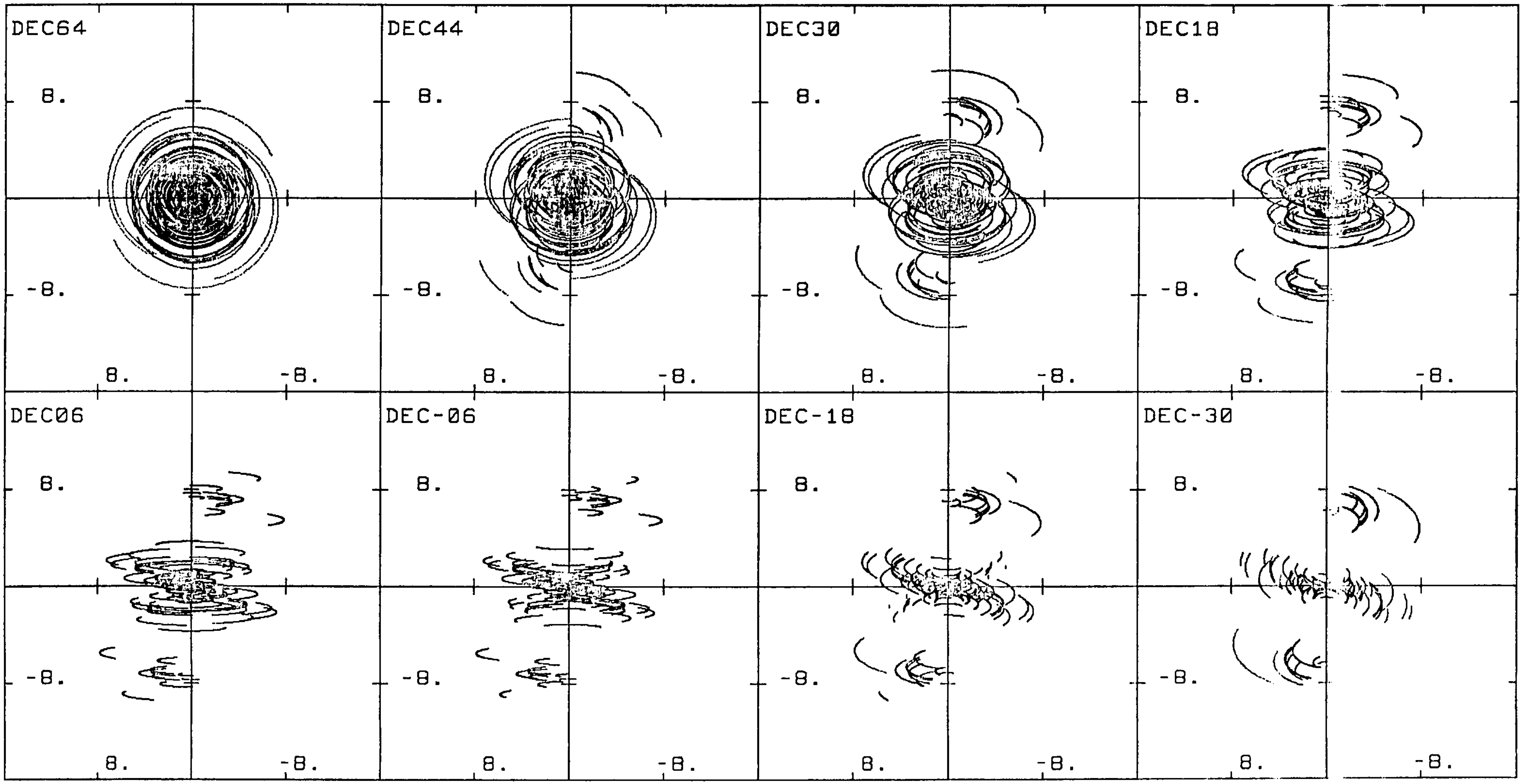
Figure IV-6: Array SE-1 of Mutel and Gaume (1982). This is basically the same array as that shown in Figure IV-4 except that Easter Island is included and the Galapagos are not.



Scale Maximum 16,000 km.

HSTK OVRO EASTER HAWAII VLA TUSC BRVL2 ARECIBO GALAPA BISMARCK

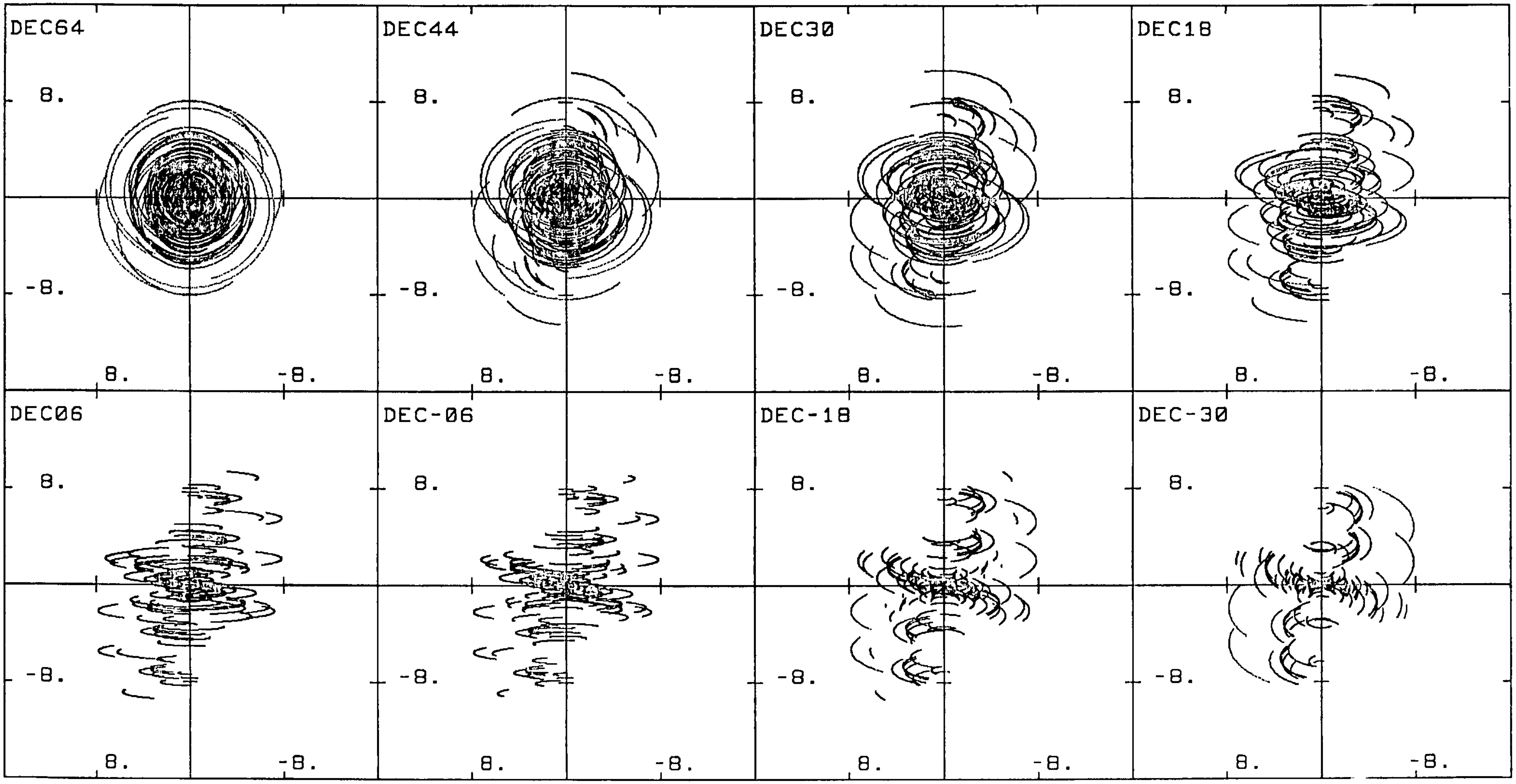
Figure IV-7: Array SEG-1 of Mutel and Gaume (1982). This is a 10 station optimized array that includes both the Galapagos and Easter Island. The coverage at low declinations is very much better than anything that is possible with an Array confined to U.S. territory. It may not be realistic to try to put some of the original 10 antennas of the array in such remote locations but the possibility of adding such stations later, possibly in cooperation with the countries involved, should be kept in mind.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ARGENT

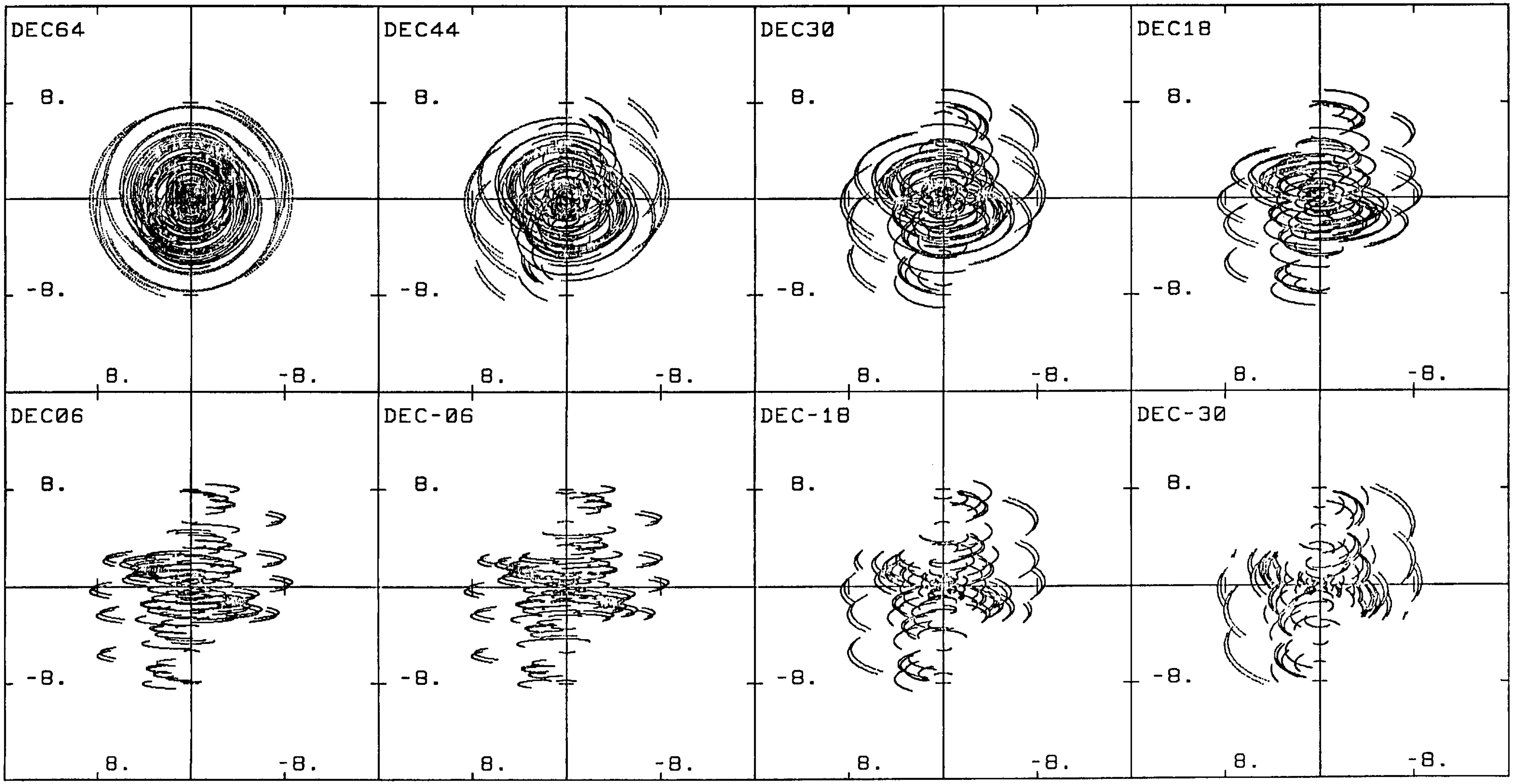
Figure IV-8: This plot shows the coverage of Array D2 plus a station in western Argentina at a site that is being developed for astronomy and has been suggested by the Argentines as a possible site for a VLBI station. The station, used without other southern stations, leaves large gaps and would be poor for image formation. See the next two figures for some possible fixes.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ARGENT QUITO

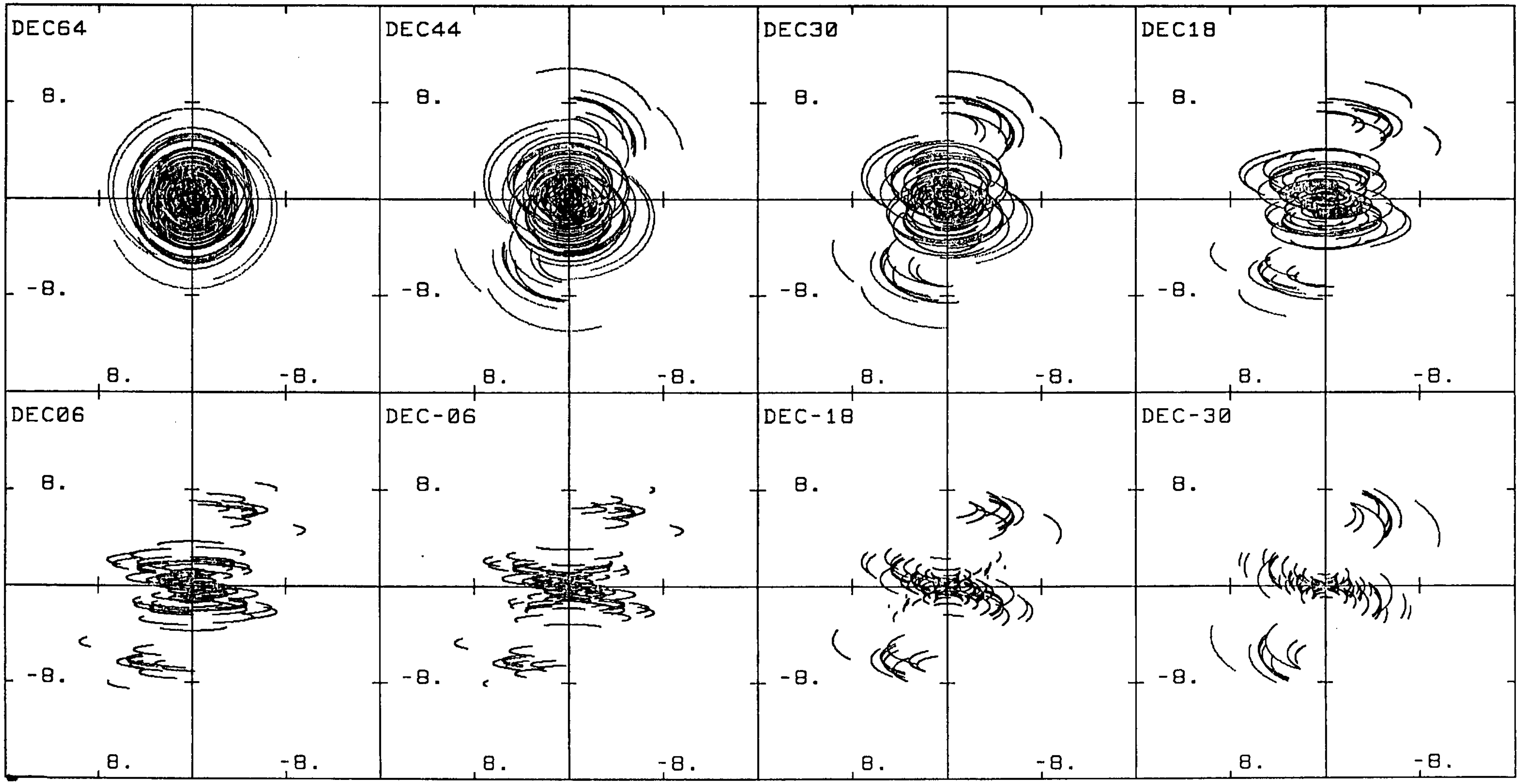
Figure IV-9: For this figure, a station in Quito, Equador has been added to the array of Figure IV-8. Much of the big north-south gap has been filled. The major hole is in the northwest and southeast quadrants. This is the result of the eastern location of South America and shows why Easter Island is preferred. The holes might be filled by another southern station in the Pacific, perhaps at an easily accessable site such as Samoa, Fiji, or Tahiti or perhaps at some U. S. military base. Australia may be too far west although it would help.



Scale Maximum 16,000 km.

KAUAI HILO SPKN TUSCNE VLASW LRDO IOWA BANGOR ARECIBO PUEBLO ARGENT QUITO

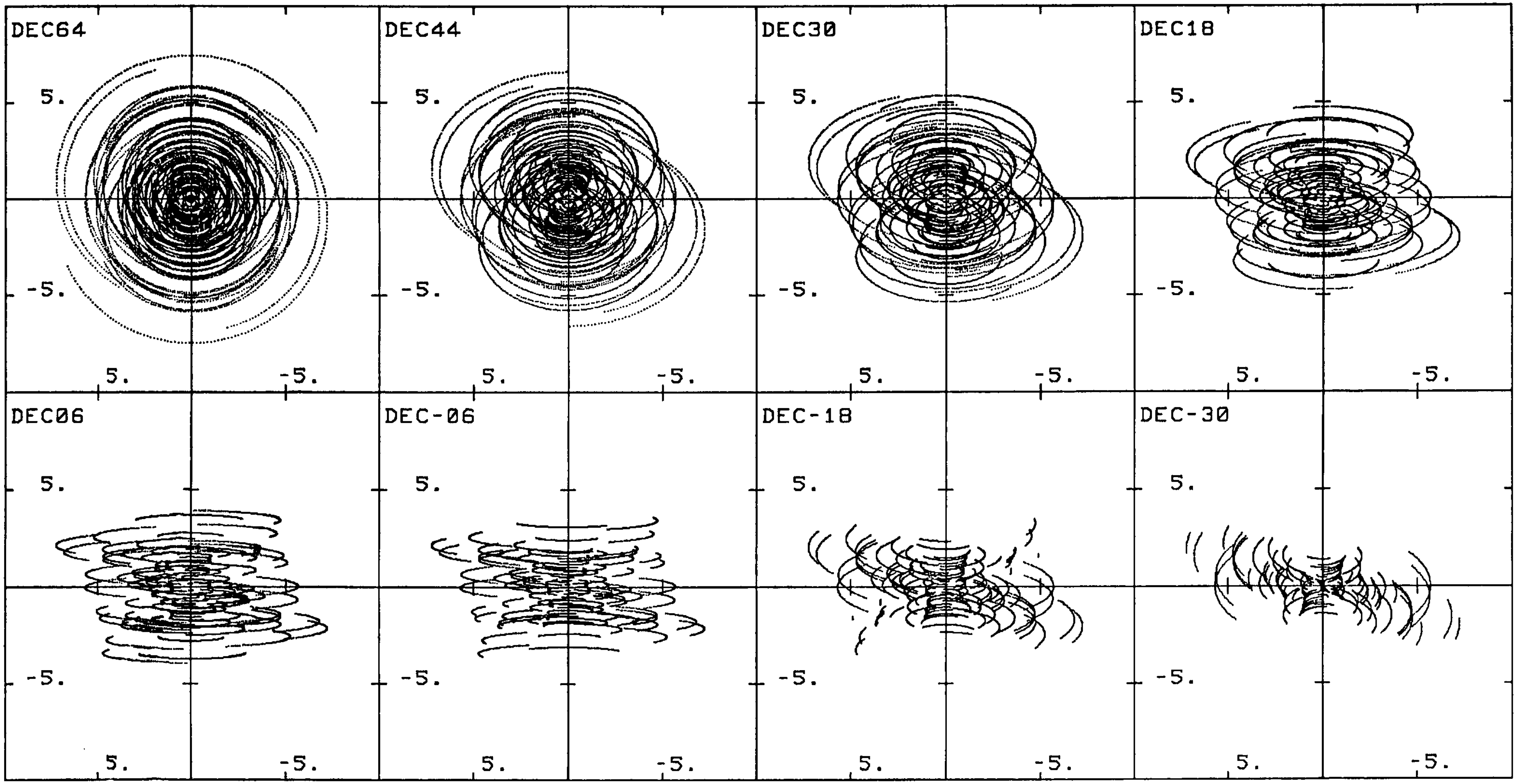
Figure IV-10: This shows the coverage of a U.S. 10 station array that includes Arecibo (the array of Figure II-4) with Quito and Argentina added. The east-west gaps seen in the last figure, which are related to the similar gaps in Figure IV-3, are gone showing that the major problem with South American sites is the missing quadrants.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ITA

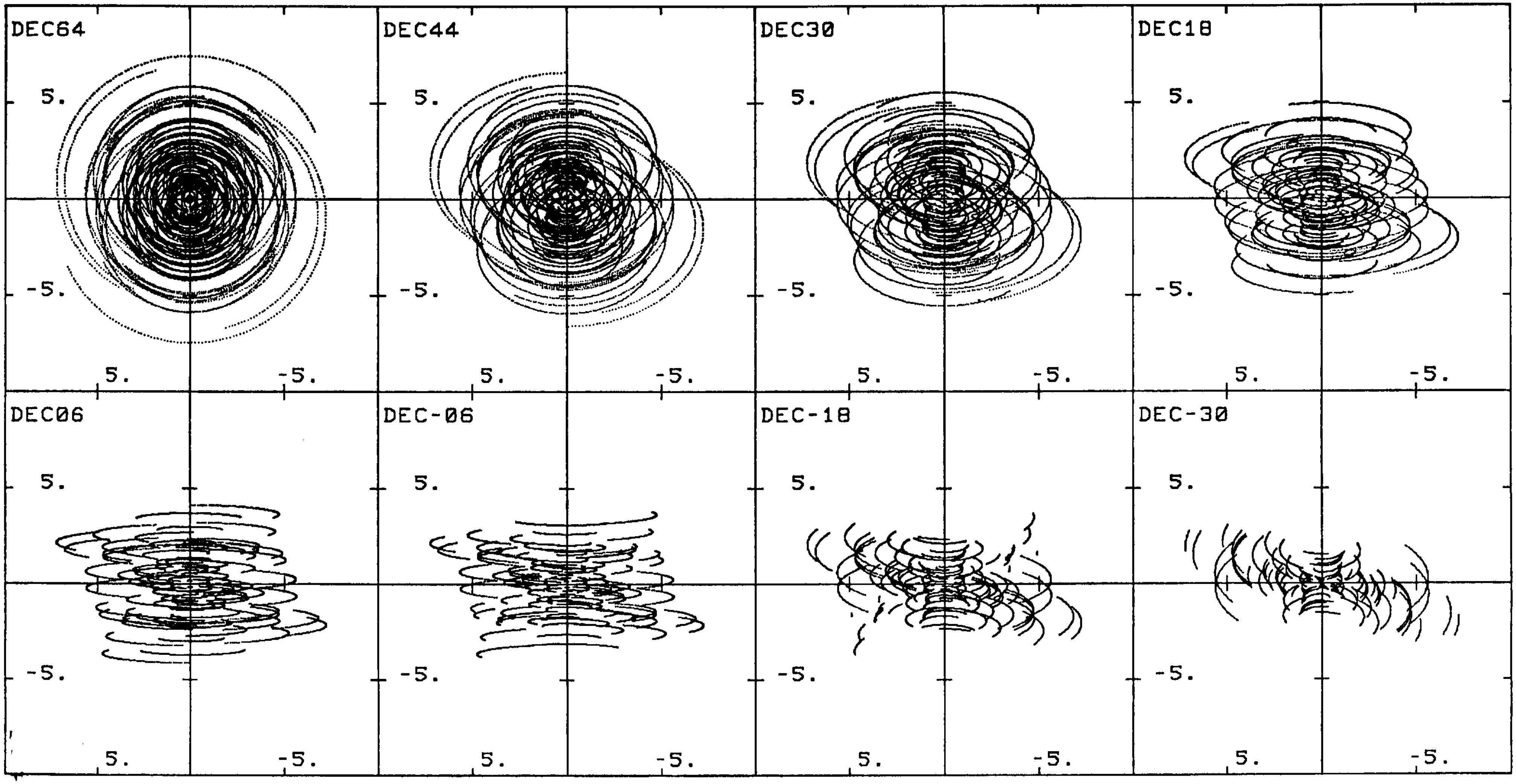
Figure IV-11: The coverage of Array D2 plus an antenna at the observatory at Itapatinga in Brazil. VLBI experiments have already been done to this station. The coverage has the same problems and advantages as the coverages for the station in Argentina. The observatory is farther east than the Argentina site so the problem with the missing quadrant is worse. However, the presence of local, interested personel and possible support make these sites worth considering for antennas that might be used with the array, although probably not for one of the original 10.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 MEXDF

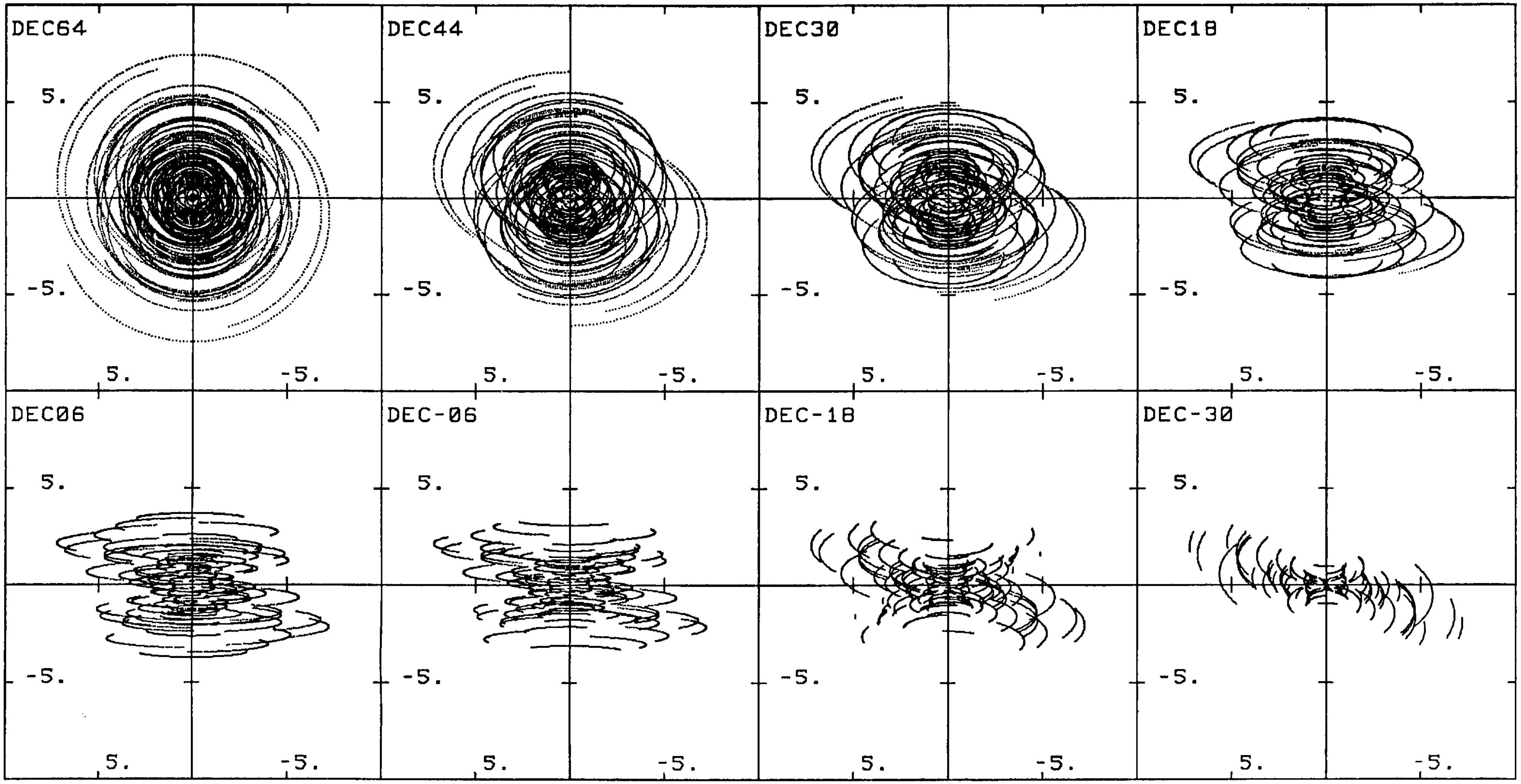
Figure V-1: The coverage of Array D2 plus a station in Mexico City. A Mexico site adds to the north-south coverage at low declinations and adds intermediate spacings. As discussed in the caption of Figure II-8, a Mexico site could have significant advantages as one of the original 10.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ACAPUL

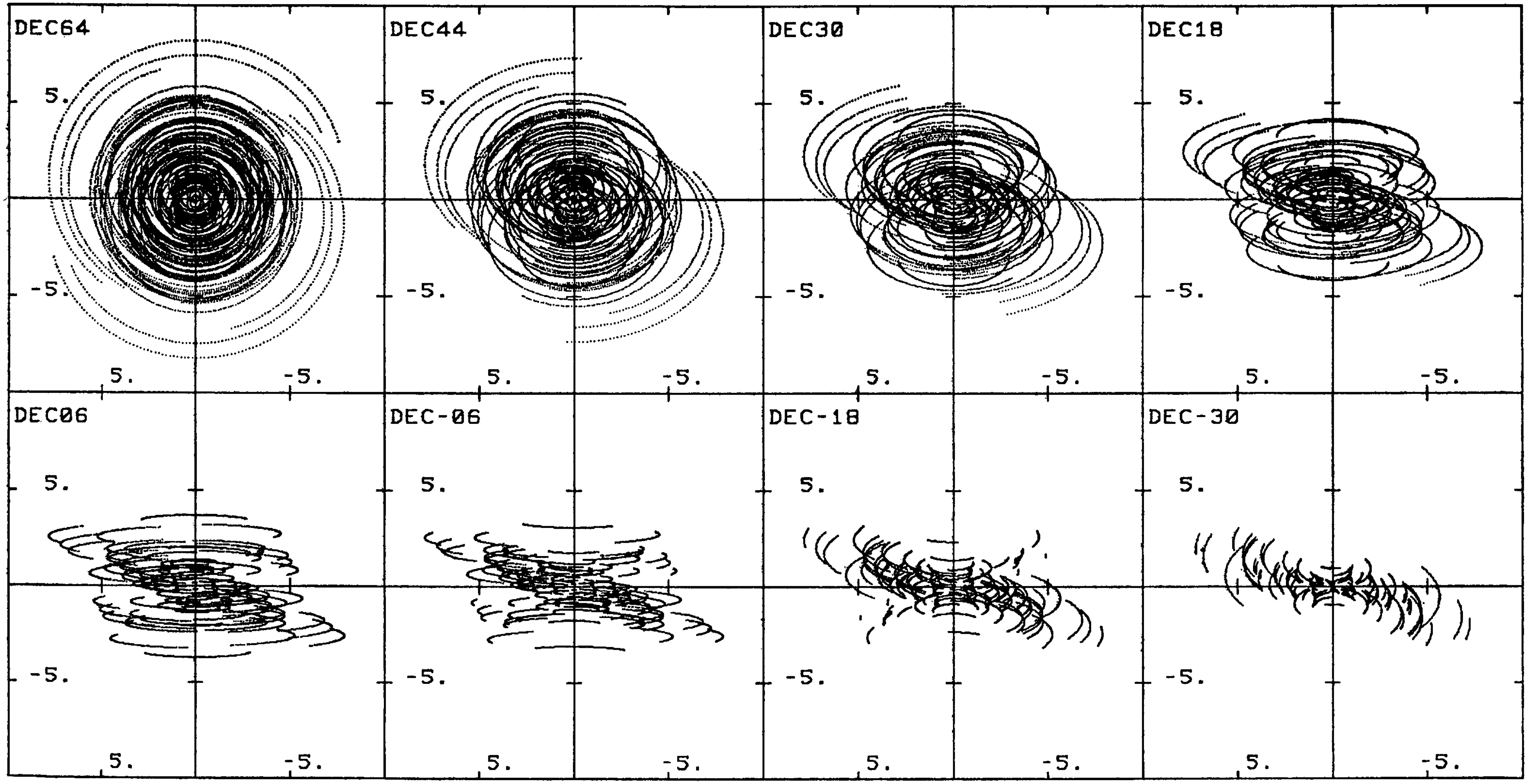
Figure V-2: The coverage of Array D2 plus a station in Acapulco. Acapulco is about as far south as one can get in Mexico and it has good transportation so it is attractive as a site although it is not a great deal from different from Mexico City.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 EDMT

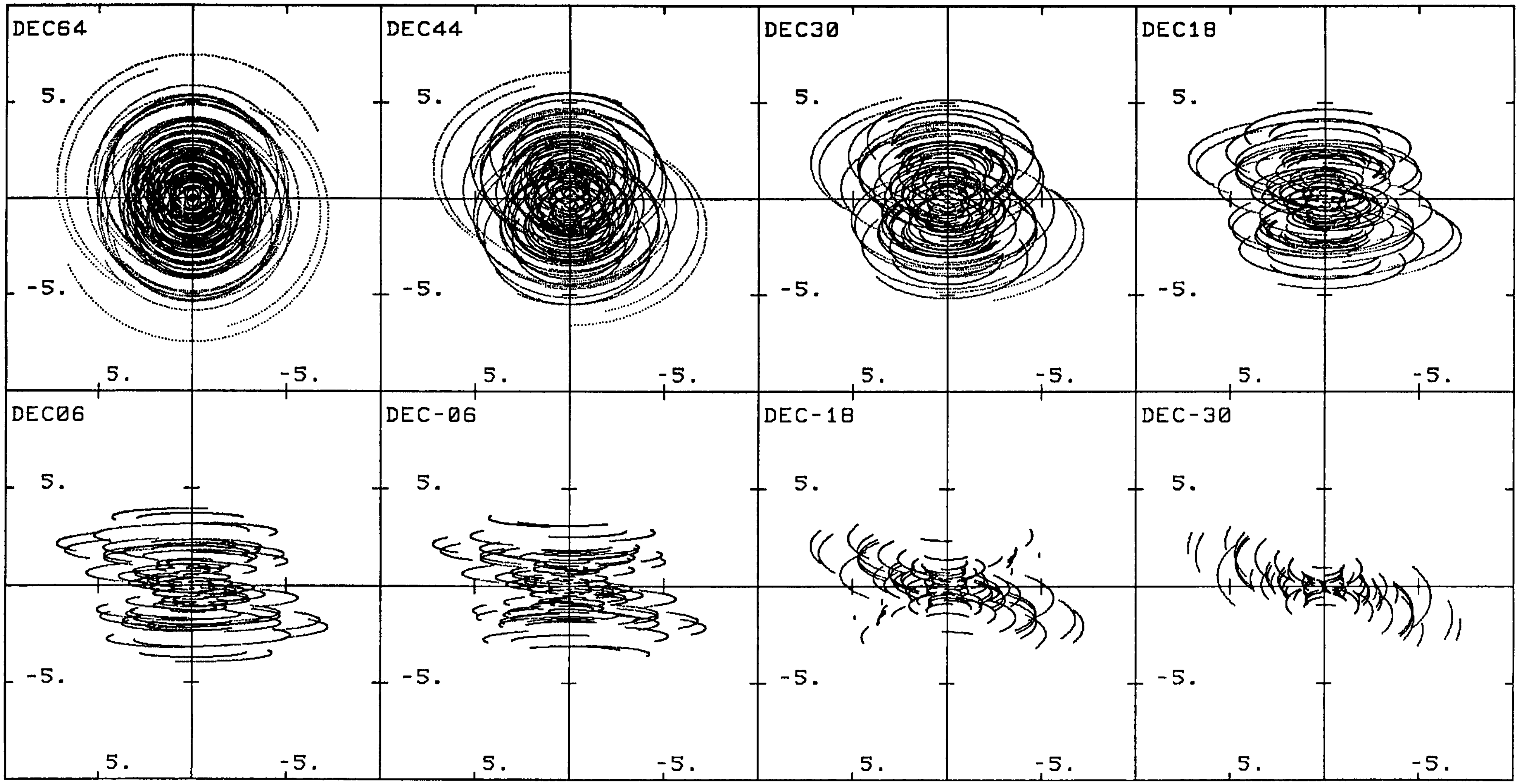
Figure V-3: The coverage of Array D2 plus a station in Edmonton, Alberta. Edmonton is one of the most northern, large population centers in Canada although it is not all that far north of the U.S. border. Any stations significantly north of the border add to the north-south coverage. Use of Canada has the advantage of the presence of interested Canadian astronomers and large pool of trained technicians. However, the Canadians have their own array project and the politics of cooperation on a formal level are not clear at this time. At the level of individual scientists and engineers, there is much ongoing communication and cooperation.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 NEWF

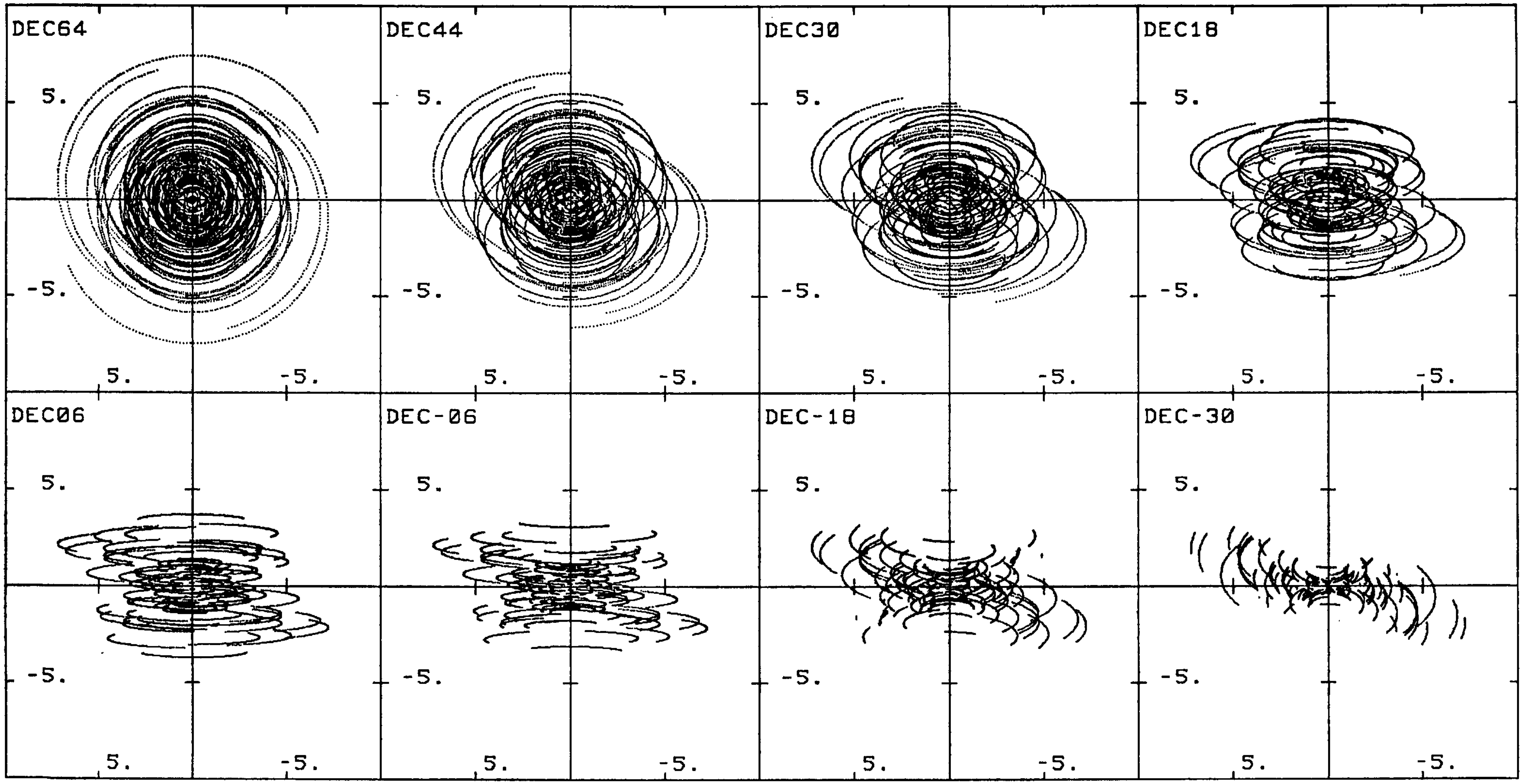
Figure V-4: The coverage of Array D2 plus a station in Newfoundland. This station mostly adds to the east-west coverage of a U.S. array. It would also add to the north-south coverage if a Puerto Rico site were included in the VLBA.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 YELKNF

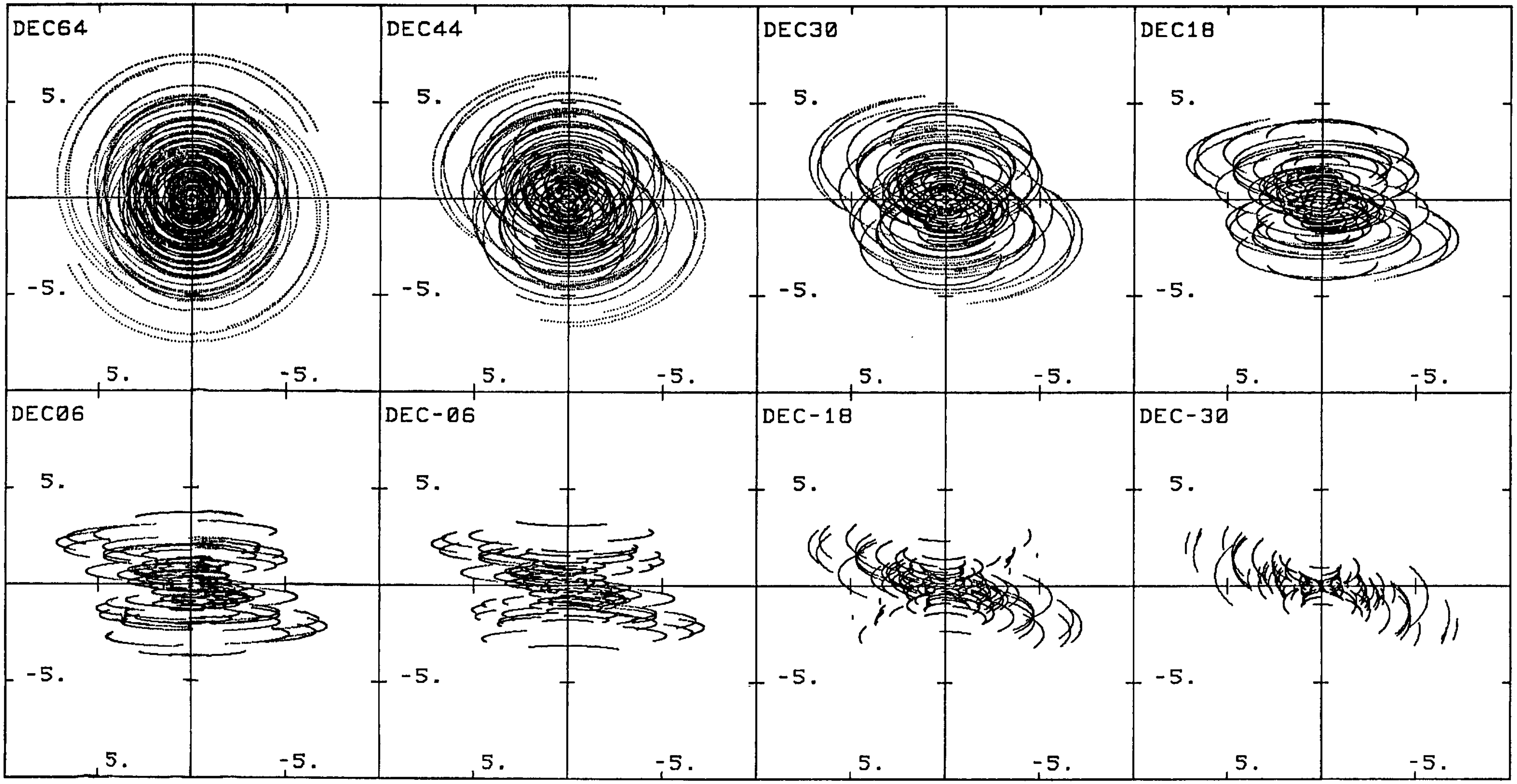
Figure V-5: The coverage of Array D2 plus a station in Yellowknife, Northwest Territories. This station is about as far north as one can go in Canada and have regular transportation and a local infrastructure of technical support. The Canadian VLB array will probably have a station in Yellowknife at the urging of the geophysicists. There is a large geophysics station in the area that could provide local support. A station this far north in Canada would make an Alaskan station unnecessary.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 PENT

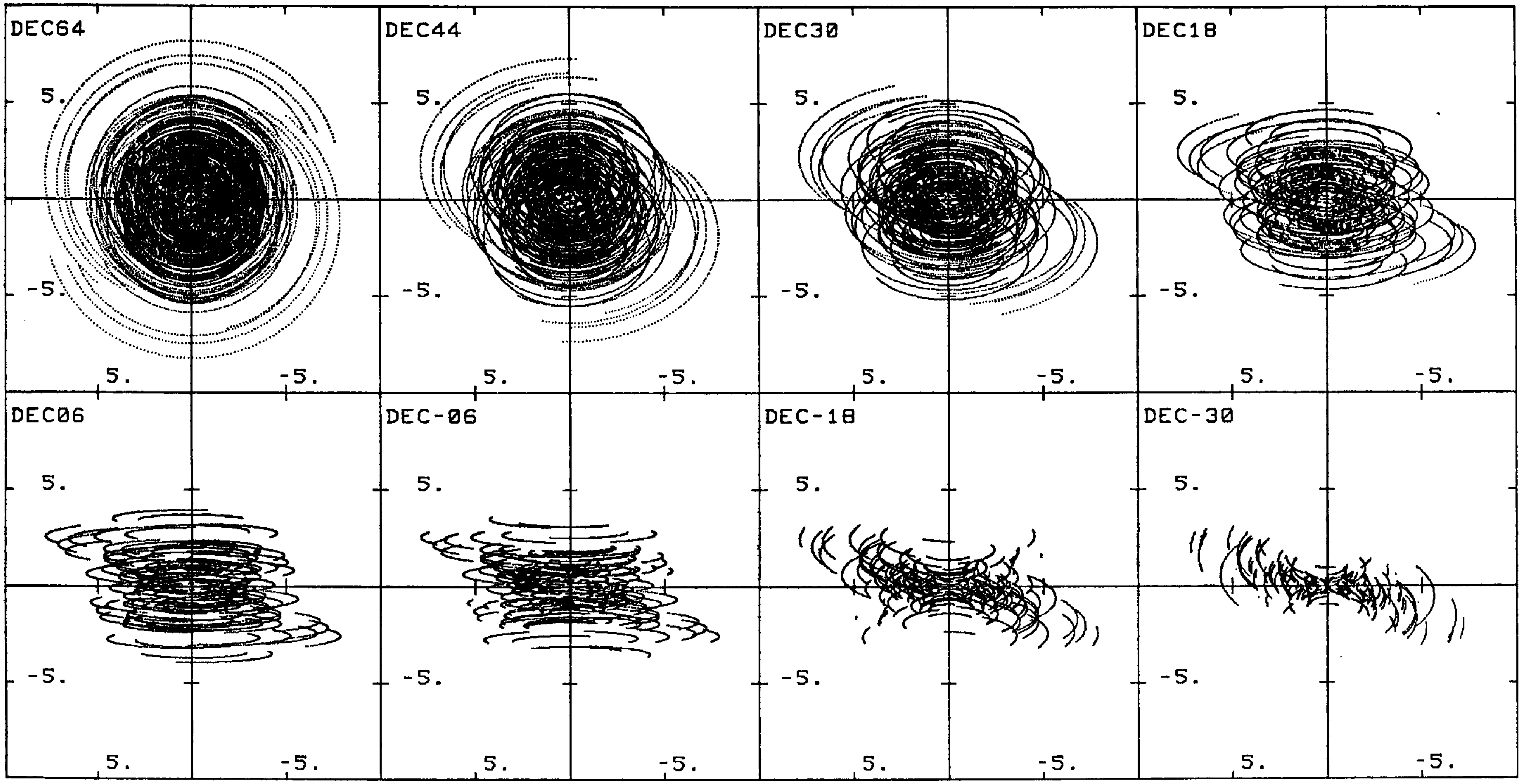
Figure V-6: The coverage of Array D2 plus a station at the radio astronomy observatory in Penticton, British Columbia. This station does not add significantly to the north-south coverage of the array because it is near the U. S. border as are most of the sites in the proposed Canadian VLB Array. However it is a developed site with local support that would make sense in a cooperative effort as long as the rest of the configuration is compatible with a Northwest station. The existing antenna at Penticton has been used for VLBI in Canada and could be used with the array at low frequencies.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ARO

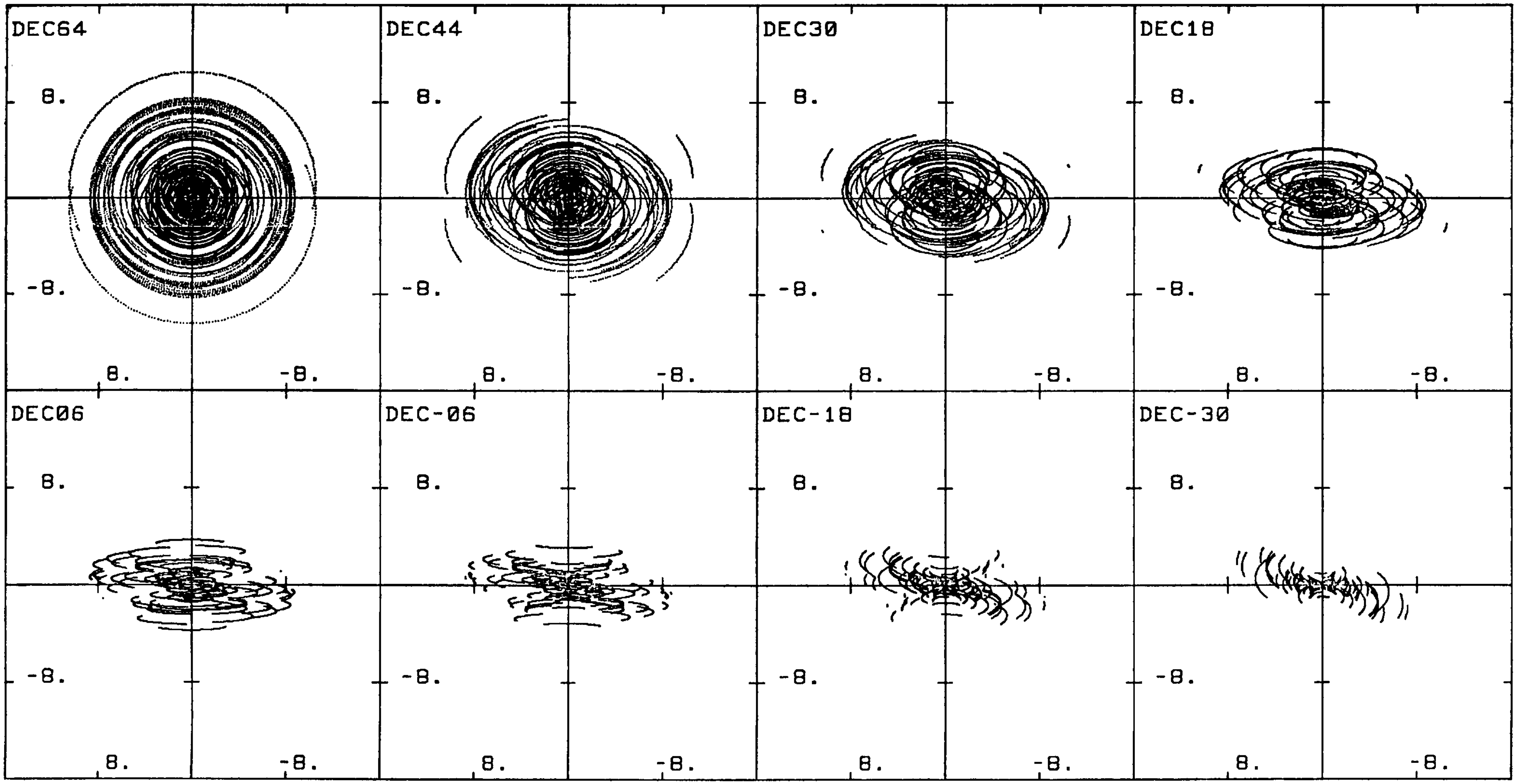
Figure V-7: The coverage of Array D2 plus a station at the Algonquin Radio Observatory. The same comments made for Penticton in Figure V-6 apply to Algonquin except that the existing antenna works up to 22 GHz and may work at much higher frequencies by the time the VLBA is built so it would make a good observatory for occasional experiments that require extra antennas.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ARO NEWF YELKNF PENT

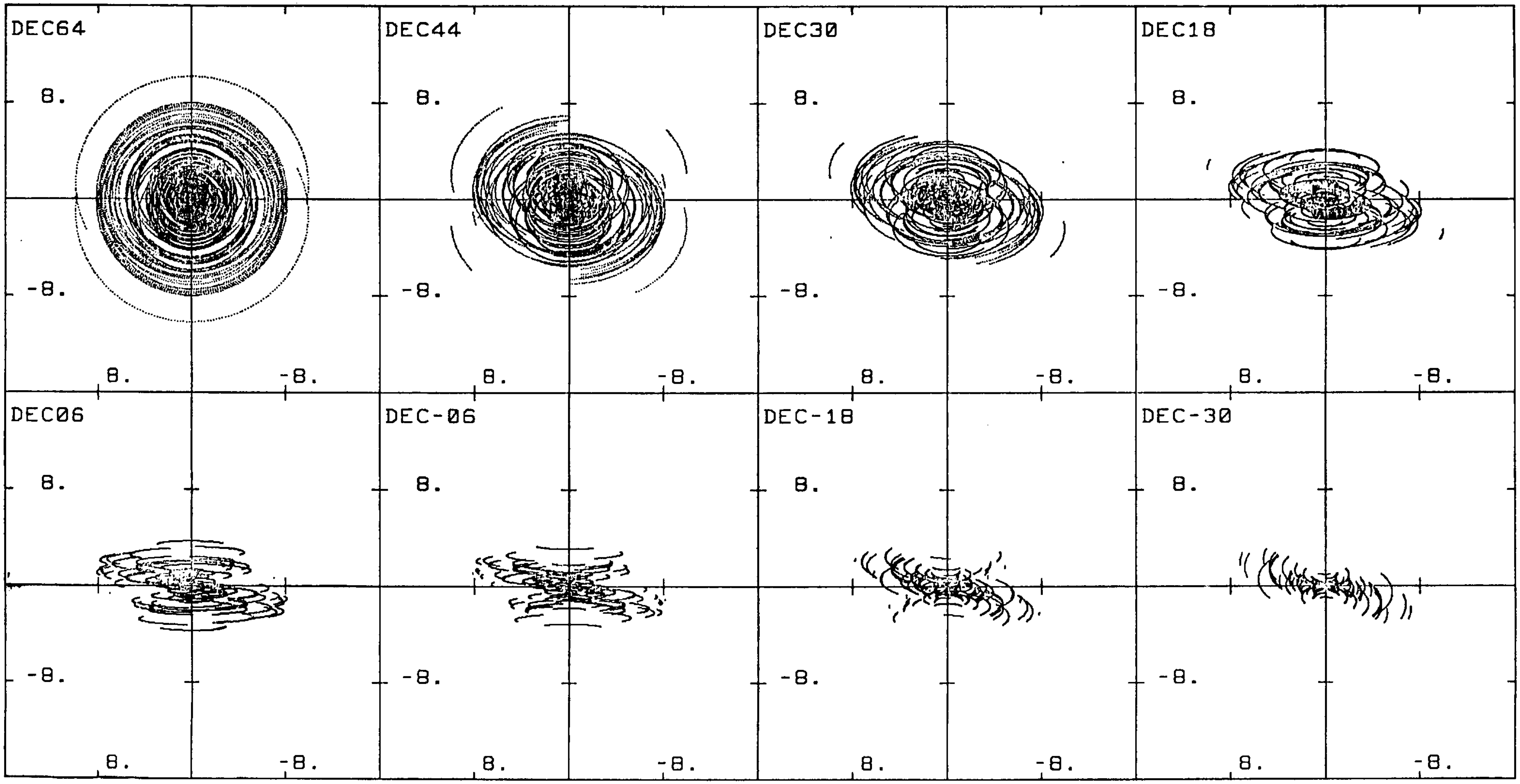
Figure V-8: The coverage of Array D2 plus the four stations shown in the last four figures - Newfoundland, Algonquin, Yellowknife, and Penticton. The main effect is to increase the density of tracks which will lead to much improved dynamic range of the maps that are made with all of these stations. The coverage shown here will be similar to the coverage that would be provided be combined observations with the proposed Canadian VLB array and the VLBA except that four additional stations would be added. The additional stations would provide short and intermediate baselines as the configuration shown includes sites near the ends of the CLBA. See Figure V-15.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 BGNA

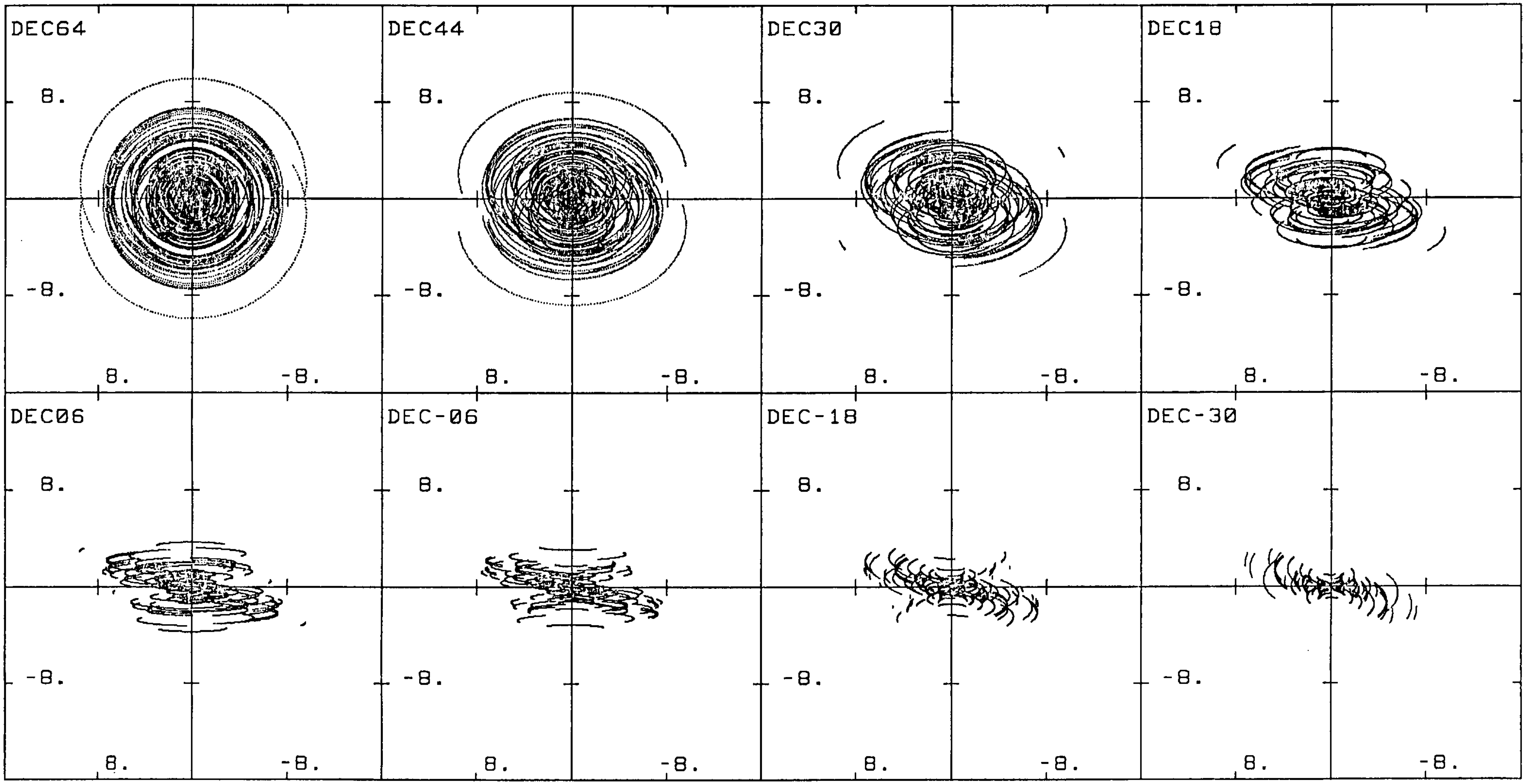
Figure V-9: The coverage of Array D2 plus a station in Bologna, Italy where a dedicated VLB antenna is currently under construction. This station has the advantage that is will be an existing, dedicated VLBI facility, but it shares the problems of all European stations - high latitude and low mutual visibility with U.S. sites for low declination sources.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 BONN

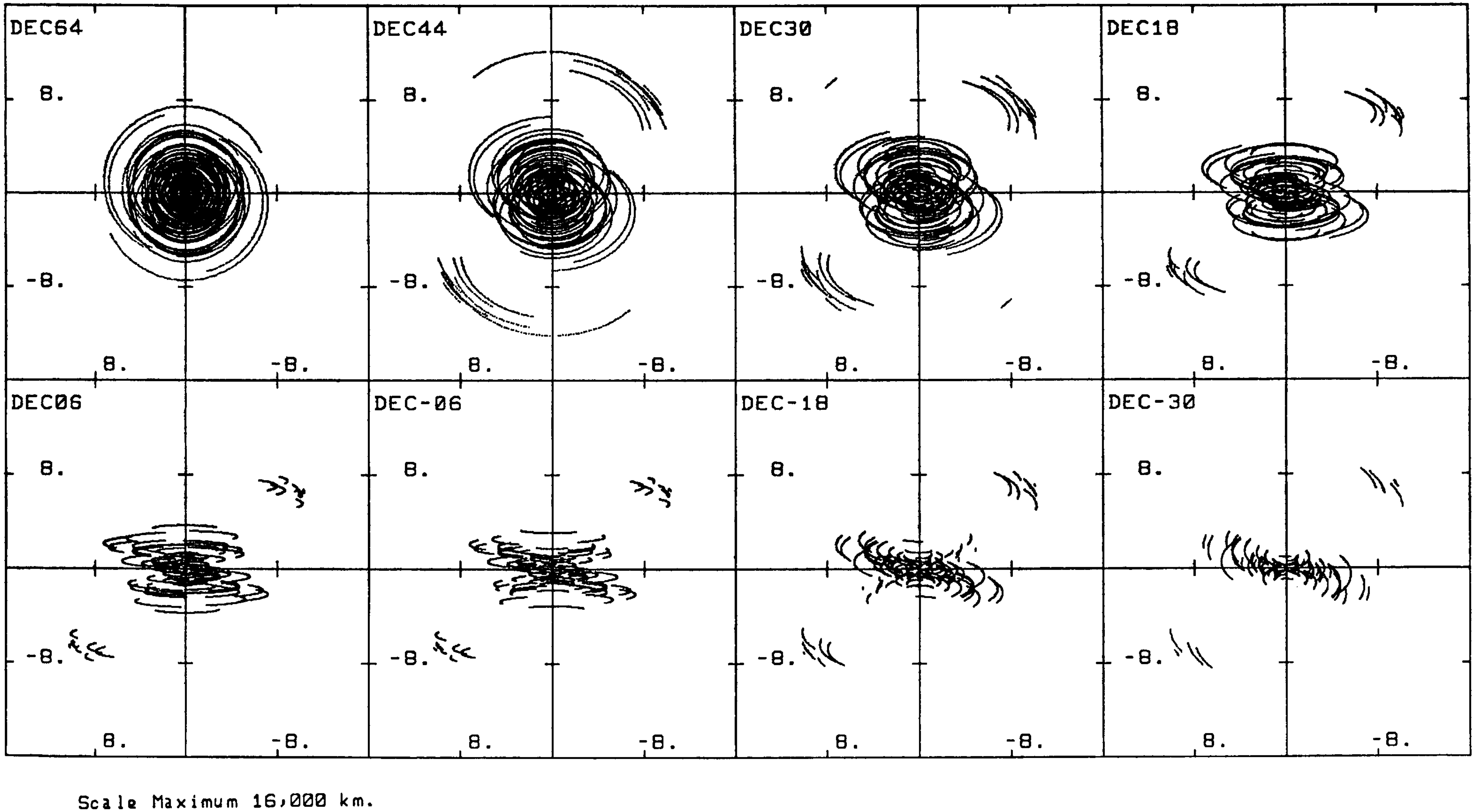
Figure V-10: The coverage of Array D2 plus a station at Bonn, West Germany where the worlds largest fully steerable antenna is now located. Observations with Bonn are hampered by the problems with Europe that have been mentioned but will be valuable, especially for high declination sources, because of the great sensitivity of the Bonn antenna.



Scale Maximum 16,000 km.

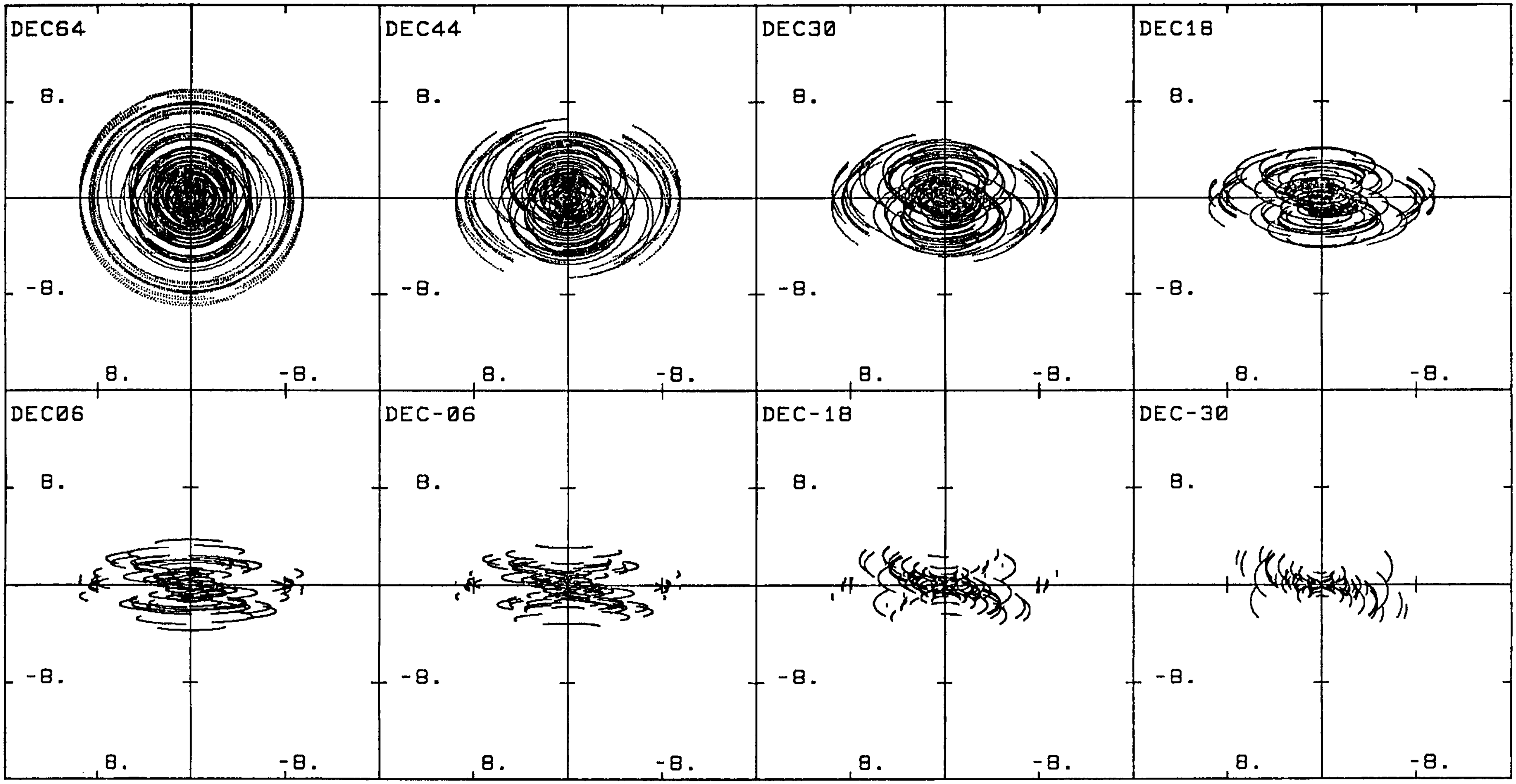
HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 JODRELL

Figure V-11: The coverage of Array D2 plus a station at Jodrell Bank, England where there are several existing telescopes and the headquarters of the Multi-Telescope-Ratio-Linked-Interferometer (MTRLI) which is the major instrument capable of filling the gap in spacings between the VLA and the VLBA.



HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 SAFR

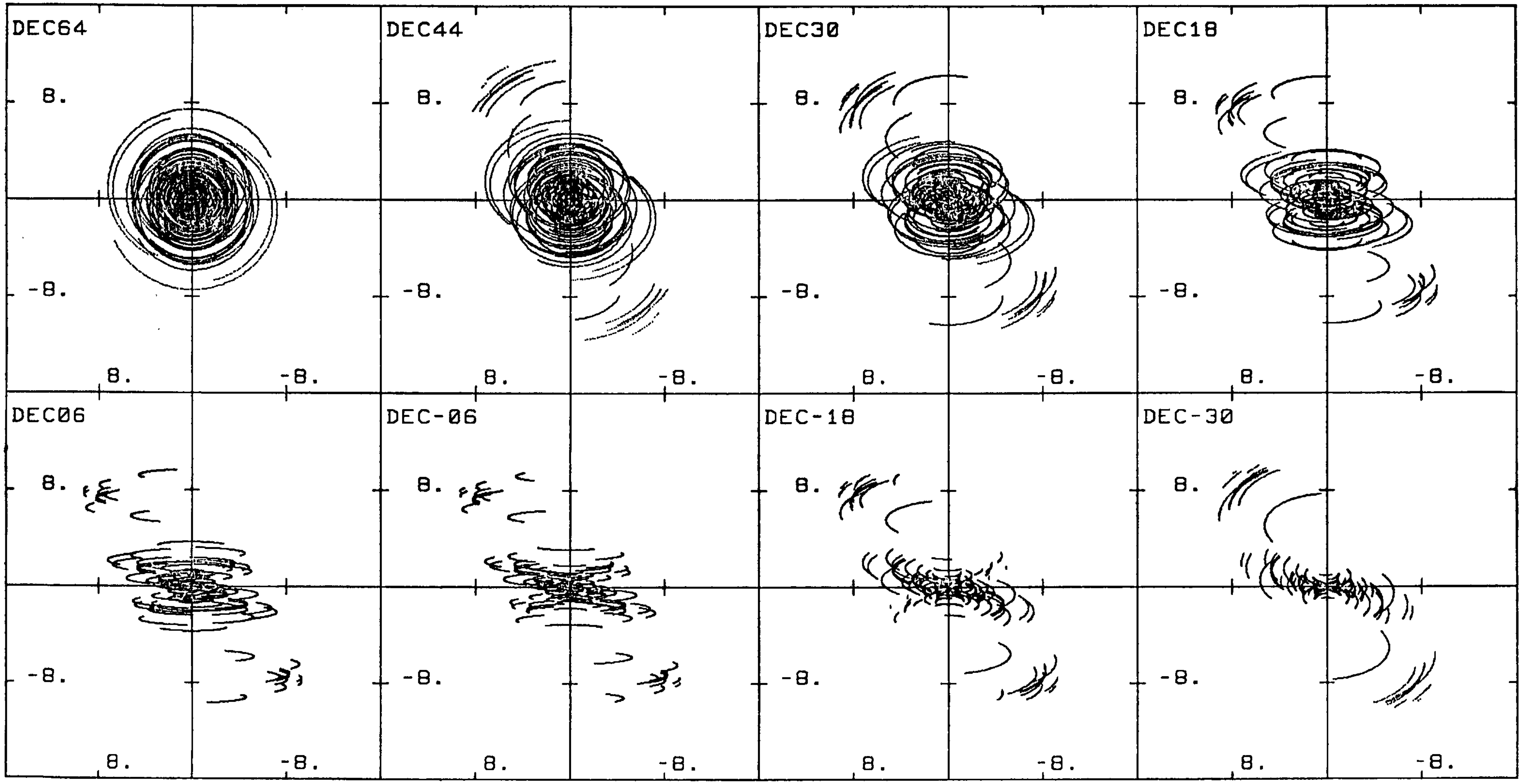
Figure V-12: The coverage of Array D2 plus a station in South Africa where there is an old NASA tracking station which is now used by the South Africans for radio astronomy, including VLBI. South Africa is so far from the U. S. that the tracks are short and there is a huge gap between the South African tracks and the tracks from stations in the VLBA. For this station to be useful, several other southern and, perhaps, European stations would be needed in order to obtain more uniform coverage.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 TOKYO

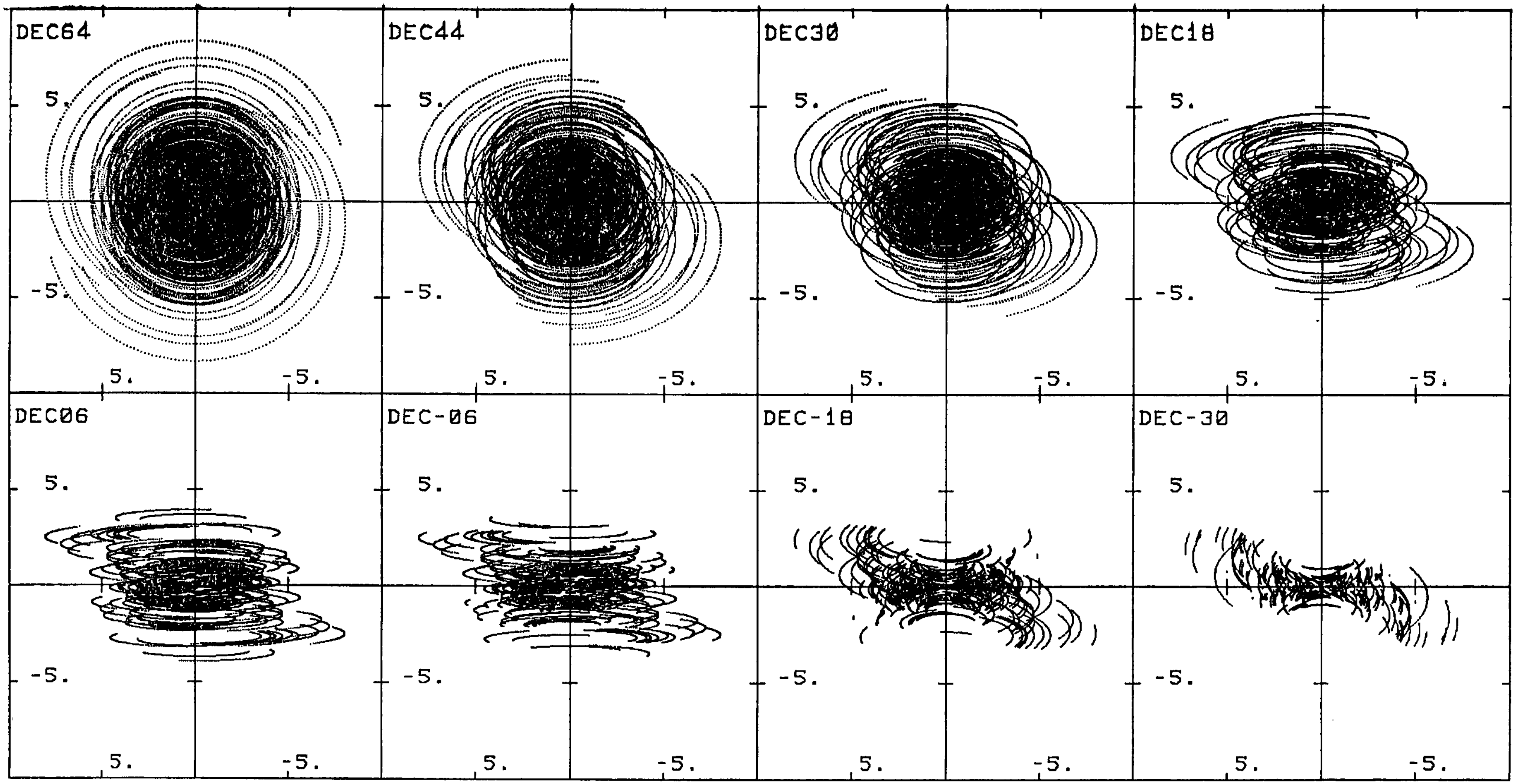
Figure V-13: The coverage of Array D2 plus a station in Japan. Japan provides some long baselines but does not dramatically help the overall u-v coverage of the VLBA. The large longitude difference between Japan and the U. S. limits mutual visibility just as in the case for Europe. However, an array of antennas scattered among Pacific islands including Japan, Hawaii, and many others plus western U.S. sites can provide very interesting coverage - much like that shown in Figure IV-7 for an array including southern stations.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 DSS43

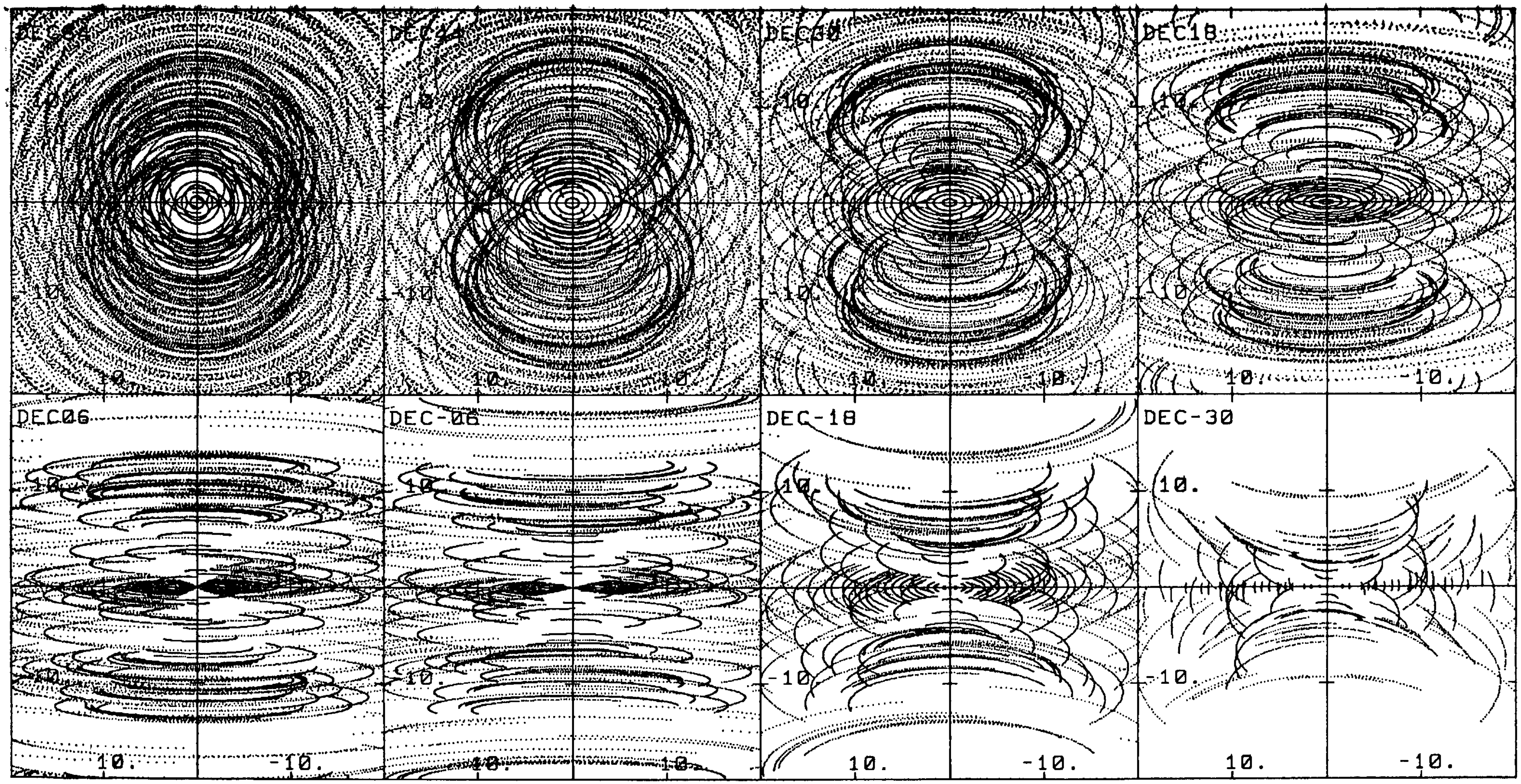
Figure V-14: The coverage of Array D2 plus a station at Tidbinbilla in Australia where NASA's Deep Space Network tracking station is located. The coverage provided by other Australian stations is similar. Australia is too far from the U.S. to provide good coverage without intermediate stations.



Scale Maximum 10,000 km.

PENT LETH MHAT SASK WEYB ATIK ARO COME YELKNF HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK

Figure V-15: The coverage of the Array D2 plus the proposed Canadian Long Baseline Array (CLBA). The CLBA has eight stations in a linear east-west configuration across Canada plus a ninth station in Yellowknife, primarily for geodedic observations. Note the great increase in the density of u-v tracks when the number of stations is nearly doubled. The number of baselines has gone up by nearly a factor of four. With the increased number of tracks, the dynamic range of maps made using both arrays will be very good. The overall boundaries of the u-v coverage of the combined array are similar to those of Array D2 alone since the CLBA does not add stations significantly outside the boundaries of Array D2. The range of spacings is increased because the CLBA has a shorter minimum spacing than Array D2.

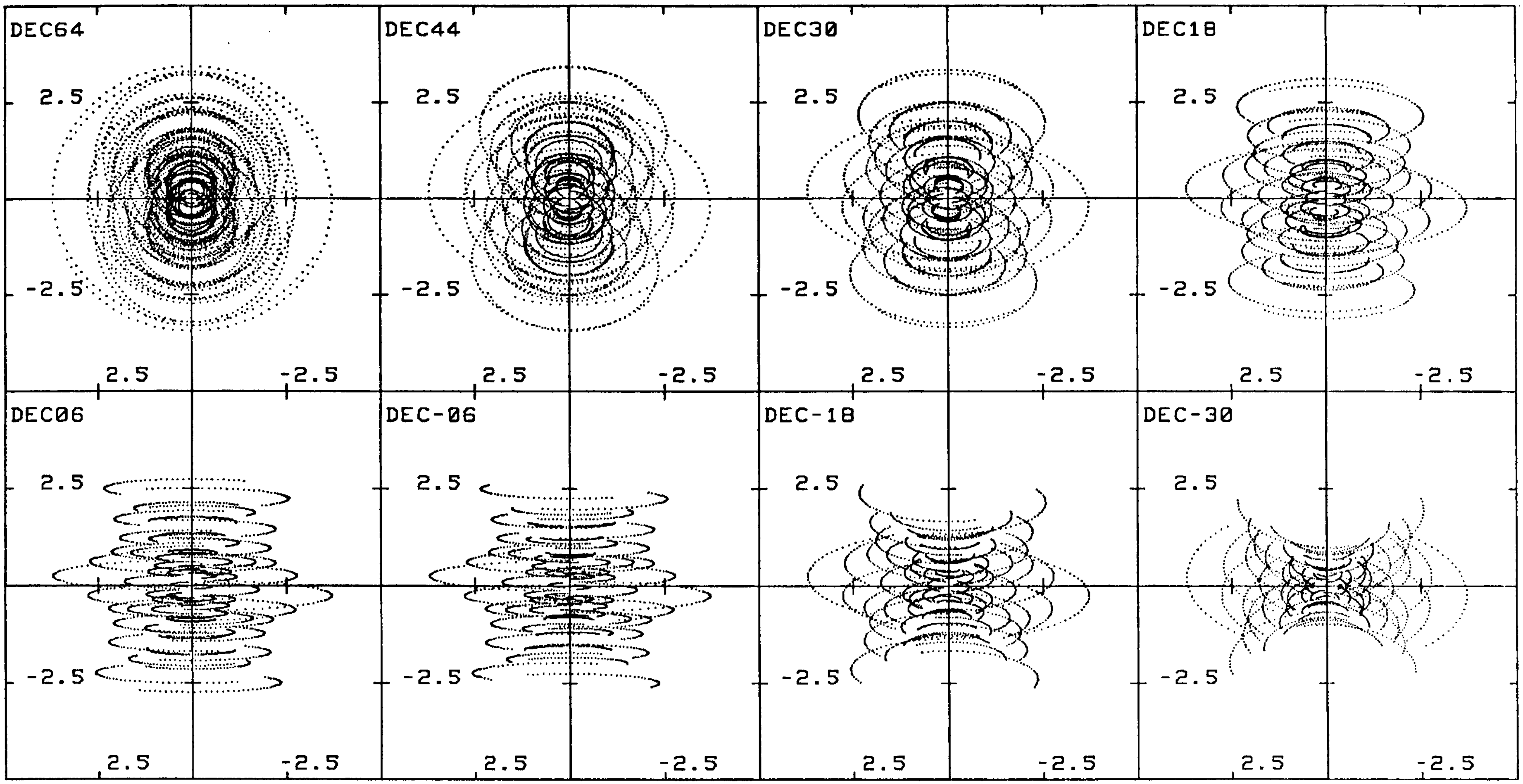


Scale Maximum 2,000 km.

BRVL2

PENT LETH MHAT SASK WEYB ATIK ARO COME YELKNF HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK

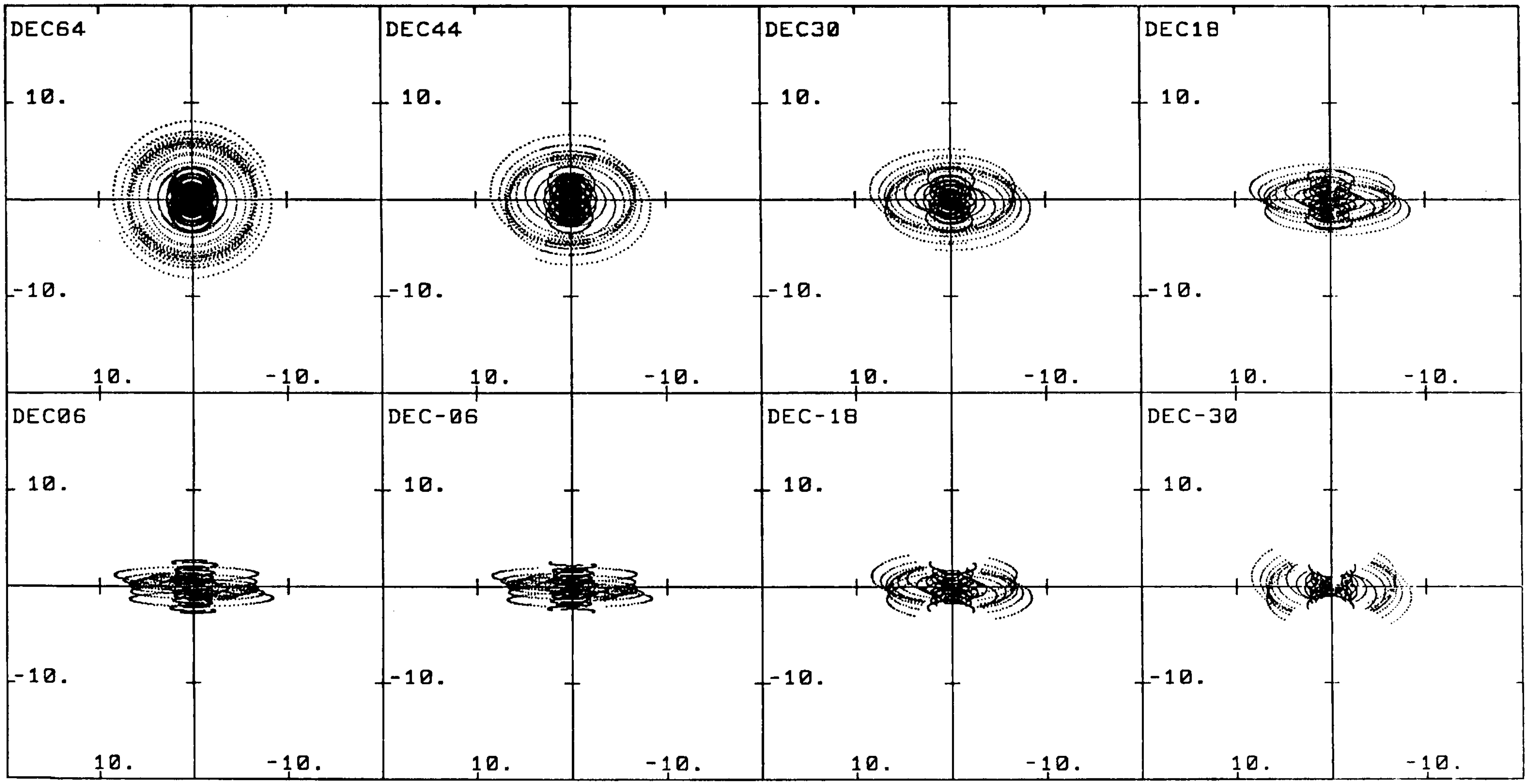
Figure V-16: The inner 2000 km of the coverage of the Array D2 plus the CLBA. Note the high density of tracks. Maps made from such coverage will begin to approach maps from the VLA in dynamic range although the VLA still has 8 more antennas than the combined VLB arrays so they still won't be as good.



Scale Maximum 50 km.

AE3 AE6 AE9 AN3 AN6 AN9 AW3 AW6 AW9

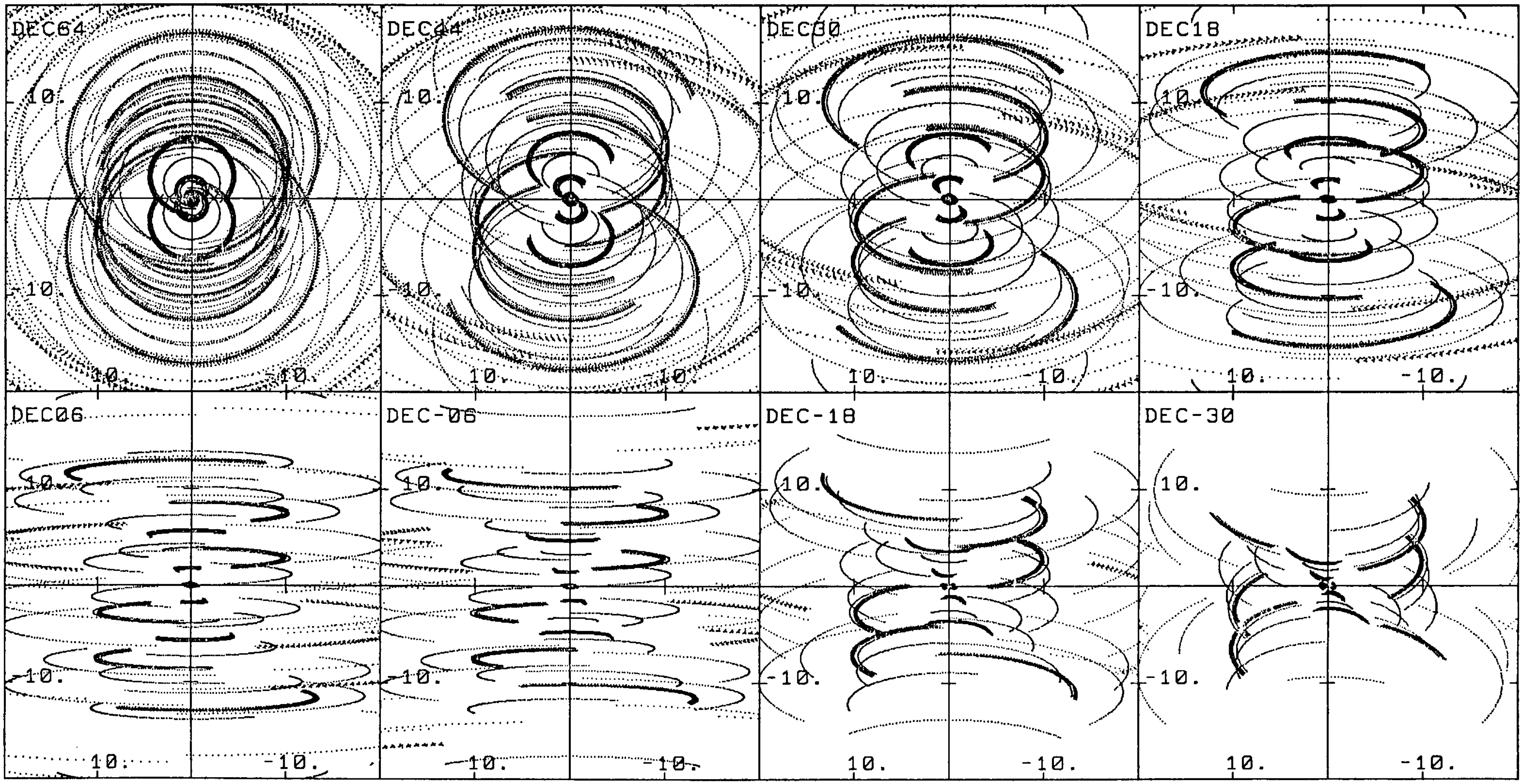
Figure VI-1: The coverage of the VLA in the A array with a scale going to 50 km. Only the tracks of every third element are shown so the overall shape and uniformity of the coverage is representative of what is normally obtained with the VLA but the density of tracks is very much lower than what is actually obtained with all 27 antennas. As can be seen, there are clear advantages in not having the geographically imposed constraints that affect the VLBA.



Scale Maximum 200 km.

AE3 AE6 AE9 AN3 AN6 AN9 AW3 AW6 AW9 SOCORRO

Figure VI-2: The coverage of the same 9 VLA antennas of Figure VI-1 plus the Socorro VLBA antenna. This may be a common observing mode for extended resolution observations with the VLA. While such observations are made, one or more of the VLA's 27 antennas could be used to replace the Socorro antenna for the ongoing VLBA observations.



Scale Maximum 2,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 AE9 AW9 AN9 AE3 AW3

Figure VI-3: The coverage out to 2000 km of Array D2 plus 5 antennas of the VLA, including the end antennas of each arm in the A configuration. The VLA plus Socorro coverage shown in Fig. VI-2 is only the dark area at the very center. There is a range of spacings arround 100-200 km that is poorly sampled.

VLB ARRAY MEMO No. 96

ARRAY DYNAMIC RANGES

Report by Richard S. Simon;

Large amounts of this work also done by:

Roger Linfield

Steve Unwin

Tom Lockhart

July 8, 1980

Array Dynamic Ranges

The following procedure was used to determine the dynamic ranges for sample arrays for the High Angular Resolution Telescope . It is a good method for ranking the quality of a given array, but only gives an approximate value for the dynamic range that can be actually be achieved.

I Test Source and Data

Dynamic ranges were determined using one of two artifical test sources, named DAISY and AMOEBA (see Table 1). For the source under consideration, an artifical data file was created. This file consisted of observations of visibility amplitude and interferometer phase for all times during a twelve hour period when the source was visible from at least 3 stations. For all positive declinations, this included the full 12 hour period. At -06 and -18 degrees declination, observing times were reduced to ~11.5 and ~9 hours, respectively. Artificial noise was added to each data point to simulate the noise for the following interferometer: 25m diameter antennae, 55% aperture efficiency, 600 second coherent integration, Tsys of 50 degrees, and 56 MHz bandwidth. This implies an actual statistical rms error of 0.005 Jy (as per MHC). Note that NO systematic errors were included in the data; this is equivalent to assuming near-perfect station calibration.

In the actual command procedures used, for convenience the noise level was scaled rather than changing the test source file. For example, the signal-to-noise ratio equivalent to a 0.5 Jy source (100:1 on zero length baseline) is correctly simulated using a 20 Jy DAISY and a statistical error of 0.2 Jy.

All things considered, I feel that DAISY is not a completely adequate test source. The extreme regularity in DAISY tends to create problems in gridding and interpolation that make for dificulties in measuring the quality of an array. These problems are easily solved, but at the expense of larger amounts of computer time because larger (finer) arrays and lower loopgains are needed to get the maximum dynamic range. A second problem is that DAISY has no large areas of very low, approximately constant surface brightness, so that dynamic ranges above ~150 may become less meaningful. If many more of these dynamic range measurements are needed in the future, I suggest that a new source be created that is similar to DAISY or AMOEBA, but with a much smoother brightness distribution and larger areas of low brightness.

II Beam Determination

Because the half-width of the dirty beam is a function of the exact way that the data is gridded into the UV plane, there is no "true" restoring beam. As a guide, however, a beam should not be too much smaller that λ/d . A uniformly weighted, filled array will give a FWHM of 1.02 λ/d; if a 30% Guassian taper is applied to a uniform array, the FWHM is 1.28 λ/d.

To find the beams used, a dirty beam was produced using uniform weighting with a 30% Guassian taper. The 50% level of this beam was assumed to be elliptical and used to define the FWHM and rotation of the restoring beam. The beams used for array 13 were found to be comparable to λ/d , in both dimensions. An alternative procedure for determining the beam might be to measure the raw FWHM of the dirty beam (from uniform, un-tapered weighting) and then scale that beam up until the shortest dimension equaled a factor times λ/d ; a typical factor might be 1.0 .

III Inversion and Cleaning

For the actual fourier inversion of the data, uniform weighting was used to avoid any complications in convolution of the map before cleaning. The dirty map was cleaned with the appropriate beam (uniform weighting of the UV points). A loopgain of 0.4 for 2500 iterations was used for the cleaning; I suspect that a lower loopgain (say, ~0.1) and more iterations (~5000?) would have given higher dynamic ranges in some cases.

Both sources had the brightest component centered at the origin. For the DAISY source, a window 20 mas on a side centered on +5,+5 was cleaned; for the AMOEBA source, the same size window was cleaned, but centered on the brightest component. The large array sizes were needed especially at the lower declinations to prevent spurious components from appearing near the edges of the clean map. The default XYINT and MAPSIZE were used in invert; this resulted in a MAPSIZE of 256 and an XYINT of 0.198 mas for IDIM=256. For declinations greater than 18 degrees, IDIM=128 gave results essentially identical to those from IDIM=256, and only took ~1/6 the elapsed time on the VAX. For this latter case, it is necessary to shift the DAISY before inversion so that the brightest component lies at -5,-5 mas.

IV Dynamic Range Calculation

The set of delta functions resulting from clean was subtracted from the original model, to produce a difference model. This difference model was then convolved with the restoring beam and plotted. If a perfect map were possible, the difference map would be of zero brightness level everywhere. Because of errors in the clean map, the difference maps all had positive and negative regions, corresponding to deficits or excesses on the clean map. The absolute value of the peak brightness on the difference map was determined (outside of the "core" region on the original map). Then, the dynamic range for a given map was defined as the ratio of the peak brightness of the original map (after convolution with the restoring beam) to the peak brightness of the difference map.

V Tables

Table 1: Test Sources

DAISY:

Flux	R	Theta	Axis	Ratio	P. A.
10.0	7.071	-135.0	0.9	1.0	0.0
0.5	5.831	-149.036	1.0	1.0	0.0
0.5	5.099	-168.690	1.0	1.0	0.0
0.5	5.099	168.690	1.0	1.0	0.0
0.5	5.831	149.036	1.0	1.0	0.0
0.5	7.071	135.000	1.0	1.0	0.0
0.5	5.165	-140.752	1.0	1.0	0.0
0.5	3.370	-152.889	1.0	1.0	0.0
0.5	2.010	174.399	1.0	1.0	0.0
0.5	2.172	117.412	1.0	1.0	0.0
0.5	3.660	90.0	1.0	1.0	0.0
0.5	5.165	-129.248	1.0	1.0	0.0
0.5	3.370	-117.111	1.0	1.0	0.0
0.5	2.010	-84.399	1.0	1.0	0.0
0.5	2.172	-27.412	1.0	1.0	0.0
0.5	3.660	0.0	1.0	1.0	0.0
0.5	5.831	-120.964	1.0	1.0	0.0
0.5	5.099	-101.310	1.0	1.0	0.0
0.5	5.099	-78.690	1.0	1.0	0.0
0.5	5.831	-59.036	1.0	1.0	0.0
0.5	7.071	-45.0	1.0	1.0	0.0

AMOEBA:

Flux	R	Theta	Axis	Ratio	P.A.
10.000	0.000	0.000	0.800	1.000	0.000
2.500	5.000	0.000	6.000	0.500	90.000
2.500	5.000	30.000	6.000	0.500	120.000
2.500	5.000	60.000	6.000	0.500	150.000
2.500	5.000	90.000	6.000	0.500	0.000

Table 2: Station Lists for Arrays Tested

Array#	# of Stations	Station List
13	10 Stations	HNLU,HSTK,ANCH,LRDO,IOWA,DSS13,BLDR,BOISE,OVRO,SALEM
15	9 Stations	HNLU,HSTK,ANCH,LRDO,IOWA,DSS13,BLDR,BOISE,PASC

Table 3: Dynamic Ranges for Array 13, for DAISY source

Flux	Declination, Degrees -->						
	64	44	30	18	06	-06	-18
10 Jy	339			266			88
2	327			265			88
0.5	204	205	206	168	95	66	73
0.2	103			105			65
0.1	61			60			38

Table 4: Dynamic Ranges for Array 13 for AMOEBA

Flux	Declination, Degrees -->						
	64	44	30	18	06	-06	-18
0.5 Jy	231			155			90

Table 5: Beams for Array 13

Declination	Short Axis	Long axis	Theta
64.	.77 mas	.80 mas	-32. degrees
44.	.76	.85	-22.
30.	.76	.94	-16.
18.	.80	1.07	-13.
06.	.85	1.24	-14.
-06.	.80	1.52	-10.
-18.	.70	2.10	-12.

Table 6: Dynamic Ranges for Array 15 for DAISY

Flux	Declination, Degrees --> 64	44	30	18	06	-06	-18
0.5 Jy	147	128	177	144	95	78	76

Table 7: Beams for Array 15

Declination	Short Axis	Long axis	Theta
64.	.72 mas	.78 mas	-17. degrees
44.	.75	.84	-15.
30.	.73	.91	-18.
18.	.81	1.03	-17.
06.	.82	1.20	-13.
-06.	.80	1.49	-10.
-18.	.70	1.96	-11.

VI Command Procedures

The following are samples of command procedures that were used to determine beams and produce clean maps for array 13. Each is more or less self contained, so that the correct version of any particular file is used. To actually measure the peak on the difference map, program MODPLOT was used, using the options: PIXELS=200 DEGREES LRTB=-15,5,15,-5 and CONTOURS . For the AMOEBA source, a window of LRTB=-10,10,10,-10 was used. Both sources had the brightest component centered at the origin.

A Beam Command Procedure:

```
$ ASSIGN [RSS]1364.LOG SYS$PRINT
$ SET WORKINGSET/LIMIT=256
$ SET DEF [VLB.RSS.DAISY]
$ ASSIGN/U 1364.LIS  FOR006
$ ASSIGN/U [VLB]STATIONS.DAT STATIONS
$ ASSIGN/U [VLB]SOURCES.DAT SOURCES
$ RUN [VLB]FAKE
  1364.MRG
  DAISY.N03
RA 00:00:01  DEC 64:00:00
START=19:00:00 STOP=06:50:00  NUP=3
  FREQ 10650  INTEG 600  SOURCE 'DAISY.N03'
NOCLOSE
STATIONS 'HNLU',
'HSTK','OVRO','BOISE','ANCH','LRDO','IOWA','DSS13','BLDR','SALEM'
TIMESCALE 40  ERRADD=0.20  /
$ ASSIGN/U [SCRATCH]1364INVP.RSS PLOTOUT
$ ASSIGN/U [SCRATCH]1364INVL.RSS FOR006
$ ON ERROR THEN GOTO END
$ INVERT/IDIM=256/MAXP=4000
FROM '[VLB.RSS.DAISY]1364.MRG'
MAPFILE 'NL:'
BEAMFILE 'NL:'
CONTOUR=-13,-11,-9,-7,-5,-3,-1,1,3,5,7,9,11,13,50
UVTAPER=.30  NOMAP
FLUX 20    PRINTUV  PLOTMAP=10 PLOTBEAM=1.0
$ RUN [VLB]UVPLOT
1364.MRG
[SCRATCH]1364.RSS

$    PRINT/NOFEE/NOFLAG/DEL/HOLD/QUE=LPA0: [SCRATCH]1364INVL.RSS,-
     [SCRATCH]1364INVP.RSS,-
     [SCRATCH]1364.RSS,-
     [VLB.RSS.DAISY]1364.BM/NODELETE
```

```
$ END:
$ SEND TTA0: JOB 1364 HAS NOW FINISHED
```

B Invert and Clean Command Procedure:

```
$ ASSIGN [RSS]1364.LOG SYS$PRINT
$ SET WORKINGSET/LIMIT=512
$ SET DEF [VLB.RSS.DAISY]
$ ASSIGN/U 1364.LIS  FOR006
$ ASSIGN/U [VLB]STATIONS.DAT STATIONS
$ ASSIGN/U [VLB]SOURCES.DAT SOURCES
$ RUN [VLB]FAKE
  1364.MRG
  DAISY.N04
RA 00:00:01  DEC 64:00:00
START=19:00:00 STOP=06:50:00  NUP=3
  FREQ 10650  INTEG 600  SOURCE 'DAISY.N04'
NOCLOSE
STATIONS 'HNLU',
'HSTK','OVRO','BOISE','ANCH','LRDO','IOWA','DSS13','BLDR','SALEM'
  TIMESCALE 40  ERRADD=0.20    ERRMULT=0.00  /
$ ASSIGN/U [SCRATCH]1364INVP.RSS PLOTOUT
$ ASSIGN/U [SCRATCH]1364INVL.RSS FOR006
$ ON ERROR THEN GOTO END
$ INVERT/IDIM=512/MAXP=4000
FROM '[VLB.RSS.DAISY]1364.MRG'
MAPFILE '[SCRATCH]MAP1364.RSS'
BEAMFILE '[SCRATCH]BEAM1364.RSS'
CONTOUR=-5,-3,-1,1,3,5,7,9,11,13,50
FLUX 20   PRINTUV  PLOTMAP=20 PLOTBEAM=1.0    /
$ ASSIGN/U [SCRATCH]1364CLNL.RSS FOR006
$ ASSIGN/U [SCRATCH]1364CLNP.RSS PLOTOUT
$ ON ERROR THEN GOTO END
$ CLEAN/SIZE=256/MAXIT=2500
BEAM=.77,.80,-32.
LOOPGAIN = 0.40 NITER = 2500
MAPFILE = '[SCRATCH]MAP1364.RSS'
BEAMFILE = '[SCRATCH]BEAM1364.RSS'
MODEL = '[VLB.RSS.DAISY]1364.MAP'
LRTB -15,5,15,-5 PLOTWINDOW
PRINTRES  NORESTORE PLOTMAP  /
$ PURGE [SCRATCH]*.RSS
$ RUN [VLB]MODSUM
DAISY.N04
1.
1364.MAP
-1.

1364.SUB
N
$ ON ERROR THEN GOTO END
$ RUN [VLB]MODPLOT
DAISY.N04
TTB4
10650.
.6
BEAM=.77,.80,-32.
LRTB -15,5,15,-5 CONT -1,-.5,.5,1,1.5,2,2.5,3,3.5,4,4.5,5,5.5,6,6.5,7,
10,50  TITLE 'DAISY.N04, DEC64 BEAM, 1364 STA  ARRAY' PIXEL 200 PPRINT   /
Y
MODFILE '1364.MAP' TITLE '1364.MAP, DEC64 BEAM, 1364 STA ARRAY' /
Y
```

```
MODFILE '1364.SUB' TITLE 'DAISY.N04-1364.MAP, 1364 STA ARRAY'
LRTB -15,5,15,-5  DEGREES  CONT (-8*7.53),
(-7*7.53),(-6*7.53),(-5*7.53),(-4.5*7.53),(-4*7.53),(-3.5*7.53),(-3*7.53),
(-2.5*7.53),(-2*7.53),(-1.5*7.53),(-1*7.53),(-.5*7.53),
(.5*7.53),(1*7.53),(1.5*7.53),(2*7.53),(2.5*7.53),(3*7.53),(3.5*7.53),
(4*7.53),(4.5*7.53),(5*7.53),(6*7.53),(7*7.53),(8*7.53)  /
N
$ RENAME MODPLOT.LIS [SCRATCH]1364PLOT.RSS
$ RUN [VLB]UVPLOT
1364.MRG
[SCRATCH]1364.RSS

$    PRINT/NOFEE/NOFLAG/DEL/HOLD/QUE=LPA0: [SCRATCH]1364INVL.RSS,-
     [SCRATCH]1364INVP.RSS,1364CLNL,1364CLNP,-
     1364PLOT,1364.RSS,-
     [VLB.RSS.DAISY]1364.HYB/NODELETE
$ END:
$ SET PROTECTION=(O:RWED,S:RE,W:RE,G:RE) [SCRATCH]*.RSS
$ SEND TTA0: JOB 1364 HAS NOW FINISHED
```

VLB ARRAY MEMO No. 49

STUDIES OF ARRAY DYNAMIC RANGES

by
Roger Linfield (Caltech)

I. INTRODUCTION

During December 1981 I did some simulations of source-mapping with a 10-station VLBI Array. In all of these simulations, I used

1) VLB:FAKE to produce data with random (and, in some cases, systematic) errors

2) The standard Caltech mapping package, involving AMPHI (when relevant), INVERT, and CLEAN

3) Array 13 (HSTK, IOWA, LRDO, BLDR, BOISE, SALEM, GSTN, OVRO, ANCH, and HNLU)

4) DECLINATION 64^{0}
(This allowed different results to be more easily compared, and also eased the computational requirements, as discussed in the Appendix)

The bulk of the simulations used DAISY as a test source, but I also did some mapping with a new test source, CEREBRUM (see Table 1 and Figure 1).

Note - AMPHI is Steve Unwin's (CIT) implementation of Tim Cornwell's MTRLI gain solution algorithm. RCW.

II. RESULTS

The dynamic ranges of the maps I made are displayed in Table 2. The variation of dynamic range with S/N for the full phase, perfect calibration case (row 1 of Table 1) can be qualitatively understood. Below ~1 Jy source strength, the dynamic range increases rapidly with increasing source strength; the S/N ratio is the main limitation to the dynamic range. Above ~1 Jy source strength, the dynamic range increases only slowly with increasing source strength. This happens because holes in the u-v coverage are the main limitation to the dynamic range in this regime.

Row 2 of Table 2 shows the results obtained when one goes to 24 hour tracks (a δ=64 source is circumpolar at 7 of the 10 stations). The increase in dynamic range is greatest for strong sources, for which the dynamic range is limited by u-v coverage, rather than by S/N.

Row 3 of Table 2 gives the dynamic range obtained with perfectly calibrated amplitudes, but random phases (i.e. only closure phases available). The degradation in dynamic range caused by the loss of full phase information is ~10%, except for the lowest S/N case, where it is 20% (closure phases are on average $\sqrt{3}$ times noisier than phases; this is an important effect at low S/N). The loss of phases reduces the amount of data (45 amplitudes + 45 phases) by 9, or 10%. The fact that this is mirrored so closely in the measured values of dynamic range is strong evidence that 1) software limitations are not significant at the 0.3% level in these simulations, and 2) the RMS measurement of dynamic range is a meaningful one.

Note that a point source starting model was used for all the hybrid mapping that went into Table 2.

The results for cases involving amplitude calibration errors are less satisfying. Rows 5 and 6 of Table 2 give results where small, systematic amplitude errors were introduced, in an attempt to simulate 10 GHz data. These errors are of three kinds

1) Station-dependent errors, correlated on a timescale of ~30 minutes. They simulated bad weather and pointing problems. For most stations, values of 0-2% were used, but they were a bit larger for HSTK and HNLU, and ranged from 0-10% for LRDO (corresponding to quite bad weather there).

2) Station GAIN errors of 0-2% (the same throughout the track)

3) Baseline errors of 0-.4% (simulating the errors of some future, well-understood correlator)

When a hybrid map was made from this data, letting AMPHI adjust the phases but not the amplitudes, a dynamic range of 168 (for S=20 Jy) resulted. When AMPHI was allowed to adjust the amplitudes as well as the phases, a much cleaner looking map resulted (i.e., the largest spurious features visible on the map were several times smaller than in the previous case). However, the relative fluxes of various features were wrong by several percent (in particular, the core was ~6% too strong), and a simple measurement of D.R. was not possible. When the D.R. was measured in the usual way, it came out to be 158. When the core flux was allowed to vary relative to the rest of the source, the D.R. increased to 207. I feel that even this is an underestimate of the quality of the map, but I see no reasonably objective way to vary component fluxes outside the core. My feeling is that for most purposes (one usually does not wish to know component fluxes to 5%), small amplitude errors have only a minor effect on the useful information that can be obtained with 10 station data. For weak (<~.5 Jy) sources, the effect should be negligible.

The bottom row in Table 2 gives the results when large systematic errors are introduced by FAKE, to simulate data at high (~20-40 GHz) frequencies. (I put in time-varying errors that at times reached 50% for the worst stations, and station GAIN errors of 0-10%). Hybrid mapping converged quickly (4 Iterations for a 20 Jy source; 2 Iterations for a .5 Jy source) from a point source starting model to a poor map, with DR~48 independent of source strength. This value of D.R. is a good measure of the quality of these maps, as there are (relatively) large, spurious features.

In this case, hybrid mapping has failed, as the resulting maps did not produce a good fit to the closure amplitudes. A better starting model is needed. Unfortunately, producing a good starting model is difficult when there are large amplitude errors. <u>I think that mapping sources using data with large calibration errors will be a major problem, even with AMPHI and 10 stations. More work on this problem is needed.</u>

OTHER TEST SOURCES

Hybrid mapping works well on DAISY (and presumable AMOEBA as well), since both are dominated by a bright, compact core. A point source works well as a starting model. Many, but by no means all, sources observed with VLBI are indeed dominated by a bright core. The values for D.R. measured for DAISY (and AMOEBA) are therefore relevant, but they do not tell the whole story. I therefore made up the test source CEREBRUM (Table 1 and Figure 1), with a complexity akin to that of 3C 84.

The full phase, perfect calibration case for CEREBRUM is illustrated in Table 3. The values are comparable to those with DAISY, but with a much steeper falloff with decreasing S/N. I do not know the reason for this difference.

I had time for only one test of hybrid mapping on CEREBRUM, and even it was not completed when I left (the files are in my disk area if someone wishes to continue the process). I started out with a point source, and ran 6 iterations. At that point, the dynamic range was only ~40, with the ratios of the two brightest features wrong by 10%. The map was converging slowly in the right direction, and with a suffient number (100?) of iterations, might have reached the correct solution. However, I chose to help the process along, by the following procedure.

I looked at the output map from the sixth iteration, picked the top 6 features, measured approximate dimensions and fluxes from the map, and made up a model of 6 Gaussian components. I then let VLBFIT adjust the component fluxes, shapes, etc. to optimize the fit. The resulting model was used as input to hybrid mapping. I think that my knowledge of the source did not influence me greatly in this procedure, but the fact that CEREBRUM is composed of Gaussians means that the procedure worked better than it would for a real source. (A large amount of effort with model fitting could make up for the non-Gaussian nature of a real source)

I then ran 11 iterations of hybrid mapping, until I ran out of time (each iteration required 70 minutes of CPU time). The map got better with each iteration; the dynamic range increased by 20-30 each time, and was 267 on the eleventh iteration. I leave it to the reader to guess how high a D.R. could ultimately be achieved. Hybrid mapping seems to converge much

– No AP

more rapidly when the source is dominated by a bright core.

The enormous computing requirements for producing high dynamic range hybrid maps provides a strong incentive for investigating other techniques (e.g. maximum entropy) for producing maps. Reliability tests of MEM mapping programs would be very useful.

APPENDIX: METHODS

I first investigated the dependence of D.R. on CLEAN parameters (NITER, LOOPGAIN, map size). I found that for $\delta=64^{\circ}$, 128x128 maps had as large a D.R. as 256x256 maps(This is not true for $\delta<=18^{\circ}$). I finally decided on NITER=4000, LOOPGAIN=.2 as producing the best maps (a smaller value of NITER, or a larger value of LOOPGAIN definitely gave poorer results). For CEREBRUM, which has large areas of low surface brightness, I needed to remove 8000 delta functions (NITER=8000, LOOPGAIN=.2). I used a CLEAN window 20 mas on a side, and then excluded a strip 2 mas wide around the border, as this contained large ridges of emission which I believe to be caused by the interaction of the regular features in DAISY with the software (a real source would have less regular structure, and the problem would not arise).

Subtracting the map from the FAKE source model produced a difference map. In the Caltech Array Report we defined the Dynamic Range as the ratio of map peak to the peak of the difference map (excluding small regions around the bright compact components). An alternative method is to take the ratio of the map peak to 5 times the RMS of the difference map (again excluding small regions around very bright components). I found that the two methods agreed fairly well, but I have used the RMS method here because 1) it is more objective in the case where there are spurious features near, but not coincident with, bright map components 2) it varies more smoothly with source strength, and 3) it is less sensitive to the details of the noise in the data (see Table 4 and accompanying description).

For the D.R.'s quoted here, I measured the RMS in a +/-8 mas window centered on the source (see Richard Simon for details on how to do this). I then measured the RMS in a square box +/-0.6 mas wide, centered on the core, and did a weighted subtraction, to obtain a net RMS (I used 160 pixels for the +/-8 mas plot, and 12 pixels for the +/-0.6 mas plot). For CEREBRUM, I used two +/-0.6 mas boxes, one centered on each of the two brightest components. The quoted D.R. is the map peak divided by 5 times the net RMS.

In cases where full phase information was available, absolute position information was retained, and map registration was not a problem. For maps made with closure phase, registration is a problem. Substantial effects arise when the map and FAKE model are misaligned by as much as 0.001 mas. A prominent feature appears at the core of the resulting difference map, positive on one side, negative on the other. When alignment is perfect, there is an alternation of positive and negative features distributed along the long axis of the beam, within ~0.5 mas of the core. To correct the registration problem, I shifted the map until the difference map had the appearance of perfect alignment (the shift was typically 0.005-0.01 mas, and was in PA 45° for DAISY, PA -95° for

CEREBRUM). When the map is shifted correctly, the RMS of the difference map is nearly at a minimum (I did not adjust the shift to minimize the RMS, because this would introduce a degree of freedom not present when I measured the RMS of full phase maps).

For maps made with data possessing calibration errors, it was necessary to adjust the flux scales, as well as the positions. The simplest way of doing this is to multiply the map by a factor which sets the peak of the convolved map equal to the peak of the convolved FAKE model.

TABLE 1

CEREBRUM MODEL

3.000	1.000	180.000	0.300	0.800	17.000	1
3.000	2.767	49.558	1.700	0.600	70.000	1
0.400	3.820	-149.690	2.000	0.800	30.000	1
5.000	1.114	-37.889	5.000	0.700	10.000	1
1.000	2.236	116.565	3.000	0.100	100.000	1
3.000	2.000	0.000	0.500	1.000	0.000	1
2.000	2.324	56.050	6.000	0.500	40.000	1
1.000	0.657	-51.367	1.200	0.500	-20.000	1
0.600	1.000	180.000	4.000	1.000	0.000	1
1.000	1.993	174.990	8.000	0.950	6.000	1

Figure 1

'CEREBRUM' test source

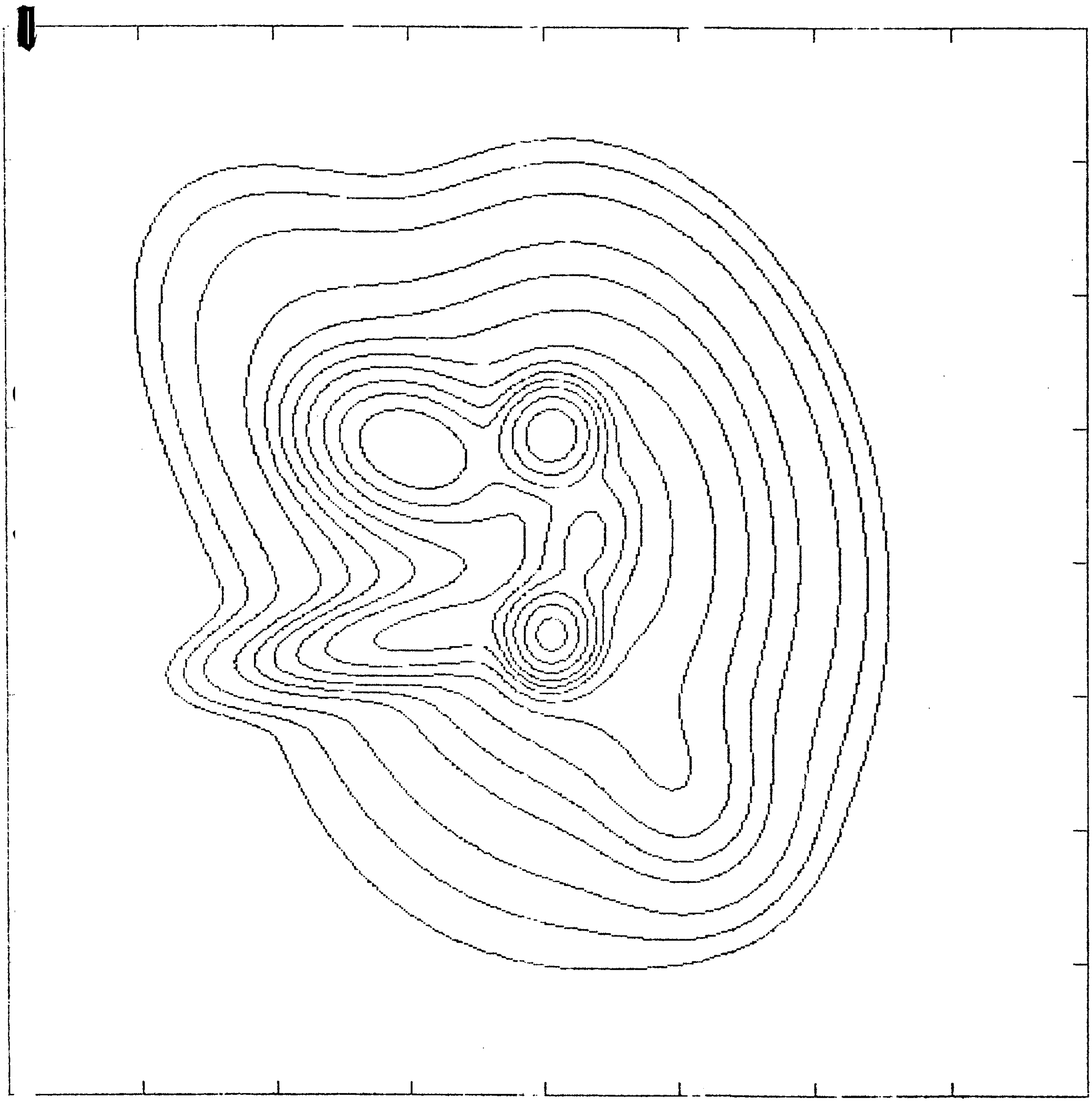


Table 2

RMS Dynamic Ranges for DAISY

	Source Strength (Jy)				
	20	2	.5	.2	.1
Full Phase 12 Hour Tracks	311	280	152	77	45
Full Phase 24 Hour Tracks	480	411	208	107	54
Closure Phase 12 Hour Tracks	278	251	137	69	36
Closure Phase 24 Hour Tracks			184		
Closure Phase Small Amp. errors (not corrected)	168				
Closure Phase Small Amp. errors (corrected by AMPHI)	158/20[illegible]				
Closure Phase Large Amp. errors	47		48		

Table 3

RMS Dynamic Ranges for CEREBRUM

	Source Strength (Jy)				
	20	2	.5	.2	.1
Full Phase 12 Hour Tracks	434		126		29
Closure Phase 12 Hour Tracks	>267				

Table 4

Scatter in Dynamic Range Measurements

Dec. 64 12 Hour Tracks Full Phase

DAISY

Source Flux (Jy)	D.R. (old)	D.R. (new)
2	270 ± 10 (4%)	279 ± 3 (1%)
.2	85 ± 6 (7%)	78 ± 2 (2.5%)

D.R. (old) is the old measure of dynamic range (map peak divided by peak of the difference map)

D.R. (new) is the RMS measure of dynamic range (map peak divided by 5 times the RMS of the difference map)

The scatter in dynamic ranges shown above were obtained from three independent reconstructions (FAKE, INVERT, and CLEAN) for each flux.

19 May 1982

VLB ARRAY MEMO No. 84

A Design Study for a Dedicated VLBI Array

by

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ABSTRACT

A design study of the optimal locations for a ten-station array of radio telescopes, using earth-rotation synthesis, has been performed. The algorithm used a weighted circular grid of points in the transfer function plane. Thirteen arrays of ten stations each were analyzed over a range of nine source declinations from -44° to +64°. The results show that there exist many arrays which provide good coverage for northern declinations but which are poor at southerly declinations. The exact location of an array element is generally not critical and can be moved by at least 100 km without significantly affecting overall coverage. The replacement of one or two northern hemisphere elements with southern hemisphere stations (for example, Galapagos Islands and/or Easter Island) dramatically improves (u,v) plane coverage at all declinations below +30° declination, or about three-fourths of the celestial sphere.

1.0 INTRODUCTION

There is now a worldwide network of radio observatories that regularly schedule joint experiments using the technique of very long baseline interferometry (VLBI). This technique allows astronomers to probe the structure of galactic and extragalactic radio sources with the angular resolution of order 10^{-3} arcsec (1 mas), far greater than observations using any other technique.

Currently, there are six U. S. observatories who regularly schedule such observations (Hat Creek, University of California, Berkeley; Owens Valley Radio Observatory, Cal Tech; Harvard Radio Astronomy Station, Harvard; North Liberty Radio Observatory, University of Iowa; Haystack Observatory, M.I.T.; and the National Radio Astronqmy Observatory). This U. S. VLBI Network, as it is called, has an established procedure for submission of proposals and regular scheduling of observations. During the past few years, these observations have produced many important scientific advances such as detailed maps of 'superluminal' extragalactic sources and proper motion studies of H_2O masers in star-formation regions. Recent successful VLBI observations at 43 GHz and 90 GHz demonstrate very short wavelengths can be used, dramatically increasing the angular resolution. This will allow investigations which can probe near or at the dimensions of the central 'engine' itself.

There are several fundamental problems with current VLBI observations in that the telescopes vary widely in their performance (especially at short wavelengths) and their availability. Furthermore, the telescopes are not optimally placed for forming a 'clean' beam using earth rotation synthesis. Finally, the number of telescopes normally available (approximately five or six) is generally inadequate to produce maps with sufficient dynamic range to reliably detect weak or complex structures. These deficiencies have prompted several groups to suggest construction of a dedicated array of approximately ten new radio telescopes placed at optimal geographic locations. In this report we analyze the problem of optimization of the array element locations and suggest a class of array, including two elements in the southern hemisphere, which dramatically improve the synthesized beam at low source declinations.

2.0 ARRAY CONFIGURATION STUDIES

Previous studies of the problem of optimal array element locations have analyzed both the image plane and transfer function (u,v) plane. The former method was used in preliminary reports on a dedicated VLB array by groups at Cal Tech and NRAO. One advantage of image plane analysis is that the 'figure of merit' for comparison among different arrays is the dynamic range of the restored image, a directly interpreted quantity. A serious disadvantage, however, is that any given test image will have a non-uniform two dimensional spatial spectrum which may favor certain array configurations which happen to be sensitive to the test image's spatial spectrum. One can devise test sources with uniform spatial spectra over the prescribed resolution range of the array but a more direct (and computationally simpler) method is to analyze the transfer plane itself. We have chosen the latter method.

Previous studies using transfer plane algorithms have been restricted to optimization of arrays with fewer elements or with some locations fixed. The algorithm itself, however, is similar to those of Phillips and Mutel (1977), Swenson (1977), and Seielstad et al. (1980).

2.1 The Algorithm for Calculating the Array Figure of Merit

The algorithm consists of gridding the transfer (u,v) plane into a matrix of uniformly spaced grid points spaced at the minimum required baseline length and computing the distance from each grid point to the nearest (u,v) point using the given array. The u,v distances are then squared and summed for all points in the grid. This procedure is repeated for a series of 'standard' declinations chosen so that each declination line is centered on an annular strip of equal area on the celestial sphere. Since the angular resolution is inversely proportional to spatial frequency (approximately baseline length), an inverse radial weighting (R^{-1}) was applied to each term in the sum. The 'u-v' tracks, i.e., the (u,v) plane coverage for each baseline using earth-rotation synthesis, were computed as discrete points using a given integration time per unit. The grand 'figure of merit' for an array is the sum over declination of the individual sums for each declination. The figure of merit, being a measure of the 'holes' in the transfer plane coverage, is inversely proportional to the effective dynamic range of a 'uniform' source brightness (as discussed above).

We have convected the computer figures of merit to dynamic range by taking the reciprocal and scaling by a factor which forces agreement with the actual dynamic ranges computed for a sample source using the D-2 and CIT-13 arrays.

The range of grid points to be analyzed depends on the design resolution of the array. Since a rectangular grid arbitrarily favors (u,v) coverage along certain position angles ($\sim \pm 45°$ and $\pm 135°$), a circular boundary was chosen with the maximum baseline length as radius. Furthermore, we used the same circle for computations at all declinations, in spite of the well-known fact that continental U. S. baselines give highly flattened (u,v) tracks at low declinations. To compensate for this with elliptical boundaries, for example, would unfairly bias the analysis toward higher declination coverage.

2.2 Array Design Parameters

We chose the following values for the parameters discussed above:

Grid Spacing:	100 km
Radius of Grid Circle:	6000 km
Integration Time per (u,v) Point:	5 min
Number of Stations:	9 or 10
Declinations:	-44, -30, -18, -6, +6, +18, +30, +44, +64

2.3 Computational Considerations

The algorithm is very computer-intensive. A typical analysis of a single ten station array at all nine declinations with the above parameters took about 1½ hours of CPU time on a VAX 11/780 computer. The program used to calculate the (u,v) tracks was adopted from the program HAZI, which is part of the Cal Tech VLBI software package. The final program, called DAZI, is executable on a VAX computer and is available from the authors as a listing or on tape.

3.0 RESULTS

We have analyzed thirteen ten-station arrays including CIT-13 (Cal Tech study) and D-2 (NRAO study). The location of the stations for each array is tabulated in Table 1. The effective dynamic range for each array as a function of declination is plotted (Figures 1 and 2) and is tabulated in Table 2. In addition, in Figure 3 we have plotted the actual (u,v) plane coverage for array SEG-1 and for D-2 at four representative declinations (+44°, 6°, -30°, -44°). The dashed circle on each plot indicates the radius 6000 km within which the analysis was made.

There are two clear results of the analysis. First, for arrays which are located entirely on U. S. soil (including Puerto Rico), there are a large number with about the same overall dynamic range (D-2, CIT-13, N-1 -- N-7). This implies that the precise location of any single array element is unimportant to an uncertainty of at least one grid cell spacing ($\gtrsim$ 100 km) and probably larger. An exception is the location of array elements on the shortest spacings since inverse radial weighting makes the location of those elements critical. In general, however, it appears that locations can be chosen to favor existing sites, nearby airports, etc., where appropriate.

The second result is that continental U. S. arrays all give very poor coverage at low declinations, but that the replacement of only two array elements with southern hemisphere locations can dramatically improve the total array response. This is clearly seen in both the dynamic range plots (Figures 2 and 3) and in the (u,v) tracks shown in Figure 4 which compare a good U. S. 'only' array with an eight-station element U. S. array plus elements in the Galapagos Islands and Easter Island. The southern array (denoted SEG-1 in this report) is better than CIT-13 at all declinations less than +30°, i.e., in 75% of the total celestial sphere. The difference is even more striking when galactic plane studies are considered, since almost all of the galactic disk interior to the sun is below +30° declination. The differences are very great at low declinations; for example, the CIT-13 array is very nearly one dimensional at -30° (near the galactic center), whereas the SEG-1 array has excellent two dimensional coverage and contains more than 1.5 times as many points.

3.1 Alternative 'Southern' Arrays

The locations of the two southern hemisphere elements is critical -- there appear to be no other nearby alternatives. The entire South American mainland is too far to the east relative to the North American continent to give uniform two-dimensional coverage. (The tracks are 'tilted' along p.a. ~ 45° and give poor coverage along -45°.) Stations in Tahiti, New Zealand, Pitcairn Island, etc. are all much too far west and also give 'tilted' arrays.

We have also investigated the possibility of adding only a single southern hemisphere station (in case either the Galapagos Islands or Easter Island locations present insurmountable problems). The resulting arrays are labeled SG-1 and SE-1, respectively, and are included in Figures 2 and 3. Note that in each case the continental U. S. stations were readjusted to optimize the entire array. This was done by trial-and-error and it is likely that the arrays could be improved further.

Inspection of figures and companion tables indicates that the Galapagos Islands site is substantially more important than the Easter Island site for arrays containing only one southern hemisphere station. The overall dynamic range for the SG-1 array is 86% that of the SEG-1 array, while the SE-2 array (Easter Island only) gives an average or 74% that of the SEG-1 array. Arrays containing either site, however, give substantially better (u,v) plane coverage than any northern hemisphere array.

APPENDIX

Geopolitical Data for Galapagos and Easter Islands

A. Galapagos Islands (Ecuador)

Location:	91° W, -2° S; 650 miles west of Ecuador
Size:	3,029 mi^2 (13 large islands)
Population:	3000 (estimate, 1970)
Topography:	Mostly lava, dense vegetation on upper slopes; volcanic mountains up to 5000 feet
Logistics:	Regular air service from Quito to Isabela (largest island)
Other:	During World War II, U. S. maintained an air base there; since abandoned. There has been a satellite tracking station there since 1967.

B. Easter Island (Chile)

Location:	109° W, 27° S; 2200 miles west of Chile
Size:	46 square miles
Population:	1600 (estimate, 1970)
Topography:	Mostly low-lying grasslands
Other:	Chile has declared the island a historical monument. The optical facility CTIO ( ) has been operated on Chilean soil since and could provide a useful comparison for cost and logistics projections. In 1981 the average costs of on-site staff at CTIO and KPNO was about the same.

Location	Abbreviation	Latitude	Longitude
Anchorage, Alaska	ANCH	61.0	150.0
Arecibo, Puerto Rico	ARECIBO	18.3	66.8
Big Pine, California	OVRO	37.0	118.3
Bismarck, North Dakota	BSMK	47.0	101.0
Boise, Idaho	BOISE	42.7	116.0
Boulder, Colorado	BLDR	40.0	105.3
Brownsville, Texas	BRVL	26.0	97.4
Colorado Springs, Colorado	COSPR	38.8	104.9
Easter Island	EASTER	-27.0	109.0
Fort Irwin, California	DSS13	35.1	116.8
Galapagos Islands	GAL	- 0.9	89.5
Grand Forks, North Dakota	GFRK	47.9	97.2
Green Bank, West Virginia	NRAO	38.3	79.8
Hawaii	HAW	19.8	155.5
Honolulu, Hawaii	HNLU	21.3	157.8
Ketchikan, Alaska	KECH	55.5	131.5
Laramie, Wyoming	LARA	41.2	105.6
Laredo, Texas	LRDO	27.5	99.0
Las Cruces, New Mexico	LASC	32.4	107.0
Miami, Florida	MIAMI	26.0	81.0
New Orleans, Louisiana	NWOR	30.0	90.0
North Liberty, Iowa	IOWA	41.6	91.6
Phoenix, Arizona	PHNX	33.4	112.0
Salem, Oregon	SALEM	45.0	123.0
Sante Fe, New Mexico	SAFE	35.6	105.9
Sioux Falls, South Dakota	SUFL	43.5	96.7
Socorro, New Mexico	VLA	34.1	107.6
Tucson, Arizona	TUCSON	32.4	111.0
Westford, Massachusetts	HSTK	42.4	71.5
West Coast, Ecuador	QITW	0.0	80.0
Quito, Ecuador	QITO	- 0.2	78.5

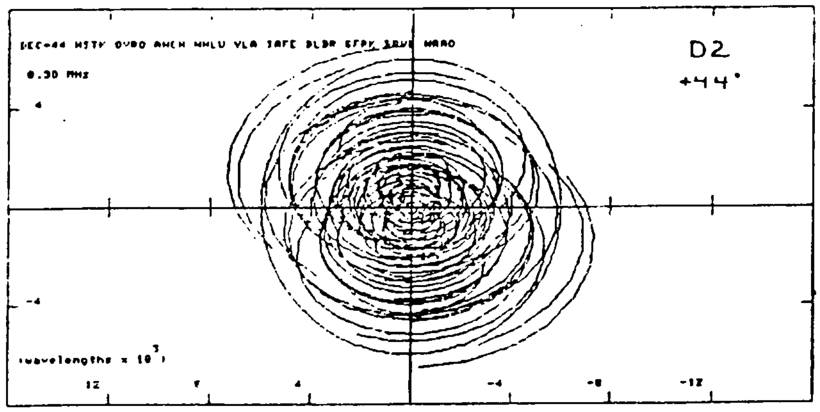
ARRAY	STATIONS				
D-2	HSTK	OVRO	ANCH	HNLU	VLA
	SAFE	BLDR	GFRK	BRVL	NRAO
CIT-13	HSTK	OVRO	ANCH	HNLU	IOWA
	LRDO	BLDR	BOISE	DSS13	SALEM
N-1	HSTK	OVRO	ANCH	HAW	VLA
	TUCSON	LARA	AREBICO	KECH	SUFL
N-2	HSTK	OVRO	ANCH	HAW	VLA
	BOISE	LASC	ARECIBO	IOWA	MIAMI
N-3	HSTK	OVRO	ANCH	HAW	VLA
	COSPR	LARA	ARECIBO	GFRK	MIAMI
N-4	HSTK	OVRO	ANCH	HAW	LASC
	COSPR	LARA	ARECIBO	GFRK	NWOR
N-5	HSTK	OVRO	ANCH	HAW	VLA
	COSPR	LARA	ARECIBO	LRDO	MIAMI
N-6	HSTK	OVRO	ANCH	HNLU	VLA
	PHNX	LARA	ARECIBO	KECH	SUFL
N-7	HSTK	OVRO	ANCH	HNLU	VLA
	LASC	BLDR	ARECIBO	SUFL	KECH
SG-1	HSTK	OVRO	SALEM	HAW	VLA
	TUCSON	BRVL	ARECIBO	GAL	BSMK
SE-1	HSTK	OVRO	EASTER	HAW	VLA
	TUCSON	BRVL	ARECIBO	ANCH	BSMK
SEG-1	HSTK	OVRO	EASTER	HAW	VLA
	TUCSON	BRVL	ARECIBO	GAL	BSMK
SEG-2	NRAO	OVRO	EASTER	HAW	VLA
	TUCSON	BRVL	ARECIBO	GAL	BSMK
SQ-1	HSTK	OVRO	SALEM	HAW	VLA
	TUCSON	BRVL	ARECIBO	QITW	BSMK
SQ-2	HSTK	OVRO	SALEM	HAW	VLA
	TUCSON	BRVL	ARECIBO	QITO	BSMK

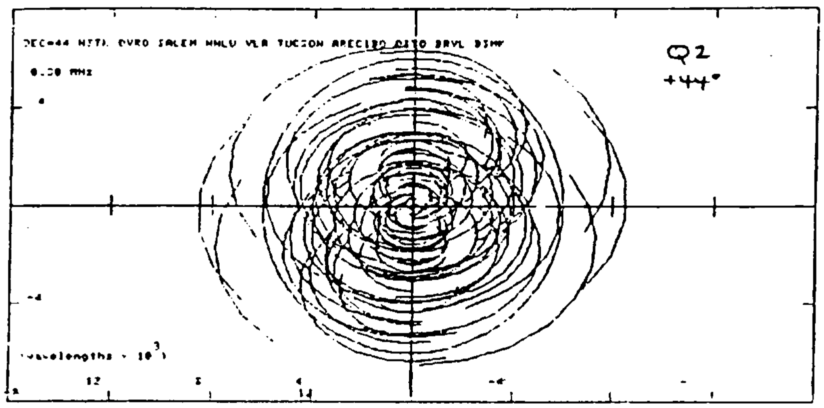
Table 1. Dynamic Range of Thirteen Ten-Station Arrays

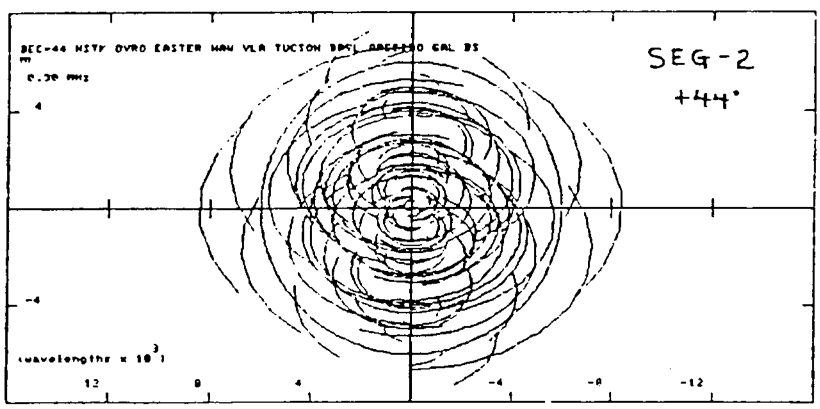
Array	D-2	CIT-13	N-1	N-2	N-3	N-4	N-5	N-6	N-7	SE-1	SG-1	SEG-1	SEG-2
Dec 64°	537	461	542	409	502	487	487	547	507	479	503	426	412
44°	423	366	379	355	370	394	384	372	351	353	384	314	297
30°	269	241	287	292	292	251	304	276	274	262	314	257	253
18°	269	149	198	198	198	194	206	180	176	210	262	216	210
6°	106	106	120	125	128	127	123	110	111	148	179	166	171
-6°	77	74	84	84	86	86	82	76	77	121	145	149	151
-18°	50	51	61	60	60	62	59	57	52	93	134	156	146
-30°	50	34	43	45	43	44	45	41	41	72	94	140	139
-44°	18	19	21	25	23	22	27	21	14	45	45	68	68
Total	63	64	75	79	78	77	82	72	61	119	139	163	161
Total (excluding -44°)	93	81	109	110	110	111	111	103	102	150	189	198	115

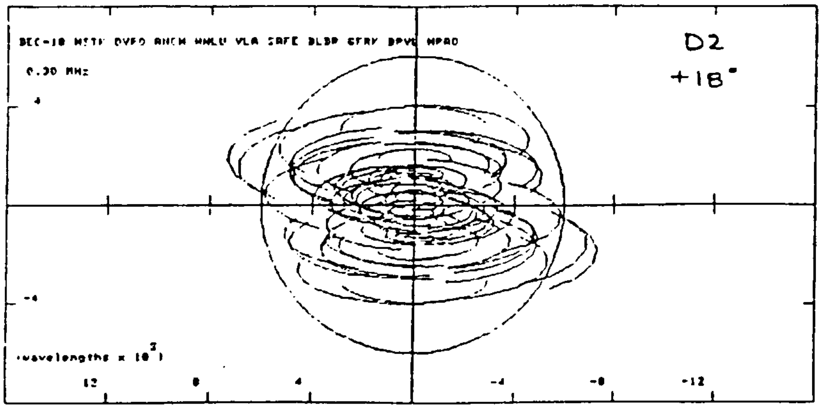
Table 2. Dynamic Range of Thirteen Ten-Station Arrays Normalized to SEG-2 Array

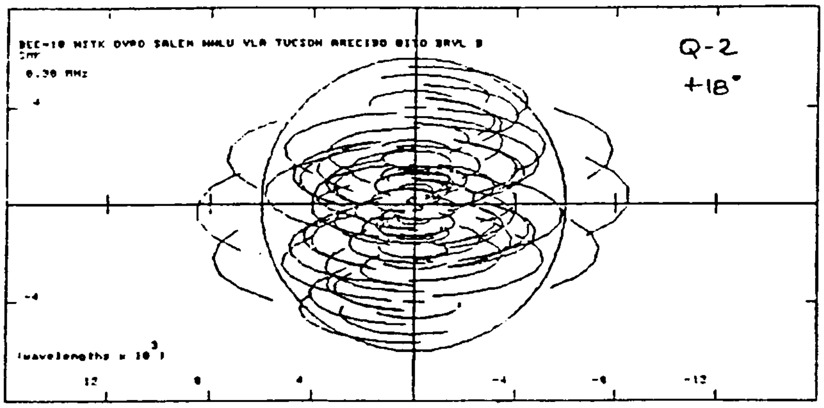
Array	D-2	CIT-13	N-1	N-2	N-3	N-4	N-5	N-6	N-7	SE-1	SG-1	SEG-1	SEG-2
Dec 64°	131	112	132	100	122	118	111	133	123	117	122	104	100
44°	142	124	128	119	125	133	130	126	118	119	129	106	100
30°	106	95	113	115	115	99	120	109	108	104	124	102	100
18°	77	71	94	95	94	92	98	86	84	100	124	103	100
6°	62	62	70	73	75	74	72	64	65	86	105	97	100
-6°	51	49	56	56	57	57	55	50	51	80	96	99	100
-18°	34	35	41	41	41	42	41	39	39	64	92	106	100
-30°	24	25	31	33	31	32	33	30	30	52	68	101	100
-44°	26	28	31	36	34	33	39	31	21	67	66	100	100
Total	39	40	46	49	48	48	51	44	38	74	86	101	100
Total (excluding -44°)	48	47	56	56	57	57	57	53	53	77	97	102	100

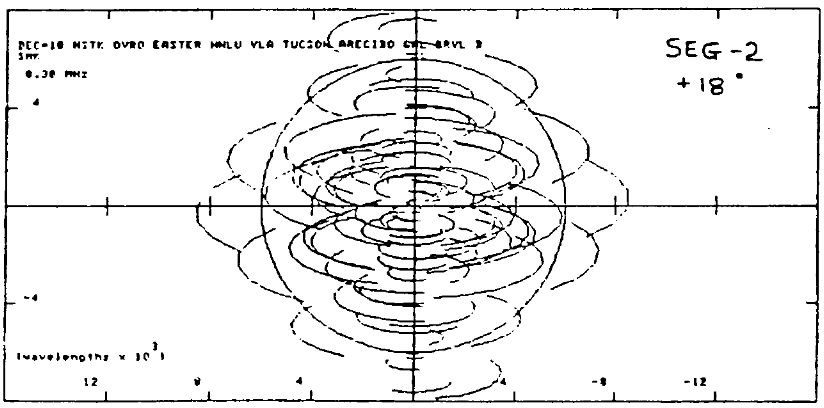

D2
+44°
4
-4
12
4
-4
-8
-12


Q2
+44°
12
4
-4


SEG-2
+44°
4
-4
12
8
4
-4
-8
-12


D2
+18°
0.30 MHz
4
-4
(wavelengths x 10^3)
12
8
4
-4
-8
-12


DEC-18 MITK OVRO SALEM HNLU VLA TUCSON ARECIBO BRVL
Q-2
+18°
0.30 MHz
4
-4
(wavelengths x 10^3)
12
8
4
-4
-8
-12


DEC-18 MITK OVRO EASTER HNLU VLA TUCSON ARECIBO BRVL
SEG-2
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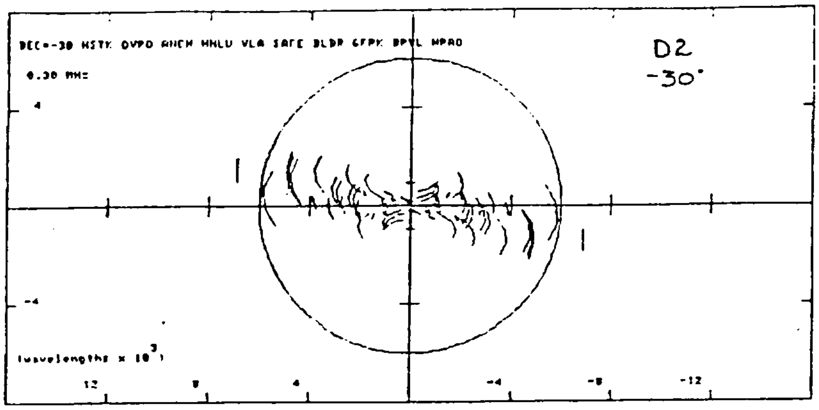
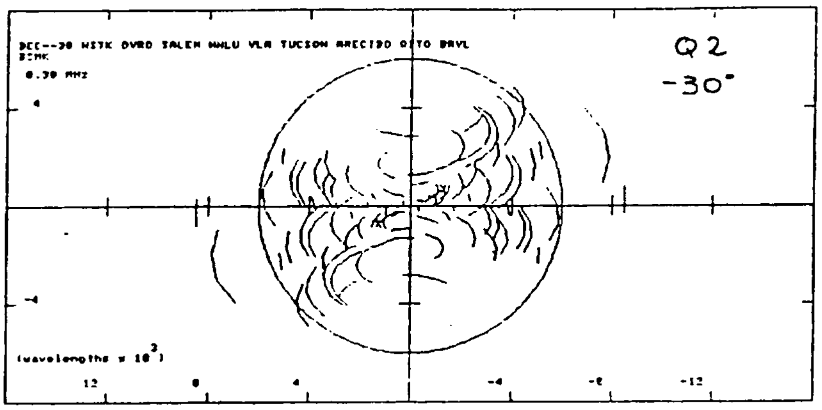
4
-4
(wavelengths x 10^3)
12
8
4
-4
-8
-12


DEC=-30 HSTK OVRO ANCH HHLU VLA SAFE BLDR GFPK BRVL HPRO
0.30 MHz
4
-4
(wavelengths x 10^3)
12
8
4
-4
-8
-12
D2
-30°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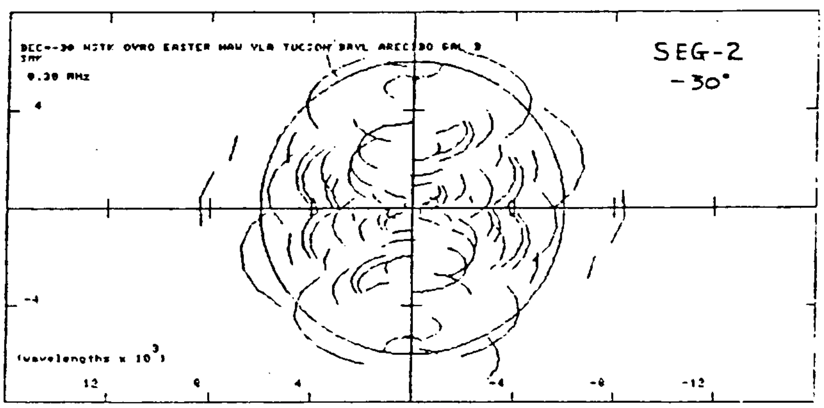
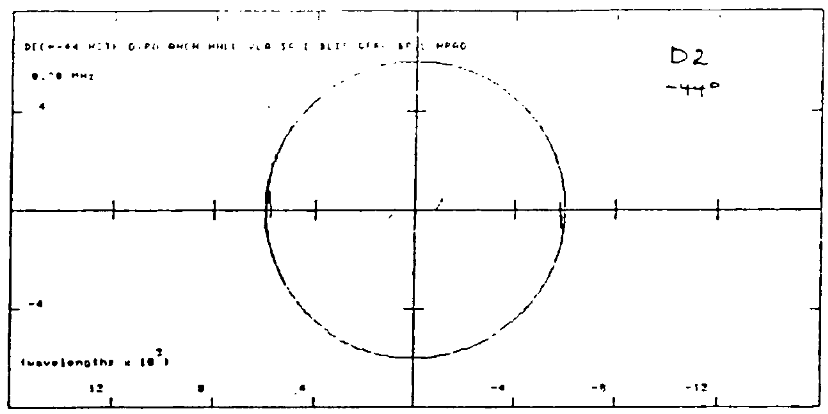
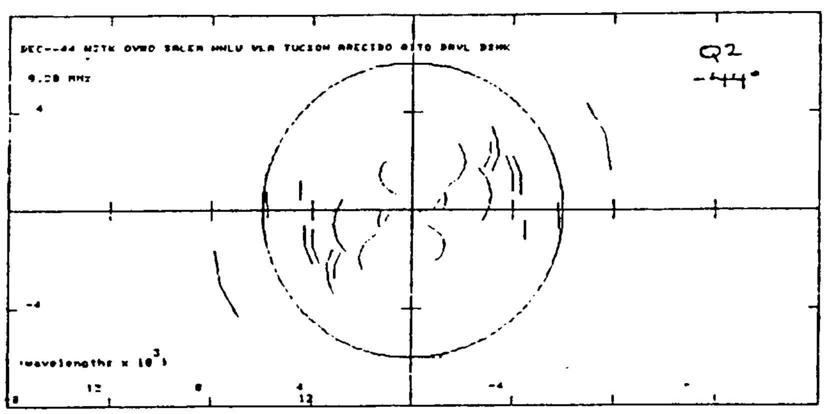
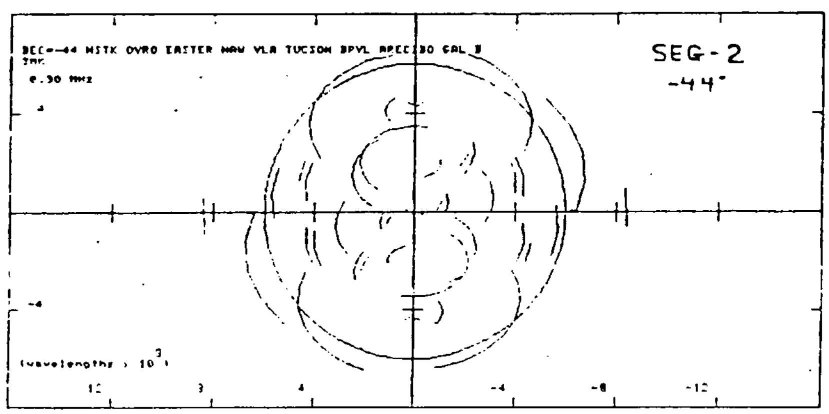
BIMK
0.30 MHz
4
-4
(wavelengths x 10^3)
12
8
4
-4
-8
-12
Q2
-30°


DEC=-30 HSTK OVRO EASTER HAW VLA TUCSON BRVL ARECIBO GAL 9
SMY
0.30 MHz
4
-4
(wavelengths x 10^3)
12
8
4
-4
-8
-12
SEG-2
-30°


D2
-44°
(wavelengths x 10^3)


Q2
-44°
9.20 MHz
(wavelengths x 10^3)


SEG-2
-44°
MSTK OVRO EASTER HAW VLA TUCSON BPVL
(wavelengths x 10^3)

II. THE ANTENNA ELEMENT

VLB ARRAY MEMO No. 2

ANTENNAS FOR THE VLBI ARRAY

John W. Findlay

06-09-80

1. Introduction

The purpose of this note is to try to give the performance specification for a 25-meter diameter antenna which would fully satisfy the needs of the VLBI array and not be too expensive nor too difficult to build.

When the performance specification is clear, it can be used to ask:

(a) What existing antennas have a performance which approaches, or equals, the specified performance

(b) What sort of engineering and costs might be involved in upgrading existing antennas?

(c) If the cost differential seems large, should this present performance specification be somewhat downgraded? If so, where, and to what extent?

2. A Specification

(a) General

The following specification is derived from a much-condensed version of the VLA antenna specification, as given in the original RFP-VLA-01 and in subsequent modifications to that document. It is assumed that the Az-El antenna is the correct choice. The VLA performance specifications have been upgraded in several places. The environmental effects paragraph is written as if the antenna were fully exposed. Perhaps, however, some thought should be given at the early stages to a radome-enclosed antenna for use at sites with high winds. Much of the rather formal material in RFP-VLA-01 has been omitted. If it becomes needed, it can be used at a later stage.

(b) The Antenna Design

(i) The antenna may resemble one of at least two concepts--the VLA antenna which is a "king-post" design or a "wheel and track" antenna. Either concept would be acceptable in the VLBI array design.

(ii) The antenna will be one of about 10 identical antennas situated on various sites in North America. The climatic conditions at the various sites will be different. However, in defining the environment, possible conditions at most sites have been included.

(iii) The antenna shall be an elevation over azimuth configuration with a 25-meter diameter solid surface of revolution as the main reflector. The observing system to be used shall be both Cassegrain and prime focus. Use of a Cassegrain observing system shall be considered the normal mode of operation, but provision for removal of the secondary reflector and installation of a receiver for operating as a prime focus instrument will require a clear opening of approximately 4 feet diameter at the apex of the feed legs symmetrical about the reflector axis. (See paragraph 3(a) for details.)

(c) Mechanical parameters

Diameter - 25 meters

Focal length - 9 meters

f/D - 0.36

Sky coverage - Elevation +5° to 125°

Azimuth ± 270°

Observing System - Cassegrain or prime focus.

The reflector system will be "shaped" so that increased aperture efficiency in the Cassegrain mode will result. The highest frequency to be used in the prime focus mode will be 800 MHz and the main reflector shaping will not be so severe as to prevent this use.

Operational Frequencies -

Cassegrain mode - 1.35 GHz to 43 GHz

Prime focus mode - Up to 800 MHz

Reflector - The reflecting surface shall be a surface of revolution composed of individually adjustable, doubly curved solid surface aluminum panels. These panels must withstand either a 20 lb/sq. ft uniform load or a concentrated load of 250 lb over a 6 inch square.

Panel Gap - The spacing between panels shall be nominally 2.0 mm with a tolerance of 0.75 mm.

Axis Alignment -

Azimuth axis to plane of telescope base -18 arc seconds

Orthogonality azimuth to elevation -18 arc seconds

Orthogonality reflector axis to elevation - 18 arc seconds

Subreflector axis to reflector - alignment of the subreflector will be accomplished by an AUI furnished adjustable mounting mechanism. The structure at the apex of the feed legs must, however, locate the center of the opening coincident within 0.1 inch and the axis of the opening parallel within 30 arc seconds to the axis of the reflector.

Counterbalance - Overbalanced to allow the antenna to return to zenith with no drive power under no wind, no ice, no snow conditions.

Drive Requirements - Azimuth and elevation drives shall have a capability of driving the antenna at a velocity of 80° per minute in azimuth and 20° per minute in elevation, with the reflector in any attitude under the specified operating conditions. Azimuth and elevation drives shall drive the antenna at sidereal tracking rates with an accuracy as specified in paragraph 2(e)(ii) below.

(d) Operating conditions

General - The antennas will be exposed to the elements at various sites, some of which may be as high as 8000 feet above mean sea level. The antennas are to be designed for a life expectancy of 20 years. No damage to the operating components of the antennas must occur due to airborne sand or dust or accumulation of frozen or liquid water. It is expected that the antennas will be operated remotely for periods of a few hours. There may be no one in attendance during such periods.

Precision operating conditions (POC) - The antenna must give its specified POC performance when the environment and the telescope structure are no more harmful to precision operation than the following:

Ambient air temperature lies in the range -10° C to +25° C.

The rate of change of ambient air temperature is no greater than ± 2° C per hour.

No parts of the telescope structure differ in temperature by more than 2.5° C.

The relative humidity is between 0 and 50%.

The wind at 12 m elevation is no greater than 6 m/sec, with gusts no greater than ± 1 m/sec superimposed.

There is no snow load, no ice and no rainfall.

Normal operating conditions (NOC)

The antenna must continue to operate under "normal" operating conditions. The performance to be expected under these conditions will be less accurate than under POC. The required performance is not specified for NOC since experience shows that, if POC performance is met, NOC performance is acceptable. Normal operating conditions are defined as:

Ambient air temperature -30° C to +40° C.

Relative humidity 0 to 98%.

Rain rate - no greater than 5 cm/hour.

Ice and snow load - none.

Wind at 12 m elevation, 18 m/sec with gusts of ± 3 m/sec superimposed.

Moving to stow and in the stow position

Slew to stow - The antenna shall be capable of being slewed to the stow position in winds of 60 miles/hour with all exposed surfaces of the structure coated with 1 cm radial thickness of ice. The slew rate may fall to 10°/minute.

Slew to dump snow - The antenna shall be capable of dumping snow by slewing at 20°/minute to any position 5° above the horizon with a wind of 25 miles/hour blowing from any direction and with an original uniform snow load in the reflector of 4 lbs/ft^2. No damage or overload shall occur to either structure or drives.

Survival - The antenna is to be designed to survive in the zenith position in winds of 110 miles/hour with 1 cm of radial ice on all exposed surfaces or when loaded with 20 lbs/ft^2 snow. When loaded under these conditions, yield stresses of materials shall not be exceeded and no permanent deformation shall occur. Stow brakes shall be provided capable of holding the antenna in the zenith position when subjected to the design survival loading.

(e) The antenna performance

(i) Surface accuracy. Under the precision operating conditions (specified in 2(d) above), the RMS of the best-fit reflector surface shall be no greater than 0.45 mm. Under these same conditions the peak deviation of the surface from the best-fit surface shall not exceed 1.5 mm.

(ii) Pointing errors. The pointing error is defined as the difference between the commanded position of the antenna and

the position of the main beam of the reflector. The repeatable pointing error is due to gravity deformation, axis alignment error, encoder offset, bearing runout and similar errors. The nonrepeatable pointing error is due to wind forces and gusts, acceleration forces, effects of temperature differences and temperature changes, encoder resolution, servo and drive errors, and random errors.
The repeatable pointing error for this antenna shall not exceed 3 minutes of arc.
The nonrepeatable pointing error is divided into two types of error with different statistical behaviour.

The first type of nonrepeatable errors behaves correctly, in a statistical sense, with errors changing in magnitude and sense within times of up to a minute. Such errors average out fairly well in observations taken over several minutes. Nonrepeating errors of this type, under the precision operating conditions (see 2(d) above) shall not exceed 7 arc seconds. This figure shall be derived by making the RSS of all error contributions with the antenna in any attitude and while tracking a source at the specified tracking rates. The values of individual errors which contribute to the RRS error budget should be RMS values wherever these can be determined. It may only be possible in some cases, such as the wind-induced distortions of the reflector, yoke, alidade and tower, to identify the reflector attitude and wind direction which gives the greatest error (the "worst case"). One half of such "worst case" error values should be used in the RRS error budget.

The second type of nonrepeatable pointing error is that which usually results from thermally induced distortions of the antenna structure. These errors have time constants typical of the times over which serious temperature changes or temperature differences occur. These times may lie between several minutes and a few hours.

It is possible to reduce the effects of such errors on the pointing by thermal control, thermal insulation or by measuring and allowing for thermal effects. After such efforts have been made the antenna must, under the precision operating conditions (see 2(d) above) suffer no nonrepeatable pointing errors of this type which exceed 7 arc seconds in magnitude.

(iii) Slewing motion. Slewing motion is defined as rapid movement of the antenna about either axis simultaneously or independently. The antenna shall be capable of driving at a rate of 20°/minute of time about the elevation axis and 80°/minute above the azimuth axis in winds to 45 miles/hour with the reflector in any attitude. It shall be possible to slew each axis independently while the other axis is stationary or moving at the tracking rate or to slew both axes simultaneously.

In the slewing mode the antenna shall be capable of accelerations of 0.25°/second^2 about both axes.

(iv) Tracking motion. The antenna shall be capable of tracking a stellar source at the azimuth and elevation rates which correspond to the sidereal rate for the star position. The cone of avoidance near the zenith when in the tracking mode shall have a half-angle less than 2.5°.

3. General Requirements

(a) Feed legs and apex. The feed leg supports shall be designed to support either a subreflector of 2.5 m diameter, weighing approximately 800 lbs, or a prime focus feed of approximately the same weight. The feed legs shall also be designed to support a cable weight of 8 lbs/foot on each leg. The apex structure shall be so designed that a clearance of 18 to 24 in. (with 18 in. preferred) exists between the bottom of the apex structure and the focal point of the main reflector. Its configuration shall be such that an opening of approximately 48 in. diameter exists on the centerline of symmetry for the location and attachment of adjustment mechanism and support of the prime focus feed. The feed legs and apex structure, including a 2.5 m subreflector, shall not cause RF blockage in excess of 6 percent of the total aperture area.

(b) Vertex equipment room and feed mounts. An approximately circular room of 78 sq. ft area, having an inside diameter of approximatley 10 ft 0 in. by 7 ft 6 in. height for mounting of feeds and equipment shall be provided by the antenna manufacturer. The floor of this room shall be parallel to the ground with the antenna pointed at zenith and shall be a minimum of 8 ft 0 in. below the vertex of the antenna. This room shall be provided with the following features:

Mounting provisions for up to five 2 ft x 2 ft x 7 ft floor mounted racks with a total weight of 2000 lbs.

An access door or hatch for access by personnel and for means of installing racks by use of hoist.

Thermal insulation and air conditioning to provide 23° C ± 1° C (74° F ± 2° F) temperature control with an interior heat input of up to 3 kW. No specific humidity conditions are required.

The roof of the building shall contain a removable mounting ring for the mounting of feeds. Dimensions of this ring shall be determined in the design stage, but it is anticipated that it will be approximately 8 ft 0 in. in diameter.

4. Conclusion

There are many further details in the VLA specification dealing with foundations, the waveguide run, power supplies, brakes, limit switches, etc., which do not seem needed yet in this document.

VLB ARRAY MEMO No. 3

A 25-m RADIO TELESCOPE DESIGN

FOR

THE VLB ARRAY PROJECT

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National Radio Astronomy Observatory*
Charlottesville, Virginia 22901

July 7, 1980

*The NRAO is operated by Associated Universities, Inc. under contract with the National Science Foundation.

CONTENTS

SUMMARY

A new 25-m telescope design for the Very Long Baseline Array project is proposed. It is an instrument specifically designed for wavelength $\lambda = 7$ mm. Except at the most unfavorable condition when the sun is shining on one part of the tower, the pointing error due to wind or temperature is sufficiently small for the short wavelength observations. The design concept is similar to the proposed 25-m mm-wavelength telescope: an al.-az. instrument supported by a wheel and track tower, with the elevation bearings located at a large distance apart, so that the thermal and wind pointing characters are intrinsically better than the compacted design. The dish structure is light in weight, simple in geometry, and consists of mainly two types of steel tubings, suggesting that it might be relatively inexpensive to build. There is a large space behind the vertex for the instrument cabin. With some further design effort, it might be possible to keep this cabin stationary in elevation motion.

A TELESCOPE DESIGN FOR THE VLBA PROJECT

In 1967, S. von Hoerner pointed out the natural limits defining the best accuracies which radio telescopes could achieve through the means of "conventional" designs. He also stated that, in order to exceed those limits, one must use homologous optimization to overcome the gravitational limit, and use environmental controls to overcome the thermal limits. A quick review of this thesis showed that it is possible to design a 25-m diameter radio telescope to operate satisfactorily in wavelengths of 6 mm to 7 mm range without the extra investments in design optimization and environmental control. Of all existing 25-m radio telescopes in this country, the VLA design is the best in terms of operating wavelength. But the demand on the proposed VLBA telescope is about a factor of 2 more than the VLA telescope can provide. Hence, in order to have telescopes capable of observing in wavelength λ = 7 mm, a new design is needed.

There are two concurrent thoughts for the VLBA 25-m telescope design. The first is to use the existing VLA telescope basic structure and upgrade the surface plates and setting accuracies; the second is to have an entirely new design.

This report advocates the second approach, and proposes a new 25-m telescope design with better surface and pointing, which could be built with a cost less than the VLA telescope.

To compare with the VLA telescope design, the new design has about 30% less in gravity distortion, and about a factor of 3 less in thermal pointing. It could be less expensive to build by virtue of its simplicity in design and light weight. Again, in comparison with the VLA design, it has about 80% less in structural joints, 70% less in structural connections, and 40% less in weight. The dish structure consists of only two major types of steel tubing; both are standard catalogue items (there are some items, such as feed supports, elevation gear, etc., which would require special design efforts).

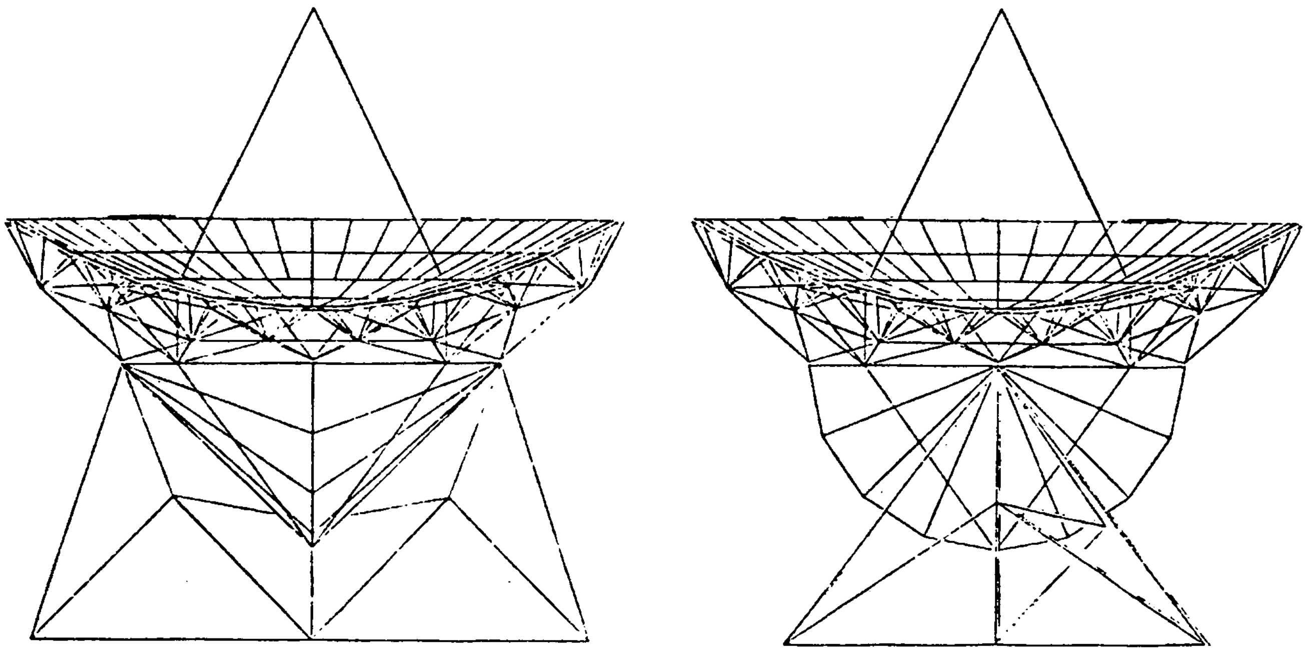


Figure 1. Two views of the proposed 25-m VLBA radio telescope. It is an al.-az. instrument, with the azimuth motion determined by a tower on wheels travelling on a circular track. It is designed to observe effectively in wavelengths λ = 7 mm during part of the day time with the normal thermal wind conditions. The vertex room, not shown in the drawings, is located below the vertex, between the two elevation bearings.

Figure 1 shows the two views of the proposed telescope with its tower structure. The design concept is influenced by the proposed 25-m mm-wavelength telescope, but the design is entirely new. The analytical model is done in detail, showing the acceptable gravitational distortion behavior and its ability to withstand heavy snow and high wind. The thermal and wind analyses are taken from the 25-m mm-wavelength telescope studies. These two telescopes have identical optical arrangements and overall physical dimensions. The thermal and wind behaviors should be similar. These analyses will be made in the future if the effort is justified.

The design provides a large space, approximately 4 meters in diameter and 2 meters high, to house the receivers in the Cassegrain system. The access to the vertex room should be easy due to the simple design of the base structure. With some further design effort, the room could be kept stationary in elevation motion.

To account for the surface plate thickness and adjustment screws, a distance of 200 mm is allowed between the parabolic surface and the structure.

In spite of its better surface and pointing characters, this new design would still be a pointing-limited instrument. In a typical sunny day, a four- to five-hour period during which the thermal condition is most unfavorable, the observations in $\lambda = 7$ mm would be possible only with a reduced efficiency. The peak thermal pointing is estimated to be about 15 arcsec, 25% the HPBW at $\lambda = 7$ mm, when the sun heats up half of the tower structure, with the other half in the shade. It is the tower which contributed most of the thermal pointing problem. Insulation of the tower would reduce this problem if the short wavelength observations are needed during the daytime.

THE ERROR BUDGET

Item	RMS Surface Error	
Surface Plate	0.28 mm	
Fabrication		0.20 mm
Temperature, dead wt. Deflection, etc.		0.20 mm
Measuring and Setting	0.20 mm	
Back-up Structure	0.27 mm	
Dead weight		0.20 mm
Wind		0.10 mm
Temperature		0.10 mm
Construction error		0.10 mm
RSS Total	0.44 mm	

Item	Worst situation noon, clear & calm sunny day	Average 0800 2100 hr sunny, no wind	Windy night 2200 0700 hr clear sky	Clear evening 2200-0700 hr calm
Servo and all corresponding error	4.0 sec	4.0 sec	4.0 sec	4.0 sec
18 mpd wind	--	--	7.1 sec	—
Temperature effects	13.9 sec	10.0 sec	0.5 sec	0.5 sec
RSS Total	14.5 sec	10.8 sec	8.1 sec	4.0 sec

THE SURFACE ERROR

The Back-up Structure's Gravitational Distortion

From the budget table, the surface distortion due to the gravity effects should be kept less than 0.20 mm rms. The two-step analysis, with the structure in stow position (g=-z) and in horizontal position (g=+y), showed the following results.

Table II. The departure from a paraboloid due to the gravity effects on the back-up structure.

Back-up str. position	rms surface error	dx	dy	dz	ϕx	ϕy	ΔF
			— mm —		$x10^{-5}$	rad	mm
Zenith (g = -z)	0.26 mm	0	0	-6.06	0	0	+2.87
Horizon (g = +y)	0.26 mm	0	-1.19	0	-51	0	0

The Calibration

If the telescope surface plates are set at zenith position Θ, the total surface error $H(\phi,\Theta)$ at any zenith position ϕ has the following expression:

$$H(\phi,\Theta) = \sqrt{H_z^2 \ (\cos\phi - \cos\Theta)^2 + H_y^2 \ (\sin\phi - \sin\Theta)^2} \qquad (1)$$

where H_z = 0.26 mm, H_y = 0.26 mm from Table II. Arbitrarily, the setting position is chosen at 40°. Then, the surface error due to gravity effects at each zenith position is predicted and listed in Table III.

Table III. The departure from a paraboloid due to gravity effect alone, but adding an advantage of setting the surface at 40° zenith angle.

Zenith angle (degree)	Surface distortion from the back-up structure (mm)
0	0.18
10	0.14
20	0.09
30	0.05
40	0.00
50	0.05
60	0.09
70	0.13
80	0.18
90	0.22
	rms error = 0.13 mm

Note that the gravity effect over the range of 90° is 0.13 rms after the calibration; it is smaller than the budget allows. The data in Table III are plotted in figure 2 as the solid line. The dotted line is the corresponding distortion curve of the VLA telescope, included for comparison purposes. The rms error of the VLA structure after the calibration in the same way is 0.21 mm. The proposed VLBA design is 38% better.

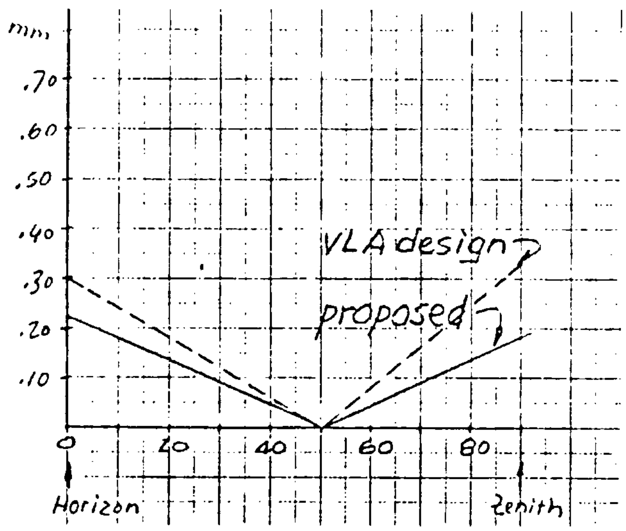


Figure 2. The distortion of the surface due to the weight of the back-up structure as the telescope tilts. The distortion is calibrated away at zenith angle of 40° by setting the surface plate to a "perfect" paraboloid. The dotted line is the VLA design, included for comparison purposes.

The Temperature Effects on the Structure

1) Temperature data - Two kinds of temperature data are required for the study of the thermal effects on the structure: temperature difference (ΔT) between any parts over the structure, and the time derivative of ambient air temperature ($\dot{T}$). Based on the past collections of these data, the highly stylized thermal data over a period of 24 hours are shown in figure 3. It is considered representative for a normal, typical cloudless day.

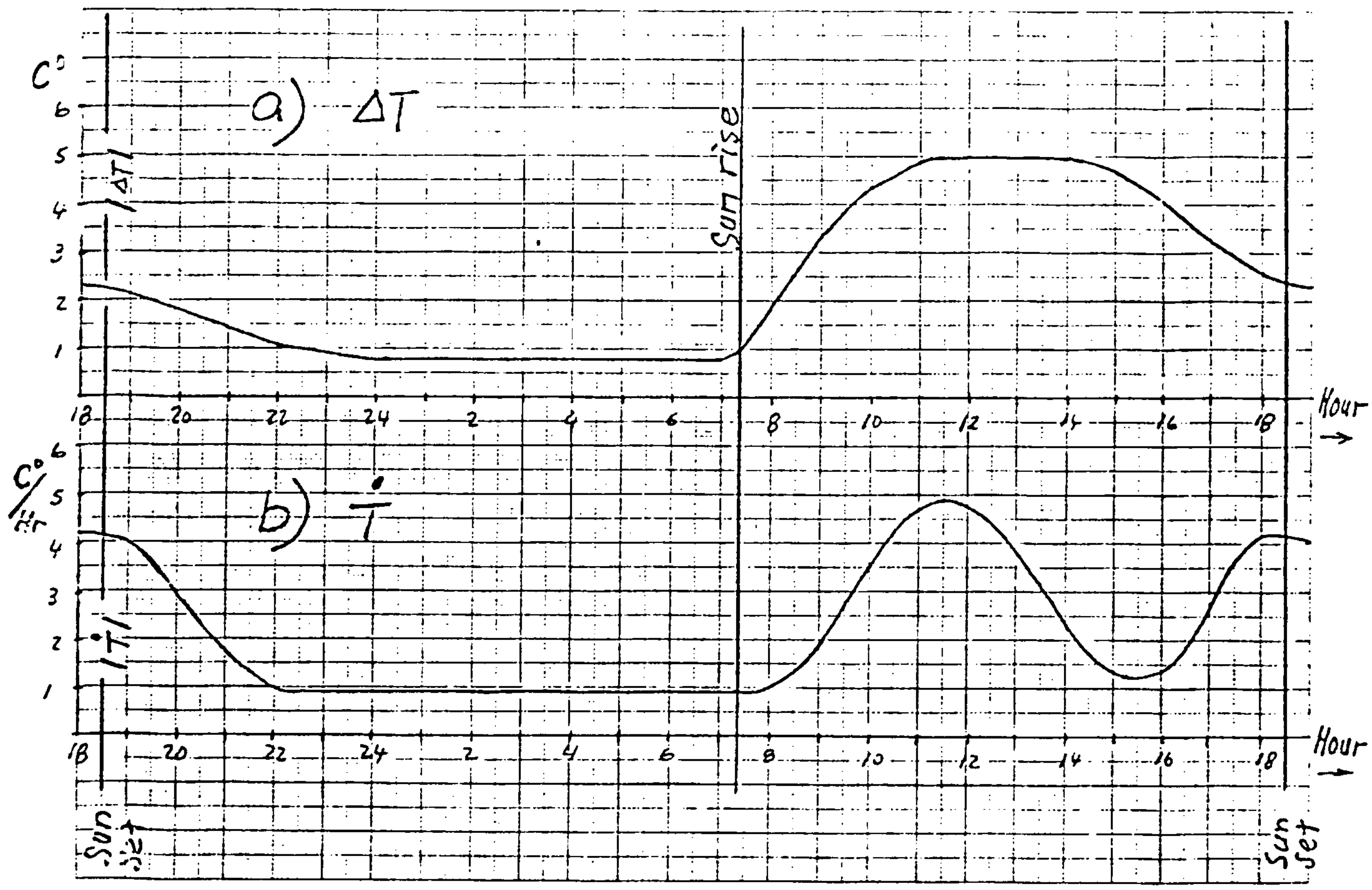


Figure 3. a) ΔT = Vertical temperature difference for the telescope structure.

b) $\dot{T}$ = The derivative of ambient air temperature.

2) Surface deformation due to 1° C temperature difference on the structure - Quoted directly from the analytical results of the 25-m mm-wavelength telescope studies, the result is summarized in Table IV. It is assumed that the telescope is not equipped with a temperature measuring device during operation, and that the defocusing effect is not adjusted away, but the telescope is calibrated before each observation.

Table IV. Influence of thermal gradient on the back-up structure without focal adjustment.

Loading	Surface error	dx	dy	dz	ϕx	ϕy	ΔF
			— mm —		10^{-5} rad		mm
$\Delta T_z = 1°$ C	0.016 mm	0	0	−0.01	0	0	--
$\Delta T_y = 1°$ C	0.000 mm	0	−0.02	0	−0.1	0	--

Taking half of the peak value (0.016 mm/°C) as the rms value, the surface error induced by a temperature difference of 1°C over the structure is

$$\text{rms } (\Delta z) = 0.008 \text{ mm/°C} \qquad (2)$$

3) Surface deformation due to 1°C/hr change of ambient air temperature - Again, since this part of the analysis was not done, the closest information available is from the analysis of the 25-m mm-wavelength telescope. It is well justified for its similarity in size and design criteria. The new design consists of only 2 types of tubing, with the difference of wall thickness of 4 mm, which is within the design criteria (4.8 mm) of the mm-wavelength telescope to keep the thermal time constant less than 30 minutes. Table V shows the analytical data.

Table V. Influence of $\dot{T}$ effect on the back-up structure without focal adjustment.

Loading	rms surface error	dx	dy	dz	ϕx	ϕy	ΔF
			— mm —		10^{-5} red.		mm
$\dot{T} = 1$°C/hr	0.040 mm	0	0	+0.013	0	0	0

Or,

$$rms(\Delta z) = 0.040 \text{ mm/°C/hr} \quad (3)$$

4) Surface error due to the combined temperature effects over a 24-hour period - Figure 3 represents the ΔT on a structure and variation of ambient air temperature on a typical day with clear sky. The temperature-induced surface error is a combination, based on these data and those analytical results given in equations (2) and (3). The following table shows the hour by hour surface error on such a typical day.

Table VI. Temperature effects on the surface on a typical day.

Hour	$\lvert\Delta T\rvert$	x8μm/°C	$\lvert\dot{T}\rvert$	x40 $\frac{\mu m \cdot hr}{°C}$	combined surface error (mm)
18	2.3	18	4.2	168	0.17
19	2.1	17	4.0	160	0.16
20	1.8	14	3.0	120	0.12
21	1.4	11	1.8	72	0.07
22	1.1	9	1.0	40	0.04
23	0.9	7	0.9	36	0.04
24	0.8	6	0.9	36	0.04
1	0.8	6	0.9	36	0.04
2	0.8	6	0.9	36	0.04
3	0.8	6	0.9	36	0.04
4	0.8	6	0.9	36	0.04
5	0.8	6	0.9	36	0.04
6	0.8	6	0.9	36	0.04
7	0.8	6	0.9	36	0.04
8	1.9	15	1.0	40	0.04
9	3.3	26	2.0	80	0.08
10	4.4	35	3.5	140	0.14
11	4.9	39	4.7	188	0.19
12	5.0	40	4.8	192	0.20
13	5.0	40	3.8	152	0.16
14	5.0	40	2.4	96	0.10
15	4.7	38	1.4	56	0.07
16	4.0	32	1.4	56	0.06
17	3.3	26	2.7	108	0.11

In summary:

$$\begin{aligned} rms(\Delta z) &= 0.10 \text{ mm} \\ pk\ (\Delta z) &= 0.20 \text{ mm} \end{aligned} \quad (4)$$

Structural Deflections Due to an 18 mph Steady Wind

The wind loadings are computed on the 25-m telescope design. Five cases with different wind directions were analyzed, and the results are listed in Table VII. The wind data were based on the wind tunnel test results published by JPL in 1962 (Internal Memorandum CP-4, "Load Distributions on the Surface of Paraboloidal Reflector Antenna" by Normal L. Fox).

Table VII. Effects on telescope surface due to an 18 mph steady wind.

Angle of Attack	RMS Surface Error
0°	0.02 mm
60°	0.05 mm
90°	0.01 mm
120°	0.02 mm
180°	0.03 mm

The averaged surface error over a range of 180^{0} elevation angle is

$$\text{rms}\ (\Delta z) = 0.03\ \text{mm} \qquad (5)$$

Surface Deformation Due to Construction Inaccuracy

Studies were made on the effects of fabrication tolerance, or the builder's inability to assemble a structure exactly as the plan called for. This is a practical problem, causing the telescope to differ from the analytical model by a distance. As a result, the surface accuracy also is affected. Analytical cases were made to simulate this problem.

A case for the proposed 65-m telescope was made so that all joints were mis-located in a random direction with a peak value up to 6 mm. Another case for the proposed 25-m telescope was made with the geometry error progressively increased from ground level in a random way in magnitude and direction, up to maximum values of 9 mm. Both cases showed that the effects on the surface are small.

Table VIII. Effect on the surface due to construction inaccuracy.

Case Study	Effect on the Surface
On 65-m telescope, with joints randomly mis-located up to 6 mm maximum.	0.03 mm rms
On 25-m telescope, with joints randomly mis-located, and progressively worse as a function of distance from ground level, up to 9 mm maximum.	0.01 mm rms

For this 25-m design, the error contribution due to constructional error adapts a value of 0.01 mm rms. The results in Table VIII shows that even for a precise instrument like the proposed mm wavelength telescope, the usual industrial practice is sufficient for the construction.

The Surface Plates

Referring to the error budget, a rms error of 0.20 mm was allowed for the fabrication tolerance, and another 0.20 mm for the deflections due to temperature and its own weight.

A review of surface plates of similar kinds showed that the demands of the plates are reasonable according to today's standard in both accuracy and size. Table IX summarizes the data on various plates.

Table IX. Surface plates of various designs.

Description	Surface Area of Each Plate (m^2)	Unit Wt. kg/m^2	Tolerance rms
ESSCO plate for the U-Mass 14-m telescope. Al. skin and rib construction.	2.36	10	0.10 mm
ASI deform. subreflector of fiberglass. Al. honey-comb epoxy construction.	7.90	10	0.19 mm
RSI plate for VLA tele-scopes. Al. skin-rib construction.	3.27		0.38 mm
Proposed VLBA plate.	4.42	10	0.20 mm

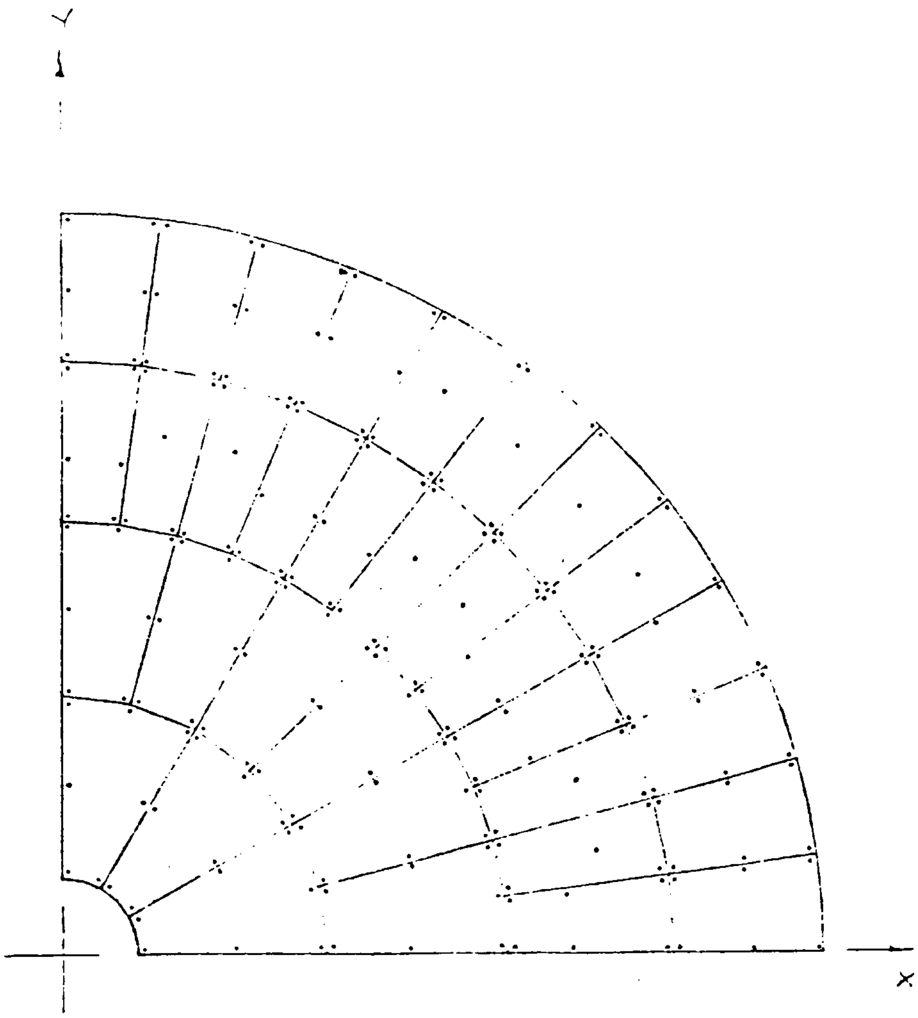


Figure 4. The surface plate arrangement shown in one quadrant. Each plate is supported at the four corners and at its mid-span. The adjustment screws, shown in dots, are arranged depending on the available supports from the back-up structure. There are 132 plates, and 788 adjustments in total. All adjustments are done behind the plates.

A proposed surface plate arrangement is shown in figure 4. Gaps of 1 to 1.5 mm should be provided between plates. The arrangement of adjustment screws, shown as dots, is also suggested. The suggested surface plate is large in size (about 1.6 m x 3.0 m) so that mid-span supports are needed to reduce the plate thickness without causing large dead weight deflections. Unlike the usual corner supports, the mid-span supports are located at the edge in some cases, and in the middle in other cases. These might add to the fabrication difficulties, but simplify the back-up structure design. All adjustments are done on the back side of the plates, made possible by the relatively simple and unobtrusive structure underneath.

It is suggested that the plates be fabricated of fiberglass epoxy-aluminum honeycomb construction. This kind of reflecting surface is common among the military and communication industries. It is light in weight, with a high stiffness-weight ratio. The 140-foot's deformable subreflector shows no noticeable sign of deterioration after two years of exposure to the environment plus constant flexure when used. On the other hand, it is suggested that an experimental plate should be made some time in the future to reassure the fabrication technique, accuracy, adjustment method, and the durability of the plate.

Measuring and Setting of the Parabolic Surface

The measuring and setting accuracies of ±0.20 mm required for a 25-m diameter telescope require no further research or development effort. A review of the existing measuring techniques used on various telescopes showed that the given demand is a reasonable and attainable one. If the new technique of stepping method is developed into a working version, the measuring error could be reduced by a factor of 4, or to ±0.05 mm.

Table X. Surveying method used on various telescopes.

Telescope	Method	Accuracy
140-foot	Stepping method	0.40 mm
36-foot	Stepping method	0.05 mm
25-m VLA	Theodolite, tape	0.46 mm
25-m Raisting	Range-angle	0.20 mm
34-m Werthoven	Range-angle	0.20 mm
Proposed 65-m	Range-angle	0.13 mm
Proposed 25-m	Stepping method	0.04 mm
Proposed 30-m	Laser interferometer	0.05 mm
Proposed 15-m	Laser interferometer	0.02 mm

The most attractive approach for the telescope would be the stepping method. The more conventional way of using pentaprism and tape could be considered as an alternative. The error of ±0.20 mm allowed for the measuring is a pessimistic one if the stepping method is used.

Once again, it is interesting to review the telescope's surface error by including all the contributions (shows as the solid curve in figure 5) over the range from zenith to horizontal positions. The VLA telescope structure with upgraded plates and better setting accuracies is shown as the dotted curve in figure 5. As far as the surface accuracy is concerned, the VLA design is an acceptable one.

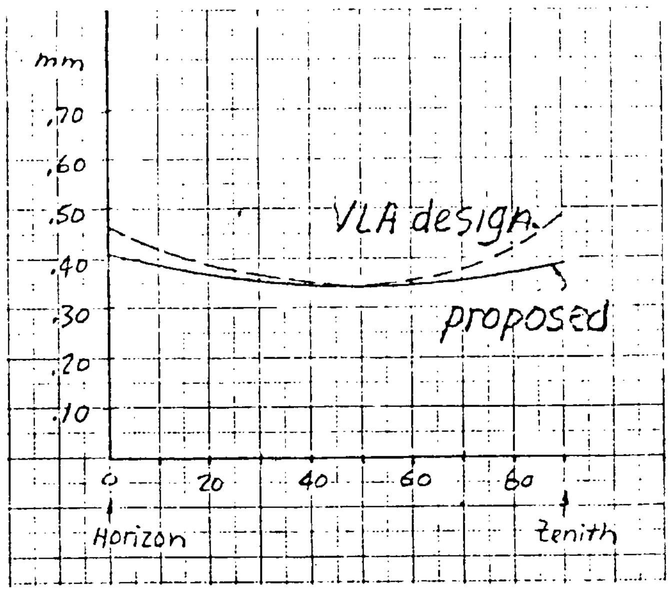


Figure 5. The telescope surface error under no temperature effects and no wind loading. Even with the combined temperature or wind error of 10 μm rms included, the change of the curve would be very slight. The solid curve denotes the behavior of the new design, and the dotted one corresponds to the VLA design.

THE POINTING ERROR

The Wind Pointing

The following analytical results on the tilts of the beam caused by wind were based on the detailed studies of the exposed 25-m mm-wavelength telescope. These results are considered acceptable because of the similarity of the two telescope designs, plus their identical towers. The wind data were based on the wind tunnel tests published by JPL in 1962 (Internal Memorandum CP-4, "Load Distributions on the Surface of Paraboloidal Reflector Antenna" by Norman L. Fox). Five wind loading conditions were computed and the results are summarized in Table XI. All studies were made with the elevation and tower structures as separate problems.

Table XI. The mechanical deflections and optical tilts of beam under 18 mph wind conditions on the reflector alone.

Angle of attack	Mechanical Deflections				
(deg)	Δm (mm)	αm (sec)	Δs (mm)	αs (sec)	αT (sec)
0	+0.076	+0.4	0.0	0.0	-1.6
60	-0.457	-4.8	+0.241	+18.2	-0.6
90	-0.330	-0.4	+0.278	+21.0	-1.4
120	-0.762	-4.0	+0.241	+18.2	-1.1
180	0.0	0.0	0.0	0.0	-1.0

Table XI (ctd.)

Angle of attack (deg)	Corresponding Optical Beam Tilts Δm (sec)	αm (sec)	Δs (sec)	αs (sec)	Sum	Mech. deflection of tower (sec)	Resultant beam tilt (sec)	Abs. value analytical results of VLA (sec)
0	- 1.2	+0.7	0.0	0.0	-0.5	-1.6	-2.1	16.0
60	+ 7.2	-8.6	+3.5	-1.6	+0.5	-0.6	-0.1	12.4
90	+ 5.2	-0.7	+4.1	-1.9	+6.7	-1.4	+5.3	*
120	+12.0	-7.2	+3.5	-1.6	+6.7	-1.1	+5.6	10.8
180	0.0	0.0	0.0	0.0	0.0	-1.0	-1.0	*

where

Δm = lateral shift of the main reflector

αm = rotation of the main reflector

Δs = lateral shift of the subreflector

αs = rotation of the subreflector

αT = rotation of the tower

* = data not available

J. Ruze formulated the tilts of the beam due to the optical characters and the mechanical deflections of the telescope parts. It was discussed in detail in his paper ("Small Displacements in Parabolic Reflectors", MIT, Lincoln Lab., Feb. 1, 1969). A summary of these formulas is included in Appendix 1 for reference.

It could be summarized from the above table that the 25-m telescopes' beam tilts in a steady 18 mph wind in the following ways:

$$\begin{aligned} &\text{rms (18 mph wind pointing)} = 4.1 \text{ sec} \\ &\text{peak(18 mph wind pointing)} = 5.6 \text{ sec} \end{aligned} \qquad (6)$$

The Temperature Pointing

The detailed analysis on the 25-m mm-wavelength telescope produced the mechanical deflections on various parts of the structure due to a unit thermal gradient across the dish structure. These results are listed in the following table. The results were then further expanded into the corresponding RF beam tilt according to J. Ruze's formulas given in Appendix 1. The following results represent only one idealized thermal gradient case: a ΔT across the aperture of the telescope between two extreme points.

Table XII. The deflection of the dish structure with the supporting point held undeformed.

Lateral shift of the main reflector	$\Delta m = -0.022$ mm/°C
Rotation of the main reflector	$\alpha m = -9 \times 10^{-}$ rad/°C or -0.19 sec/°C
Lateral shift of the subrelfector	$\Delta s = +0.056$ mm/°C
Rotation of the subreflector	$\alpha s = +1.7$ sec/°C

Referring to Table VI, the temperature difference over a 24-hour period on a typical sunny day can be separated into the following cases:

$$\begin{array}{lll} \text{Case 1:} & \Delta T \text{ (peak)} = 5.0^\circ\text{C} & \text{day, noon} \\ \text{Case 2:} & \Delta T \text{ (avg. over 0800–2100 hr)} = 3.6^\circ\text{C} & \text{day, average} \\ \text{Case 3:} & \Delta T \text{ (avg. over 2200–0700 hr)} = 0.8^\circ\text{C} & \text{night, avg} \end{array} \tag{7}$$

From Appendix 1, Table XII, and equation (7), the beam tilt θ_T on the reflector alone is as follows:

Case 1: Θ_T = 3.4 sec rms peak

Case 2: Θ_T = 2.4 sec rms daytime average (8)

Case 3: Θ_T = 0.5 sec rms nighttime average

Additionally, the analysis of the tower structure yielded the following results:

$$\alpha T = 2.1 \text{ sec/°C} \quad (9)$$

By combining (7) and (9), the mechanical deflections αT on the tower alone are:

Case 1: αT = 10.5 sec peak

Case 2: αT = 7.6 sec day, average (10)

Case 3: αT = 0 sec night

During a calm evening, the temperature difference on the structure appears to lie in a vertical direction due to the air temperature stratification. Hence, Case 3 produces no differential deflection on the tower's bearing supports, but could still affect the dish structure since the dish is most unlikely in stow position.

The thermal pointings of the telescope could then be summarized and listed in Table XIII.

Table XIII. Thermal pointing of the telescope during a typical sunny day.

Case	Beam tilt dish structure (8)	Beam tilt tower structure (10)	Combined
Peak, at noon, worst case	3.4	10.5	13.9 sec
Average during day (0800-2100)	2.4	7.6	10.0 sec
Average during night (2200-0700)	0.5	0	0.5 sec

Steven Spangler's measurement on the tilt of yoke on the VLA structure showed at the peak (ΔT = 5°C), the amount of tilt was 50 arcsec, compared with the corresponding 10.5 arcsec tilt. The worst thermal pointing of the VLA telescope is about 5 times higher.

APPENDIX 1

Pointing Error of Cassagrain System for the 25-m

The pointing error of a Cassegrain System is a combination of beam tilting caused by

1) Lateral shift of the best fit paraboloid Δm, the tilt of beam is

$$\theta_{\Delta m} = -(BDF) \frac{\Delta m}{fm} \qquad (1)$$

2) Rotation of the best fit paraboloid αm, the tilt of beam is

$$\theta_{\alpha m} = + (1+BDF) \quad \alpha m \qquad (2)$$

3) Lateral shift of the subreflector ΔS, causing the tilt of beam,

$$\theta_{\Delta s} = +(BDF) \frac{\Delta S}{fm} (1 - \frac{fs}{L}) \qquad (3)$$

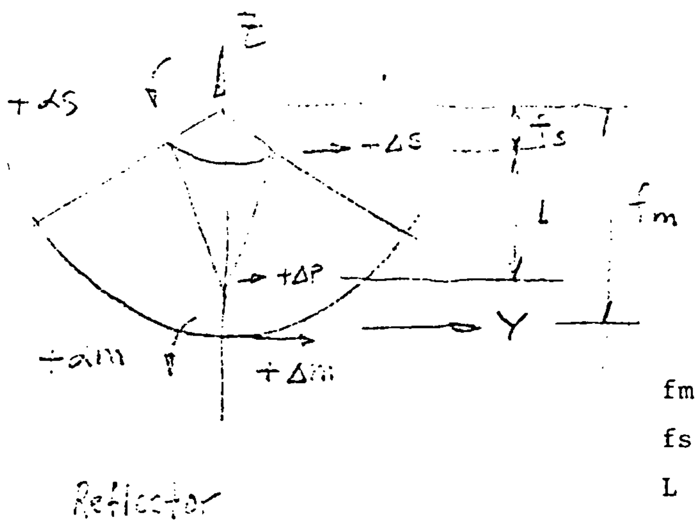
4) Rotation of the subreflector αS causing a tilt of the beam

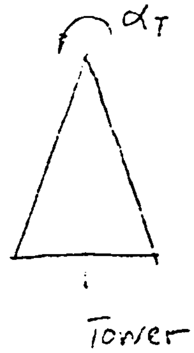
$$\theta_{\alpha s} = -2 \times BDF \times \alpha S \times \frac{fS}{fm} \qquad (4)$$

5) Lateral displacement of the Cassegrain receiver and its corresponding tilt of beam,

$$\theta_{\Delta p} = -BDF \quad \frac{\Delta P}{L} \frac{fs}{fm} \qquad (5)$$

The geometry and the sign convention are shown in the following figure:





fm = 10,500 mm

fs = 589.3 mm

L = 9,310.7 mm

BDF= 0.8

With the given geometry and equation (1) through (5), the combined tilt of beam is as follows, with displacement in mm and sec.

$$\theta_T = \theta_{\Delta m} + \theta_{\alpha m} + \theta_{\alpha s} + \theta_{\Delta P} + \theta_{\Delta S}$$

$$= -15.695\ (\Delta m) + 1.8\ (\alpha m) + 14.702\ (\Delta S) - 0.09(\alpha S) - 0.993(\Delta P)$$

APPENDIX 2 - WEIGHT OF VARIOUS COMPONENTS

Estimated weight of the 25-m VLBA Telescope

	Kg	
Elevation structure		
Surface plate	5,800	
Back-up structure	54,600	
Counter weight	10,500	
Subreflect and focal adj.	1,000	
Subtotal		71,900 Kg
Azimuth structure		
Tower	37,300	
Elev. brg.	500	
Elev. drive	1,800	
Az. drive	1,800	
Subtotal		41,400 Kg
		113,300 Kg
		(250,000#)

Size of Antenna Elements for the VLB Array

K. I. Kellermann

During the past few months, several people have pointed out the sensitivity limitations of the VLB Array, and have questioned the choice of 25m as the element size. This problem is particularly accute for spectral line observations.

Our original specification of 25m for the antenna size was predicated on the assumption that the array would use a modified VLA type antenna, and that the cost of any modification to the dimensions would be incommensurate with the increased collecting area.

Since that time, our thinking has evolved toward a completely new wheel and track design, although we have somewhat arbitrarily retained the 25m size. Using normal scaling laws, the collecting area of a 25 meter antenna would be 44% greater at the expense of a 63% increase in cost. W. Y. Wong has suggested that for "suitably small" deviations, the correct scale factor might be considerably less, since the only significant increase is that due to the increased cost of materials.

Because both the cost of a 25m WYW antenna, and the appropriate scaling factor are uncertain, it is probably appropriate at this time not to consider the antenna dimensions as fixed. Although I suspect in the end we will still end up with 25m, at a very minimum this will have to be more thoroughly justified in terms of cost-performance tradeoffs.

7/16/81

Interoffice

National Radio Astronomy Observatory

Very Large Array

December 4, 1981

VLB ARRAY MEMO No. 50

To: H. Hvatum

From: W. Horne

Subject: VLBI ~ Cost Estimate Antennas

Price of VLA type antenna purchased in 1982 for delivery in 1983.

Estimated 1977 price	$916.5^K
Improved performance costs	60.0^K
(Panel acc., feed legs, yoke str., Ins. & Shielding)	
	$976.5^K

Escalation	1977 - 78	6.5%
	78 - 79	8 %
	79 - 80	12 %
	80 - 81	12 %
	81 - 82	10.5%
	82 - 83	10.5%
		176 %

Making the cost of <u>one</u> VLA type antenna = 976.5^K X 1.76 = 1718.6^K

Plus tooling cost 114.4^K

Engineering cost 585.0^K

(1) Five Antennas delivered in 1983

1718.6 X 5 X .935	=	8,034.5^K
Tooling		114.4^K
Engineering		585.0^K
		$8,734.0^K

(2) Five Antennas delivered in 1884

1718.6 X 1.105 X 5 X .935	=	8,878.0^K
TOTAL	=	$17,612.0^K

Table VI - 1

(1) Feed mounting ring (vertex cover)	12.5^K
(2) Subreflector and support structure	22 ^K
(3) Focus and rotation mount (lateral adj.)	24.5^K
(4) Electrical installation	4.0^K
Total each antenna	63.0^K

VI - 7 Site Development. (I'm not sure where all these amounts in the February '81 report came from but some of them are quite low while others are fairly accurate).

(a)	Site acquisition	25K
(b)	Control Building (1400 ft.^{2} X \$70/ft.^{2})	98K
(c)	Telescope Fndns'	48K
(d)	Emergency Generator & Controls	35K
(e)	Roads	12K
(f)	Power Installation	8K
(g)	Water Supply and Disposal	10K
(h)	Furniture	6K
(i)	Maintenance equipment	20K
		262K

I haven't had time to review extensively a lot of the operating costs but certainly staff costs have been increased by excalation as well as materials and supplies.

Utilities were underestimated in my opinion in the original estimate by about 50% (I estimate 60 KVA for each site with a 150 KVA demand).

Travel was underestimated also but with tightened travel restrictions I couldn't ~~I couldn't~~ guess at what the figure should be but remember we are talking about 10 wide spread sites.

Note that the 1981 operating cost for Tucson (1 telescope site, 1 office site, considerably less equipment, no management fee, much smaller staff) is budgeted at 980.0K per year.

VLB ARRAY MEMO No. 8

8/14/8[illegible] Wong

Part	Item from VLA contract VLA-6 4/4/78	1973 quoted price ($) per antenna	Total (x1000 $)
A	1) Structure	279,332	366.
	8) Field erection	77,007	
	9) Trial assembly	9,625	
B	3) Surface panels + Shipment	57,881	58.
C	2) Servo	33,059	173.
	4) Equipment	105,445	
	5) Misc. items	34,220	
	10) Air cond. mod.	605	
D	6) Eng. + Proj. mgmt.	9,550	28.
	7) Other charges	18,064	

Part	As appeared on the invoice- no. 10, VLA-6	Adj. + Mod. due to more real. price, (73')	Fr. 73'→80' escalation $(1+i)^n$, $i=.06$, $n=7$,	E system to U. Manchester	E system to B. Horn
A	366.	338.	508.		up-grade VLA antenna
B	58.	81.	122.	1.2 M$ (1978)	
C	173.	173.	260.		
D	28.	28.	41.		
Total	624. (1973)	619. (1973)	931. (1980)	1.4 M$ (1980)	1.6 M (1980)

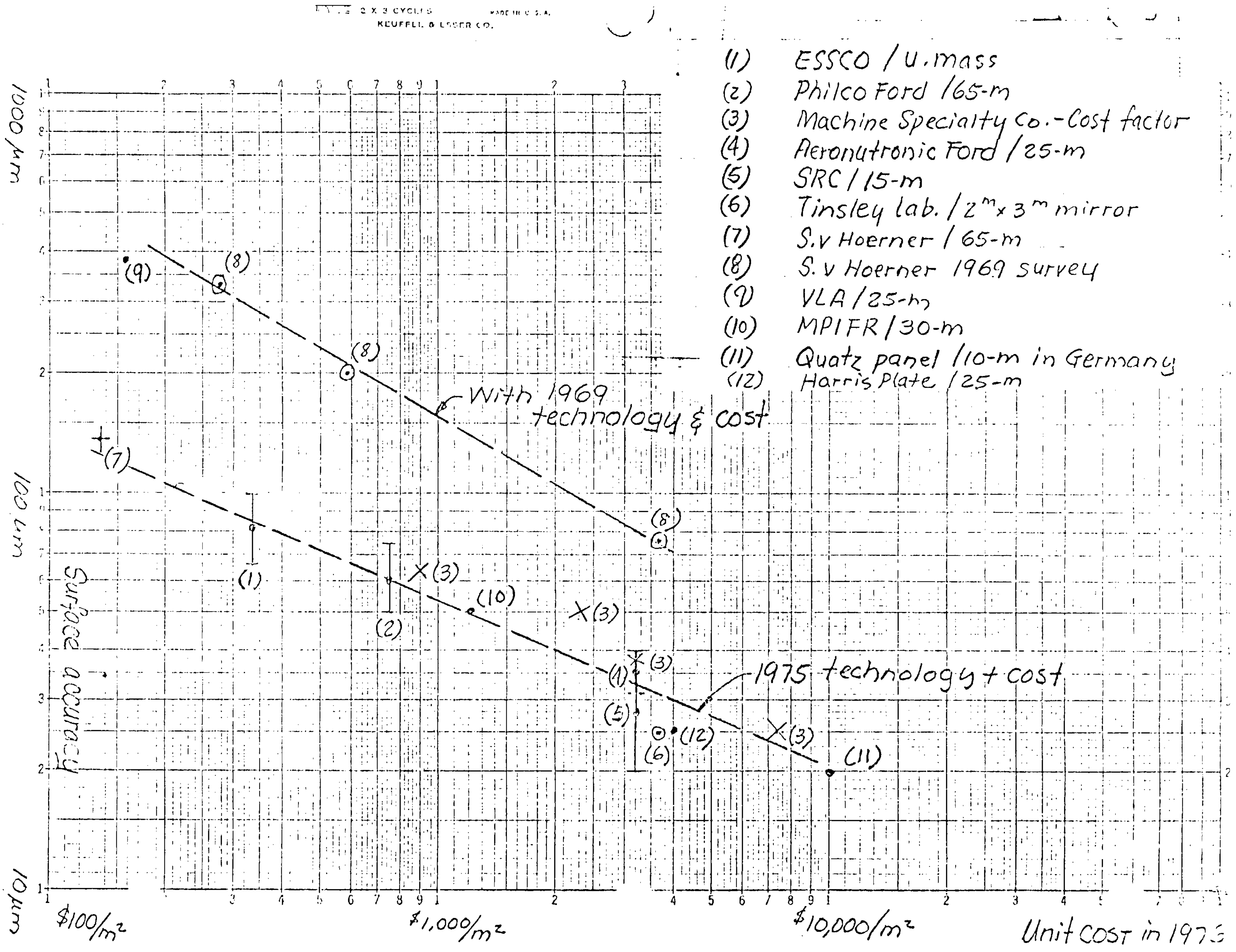
Discussion: 1) Wong antenna + VLA antenna are having approx same amount of steel (62 T vs. 63 T). Part A probably will have no change. Use a round off figure 500 K

2) Spec. for drive & control are same for both antenna Meaning no change on part C. Use a ~~conservative~~ figure 250

3) Engineering + proj. management is more flexible. presently, use part D. Use a round off figure 100 K.

4) Ref. to chart, VLA surface panel are expensive. Roughly adapting $200/m^2$ for 0.20 mm plate, with total surface of 526 m², the estm. cost is 200 x 526 = 105 K, use 150 K.

5) 500 + 250 + 100 + 150 = 1,000. K (1980)



2 X 3 CYCLES
KEUFFEL & ESSER CO.
(1) ESSCO / U.mass
(2) Philco Ford / 65-m
(3) Machine Specialty Co.-Cost factor
(4) Aeronutronic Ford / 25-m
(5) SRC / 15-m
(6) Tinsley lab. / 2m x 3m mirror
(7) S.v Hoerner / 65-m
(8) S.v Hoerner 1969 survey
(9) VLA / 25-m
(10) MPIFR / 30-m
(11) Quatz panel / 10-m in Germany
(12) Harris Plate / 25-m
With 1969 technology & cost
1975 technology + cost
1000 μm
100 μm
10 μm
Surface accuracy
$100/m²
$1,000/m²
$10,000/m²
Unit cost in 197?

National Radio Astronomy Observatory

Green Bank, West Virginia

August 22, 1980

To: H. Hvatum

VLB ARRA[illegible] [illegible]O No. 14

From: K. I. Kellermann

Subject:

On the attached sheet is a summary of my understanding of the VLBA antenna construction program resulting from a discussion between Peery, Horne, Wong, and myself on August 20.

I assume that you will integrate this with schedules for the design, construction, installation and testing of the antenna electronics, site development; Processor, design, prototype, construction and testing; maser procurement; record system design (?), construction and testing; computer acquisition and software development; and initial part time observing.

WYW wishes to construct a model of his antenna element. I think that this is a good idea. He has suggested getting a student to do the construction following his design plans. Recognizing the impracticality in hiring someone for this task, can we either purchase the model at a pre-negotiated price, or pay someone for his services in the same way we would pay someone to paint an antenna or cut the grass? WYW estimates a total price of ∿ $400 including materials and labor.

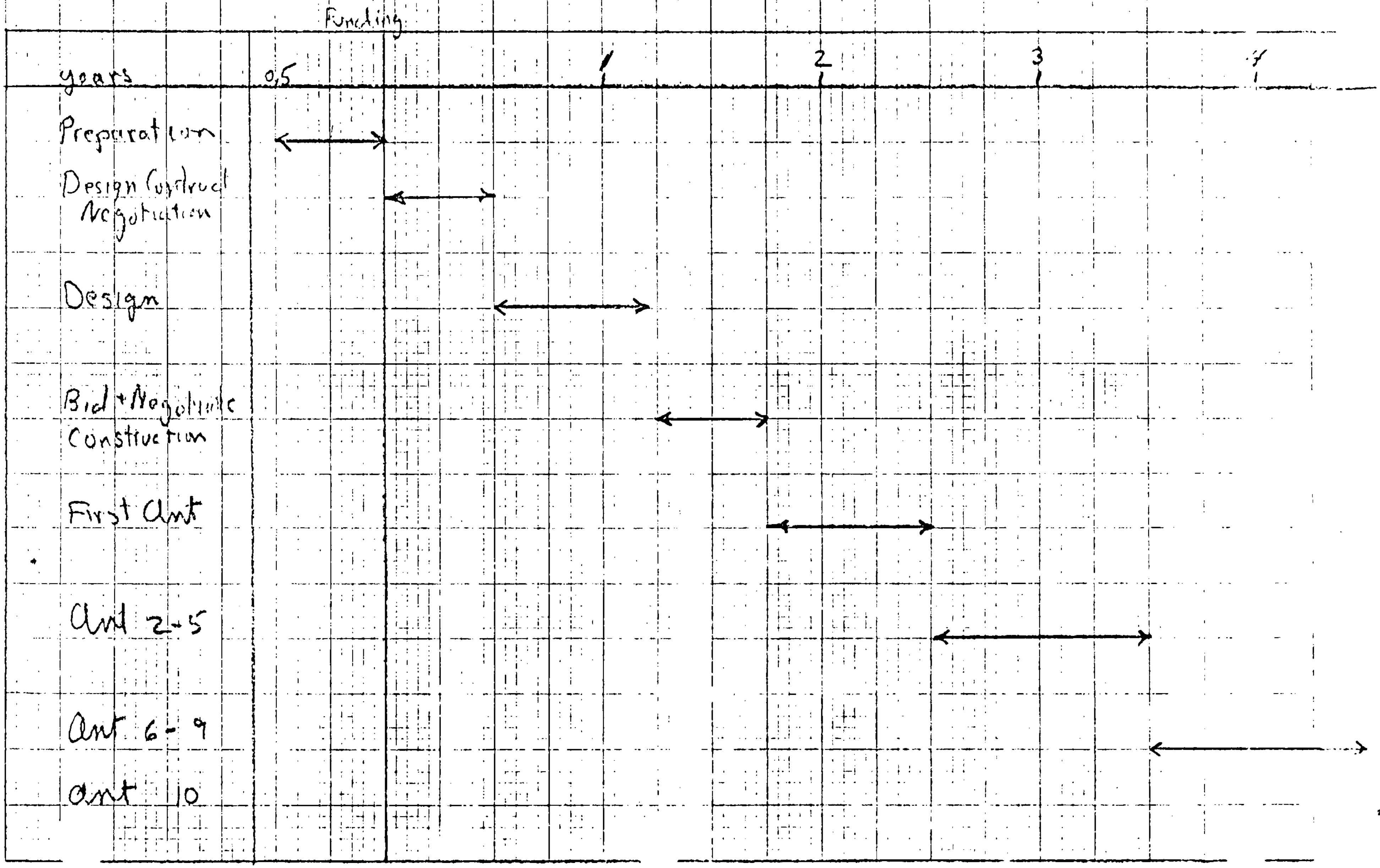
KIK/bbs

Enc.

xc: B. Peery

VLB Array
Antenna Construction

8/11/80



Interoffice

National Radio Astronomy Observatory

Charlottesville, Virginia

July 17, 1980

To: Bill Horne

From: Woon-Yin Wong

Subject: Balsa-wood-core Test Plates

VLB ARRAY MEMO No. 9

Fiberglass-epoxy-balsa-wood-core sandwich construction might be an inexpensive way to build the proposed VLBI antennas' surface. The demanded accuracy of 0.007 inch rms is within the working tolerance of firms producing reflectors. The approach of using balsa wood core has been proven economical (it is about 10 times less than the al. honeycomb core, better in bonding, and more plentiful in supply). If it's also proven thermally well behaved and structurally stable, then it might be a good alternative to the stretch-formed al. plate. It would be reassuring if this approach reprecates the mold. It is important to evaluate its behavior under various environmental conditions. I suggest we order two or more plates for our evaluations in Green Bank.

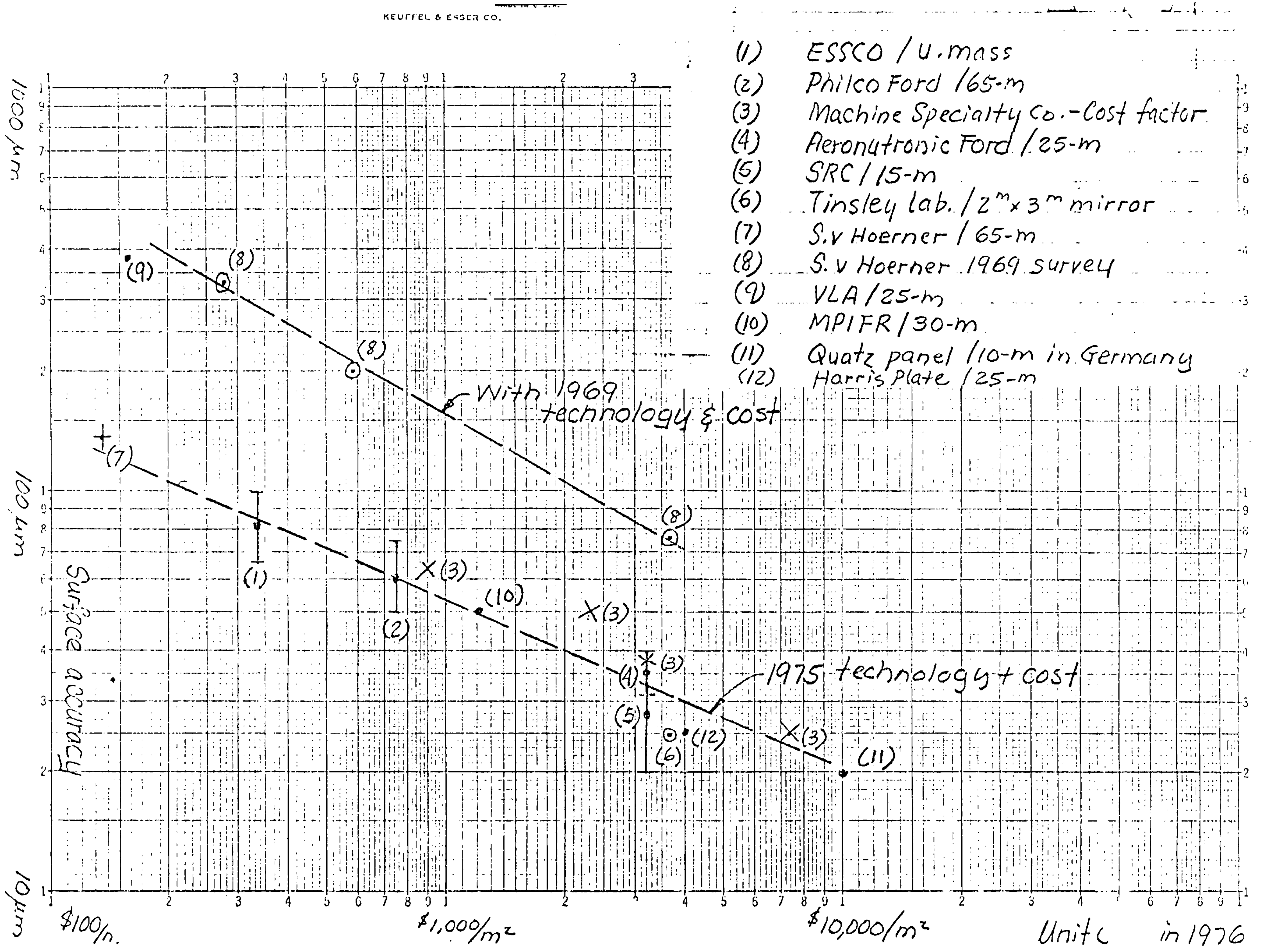
ASI of California would like to give it a trial. They will use one of their existing molds and fabricate the plates with a nominal cost of $300 each. They agreed to provide a realistic cost estimate for the 25-M VLBI antenna surface after the experiments. They will allow NRAO people to make measurements of the mold in the shop to evaluate the reprecation. Then the plates will be sent to Green Bank for further studies. The test plates would be 10' X 4', elliptical in shape. The core is about 2 inches thick. There will be 6 tie-down points on the back.

Please review my suggestion and please inform me as to what should be the next step.

W-YW/lc

cc: M. Balister
J. Findlay
H. Hvatum
K. Kellermann
B. Peery

KEUFFEL & ESSER CO.



VLB ARRAY MEMO No. 15

July 24, 1980

WONG

Bill,

I am sending you all the informations on this VLBA 25-m telescope design. They includes joint coordinates, member connections and 100th scale drawings. They are self-explanatory, and are given in one quadrant only due to symetry. I hope you can proceed with your cost estimate work. Please call in case you have any questions There is an agreement that all cost estimates are present in 1980 dollar.

Are you planning to go to this mid-Sept. VLBA workshop in G.B.? It would be great if you can present the cost estimate in that meeting. Meanwhile, I am working on the cost of the surface panels.

Greetings

Woon-Yin

Item	Estm. weight
Surface plate,	12,766 lbs
Backup str.	120,419 lbs
Counter wt.	23,107 lbs
Subreflector, sterling mt.	2,000 lbs
	158,291 lbs
Tower	82,400 lbs
2 elev. brgs	1,000 lbs
Elev. drive	4,000 lbs
Az. drive	4,000 lbs
	91,400 lbs

158 291
91 400
250,000 lb

Moment of inertia

Dish str. about the elev. axis :
82×10^6 # ft^2

Total structure about the azimuth axis :
293×10^6 # ft^2

POINT	COORDINATES Y	X	-Z	RESTRAINTS OMEGA=1 X Y Z	OMEGA=2 X Y Z	OMEGA=6 X Y Z	POINT LOADS	MU	H	AF Z
1	47.820	0.0	6.630	0 1 0	0 1 0	1 0 1	79.00	2	0.0	1.00
2	0.0	47.820	6.630	1 0 0	0 1 1	1 0 0	79.00	2	0.0	1.00
3	166.006	0.0	-8.508	0 1 0	0 1 0	1 0 1	119.20	2	0.0	1.00
4	117.384	117.384	-8.508	0 0 0	0 0 0	0 0 0	238.40	4	0.0	1.00
5	0.0	166.006	-8.508	1 0 0	0 1 1	1 0 0	119.20	2	0.0	1.00
6	281.029	0.0	-39.317	0 1 0	0 1 0	1 0 1	99.30	2	0.0	1.00
7	259.637	107.545	-39.317	0 0 0	0 0 0	0 0 0	198.70	4	0.0	1.00
8	198.718	198.718	-39.317	0 0 0	0 0 0	0 0 0	198.70	4	0.0	1.00
9	107.545	259.637	-39.317	0 0 0	0 0 0	0 0 0	198.70	4	0.0	1.00
10	0.0	281.029	-39.317	1 0 0	0 1 1	1 0 0	99.30	2	0.0	1.00
11	391.374	0.0	-83.790	0 1 0	0 1 0	1 0 1	112.60	2	0.0	1.00
12	372.219	120.941	-83.790	0 0 0	0 0 0	0 0 0	225.20	4	0.0	1.00
13	316.628	230.044	-83.790	0 0 0	0 0 0	0 0 0	225.20	4	0.0	1.00
14	230.044	316.628	-83.790	0 0 0	0 0 0	0 0 0	225.20	4	0.0	1.00
15	120.941	372.219	-83.790	0 0 0	0 0 0	0 0 0	225.20	4	0.0	1.00
16	0.0	391.374	-83.790	1 0 0	0 1 1	1 0 0	112.60	2	0.0	1.00
17	496.297	0.0	-139.639	0 1 0	0 1 0	1 0 1	53.00	2	0.0	1.00
18	479.386	128.451	-139.639	0 0 0	0 0 0	0 0 0	106.00	4	0.0	1.00
19	429.806	248.149	-139.639	0 0 0	0 0 0	0 0 0	106.00	4	0.0	1.00
20	350.935	350.935	-139.639	0 0 0	0 0 0	0 0 0	106.00	4	0.0	1.00
21	248.149	429.806	-139.639	0 0 0	0 0 0	0 0 0	106.00	4	0.0	1.00
22	128.451	479.386	-139.639	0 0 0	0 0 0	0 0 0	106.00	4	0.0	1.00
23	0.0	496.297	-139.639	1 0 0	0 1 1	1 0 0	53.00	2	0.0	1.00
24	193.676	72.955	60.462	0 0 0	0 0 0	0 0 0	0.0	4		
25	72.955	193.676	60.462	0 0 0	0 0 0	0 0 0	0.0	4		
26	439.879	90.443	-28.547	0 0 0	0 0 0	0 0 0	0.0	4		
27	332.382	163.312	7.475	0 0 0	0 0 0	0 0 0	0.0	4		
28	319.426	319.426	-28.647	0 0 0	0 0 0	0 0 0	0.0	4		
29	163.312	332.382	7.475	0 0 0	0 0 0	0 0 0	0.0	4		
30	90.444	439.879	-28.547	0 0 0	0 0 0	0 0 0	0.0	4		
31	193.676	0.0	60.462	1 1 1	1 1 1	1 0 1	0.0	0		
32	0.0	193.676	60.462	1 1 1	0 1 1	1 1 1	0.0	0		
33	439.879	0.0	-28.547	1 1 1	1 1 1	1 0 1	0.0	0		
34	0.0	439.879	-28.547	1 1 1	0 1 1	1 1 1	0.0	0		
35	307.087	0.0	92.520	0 1 0	0 1 0	1 0 1	0.0	2		
36	217.142	217.142	98.425	0 0 0	0 0 0	0 0 0	0.0	4		
37	0.0	307.087	92.520	1 0 0	0 1 1	1 0 0	0.0	2		
38	0.0	0.0	98.425	1 1 0	0 1 1	1 0 1	0.0	1		
39	0.0	0.0	405.512	1 1 0	1 1 1	1 1 1	5776.69	1		
40	0.0	0.0	-492.126	1 1 0	0 1 1	1 0 1	500.00	1		
41	307.087	0.0	98.425	0 1 0	0 1 0	1 0 1	0.0	2		
42	0.0	307.087	98.425	1 0 1	1 1 1	1 0 1	0.0	2		
43	283.713	0.0	215.941	0 1 0	0 1 0	1 0 1	0.0	2		
44	217.142	0.0	315.567	0 1 0	0 1 0	1 0 1	0.0	2		
45	117.516	0.0	382.138	0 1 0	0 1 0	1 0 1	0.0	2		

x | 19 | 0.734E 00 | 0.100E 01 | 0.283E 00

LOADING AND WEIGHT ON 4 QUADRANTS

BAR	POINT	NU	RC	L	AREA	DA IN %	COB	STRESS 1	2	3	4	5	6	MAX. STRESS	L/R	Q	T	T'
1	1- 3	3	0.28	119.15	1.34	0.0		0.57	0.36	0.05	1.35	0.29	0.0	1.35	88	0.11	1	
2	3- 6	3	0.28	119.08	1.34	0.0		0.55	0.45	0.05	1.29	0.47	0.0	1.29	88	0.11	1	
3	6- 11	3	0.28	118.97	1.34	0.0		0.29	0.28	0.02	0.66	0.54	0.0	0.83	88	0.08	1	
4	11- 17	3	0.28	118.86	1.34	0.0		0.23	0.18	0.02	0.57	0.36	0.0	0.59	88	0.06	1	
5	2- 5	3	0.28	119.15	1.34	0.0		0.70	0.0	0.05	1.54	0.0	0.30	1.54	88	0.13	1	
6	5- 10	3	0.28	119.08	1.34	0.0		0.61	0.0	0.05	1.39	0.0	0.47	1.39	88	0.12	1	
7	10- 16	3	0.28	118.97	1.34	0.0		0.42	0.0	0.03	0.86	0.0	0.55	0.97	88	0.09	1	
8	16- 23	3	0.28	118.86	1.34	0.0		0.34	0.0	0.03	0.73	0.0	0.37	0.73	88	0.07	1	
9	1- 4	4	0.28	137.29	2.68	0.0		0.55	-0.19	0.04	1.19	-0.28	0.19	1.19	102	0.12	1	
10	2- 4	4	0.28	137.29	2.68	0.0		0.45	0.13	0.04	1.04	0.21	-0.26	1.04	102	0.11	1	
11	3- 7	4	0.28	145.88	2.68	0.0		0.29	-0.08	0.02	0.65	-0.14	0.59	0.90	108	0.10	1	
12	4- 7	4	0.28	145.88	2.68	0.0		0.42	0.52	0.03	0.94	0.70	-0.42	1.24	108	0.13	1	
13	4- 8	4	0.28	119.08	2.68	0.0		0.74	0.02	0.06	1.62	0.04	0.03	1.62	88	0.13	1	
14	4- 5	4	0.28	145.88	2.68	0.0		0.44	-0.26	0.03	0.97	-0.46	0.67	1.25	108	0.13	1	
15	5- 9	4	0.28	145.88	2.68	0.0		0.29	0.39	0.02	0.65	0.63	-0.13	0.94	108	0.11	1	
16	6- 12	4	0.28	157.86	2.68	0.0		0.03	-0.06	0.01	0.16	-0.07	0.54	0.62	117	0.09	1	
17	7- 12	4	0.28	121.79	2.68	0.0		0.66	0.40	0.05	1.48	0.62	0.20	1.48	90	0.12	1	
18	7- 13	4	0.28	142.24	2.68	0.0		0.06	-0.24	0.00	0.13	-0.30	0.44	0.60	106	0.08	1	
19	8- 13	4	0.28	129.85	2.68	0.0		0.27	0.37	0.02	0.55	0.58	-0.23	0.89	96	0.09	1	
20	8- 14	4	0.28	129.85	2.68	0.0		0.24	-0.13	0.02	0.51	-0.24	0.56	0.85	96	0.09	1	
21	9- 14	4	0.28	142.24	2.68	0.0		0.07	0.28	0.00	0.15	0.47	-0.29	0.62	106	0.08	1	
22	9- 15	4	0.28	121.79	2.68	0.0		0.70	0.23	0.05	1.54	0.18	0.61	1.54	90	0.13	1	
23	10- 15	4	0.29	157.86	2.68	0.0		0.12	0.32	0.01	0.23	0.56	-0.05	0.68	117	0.10	1	
24	11- 18	4	0.28	165.42	2.68	0.0		0.08	-0.05	0.01	0.24	-0.04	0.42	0.50	123	0.09	1	
25	12- 18	4	0.28	121.08	2.68	0.0		0.14	0.22	0.01	0.30	0.38	-0.39	0.68	90	0.07	1	
26	12- 19	4	0.28	150.39	2.68	0.0		-0.00	-0.11	0.00	0.03	-0.15	0.22	0.27	112	0.05	1	
27	13- 15	4	0.28	127.50	2.68	0.0		0.37	0.27	0.03	0.84	0.42	-0.08	0.84	95	0.08	1	
28	13- 20	4	0.28	137.52	2.68	0.0		0.03	-0.09	0.00	0.07	-0.17	0.26	0.34	102	0.05	1	
29	14- 20	4	0.28	137.52	2.68	0.0		0.10	0.07	0.01	0.18	0.28	-0.16	0.42	102	0.06	1	
30	14- 21	4	0.28	127.50	2.68	0.0		0.40	-0.02	0.03	0.90	-0.08	0.41	0.90	95	0.09	1	
31	15- 21	4	0.28	150.39	2.68	0.0		-0.02	0.11	0.00	-0.00	0.23	-0.15	0.30	112	0.06	1	
32	15- 22	4	0.28	121.08	2.68	0.0		0.26	-0.31	0.01	0.48	-0.39	0.39	0.81	90	0.08	1	
33	16- 22	4	0.28	165.42	2.68	0.0		0.07	0.25	0.01	0.22	0.42	-0.04	0.49	123	0.09	1	
34	1- 2	4	0.28	67.63	2.68	0.0		0.82	0.25	0.05	1.53	0.17	0.19	1.53	50	0.09	1	
35	3- 4	4	0.28	127.06	2.68	0.0		0.43	0.28	0.03	0.87	0.38	0.91	1.41	94	0.13	1	
36	4- 5	4	0.28	127.06	2.68	0.0		0.35	0.90	0.03	0.75	0.89	0.39	1.31	94	0.12	1	
37	6- 7	4	0.28	109.65	2.68	0.0		0.36	0.28	0.03	0.85	0.27	0.52	0.94	81	0.06	1	
38	7- 8	4	0.28	109.65	2.68	0.0		0.41	0.33	0.04	0.97	0.37	0.49	1.03	81	0.08	1	
39	8- 9	4	0.28	109.65	2.68	0.0		0.32	0.48	0.03	0.83	0.47	0.38	0.93	81	0.08	1	
40	9- 10	4	0.28	109.65	2.68	0.0		0.25	0.49	0.03	0.69	0.49	0.28	0.82	81	0.07	1	
41	11- 12	4	0.28	122.45	2.68	0.0		-0.42	0.06	-0.02	-0.76	0.06	-0.06	0.76	91	0.07	1	
42	12- 13	4	0.28	122.45	2.68	0.0		0.28	0.19	0.03	0.82	0.28	0.74	1.06	91	0.10	1	
43	13- 14	4	0.28	122.45	2.68	0.0		0.23	0.42	0.03	0.72	0.49	0.51	0.94	91	0.09	1	
44	14- 15	4	0.28	122.45	2.68	0.0		0.08	0.58	0.03	0.52	0.70	0.27	0.83	91	0.08	1	
45	15- 16	4	0.28	122.45	2.68	0.0		-0.58	0.01	-0.03	-1.00	-0.07	0.05	1.00	91	0.09	1	
46	17- 18	4	0.28	129.56	2.68	0.0		-0.30	0.08	-0.00	-0.38	0.24	0.37	0.75	96	0.08	1	
47	13- 19	4	0.28	129.56	2.68	0.0		-0.33	0.02	-0.01	-0.46	0.19	0.42	0.79	96	0.08	1	
48	15- 20	4	0.28	129.56	2.68	0.0		-0.07	0.38	0.02	0.21	0.53	0.56	0.86	96	0.09	1	
49	20- 21	4	0.28	129.56	2.68	0.0		-0.12	0.40	0.02	0.16	0.54	0.54	0.88	96	0.09	1	
50	21- 22	4	0.28	129.56	2.68	0.0		-0.63	0.44	-0.02	-0.91	0.40	0.16	1.07	96	0.10	1	
51	22- 2[illegible]	4	0.28	129.56	2.68	0.0		-0.56	0.35	-0.01	-0.77	0.36	0.22	0.98	96	0.10	1	
52	1-		0.28	171.74	2.68	0.0		0.02	0.0	.02	-0.23	-0.04	-1.04	1.06	128	0.16	1	
53	3-		0.28	104.14	2.68	0.0		-0.03	0.0	.01	-0.14	0.02	-2.03	2.05	77	0.15	1	
54	4- [illegible]	4	0.28	112.03	2.68	0.0		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		

fig. 1
+
fig 1

51	22	4	0.28	129.56	2.68	0.0	-0.56	0.3	-0.01	-0.77	0.36	0.22	0.98	96	0.10	1
52	1- 24	4	0.28	171.74	2.68	0.0	0.02	0.01	-0.02	-0.23	-0.04	-1.04	1.06	128	0.16	1
53	3- 24	4	0.28	104.14	2.68	0.0	-0.03	0.03	-0.01	-0.14	0.02	-2.03	2.05	77	0.15	1
54	4- 24	4	0.28	112.03	2.68	0.0	-0.05	-0.01	-0.01	-0.14	-0.26	0.33	0.47	83	0.05	1
55	6- 24	4	0.28	151.36	2.68	0.0	-0.15	-0.06	-0.01	-0.38	0.03	-1.34	1.49	112	0.16	1
56	7- 24	4	0.28	124.51	2.68	0.0	-0.16	-0.07	-0.02	-0.49	0.02	0.28	0.49	92	0.06	1
57	8- 24	4	0.28	160.62	2.68	0.0	-0.39	-0.19	-0.03	-0.84	-0.30	0.53	0.99	119	0.13	1
58	2- 25	4	0.28	171.74	2.68	0.0	0.01	-0.90	-0.02	-0.24	-1.06	-0.03	1.07	128	0.16	1
59	4- 25	4	0.28	112.03	2.68	0.0	0.06	0.12	-0.00	0.02	0.37	-0.22	0.49	83	0.05	1
60	5- 25	4	0.28	104.14	2.68	0.0	-0.03	-1.76	-0.01	-0.14	-2.04	0.02	2.07	77	0.15	1
61	8- 25	4	0.28	160.62	2.68	0.0	-0.12	0.36	-0.02	-0.43	0.56	-0.27	0.74	119	0.11	1
62	9- 25	4	0.28	124.51	2.68	0.0	-0.11	0.21	-0.02	-0.42	0.28	0.02	0.42	92	0.05	1
63	10- 25	4	0.28	151.36	2.68	0.0	-0.14	-1.11	-0.01	-0.36	-1.35	0.04	1.49	112	0.16	1
64	6- 26	4	0.28	183.11	2.68	0.0	0.16	-0.05	0.01	0.36	-0.07	0.27	0.45	136	0.10	1
65	11- 26	4	0.28	116.55	2.68	0.0	-0.18	-0.06	-0.02	-0.46	-0.06	-0.53	0.72	86	0.07	1
66	12- 26	4	0.28	92.52	2.68	0.0	0.54	0.00	0.04	1.22	0.04	0.97	1.51	68	0.10	1
67	17- 26	4	0.28	153.96	2.68	0.0	-0.17	-0.06	-0.02	-0.55	-0.12	-0.88	1.06	114	0.13	1
68	18- 26	4	0.28	123.88	2.68	0.0	-0.25	-0.09	-0.04	-0.83	-0.18	0.05	0.83	92	0.08	1
69	19- 26	4	0.28	193.17	2.68	0.0	0.19	0.24	0.02	0.48	0.26	0.37	0.63	144	0.14	1
70	6- 27	4	0.28	177.48	2.68	0.0	-0.26	0.08	-0.01	-0.49	0.01	-0.60	0.86	132	0.15	1
71	7- 27	4	0.28	102.91	2.68	0.0	0.05	0.08	0.00	0.05	0.00	-0.11	0.16	76	0.02	1
72	8- 27	4	0.28	145.98	2.68	0.0	0.05	-0.04	0.00	0.12	-0.10	-0.04	0.16	108	0.04	1
73	12- 27	4	0.28	108.22	2.68	0.0	-0.89	-0.08	-0.08	-2.12	-0.14	-1.07	2.12	80	0.15	1
74	13- 27	4	0.28	114.15	2.68	0.0	-0.21	0.14	-0.02	-0.53	0.07	-0.04	0.53	85	0.05	1
75	19- 27	4	0.28	195.78	2.68	0.0	-0.29	0.01	-0.03	-0.82	-0.07	-0.31	0.82	146	0.18	1
76	8- 28	4	0.28	171.04	2.68	0.0	0.12	-0.07	0.01	0.25	-0.06	-0.06	0.25	127	0.07	1
77	13- 28	4	0.28	105.06	2.68	0.0	0.01	-0.15	-0.00	-0.04	-0.10	0.09	0.14	78	0.02	1
78	14- 28	4	0.28	105.06	2.68	0.0	-0.16	0.17	-0.01	-0.29	0.08	-0.11	0.30	78	0.03	1
79	19- 28	4	0.28	172.00	2.68	0.0	-0.33	-0.34	-0.04	-0.98	-0.34	-0.04	0.98	128	0.15	1
80	20- 28	4	0.28	119.60	2.68	0.0	-0.20	0.01	-0.03	-0.68	-0.05	-0.04	0.68	89	0.07	1
81	21- 28	4	0.28	172.00	2.68	0.0	-0.64	0.10	-0.05	-1.37	-0.04	-0.36	1.37	128	0.20	1
82	8- 29	4	0.28	145.98	2.68	0.0	0.01	-0.04	0.00	0.05	-0.05	-0.11	0.13	108	0.04	1
83	9- 29	4	0.28	102.91	2.68	0.0	0.00	-0.06	-0.00	-0.02	-0.11	-0.00	0.11	76	0.02	1
84	10- 29	4	0.28	177.48	2.68	0.0	-0.16	-0.52	-0.01	-0.34	-0.58	0.03	0.74	132	0.13	1
85	14- 29	4	0.28	114.15	2.68	0.0	-0.04	-0.14	-0.02	-0.28	-0.04	0.09	0.28	85	0.04	1
86	15- 29	4	0.28	108.22	2.68	0.0	-0.80	-0.91	-0.08	-1.99	-1.04	-0.12	1.99	80	0.15	1
87	21- 29	4	0.28	195.78	2.68	0.0	-0.18	-0.31	-0.03	-0.66	-0.30	-0.06	0.66	146	0.15	1
88	10- 30	4	0.28	183.11	2.68	0.0	0.05	0.24	0.01	0.19	0.27	-0.09	0.34	136	0.09	1
89	15- 30	4	0.28	92.52	2.68	0.0	0.46	0.82	0.04	1.09	0.94	0.03	1.39	68	0.10	1
90	16- 30	4	0.28	116.55	2.68	0.0	-0.19	-0.40	-0.02	-0.48	-0.52	-0.06	0.72	86	0.07	1
91	21- 30	4	0.28	193.17	2.68	0.0	0.32	0.23	0.02	0.69	0.35	0.27	0.77	144	0.16	1
92	22- 30	4	0.28	123.88	2.68	0.0	-0.31	0.07	-0.04	-0.92	0.04	-0.18	0.92	92	0.09	1
93	23- 30	4	0.28	153.96	2.68	0.0	-0.20	-0.71	-0.03	-0.61	-0.86	-0.12	1.07	114	0.13	1
94	24- 31	2	0.28	72.95	2.68	0.0	-0.03	0.00	-0.01	-0.17	-0.56	0.0	0.59	108	0.08	1
95	24- 25	4	0.28	170.73	2.68	0.0	1.11	0.45	0.08	2.33	0.37	0.36	2.33	127	0.30	1
96	25- 32	2	0.28	72.95	2.68	0.0	1.41	0.00	0.04	2.01	0.00	-0.33	2.01	108	0.20	1
97	24- 27	4	0.28	173.81	2.68	0.0	1.39	0.33	0.10	2.89	0.32	1.35	2.89	129	0.39	1
98	25- 29	4	0.28	173.81	2.68	0.0	1.35	1.33	0.10	2.82	1.33	0.31	2.82	129	0.38	1
99	26- 33	2	0.28	90.44	2.68	0.0	-0.04	0.62	0.01	0.10	0.49	0.00	0.53	134	0.11	1
100	26- 27	4	0.28	134.77	2.68	0.0	-0.81	0.45	-0.07	-1.82	0.12	-1.98	2.79	100	0.24	1

fig 2a + fig 2b

fig 3a + fig 3b

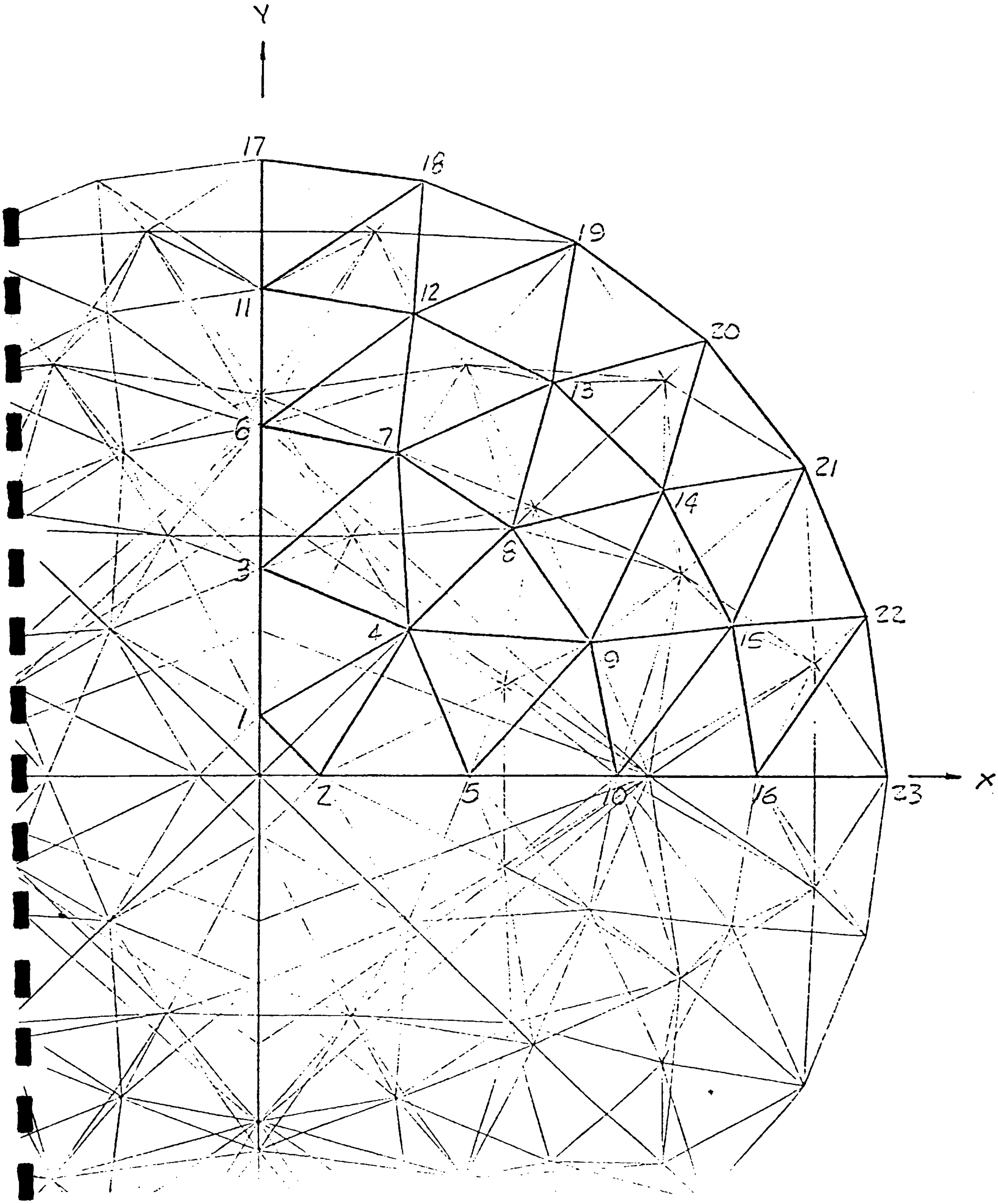
101	27- 28	4	0.28	160.76	2.68	0.0	1.13	0.67	0.10	2.61	0.67	0.23	2.61	119	0.29	1
102	28- 29	4	0.28	160.76	2.68	0.0	1.52	0.16	0.11	3.20	0.22	0.71	3.20	119	0.35	1
103	29- 30	4	0.29	134.77	2.68	0.0	-0.42	-1.75	-0.05	-1.23	-1.92	0.17	2.34	100	0.21	1
104	30- 34	2	0.29	90.44	2.68	0.0	0.44	0.0	0.03	0.83	0.0	0.55	0.99	134	0.17	1
105	24- 25	4	0.28	138.61	2.68	0.0	0.05	-0.04	-0.00	-0.02	-0.12	-0.82	0.88	103	0.10	1
106	26- 25	4	0.28	201.17	2.68	0.0	0.05	-0.23	-0.01	-0.08	-0.23	0.80	0.88	150	0.19	1
107	27- 35	4	0.28	185.86	2.68	0.0	0.08	0.33	0.01	0.28	0.36	0.08	0.45	138	0.11	1
108	24- 26	4	0.28	150.94	2.68	0.0	-1.29	-0.36	-0.11	-3.00	-0.73	-4.73	6.08	112	0.59	1
109	25- 36	4	0.28	150.94	2.68	0.0	-0.12	-4.41	-0.07	-1.22	-4.77	-0.52	4.92	112	0.48	1
110	27- 26	4	0.29	156.36	2.68	0.0	-3.13	0.19	-0.25	-6.94	-0.38	-3.99	7.14	116	0.74	1
111	28- 36	4	0.28	192.54	2.68	0.0	-2.58	-0.50	-0.21	-5.76	-0.75	-0.80	5.76	143	1.04	1
112	29- 36	4	0.29	156.36	2.68	0.0	-2.64	-3.67	-0.23	-6.20	-3.87	-0.31	6.52	116	0.67	1
113	25- 37	4	0.28	138.61	2.68	0.0	-0.10	-0.85	-0.01	-0.25	-0.77	-0.14	0.89	103	0.10	1
114	29- 37	4	0.28	185.86	2.68	0.0	0.52	0.03	0.03	0.94	0.07	0.41	0.94	138	0.17	1
115	30- 37	4	0.28	201.17	2.68	0.0	-0.23	0.76	-0.02	-0.50	0.76	-0.26	1.04	150	0.22	1
116	36- 41	4	0.28	235.03	14.58	0.0	-0.32	0.74	-0.00	-0.39	0.35	0.00	0.68	53	0.06	2
117	36- 42	4	0.28	235.03	14.58	0.0	-0.53	2.00	-0.01	-0.70	1.34	-1.03	2.22	53	0.15	2
118	39- 41	3	0.28	307.09	7.29	0.0	0.27	-0.44	0.00	0.32	-0.27	0.0	0.54	70	0.07	2
119	39- 36	4	0.28	307.09	14.58	0.0	1.35	0.78	0.06	2.34	0.63	1.62	3.10	70	0.23	2
120	38- 42	3	0.28	307.09	7.29	0.0	-4.68	0.0	-0.16	-7.20	0.0	-2.30	7.20	70	0.49	2
121	38- 39	1	0.28	307.09	3.64	0.0	2.62	0.0	0.13	4.64	0.0	0.0	4.64	70	0.33	2
122	36- 39	4	0.28	434.29	14.58	0.0	-1.99	-1.42	-0.12	-3.84	-1.13	-1.13	3.84	99	0.39	2
123	39- 42	3	0.28	434.29	7.29	0.0	3.72	0.0	0.15	5.98	0.0	4.37	8.09	99	0.77	2
124	38- 43	3	0.28	307.09	7.29	0.0	0.53	-0.59	0.02	0.78	-0.38	0.0	0.91	70	0.09	2
125	38- 44	3	0.28	307.09	7.29	0.0	-0.67	-0.48	-0.03	-1.10	-0.29	0.0	1.10	70	0.11	2
126	38- 45	3	0.28	307.09	7.29	0.0	-1.47	-0.31	-0.06	-2.35	-0.16	0.0	2.35	70	0.18	2
127	42- 43	4	0.28	434.29	14.58	0.0	-0.26	0.54	-0.01	-0.43	0.27	0.00	0.53	99	0.12	2
128	42- 44	4	0.28	434.29	14.58	0.0	0.68	0.40	0.02	0.98	0.21	0.0	0.98	99	0.16	2
129	42- 45	4	0.28	434.29	14.58	0.0	1.31	0.19	0.04	1.93	0.11	0.00	1.93	99	0.23	2
130	41- 43	3	0.28	119.82	7.29	0.0	-0.13	-0.00	0.00	-0.13	0.00	0.0	0.13	27	0.01	2
131	43- 44	3	0.28	119.82	7.29	0.0	-0.32	0.08	0.00	-0.32	0.00	0.0	0.32	27	0.02	2
132	44- 45	3	0.28	119.82	7.29	0.0	-0.46	0.22	-0.00	-0.46	0.00	0.0	0.46	27	0.03	2
133	39- 45	3	0.28	119.82	7.29	0.0	-0.54	0.41	0.00	-0.54	-0.00	0.0	0.54	27	0.03	2
134	36- 40	4	0.28	665.62	14.58	0.0	-0.14	-0.39	0.00	-0.14	0.00	-0.00	0.14	151	0.21	2

fig 3a + fig 3b (members 101–115)

fig 4a, 4b, 5a, 5b, 5c (members 116–134)

$3\frac{1}{2}$" sch 40 A = 2.68 in² OD = 4.00", t = .226" (use in member # 1 ~ 115)

12" sch 40 A = 14.58 in² OD = 12.75", t = .375" (" " " 116 ~ 134)



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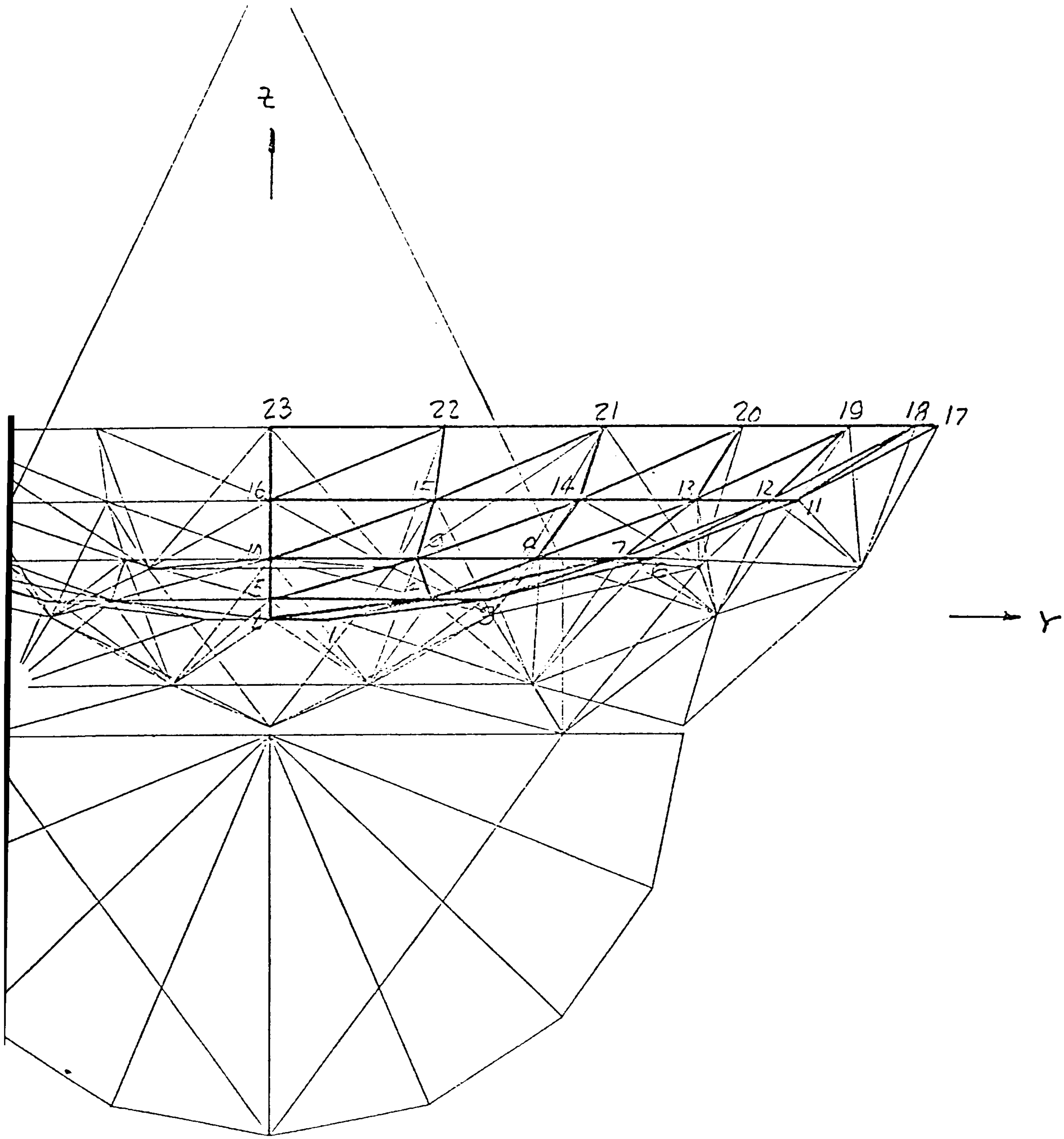

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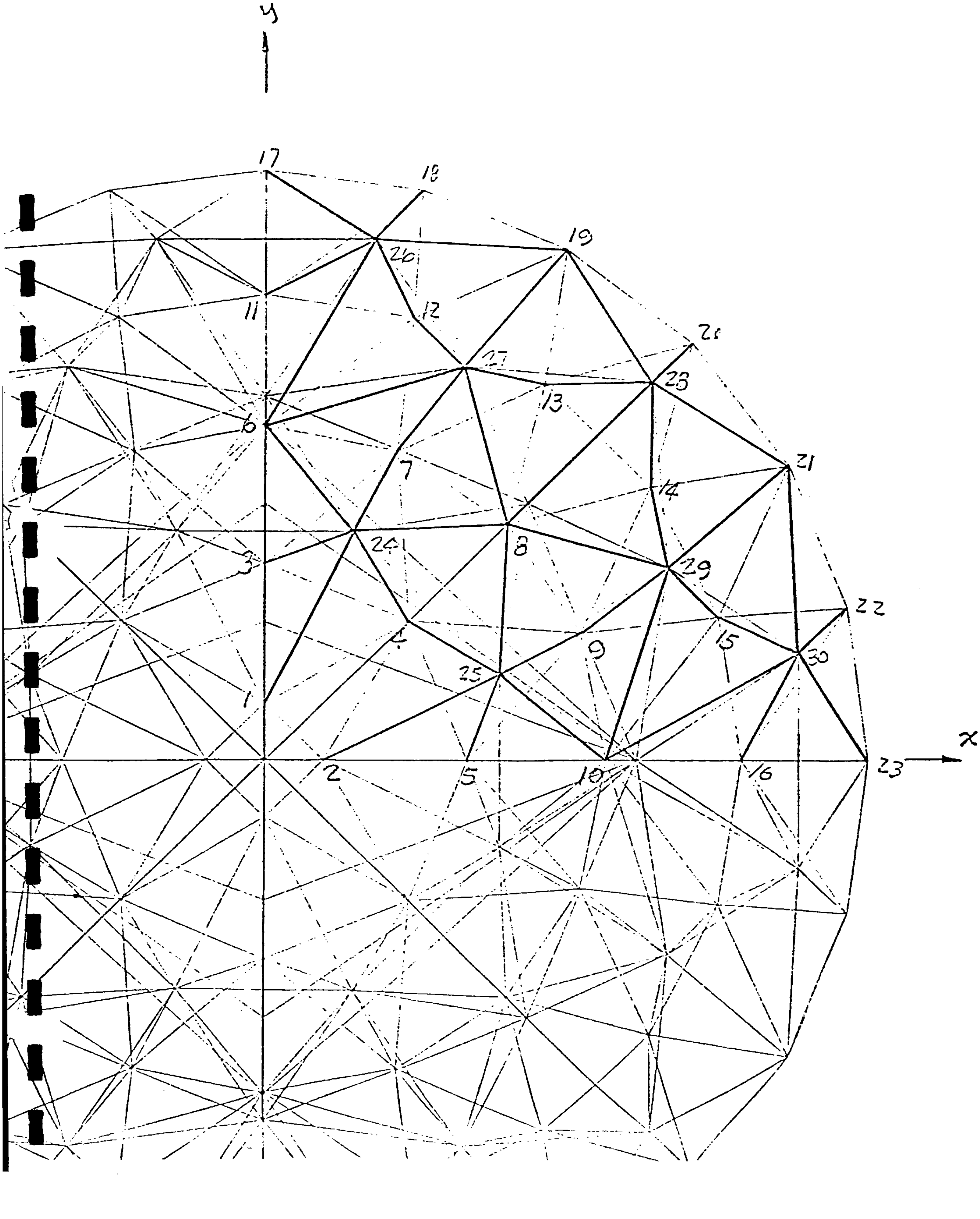
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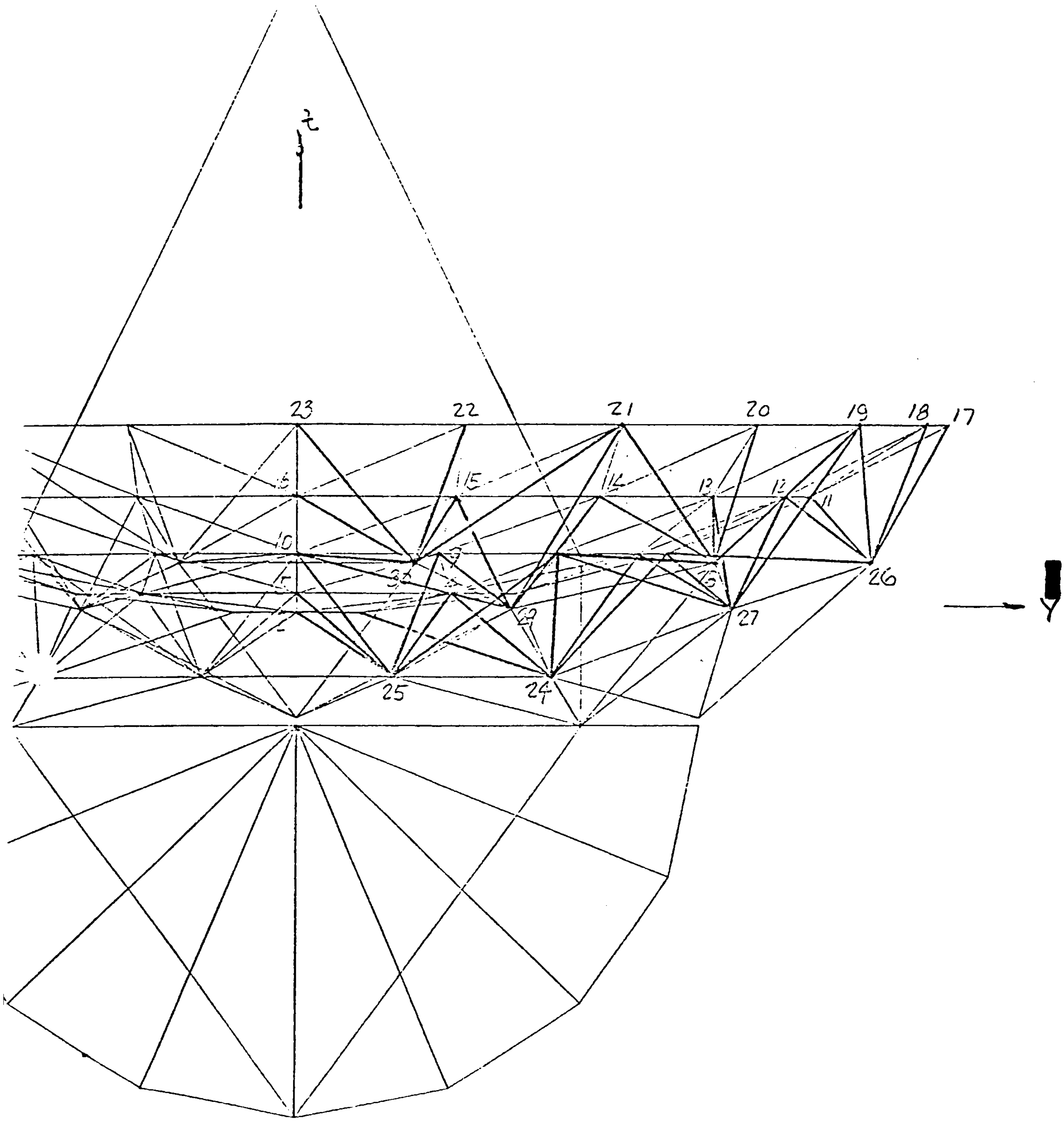

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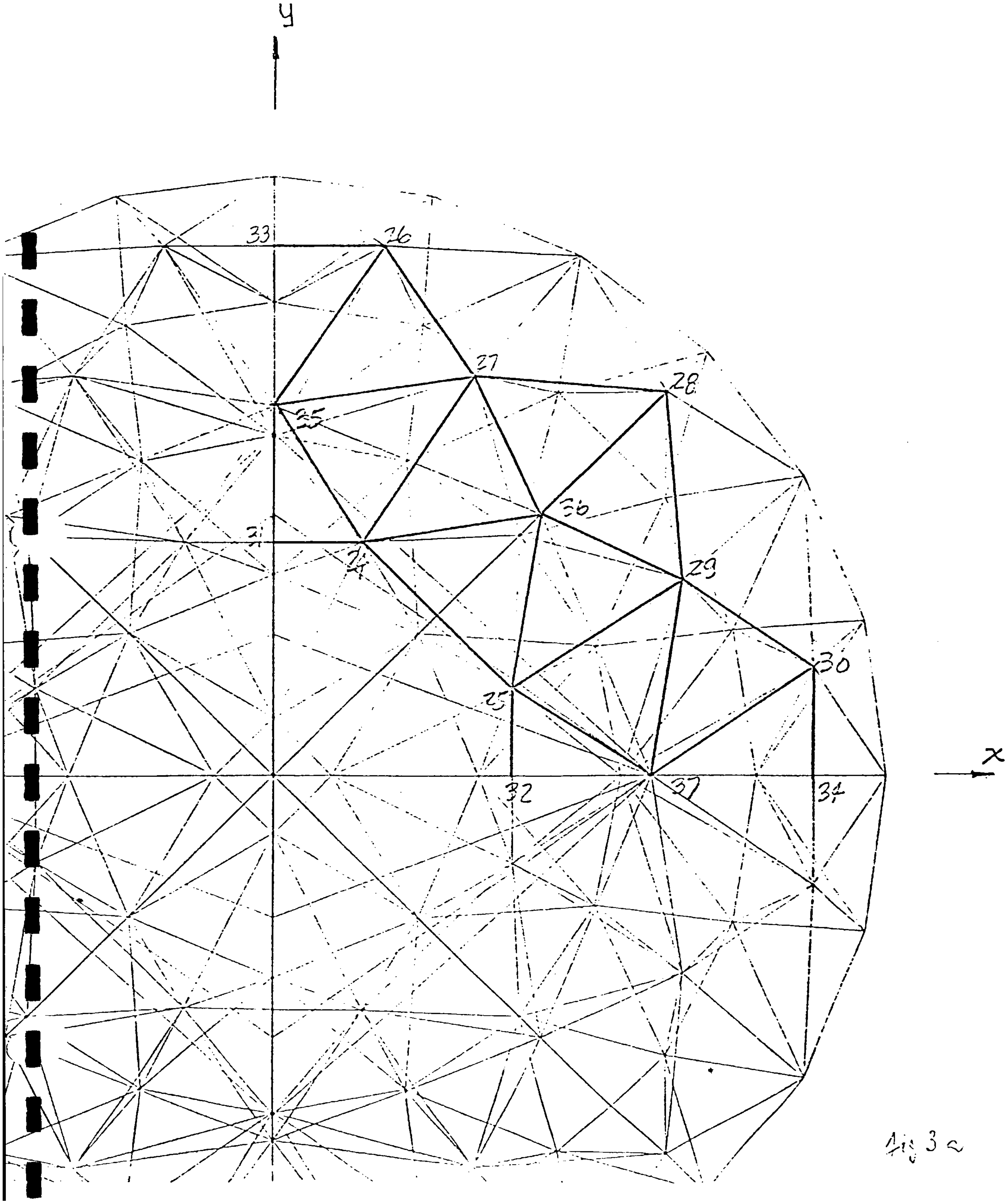
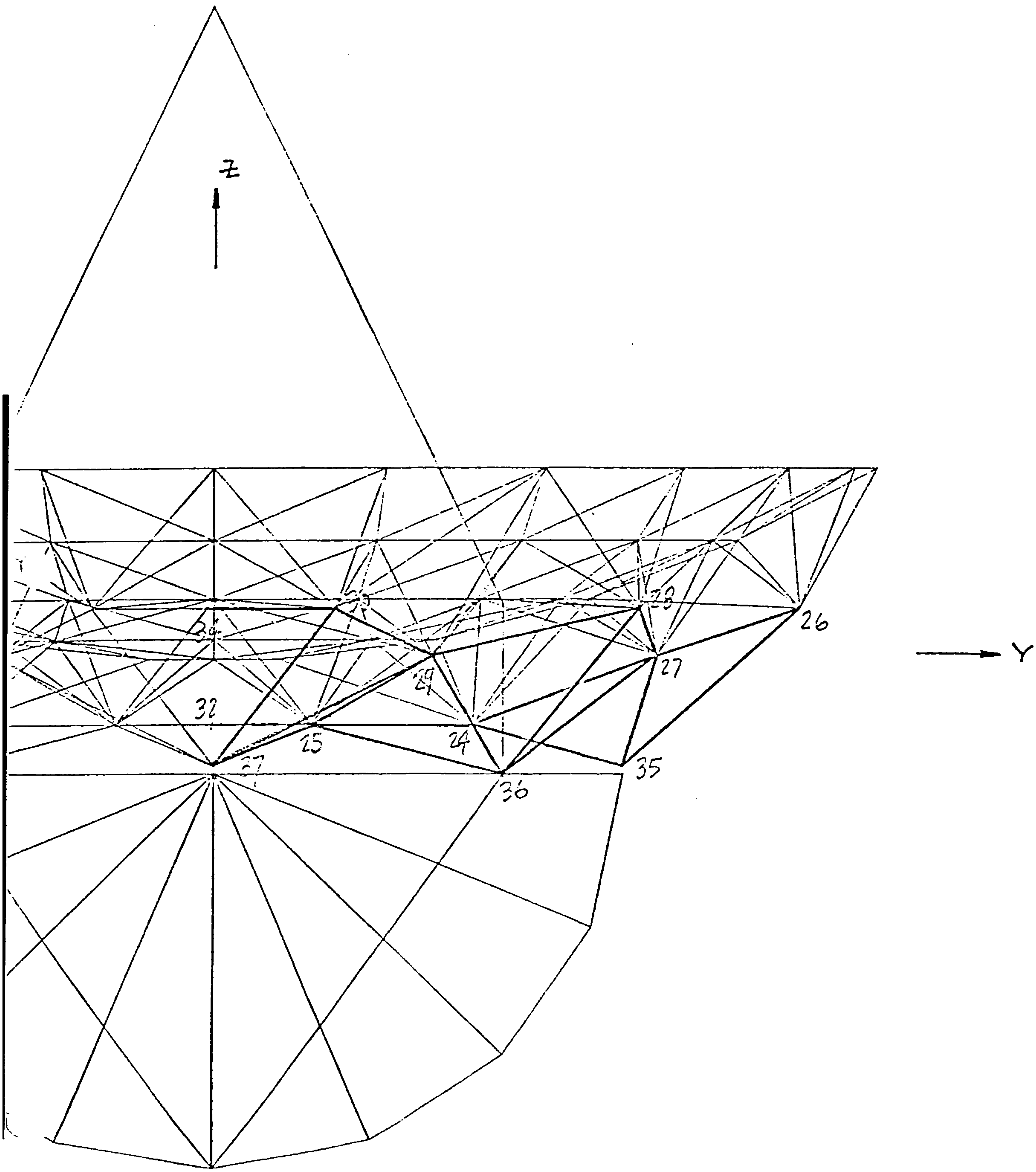


fig 3a



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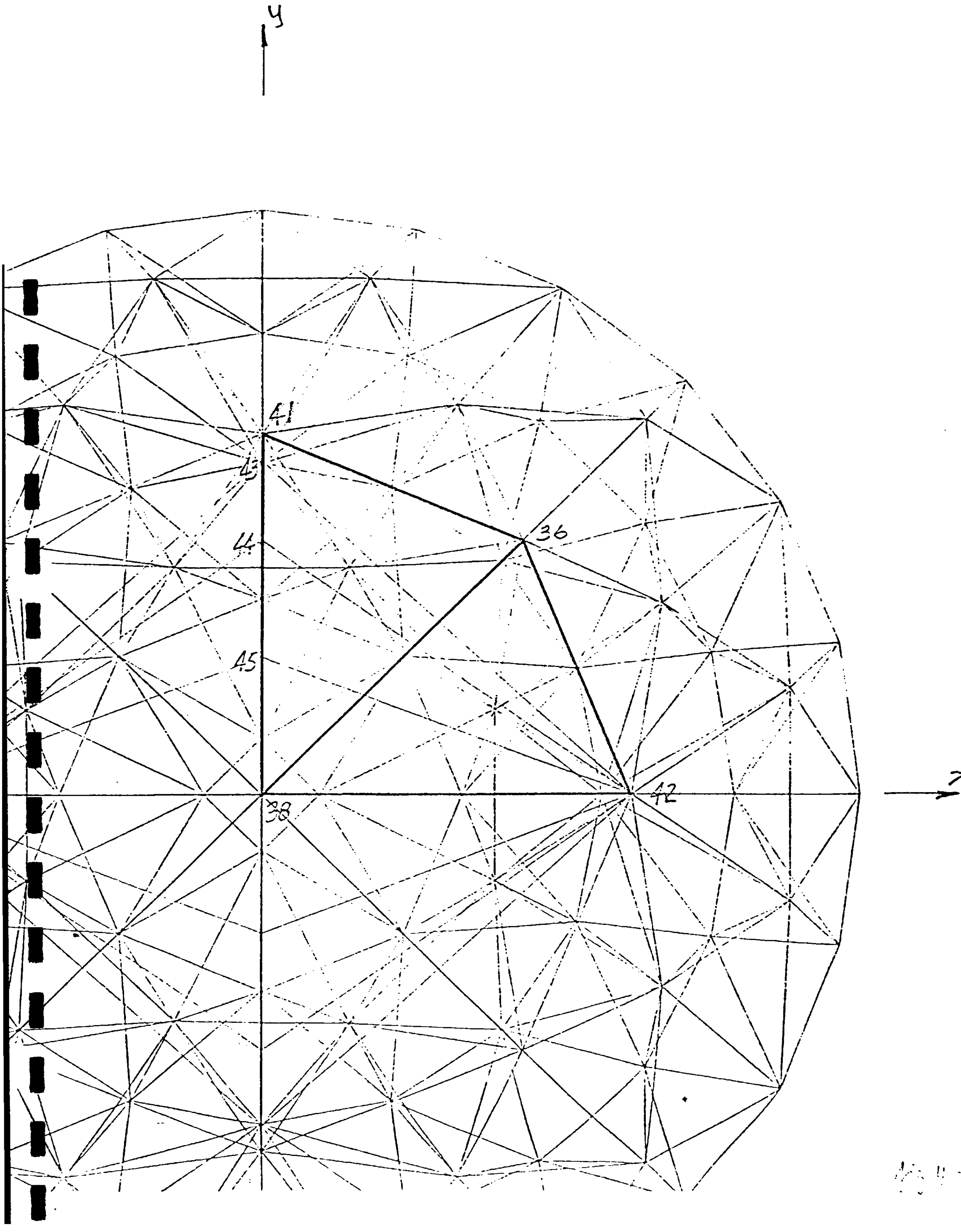

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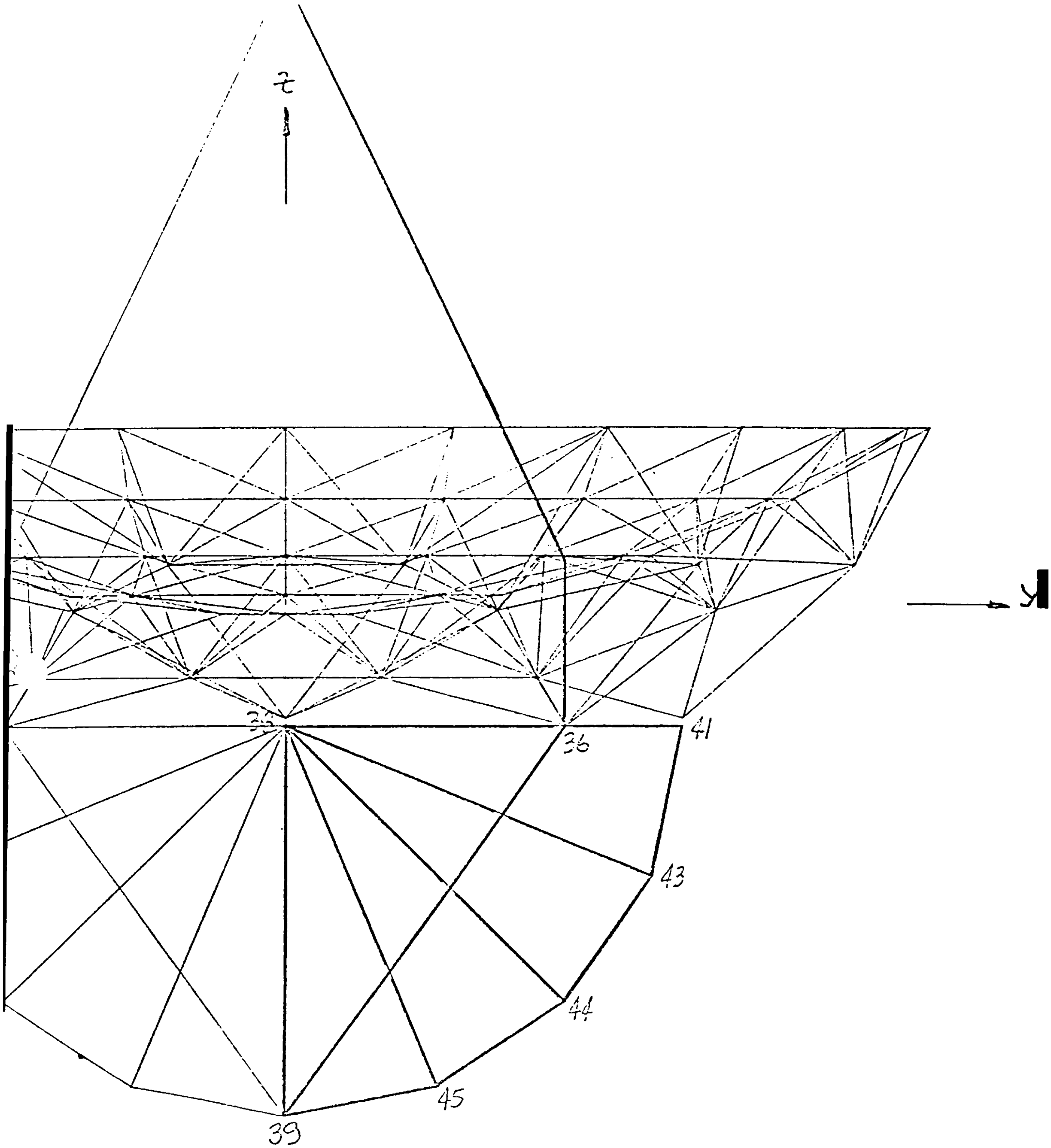
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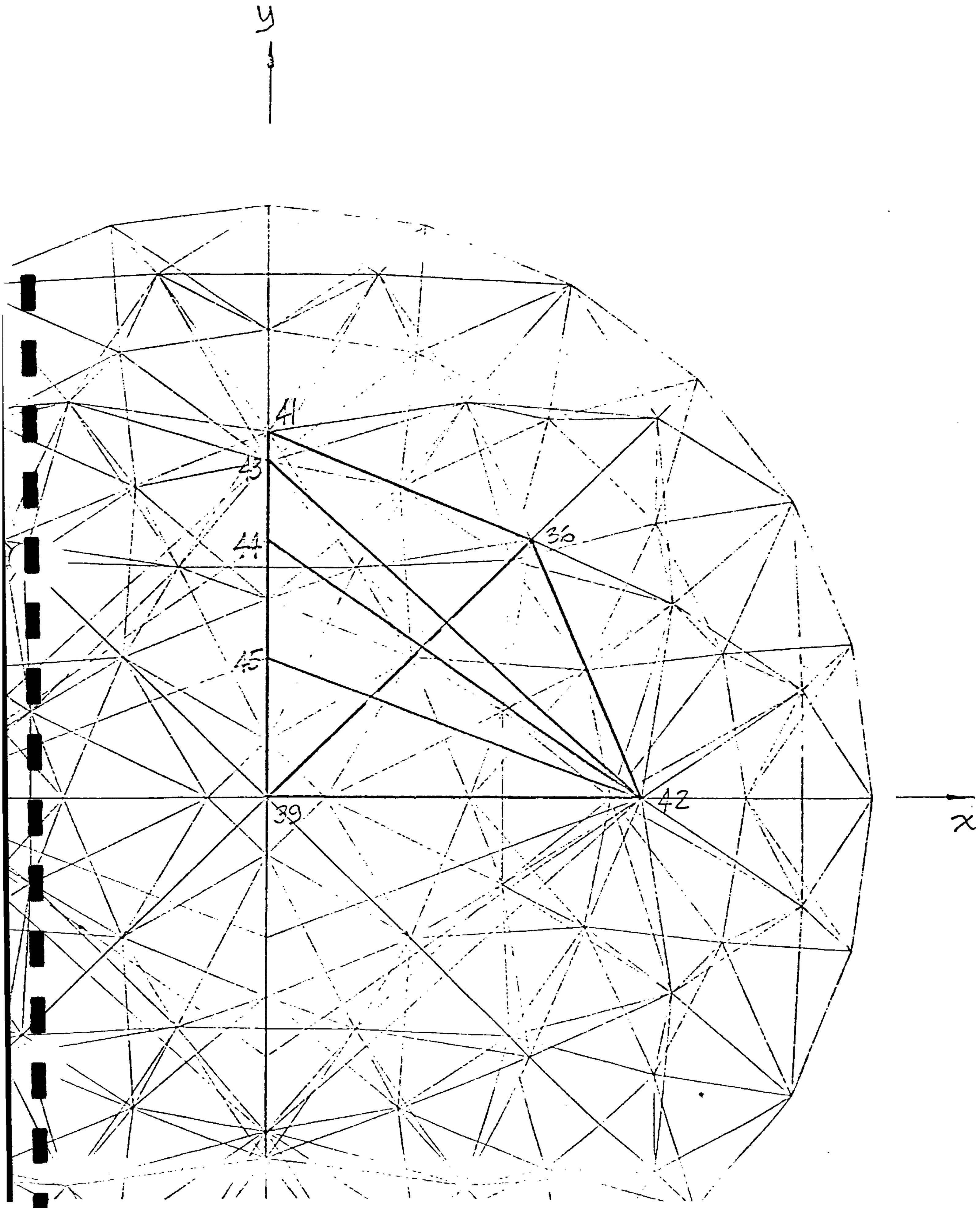

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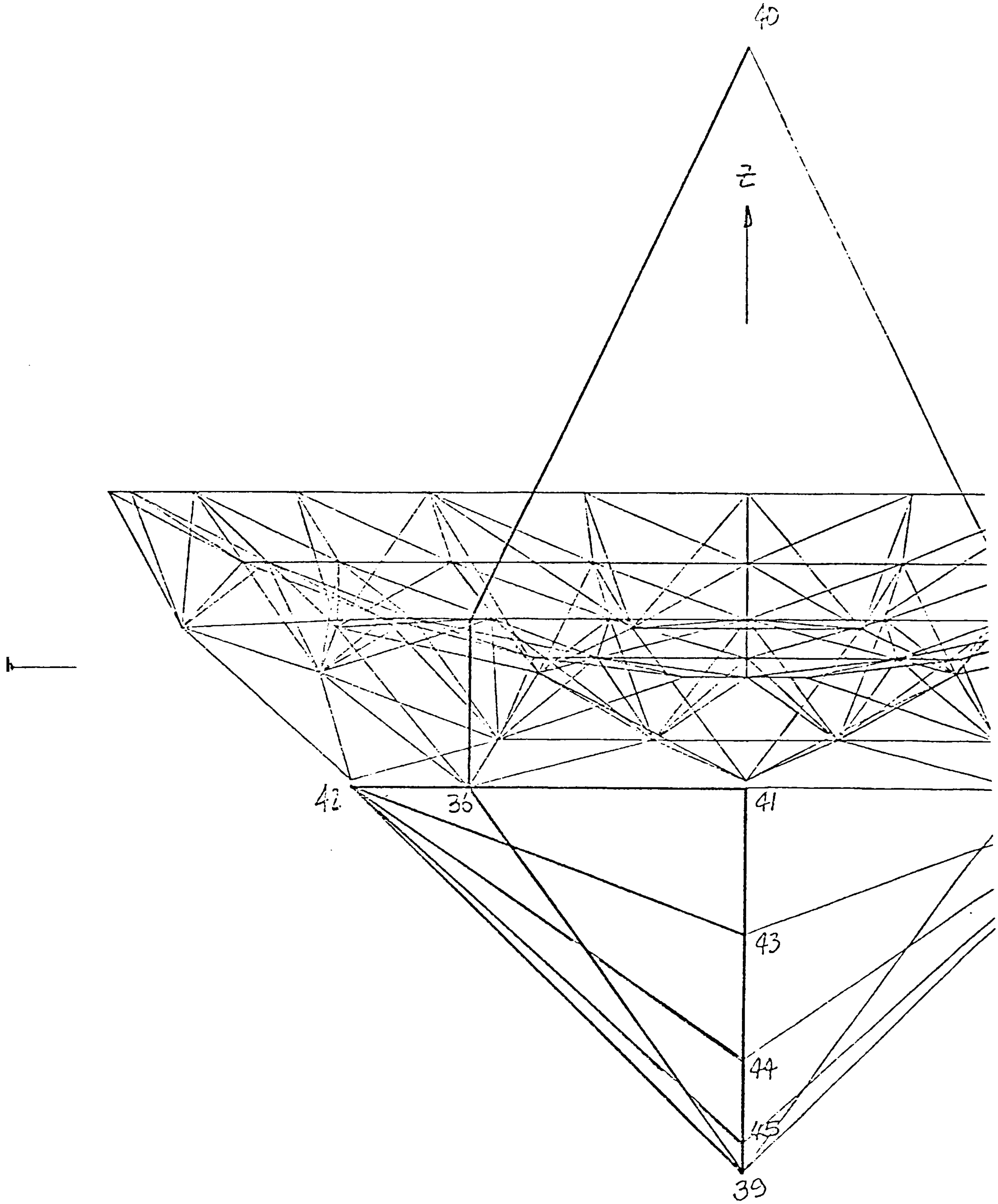


Fig. 5c

III. FRONT END AND FEED SYSTEMS

VLB ARRAY MEMO No. 22

VLBA Memo No P. J. Napier 8/26/80

A Possible Feed System For the VLBA Antenna

Introduction: This memo describes a possible feed system for the VLBA antenna which will allow operation of the antenna at 330 Mhz, 610 Mhz, 1.4-1.7 Ghz, 2.2 Ghz, 5 Ghz, 8.85 Ghz, 10.7 Ghz, 15.4 Ghz, 22 Ghz and 43 Ghz. There are three main features of the design:

(1) Remote Operation. Since it is important to minimize the operating manpower at the antennas it is important that frequency changing require a minimum of hardware changes on the antenna. An offset Cassegrain reflector geometry, similar to the VLA, is proposed, with all feeds between 610 Mhz and 43 Ghz inclusive located at the secondary focus. Frequency changes over this frequency range will simply require rotation of the subreflector about the main reflector axis, as is done at the VLA. The reflectors will be shaped for high efficiency. The 300 Mhz feed will be located at the primary focus. It can be located on axis if the subreflector is removed, or off axis, at the edge of the subreflector, if reduced performance is acceptable.

(2) Large Subreflector. A much larger than usual subreflector is proposed. This will reduce subreflector diffraction loss at the lower frequencies and allow all feeds to be smaller, simpler to design and less expensive. The reduced feed size will allow the feeds to be arranged in a smaller circle around the main reflector axis so that the circular cross polarization problem, present in the VLA antennas, is reduced. Also the smaller feeds will prevent the subreflector being in the near field of the feeds. A 3.66 m diameter subreflector is proposed.

(3) Dual Frequency Feeds. Since 9 frequencies must be accommodated at the Cassegrain focus, dual frequency feeds are used whenever possible to make more efficient use of space. The dual frequency feeds will also be valuable for special experiments such as verifying general relativity by measuring apparent source movement during occultation

The Feed Elements: The high performance dual frequency feed recently developed by JPL (Williams and Withington, 1979; Williams et al, 1979) is suitable for the 1.55/5.0 Ghz, the 2.2/8.8 Ghz, the 10.7/22 Ghz and the 15.4/43 Ghz frequency ranges. The JPL and VLBA subreflectors subtend very nearly the same angle (32.7° and 30.5° respectively) so that an almost identical design, scaled for frequency, can be used. This dual frequency feed works on the principle that when the length of a horn of fixed flare angle is made sufficiently long, the increasing phase error in the horn aperture prevents the radiation pattern from getting any narrower and the beamwidth of the horn is determined only by the flare angle. If a dual frequency horn is operated in this "beamwidth saturation" mode at both frequencies, its radiation patterns will be very nearly the same at both frequencies. The second feature of the JPL design is that at the lower frequency the horn corrugations are in the range $\frac{\lambda}{4}$ to $\frac{\lambda}{2}$, whilst at the upper frequency they are in the range λ (2N-1)/4 to λ(2N/4) where N=2 or 3.

For the 600 Mhz feed it is proposed to use a single ring of 600 Mhz helices. This feed is chosen because, for a given maximum aperture diameter, an annular aperture distribution has the narrowest beamwidth of any circularly symetric distribution. This is therefore the smallest possible feed. Although the spillover efficiency is low, this is made up for by having cryogenics available at the Cassegrain focus. If a room temperature receiver were used at the prime focus it is estimated that the system temperature would be 1.78 times the system temperature of a 600 Mhz cryogenic receiver.

The 300 Mhz feed at the prime focus will be a scalar or Claven feed with total aperture efficency approximately 50%. If it is located 1.83m off axis at the edge of the subreflector a gain loss of 2dB can be expected and coma aberation will increase the first sidelobe level by 10 dB.

Proposed Feed Layout. Figures 1 and 2 show the proposed Cassegrain Geometry and feed layout.

System Performance. The shaped reflector system should provide uniform illumination in the aperture of the main reflector with a -14dB illumination on the edge of the subreflector. This will keep the low frequency feeds to a manageable size and allow an almost direct scaling of the JPL dual frequency feed design. The shaped main reflector should not give significant gain loss at 300 Mhz. For this reason the difference between the shaped main reflector and its best fit parabola should not exceed 1.8cm rms (for the VLA this difference is 0.97 cm rms). The main reflector surface accuracy will be .044 cm (λ at 43 chz). A reasonable goal for the subreflector accuracy is 0.15 012cm, giving a combined surface rms of .046 cm. Table 1 shows the aperture illimination efficiency and the surface accuracy efficiency to be expected across the range of observing frequencies.

(b) Subreflector Diffraction Table 1 gives estimates of the energy lost due to subreflector diffraction with a - 14 dB edge illimination on the subreflector (Rusch, 1963)

(c) Spillover Efficiency Table 1 gives estimates of the fraction of the feed energy incident on the subreflector. For the dual frequency feeds these are taken from (Williams and Wittington, 1979) and for the 600 Mhz feed they are computed from the theoritical radiation pattern of a circular array of 20 helices, each helix having 15 turns

(d) Blockage. A reasonable goal for total blocked area, including the blockage of the 3.66 m diameter subreflector is 7%. This gives a blockage efficiency of .86 in a uniformly illiminated reflector.

(e) Phase Efficiency The nominal phase center of the Cassegrain geometry, as shown in fig 1, is 1.7 m in front of the main reflector vertex. Since the dual frequency horns have their phase centers at their throats, it will be necessary to refocus the subreflector. With a Cassegrain magnification of 5.2, this should not result in significant loss of phase efficiency.

(f) Sidelobes. A 25 m circular aperture with uniform illimination and or 3.7 m diameter circular blockage at its center has a first sidelobe level of -13.7 dB. Feed leg blockage will increase this further at some angles. However, for most VLBI observations, this high first sidelobe level is not expected to be a problem. The VLA antennas have sidelobes of this level.

(g) Polarization. Since the feeds of this VLBA antenna are somewhat closer to the main reflector axis than they are on the VLA antenna, the circular polorization problem present on the VLA antennas (Napier and Austinec, 1977) will be slightly reduced. A separation between the circularly polarized beams of 0.047 beamwidth can be expected. In general this should not be a problem since most VLBI sources will be confined to the antenna axis. At the highest observing frequency pointing problems will cause a circular polarization uncertainty of approximately 3%.

Frequency	Esurf	Eillum	Ediff	Espil	E Block	Ephase	Emisc	Etotal
600 Mhz	1.0	.95	.87	.64	.86	.98	.95	.42
1.5 Ghz	1.0	.98	.92	.90	.86	.98	.95	.65
5.0 Ghz	.99	.99	.96	.90	.86	.98	.95	.68
10.7 Ghz	.96	.99	.99	.90	.86	.98	.95	.68
22 Ghz	.84	.99	.99	.90	.86	.98	.95	.59
43 Ghz	.50	.99	.99	.90	.86	.98	.95	.35

Table 1. Predicted Feed Performance

Esurf = Surface Accuracy Efficiency

Eillum = Aperture Illimination Efficiency

Ediff = Subreflector Diffraction Efficiency

Espill = Feed Spillover Efficiency

Eblock = Blockage Efficiency

Ephase = Phase Efficiency

Emisc = Efficiency due to miscellaneous effects eg VSWR efficiency, loss in the feed and its window.

References

N. Williams, D. Nixon H. Reilly, J. Withington, D. Butcher, " A Prototype DSN x-s Band Feed ", JPL Deep Space Newtwork Progress Report DSN PR 42-52, May-June 1979.

W. Williams, J. Withington, " A Common Aperture S-and X-Band Feed for the Deep Space Network ", 1979 Antenna Applications Symposium, University of Illinois, September 1979.

W. V. T. Rusch, " Scattering from a Hyperboloidal Reflector in a Cassegrain Feed System ". IEEE Trans Antennas and Prop., Vol AP11, No 4, p414-421.

P. J. Napier and J. J. Austincec, " Polarization Properties of a Cassegrain Antenna with off - Axis Feeds and On- Axis Beam", IEEE Antennas and Propagation Soc., Digest International Symposium, PP 452-454, June 1977.

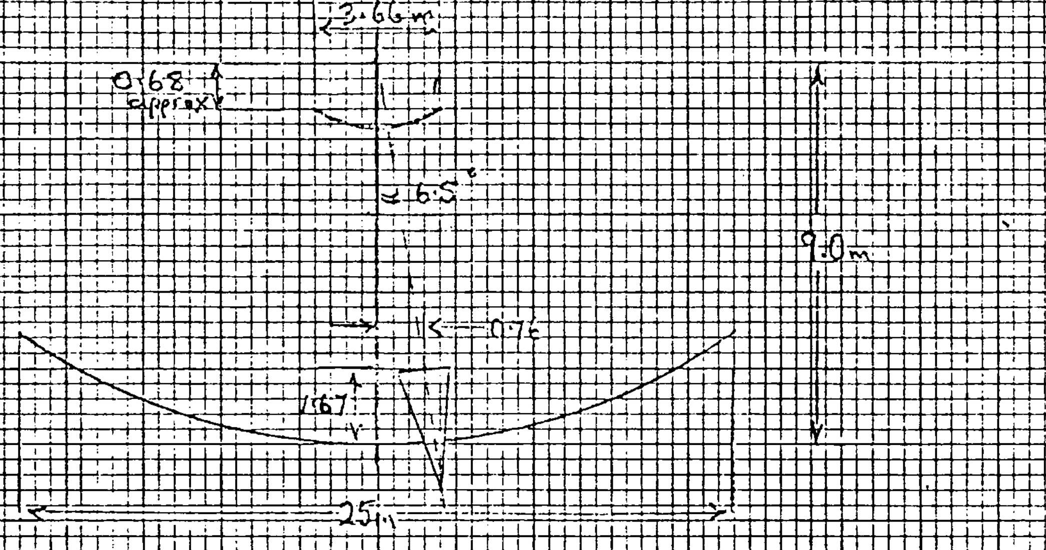
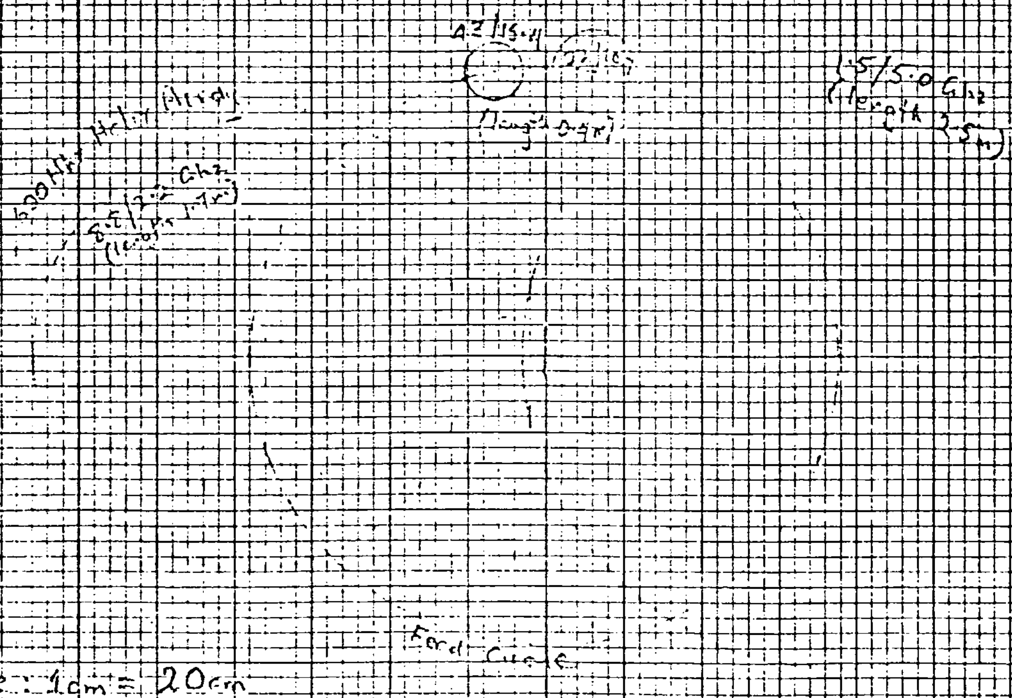


Fig 1. Proposed Cassegrain Geometry



Scale: 1cm = 20cm

Fig 2 Proposed Feed Layout

VLB ARRAY MEMO No. 59

A REVISED PROPOSAL FOR A FEED SYSTEM FOR THE VLBA ANTENNA

P. J. NAPIER 1/11/82

INTRODUCTION

In a previous report[1] a concept for a feed system for the VLBA antenna was presented. Further study of the problem has shown several deficiencies in this concept. The Jet Propulsion Lab dual frequency feed has insufficient bandwidth to support both 21cm and 18cm (H and OH) observations from a single lower band output. Also, because of the phase error needed in the aperture, the feed aperture is relatively large. This, together with the complicated waveguide network needed for the lower band port makes the the feed expensive. Finally, significant development work would be needed to make the feed work at frequencies where the ratio between upper and lower frequency bands is different to the prototype JPL S and X Band. In this new proposal, instead of the JPL dual frequency feed, individual corrugated horns will be used for each frequency with dual frequency capability being obtained, where necessary, by using dichroic reflectors of the type developed at JPL[2] and the VLA[3]. A second problem with the previous proposal was the design goal of keeping the 610Mhz feed at the Cassegrain focus. Further study has shown that the helix-array feed would have lower efficiency than expected due to mutual coupling problems and would cause aperture blockage for the other Cassegrain feeds. In this proposal the 610Mhz feed will be permanently mounted in the middle of the subreflector. The subreflector drive mechanism and the feed legs will be designed to allow the subreflector to be driven up until the 610Mhz feed is sufficiently close to the primary focal point.

Modifications to the original proposal[1] are detailed below.

The Cassegrain Geometry.

The proposed shaped Cassegrain geometry is show in Figure 1. A large subreflector of diameter 3.18m is used to keep the feeds and feed circle as small as possible. The geometry is optimized so that aperture blockage due to the subreflector and feed system are equal. The feeds are arranged in a circle of radius 85cm around the main reflector axis, with the secondary focal point being 1.67m in front of the main-reflector vertex. The 610Mhz feed is located at the center of the subreflector and the 327Mhz feed is mounted at the side of the subreflector.

The Feed Elements

A circle approximately 0.5m in diameter in the middle of the subreflector is shadowed by the subreflector itself. A 610Mhz feed, of either the Clavin or crossed double dipole type, can be permanently located in this area without significantly effecting the performance of the cassegrain feeds. The subreflector will have to be capable of moving axially to place the phase center of the 610Mhz feed within 10cm of the prime focal point, to reduce defocussing loss to less than 5%.

The feed for 18 to 21cm wavelength will be a hybrid-lens feed of the VLA type[4], scaled to provide the smaller aperture needed to illuminate the subreflector which subtends an angle of $\pm 13.1^{\circ}$. The feeds for the 7 frequency bands from 13cm to 0.7cm wavelength will be corrugated horns all scaled exactly according to wavelength from the same design. This approach has the advantage of low risk, since the design of corrugated horns is well established[5]. The corrugated horn has high performance in terms of spillover efficiency and cross polarization. The prototype feed design[5] gives the following parameters; phase error in aperture 0.2λ, horn aperture 6.04λ, horn length 19.2λ, corrugation depth 0.25λ, corrugation width 0.2λ, corrugation period 0.25λ, number of corrugations 76. This horn has a 14dB taper at the edge of the subreflector with a spillover efficiency of 93%. The table in Figure 1 shows the outside dimensions for the horns. All horns have their apertures in the same plane. The 1.3 cm and 0.7cm wavelength horns feed into the same cryogenic dewar requiring the 0.7cm feed to be stretched to the same length as the 1.3cm feed using single mode circular waveguide. All other Cassegrain feeds will feed directly into their own dewars allowing the orthomode junction to be cooled for best noise performance. Circular polarization will be obtained by using a quarter-wave waveguide phase shifter of the VLA L Band type for the lower frequency bands and quasi optical quarter-wave plates of the Greenbank type at the higher bands. For the higher bands, the feeds will be mounted directly onto the cryogenic dewars. The Cassegrain vertex room will be designed to provide convenient access to the higher frequency dewars which will be approximately 3.8m above floor level.

Dual frequency operation will be provided for the 13cm and 3.6cm wavelength feeds using a combination of dichroic and ellipsoidal reflectors. If dual frequency operation between frequency bands higher than this is needed, there is room around the feed circle to provide for additional reflectors.

System Performance

Since the 610Mhz feed is at the prime focus the shaped main reflector must deviate from a parabola by as little as possible. The VLA shaped geometry produces uniform illumination from an 11.5dB illumination taper on the edge of the subreflector. The VLA main reflector deviates from a parabola by 0.97cm rms. The VLBA antenna will be more shaped to produce uniform illumination from a 14dB subreflector taper. The deviation from a parabola is not known for the VLBA antenna, but a reasonable design goal would be 1.2cm rms. This will result in a gain loss of 9% at 610Mhz which is bearable. Table 1 shows the expected feed performance for all bands. The low phase efficiency for the 327Mhz feed results from its off-axis location. If this efficiency is unacceptable, it can be manually mounted on the subreflector whenever 327Mhz is scheduled.

The spillover efficiencies in Table 1 are reasonable goals for the prime focus feeds. The 1.5Ghz feed spillover is estimated from VLA experience and the spillover efficiencies for the corrugated horns are taken from Reference 5.

The subreflector support structure should be designed to minimize blockage. A total blocked area of 7%, including the blockage of the 3.18m diameter subreflector is a reasonable goal. With this much blockage the worst first sidelobe level should be approximately -15dB (the estimate of -13.7dbm in the previous proposal[1] was too pessimistic).

As described in the previous proposal[1] the circular polarization performance of the antenna will be degraded by the assymetric geometry. Circular polarization measurements will be made even more difficult because the feeds themselves are circularly polarized.

Cost

The proposed feed system has been costed based on VLA experience.

It is assumed that all feeds will be designed and developed in house and built in quantity by outside machine shops. This is a safe approach since all feed components have been previously built at NRAO either at the VLA or at Greenbank. Testing will be done on a rented antenna range by the VLBA Feed Engineer.

Development Cost:	Build 1 prototype of each feed at twice the production cost.	$K 150
	3 Man Years Engineering	
	½ Man Year Drafting	
Construction Cost:		$K
	327Mhz Feed	2
	610Mhz Feed	2
	1.5Ghz Feed	13
	2.2Ghz Horn	11.7
	5.0Ghz Horn	3.6
	8.4Ghz Horn	1.8
	10.7Ghz Horn	1.8
	15Ghz Horn	1.5
	22Ghz Horn	1.5
	44Ghz Horn	1.5
	Polarizers	8
	Dichroics	10
	Windows, Waveguides etc.	4
	Pattern Measurement, VSWR Test	10
		72.4
	Amortize $150K development over 10 ant	15
	Cost per antenna	87.4K

During construction need 1 feed engr full time.
Subreflector cost: Budgetry estimate from Milliflec Inc.,

NRE and NRT	50 K
Each subreflector	20 K

Refrences

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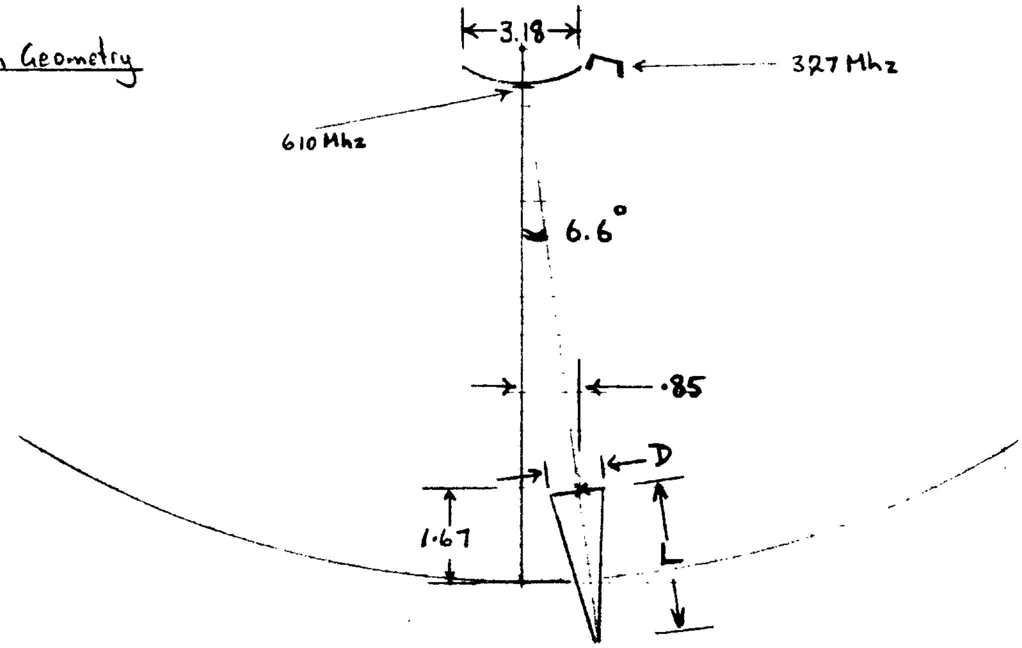
4. J. J. Gustincic, P. J. Napier, "A Hybrid Lens Feed For The VLA," Digest of the IEEE International Symposium (Stanford: IEEE Antennas and Propagation Society) p361, 1977.

5. B. Thomas, " Design of Corrugated Horns, "IEEE Trans., Vol AP-26, No 2, March 1978, pp 367-372.

Frequency	Esurf	Eillum	E Diff	Espil	E Block	Ephase	E Misc	E Total
327Mhz	.97	.78	1.0	.78	.86	.63	.95	.31
610Mhz	.91	.78	1.0	.78	.86	.95	.95	.47
1.5Ghz	1.0	.95	.90	.85	.86	.98	.95	.58
2.3Ghz	1.0	.99	.93	.93	.86	.98	.95	.69
5Ghz	.99	.99	.95	.93	.86	.98	.95	.69
84Ghz	.98	.99	.98	.93	.86	.98	.95	.71
10.7Ghz	.96	.99	.99	.93	.86	.98	.95	.70
15Ghz	.92	.99	.99	.93	.86	.98	.95	.67
22Ghz	.84	.99	.99	.93	.86	.98	.95	.61
44Ghz	.50	.99	.99	.93	.86	.98	.95	.36

Table 1. Predicted Feed Performance
Esurf = Surface Accuracy Efficiency
Eillum = Aperture Illumination Efficiency
Ediff = Subreflector Diffraction Efficiency
Espill = Feed Spillover Efficiency
Eblock = Blockage Efficiency
Ephase = Phase Efficiency
Emisc = Efficiency due to miscellaneous effects eg VSWR efficiency, loss in the feed and its window.

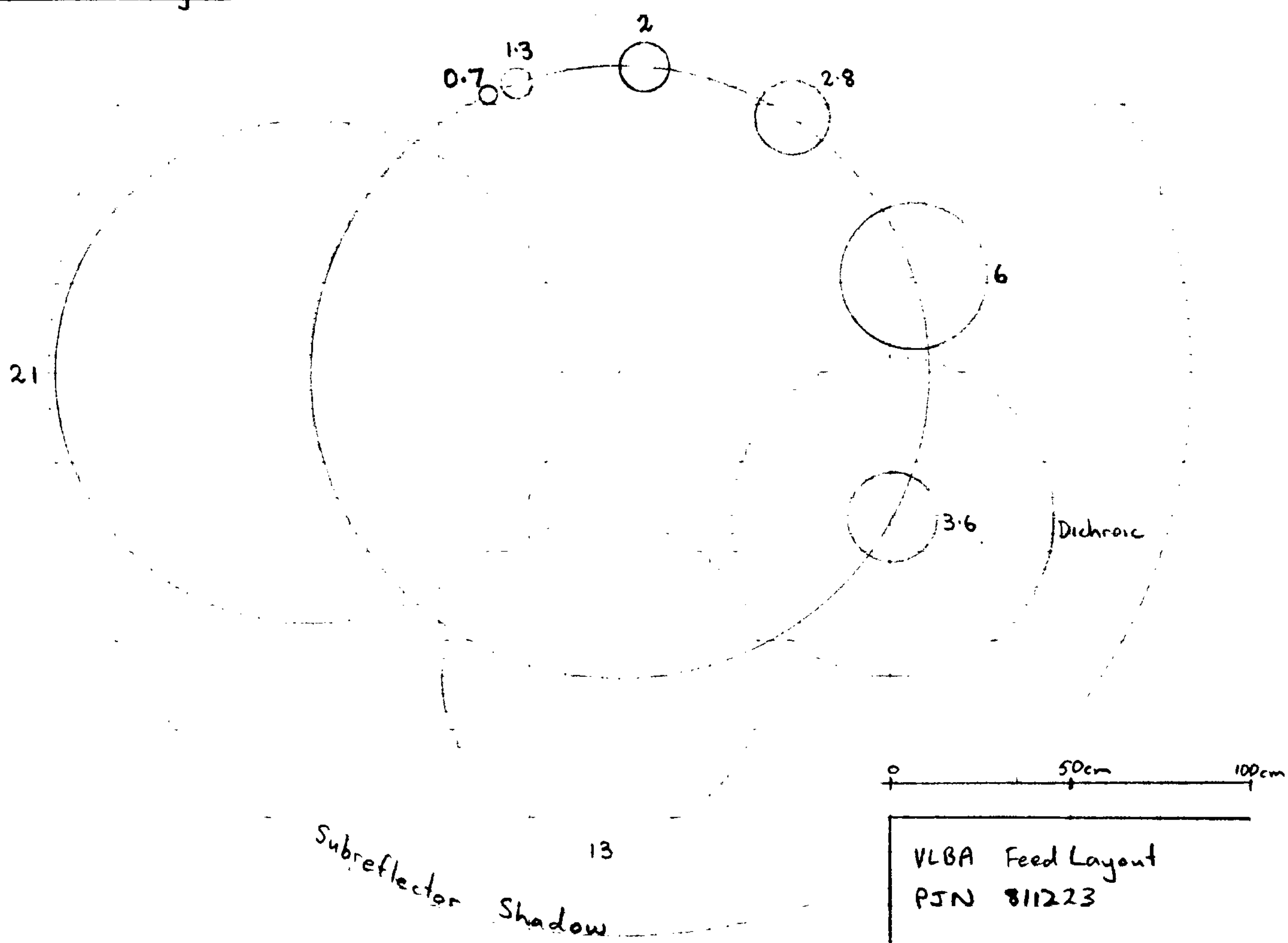
Cassegrain Geometry



λ_{cm}	92	49	21	13	6	3.6	2.8	2.0	1.3	0.7
D_{cm}	PF	PF	142	90	41	24	19	14	9	5
L_{cm}	PF	PF	228	256	119	71	56	41	27	16

PF = Prime Focus

Feed Circle Layout



VLBA Feed Layout
PJN 811223

Interoffice

National Radio Astronomy Observatory

Charlottesville, Virginia

January 11, 1982

To: K. Kellermann

From: M. Balister

VLB ARRAY MEMO No. 52

Subject: VLBA Proposal

Front End System

We have considered several types of low-noise front ends to satisfy the sensitivity requirements. Appendix I* covers this comparison in some detail. Table I summarizes the proposed front end type and performance for the various proposed VLBA frequencies.

In order to obtain the minimum possible downtime for any observing frequency, we are proposing to package individually each GASFET front end in its own dewar. Cooled dual polarization waveguide transitions will be integrated into the dewar to minimize the added noise due to loss between the feed and GASFET amplifiers. This technique of cooling the dual polarization transitions has been successfully used by other radio astronomy observatories over relatively narrow bandwidths. NRAO is currently supporting development of a wide band dual polarization transition which is ideally suited for the wider bandwidths needed by the 1.55 GHz front end. This plan will result in 6 cooled GASFET receiver packages, each with its own refrigerator, mounted on the end of its respective feed horn.

The two maser receivers will be mounted on a single 4K refrigerator. Since the 22.2 and 43 GHz feed output flanges are close together, this will not result in a loss in performance due to long input lines. The use of a common 4K refrigerator and dewar will result in a cost saving of approximately 50k$ per antenna.

NRAO has developed a 43 GHz maser which is currently being used by Haystack Observatory. The system noise temperature is 90K including a contribution from the radome at that site. We are proposing that the 43 GHz front end be single channel due to lower maser gain, higher pump power requirements and lack of a suitable low-noise second stage, compared to the 22 GHz maser which will be dual channel. If a second channel is considered of great importance, some development would be required to overcome the current shortcomings.

*to be written by Craig Moore.

Figure 1 shows the proposed receiving system components that will be in the vertex cabin. The IF output frequency bands will lie in the range 250-1500 MHz. Since 9 frequencies are dual polarization and 43 GHz is single, there will be 19 IF outputs. These signals will go to an IF switching matrix to connect the front ends in use to the 4 IF input distributor in the record terminal.

A phase calibrator consisting of frequency pickets with 5 MHz spacing will be placed at the vertex to radiate into the Cassegrain feeds. This system will permit calibration of the delay through a complete receiver channel. The vertex phase calibrator will be optimized for the S and X-band frequencies but will possibly be useable up to 22 GHz. A solid state noise source will be coupled into each feed horn with nearly equal intensity at the two polarizations. The added noise intensity will be approximately 3 times the system temperature -- strong enough to allow the system to be used as a noise adding radiometer with 25% duty cycle for periodic pointing checks. The noise intensity will also be reduced to approximately 10% of the system temperature for measurement of source and system temperatures.

Cryogenic System

The front end system proposed for the VLB array requires one 4K refrigerator and six 20K refrigerators per antenna.

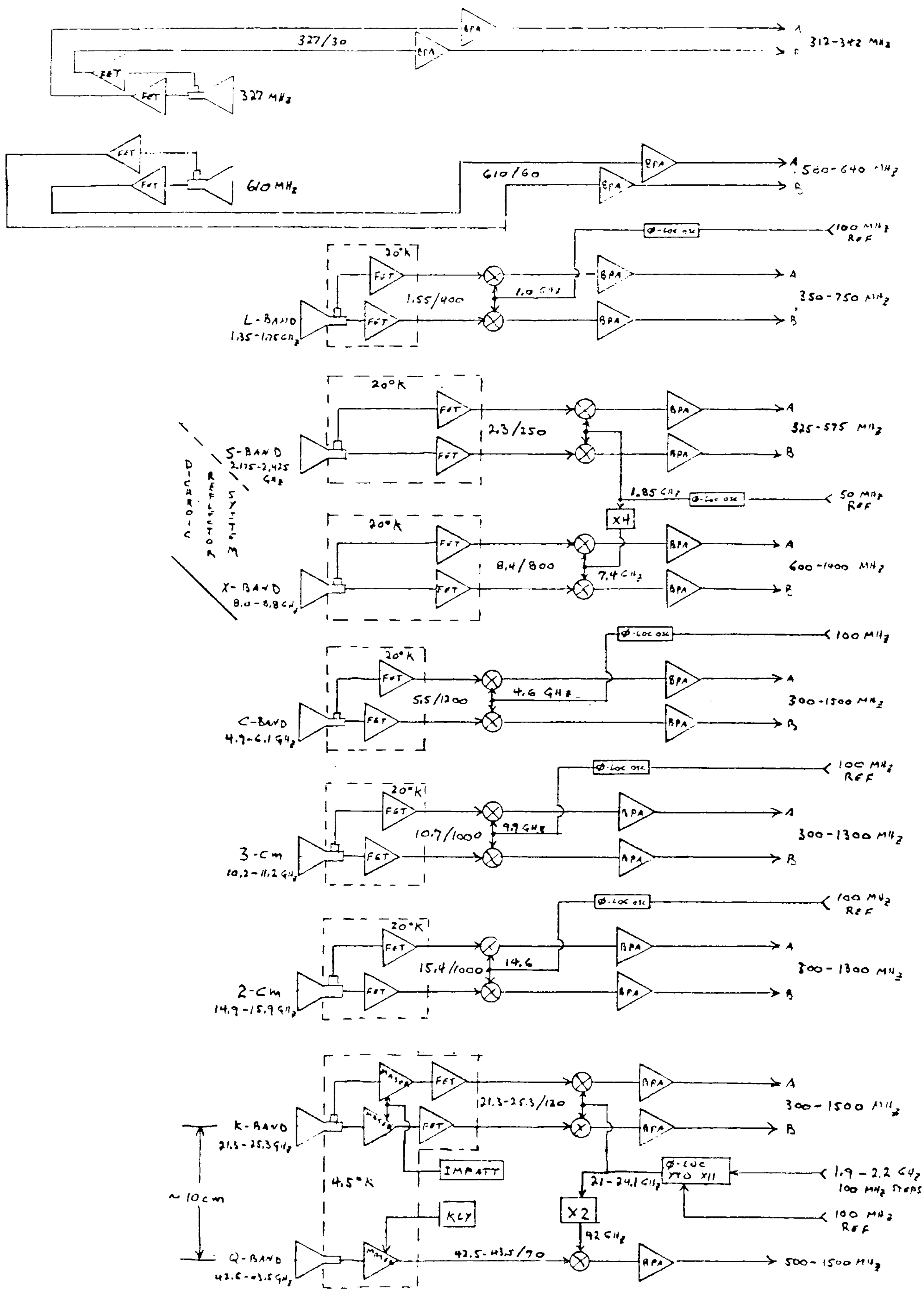
We are proposing to use CTI Model 350CP refrigerators; these have a 3W load capability and similar reliability as the larger CTI Model 1020 unit used at the VLA and other observatories. The 3W load capability is sufficient and the smaller unit is significantly cheaper than the 1020 unit. We also propose to use three CTI 1020 style compressors to drive the six 20K front ends. If one compressor fails, at least four of the six front ends can be kept cold; electrically controlled valves can be used to interchange compressors and receivers to keep the required frequencies operational.

The 4K refrigerator used to cool the two masers would be the JPL/NRAO Joule-Thompson circuit on a CTI 1020 refrigerator. This system is now marketed by CTI and Cryosystems, Inc. The reliability of these 4K systems is close to that obtained with the 20K systems.

TABLE I

Frequency GHz	Instantaneous Bandwidth MHz	Front End Type	Physical Temp	Receiver Noise Temp 1981	Receiver Noise Temp 1986	Antenna Noise Temp*	1986 System Noise Temp	Notes
0.33	30	GASFET	300	40	30	35	65	Prime
0.61	60	GASFET	300	45	30	30	60	Prime
1.55	400	GASFET	20	12	9	20	29	Cassegrain
2.3	250	GASFET	20	15	11	20	30	Cassegrain
5.5	1,200	GASFET	20	20	17	20	37	Cassegrain
8.4	800	GASFET	20	30	20	20	40	Cassegrain
10.7	1,000	GASFET	20	35	25	20	45	Cassegrain
15.4	1,000	GASFET	20	55	40	25	65	Cassegrain
22.2	120	Maser	4	10	10	35	45	Cassegrain
43	70	Maser	4	35	30	40	70	Cassegrain

*Noise due to atmosphere, antenna spillover and feed losses.



KEY: X/Y
X = CENTER FREQ. - MHz or GHz
Y = 1dB BW - MHz

RECEIVER/LO BLOCK DIAGRAM
VLB ARRAY PROPOSAL
BRM 12-21-81
REVISED 1-11-82

Figure 1.

FRONT END COSTS

Cryogenic Costs		Materials $k	Labor (Man Months)	
20K Cryogenics				
Refrigerators	6 x 6K	36		
Compressors	3 x 8K	24		
4K Cryogenics				
Refrigerator and Compressor		50		
Helium Lines				
4K and 20K systems		20		
Total Cryogenics				130k
300K Front End Costs				
327 and 610 GASFET's Dual Pol.	4 x 1K	4	2	
Local Oscillator	2 x 0.5K	1	2	
Mixer IF Amplifier	4 x 0.25	1	2	
Labor		19		
Total 300K Front Ends				25k
20K Front End Costs				
Dewars, input lines, etc.		20	6	
GASFET Amplifiers at 1.55, 2.3, 5.5, 8.4, 10.7 and 15.4 GHz 6 frequencies x 2 polarizations		12	6	
Local Oscillator System		20	9	
Mixer/IF		12		
Labor		66		
Total 20K Front Ends				130k
4K Front End Costs				
Dewar, input lines, etc.		20	6	
Masers 22, 43 GHz		20	12	
Solid state and klystron pumps		20		
Local Oscillator System		10	6	
Mixer/IF		10		
Labor		76		
Total 4K Front Ends				156k
Miscellaneous				
IF Switching matrix		5		
System noise calibration		15		
Phase Calibration		15		
Power Supplies, etc.		10		
Total Miscellaneous				45k
TOTAL FRONT END SYSTEM PER ANTENNA				486k

Interoffice

National Radio Astronomy Observatory

Charlottesville, Virginia

To: K. Kellerman

August 15, 1980

From: M. Balister

VLB ARRAY MEMO No. 16

Subject: Masers and VLBI Array

NRAO has built 4 K-band masers for use in receivers for Green Bank and Tucson. The most recent masers have approximately 500 MHz bandwidth, 30 dB gain, and are tunable over the 18-26 GHz frequency range. The JPL prototype for these amplifiers has operated on the 140' very reliably for two years and users have been enthusiastic about its performance.

Development work on a 40-50 GHz maser started two years ago. A single stage prototype amplifier has been successfully tested and a four stage version is currently being fabricated in Green Bank and will be tested shortly. The reliability of this maser is expected to match that obtained with the K-band maser.

It is anticipated that in a year or so that solid state sources will be available with sufficient power output and electronic timing range to replace BWOs and klystrons that are usually used to pump masers in this frequency range. When this occurs the maser reliability will be determined by the reliability of the cryogenics. Experience at Green Bank has shown that generally speaking the reliability of 4K systems is comparable to that of 20K systems. Since 4K systems are now widely used at Green Bank on the 140', we should get a lot of reliability data under operational conditions over the next few years.

MB/jm

C. Moore
6/22/82

APPENDIX I

FRONT-END SYSTEM

A number of front-end configurations were considered for the VLB Array receivers. During the course of these deliberations a general design philosophy emerged that is felt will insure a low percentage of down time in a semi-attended operation staffed by personnel not expected to be highly skilled in the operation and maintenance of microwave and cryogenic equipment. We have attempted to achieve reliability through simplicity of design and a high degree of modularity. The resultant commonality of spare parts will reduce operating costs and the initial acquisition cost will be lower than for a system featuring redundant sub-systems to achieve reliability. The proposed design calls for mounting the dual polarization receivers for each frequency on a separate closed cycle refrigerator (CCR). This facilitates the low noise objective by permitting each receiver to be mounted in close proximity to the appropriate feed horn, eliminating transmission line runs to a single large receiver dewar as in the VLA. Additionally, it permits integration of the polarization separating orth-mode junction and the throat section of the feed horn onto the cryogenic refrigerator, thus reducing the noise contribution of these components. The low cost of GASFET amplifiers makes this approach affordable.

Because of feed considerations the two lowest frequency receivers must be located near the prime focus of the antenna. We have considered both uncooled and cooled GASFET amplifiers as well as cooled varactor upconverters followed by a cooled C-band GASFET as receivers for these frequencies. The later system would be similar to one implemented for the NRAO 140-foot and 300-foot telecopes in Green Bank. This system currently offers 40 K system temperature with a 10 K receiver temperature over the frequency band of 300 to 400 MHz. A second band from 500 to 750 MHz is covered with 60 K system temperature and a receiver temperature of 20 K. Noise temperatures in the galactic plane are, of course, higher. System noise, if implemented on the VLB Array, would probably by 10 to 15 K higher because of losses in the transmission lines required to link the single receiver dewar to the feeds located outboard of the subreflector on the support legs. Since the bandwidth offered by upconverters is not needed by the VLB Array at these frequencies, GASFET amplifiers at each frequency are more cost/performance effective. Cooled GASFETs are estimated to provide 30 and 60 MHz bandwidth at 327 and 610 MHz center frequency, respectively, and a receiver temperature using present technology of 10 K, reducing in 1986 to 7 K. The receiver for each frequency could be mounted on a separate CCR and located with the appropriate feed, thus offering an ultimate system temperature with 1986 technology of 42 and 37 K, respectively, exclusive of any noise contribution from the galactic plane. Uncooled GASFET amplifiers are estimated to increase the noise temperature at each frequency by 23 K with 1986 technology.

The uncooled amplifier configuration would be the least costly to acquire and maintain. Cooling both receivers on separate refrigerators would add $30 K in material and 3 man-months in labor to the front-end cost estimate. Dual channel upconverters/C-band GASFET amplifiers for these two frequencies mounted on a single CCR would increase the front-end cost estimate by $30 K in material and 5 man-months of labor.

The galactic noise at 327 MHz ranges from $\sim$ 100 K to $\sim$ 1000 K in the region $\pm$ 10° around the galactic plane. The extragalactic component elsewhere in the sky is $\sim$ 15 K, which is included in the system temperature estimate. Comparable positions at 610 MHz are 4 to 5 times smaller [5]. Since VLB experiments at these frequencies are usually done with sources outside the galactic plane, the receiver noise temperature improvement would not be masked by galactic noise for any appreciable number of observations. However, increased sensitivity at these wavelengths is not considered sufficiently important to offset the increased costs of front-end acquisition as well as mechanical considerations for higher load bearing prime focus support legs and prime focus access by cryogenic maintenance personnel.

Ruby masers are the lowest noise microwave amplifiers available. Consideration of these devices for the shorter wavelength receivers is summarized in Table I-1. Experimental performance obtained by the Jet Propulsion Laboratory with traveling wave masers (TWM) is indicated for 2.3, 8.4, and 15.4 GHz [1]. Experimental performance for NRAO reflected wave masers (RWM) are included at 22.2 GHz and 43 GHz [2]. Performance at other frequencies is extrapolated from these values. The projected improvement in TWM performance by 1986 arises from use of a superconducting material as a printed comb structure. This dramatically lowers the forward loss, thus reducing the noise temperature and allowing a tighter pitch slow wave structure for increased bandwidth and tuning range. The half wave printed comb slow wave sturcture, pioneered by JPL, provides a considerable increase in bandwidth and tuning range over the conventional quarter wave comb structure TWM. The RWM, pioneered by JPL/NRAO at 22 GHz [3], offers the widest tuning range and broadest bandwidth of any maser yet reported [4]. The RWM maser could be built at lower frequencies, but the input circulator loss would result in a receiver temperature 2 to 3 times that of a TWM. Obviously, masers could meet the tuning range required from L-band (400 MHz range to cover 21 and 18 cm molecular lines) on through 2-cm wavelength with receiver temperatures 1/10 to 1/25 of that projected for a cooled GASFET amplifier. System temperatures would improve by 30% to 60%.

It is highly desirable to be able to use the frequency synthesis technique to "fill-in" the u-v coverage of this array. This requires the receivers to have a center frequency range of 10% of nominal and be switchable over this frequency in an integration period (on the order of 1 second or less). This requirement precludes the use of masers at most VLB Array frequencies because the tuning rate is limited by the superconducting magnet to several seconds, and the instantaneous bandwidth will be less than that shown in Table I-1 because of limitations of the microwave pump source. The only possible exceptions would be at L-band and at S-band, where the pump frequencies are low enough to provide the projected bandwidth of 200-250 MHz. A further disadvantage of masers is the acquisition cost. The cost increase to replace one cooled GAS-FET receiver with a dual channel maser would be approximately $50 K in materials and 5 man-months in labor. For these reasons masers are only proposed for use at the two shortest wavelengths where the noise temperature improvement is significant enough to warrant the added cost and the loss of the u-v "fill-in" technique is accepted. Also, masers for these two frequencies have already been developed by NRAO, so no additional development costs will be incurred.

We have also considered upconverter/maser type receivers for the microwave frequencies. This type receiver offers maser-like receiver temperatures with wider bandwidth and tuning range than masers alone. NRAO has implemented an upconverter/maser receiver for the 140-foot telescope at Green Bank which achieves system temperatures in the range 30 K to 60 K between 4.6 and 25 GHz. The system employs three upconverters and a single K-band maser mounted on a 4.5 K CCR. The four frequency bands have instantaneous bandwidths of 300 to 500 MHz and tuning ranges of 2.5 GHz to 7 GHz.

Table I-2 is a comparison of receiver temperatures for upconverter/K-band maser type receivers, masers and cooled or uncooled GASFET amplifiers. Although the low noise temperature is attractive, the versatility of the upconverter/maser receiver requires complexity in the hardware implementation which has the disadvantage of high operating cost because of the need for skilled personnel to operate and maintain such a system. Additionally, the tuning speed and bandwidth preclude using the frequency synthesis technique for u-v "fill-in" at all but the L-band and S-band frequencies.

We can consider including upconverters at either of these frequencies on the same CCR with the dual channel K-band maser. The Q-band, K-band, and either S-band or L-band feeds could then be located near enough to one another to make the transmission line losses at the lowest frequency not excessive. The increased acquisition cost for such a system compared to the separate cooled GASFET amplifier would be $20 K in material and three man-months of labor. Such a system would only provide about 20% improvement in system temperature, which is not considered enough to offset the increased operating cost due to the lower reliability of such a complex receiver. By comparison, the reduction in acquisition cost of not cooling any one of the dual-channel GASFET receivers is estimated to be $15 K in material and 1.5 man-months of labor. This would result in a doubling of the system temperature at L-band, rising to three times at 2 cm. The system performance improvement in this case justifies the increase in complexity and costs.

For these reasons the proposed receiver complement consists of uncooled GASFET amplifiers near the prime focus for 327 MHz and 610 MHz, cooled GASFET amplifiers at the Cassegrain focus for six receivers between 21 cm and 2 cm and reflected wave ruby masers for the two shortest wavelengths of 1.2 cm and 0.7 cm. Table I-3 compares the cost increase to replace any of those receivers with the lowest noise alternative. Although the system temperature improvement in most cases is significant, the acquisition cost increase is also significant except for the prime focus frequencies of 327 MHz and 610 MHz. The development of traveling wave masers for the other frequencies would also require a sizeable engineering effort, which is not included in the cost column of Table I-3. Additionally, there is always the risk that the projected performance objective will not be achieved in the allotted time when such a significant advance in state of the art is attempted. It should also be pointed out that the lowest noise alternative considered here would preclude use of the u-v "fill-in" technique of frequency synthesis at all frequencies higher than 2.3 GHz. This is due to the limitations of bandwidth and tuning speed of the masers.

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[2] Private communication, S. Zisk, Haystack Observatory, Westford, MA.

[3] Moore, C. R. and Clauss, R. C., "A Reflected Wave Ruby Maser with K-Band Tuning Range and Large Instantaneous Bandwidth," IEEE Trans. MTT, Vol. MTT-27, p. 249 (March 1979).

[4] Moore, C. R., "A K-Band Ruby Maser with 500 MHz Bandwidth," IEEE Trans. MTT, Vol. MTT-28, p. 149 (February 1980).

[5] Private communication, R. Brown, NRAO, Charlottesville, VA.

TABLE I-1

Experimental and Estimated Performance of Ruby Masers at the VLB Array Frequencies

Frequency (GHz)	Maser Type	Tuning Range (GHz) (1)	Bandwidth (MHz) (1)	Receiver Temperature (Kelvin)	Experimental System Temperature (Kelvin) (4)	1986 System Temperature (Kelvin)
1.55	TWM	0.1 (0.4)	40 (200)	3 (1)		21
2.3	TWM (2)	0.1 (0.5)	40 (250)	2 (1)	13.5 (2)	
5.5	TWM	0.5 (1.5)	100 (300)	3 (1)		21
8.4	TWM (2)	0.5 (2.0)	110 (300)	3.5 (1)	19.5 (2)	
10.7	TWM	1.5 (3.0)	180 (350)	4 (1)		21
15.4	TWM (2)	2 (4.0)	20 (400)	9 (1.5)	27 (2)	
22.2	RWM (3)	7	500	10 (7)	50 (3)	42
22.2	TWM	(4.0)	(500)	(2)		37
43	RWM (3)	6	250	35 (30)	90 (3)	70
43	TWM	(3.0)	(500)	(5)		45

NOTES:
(1) Independent of pump source limitations
(2) JPL Experimental Performance of Traveling Wave Maser [1].
(3) NRAO Experimental Performance of Reflected Wave Maser [2] [4].
(4) Includes noise due to transmission lines, antenna losses and atmosphere.
( ) Values in parenthesis are 1986 projected performance with superconducting half-wave printed comb structure.

TABLE I-2

Noise Temperature for Various Types of Receivers at the VLB Array Frequencies

Frequency (GHz)	Receiver Noise Temperatue (Kelvin)				Additional* Noise (Kelvin)
	GASFET at 300 K	GASFET at 20 K	Upconverter/ K-Band Maser	Ruby Maser	
0.33	40 (30)	10 (7)			35**
0.61	45 (30)	10 (7)			30**
1.55	50 (40)	12 (9)	5	3 (1)	20
2.3	60 (50)	15 (11)	5	2 (1)	20
5.5	90 (70)	20 (17)	5	3 (1)	20
8.4	130 (110)	30 (20)	10	3.5 (1)	20
10.7	170 (140)	35 (25)	10	4 (1)	20
15.4	280 (170)	55 (40)	15	9 (1.5)	25
22.2	470 (200)	130 (60)	10	10 (2)	35
43	--- (800)	--- (200)		35 (5)	40

* Noise due to atmosphere, antenna spillover, and feed losses.

** Exclusive of noise in the galactic plane.

() Values in parentheses are 1986 projections.

TABLE I-3

Cost/System Temperature Improvement Summary for Lowest Noise Alternative Relative to Proposed Front-End System at the VLB Array Frequencies

Frequency (GHz)	Proposed System Temperature (Kelvin)	Lowest Alternate System Temperature (Kelvin)	Cost Increase over Proposed System to Achieve Lowest Temperature		System Temperature Improvement (Percentage)
			Material ($)	Man-Months	
0.33	*75 (65)	*45 (42)	15 K	1.5	40 (35)
0.61	*75 (60)	*40 (37)	15 K	1.5	47 (38)
1.55	32 (29)	23 (21)	50 K	5	28 (28)
2.3	35 (31)	22 (21)	50 K	5	37 (32)
5.5	40 (37)	23 (21)	50 K	5	43 (43)
8.4	50 (40)	24 (21)	50 K	5	52 (48)
10.7	55 (45)	24 (21)	50 K	5	56 (53)
15.4	80 (65)	34 (27)	50 K	5	58 (58)
22.2	45 (45)	45 (37)	None	None	0 (18)
43	75 (70)	75 (45)	None	None	0 (36)

* Exclusive of noise in the galactic plane.

() Values in parentheses are 1986 projections.

Note: The lowest noise alternate precludes the frequency synthesis u-v "fill-in" at all frequencies higher than 2.3 GHz.

VLB ARRAY MEMO No. 53

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

MEMORANDUM

January 19, 1982

To: M. Balister

From: C. Moore

Subj: VLBA Proposal - Front-End System: VLB Array Memo No. 52

In light of recent developments, I have a few suggested changes to the front-end write-up.

(1) In writing the appendix it becomes clear that cooled prime focus receivers at 327 and 610 MHz are a cost-effective approach -- 35% to 40% improvement in sensitivity at only 8% cost increase. I think we should think about this some more.

(2) Since the local oscillator is included in the front-end cost, I think we should discuss it here in the write-up. By LO I mean the phase-lock oscillators or multipliers, not the H-maser frequency standard. If you have no objections, I will write a paragraph for insertion next to the noise/phase cal paragraph.

(3) Since the block diagram has changed to eliminate the 610 MHz mixer, I think the cost headings under 300 K front-ends should read:

327 and 610 MHz GASFET's Dual Polarization ..	4 x 1 K
Weatherized Package	2 x 0.5 K
Buffer Amplifiers	4 x 0.25 K

Of course, if we elect to change to cooled receivers here, then a heading of "Dewar input lines, etc." would have to be added as well as changes to the cryogenic costs.

(4) Table I should have the four temperature columns labeled as units of Kelvin. Also, antenna noise and system noise for .33 and .61 GHz should have a double asterisk (**) notation: Exclusive of galactic noise.

CRM/cjd

IV. LOCAL OSCILLATOR SYSTEM

VLB ARRAY MEMO No. 62

NATIONAL RADIO ASTRONOMY OBSERVATORY
Charlottesville, Virginia

January 15, 1982

MEMORANDUM

TO: B. Clark
K. Kellermann
S. Knowles (NRL)

FROM: S. Weinreb/C. Moore

SUBJECT: Local Oscillator System Draft

Attached is a draft of the local oscillator system write-up for your critique.

Attachments

cc: A. Rogers (Haystack)

NATIONAL RADIO ASTRONOMY OBSERVATORY

VLBA PROPOSAL

Craig R. Moore

January 13, 1982

Local Oscillator System

The requirement to operate at wavelengths shorter than 1 cm and with long coherent integrations for maximum interferometer sensitivity places severe requirements on the stability of the frequency standard(s) employed. The statistics of the stability of frequency and time standards is best expressed as the 2-sample Allan variance, $\sigma^2 y(\tau)$ [1] and is plotted as a function of the integration period, τ. The square root of the Allan variance of a hypothetical frequency standard is plotted in Figure 1 to show the four regimes of noise characterized by the slope on a log-log plot. Figure 2 shows the square root of the Allan variance for various state-of-the-art frequency standards. The data for quartz, rubidium and cesium standards are taken from manufacturers' catalogs. The passive hydrogen maser performance, both experimental and projected, is taken from Walls and Howe [2] while the active hydrogen maser experimental data was published by Rueger [3] and the staff of SAO [4]. The superconducting cavity stabilized oscillator performance comes from work by Stein [5].

The coherence of a VLB interferometer is related to the observing frequency and to the Allan variance of the frequency standards used. This relationship is different for each of the four noise regimes of Figure 1. Rogers and Moran [6] have investigated this relationship and calculated a coherence function for several of the frequency standards shown in Figure 2. A portion of their results are plotted in Figure 3 to show the loss of coherence with increases in integration time and observing frequency for the case of a two element interferometer utilizing two active hydrogen masers, or two rubidium frequency standards. It is obvious that each element of the proposed array must have a frequency standard with stability comparable to a hydrogen maser if observations at 22 and 43 GHz are to be useful.

The above analysis considered only the effect of instability of the frequency standard on the coherence. Ionospheric and atmospheric phase fluctuations will affect the received signals and result in loss of coherence as well. Ionospheric fluctuations dominate at wavelengths longer than 15 cm while atmospheric fluctuations, due mainly to tropospheric water vapor, limit coherence of shorter wavelengths. Rogers and Moran [6] have attempted to estimate the Allan variance of the atmospheric fluctuations and their values are plotted in Figure 2. From this it is seen that for coherent integrations less than 10^4 seconds, interferometers employing active hydrogen masers will be limited by ionospheric and atmospheric fluctuations and not by the performance of the frequency standards.

Currently, active hydrogen masers are in widespread use in VLBI for radioastronomy, astrometry and geodesy. The newer units developed at NASA/Johns Hopkins Applied Physics Lab (NR) and at the Smithsonian Astrophysical Observatory (VLG-11) are a significant advance both in performance and in field reliability. OSA, Oscilloquartz in Switzerland, has developed an active hydrogen maser and is currently building several units for customers in Europe. Sigma Tau Standards Corporation of Tuscaloosa, Alabama is developing, with Air Force support, a small, active hydrogen maser which has the potential for considerable cost reduction with, it is hoped, only a modest reduction in performance from that of the large units. In addition, Hughes Research Laboratories, Malibu, California is developing a space qualified hydrogen maser for use on one of the NAVSTAR Global Positioning Satellites.

In the past there has been concern about the use of hydrogen masers in VLB interferometer systems relative to rubidium or cesium beam standards because of initial cost, difficulty in maintenance or repair, and susceptibility to environmental effects which limited long-term (> 3 hour) stability. With all of the development activity noted above, these disadvantages have been, and will continue to be, reduced in importance.

Another device under development is the Superconducting Cavity Stabilized Oscillator (SCSO) which can give an order of magnitude improvement in phase stability over an active hydrogen maser out to several hundred seconds. However, the SCSO is not stable over longer time scales and must be locked to another frequency standard in order to be useful for high sensitivity experiments. The SCSO is a laboratory device at present which is inherently susceptible to mechanical shock and vibration and must be cooled to near the λ point of He^4. As such, the real cost, performance, and reliability in the field have not been demonstrated. A single SCSO is being evaluated at Owens Valley Radio Observatory and is expected to give valuable information on their suitability as a frequency standard for independent oscillator interferometers.

We have also considered the use of a direct round trip phase link using a geostationary satellite. Several successful experiments have already been performed using the Hermes [7] and ANIK-B [8] satellites with encouraging results. In addition, the European Space Agency ECS satellite is being used by Dutch radio astronomers as part of a program aimed toward developing a phase-stable link to join radio telescopes in the UK, The Netherlands, Germany, Sweden, and Italy to form a truly phase-stable array. A major problem in implementing a geostationary satellite phase link is the motion of the satellite which introduces phase shifts of up to 10^6 turns per day. However, it seems that this can be satisfactorily cancelled by using a two-way link [7]. The problem of differential dispersion in the up and down link frequencies can be mitigated by employing one of the newer satellites with the 12/14 GHz link frequencies. The problem of atmospheric phase fluctuations will remain, however.

The cost of a suitable satellite circuit is not well established, nor, in fact, is there a straightforward mechanism for the use of satellite transponders with one's own ground equipment. All of the exerpiments to date have used experimental satellites, and it is not clear if a satisfactory solution can be found to the full time use of a satellite phase link. We note also that all of the previous experiments have used radio telescopes already available at the site for the up and down links. While the requirements on the ground station to support a satellite phase link are not excessive, the cost of acquisition and maintenance of the necessary ground stations is not negligible.

For these reasons we consider a hydrogen maser at each array element as the best method at present of obtaining a stable local oscillator system. We shall, however, continue to follow the progress of the Canadian-American ANIK-B and Dutch ECS experiments, and at the same time explore the cost and availability of other suitable satellite facilities.

BIBLIOGRAPHY

[1] Barnes, J. A., *et al.*, "Characterization of Frequency Stability," NBS Technical Note 394; October 1970.

[2] Walls, F. L. and Howe, D. A., "Precision Timekeeping Using a Small Passive Hydrogen Maser," Frequency and Time Standards Group, NBS, Boulder, CO; 1980.

[3] Rueger, L. J., "Characteristics of the NASA (NR) Hydrogen Maser," International Symposium on Time and Frequency, New Delhi, India; February 1981; work performed by Johns Hopkins Applied Physics Laboratory.

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[5] Stein, S. R., "The Superconducting Cavity Stabilized Oscillator and an Experiment to Detect Time Variation on the Fundamental Constants," High Energy Physics Laboratory, Stanford University, HEPL 741; October 1974.

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[7] Waltman, W. B., Knowles, S. H., Yen, J. L., Fort, D. N., Swenson, G.W., Cannon, W. H., and Galt, J., "Radio Interferometery Techniques for Geodesy," NASA Conference Publication 2115, p. 89; 1979.

[8] Cannon, W. H., Petrachenko, W. T., Yen, J. L., Galt, J. P., Waltman, W. B., Knowles, S. H., Popeler, J., "Radio Interferometry Techniques for Geodesy," NASA Conference Publication 2114, p. 461; 1980.

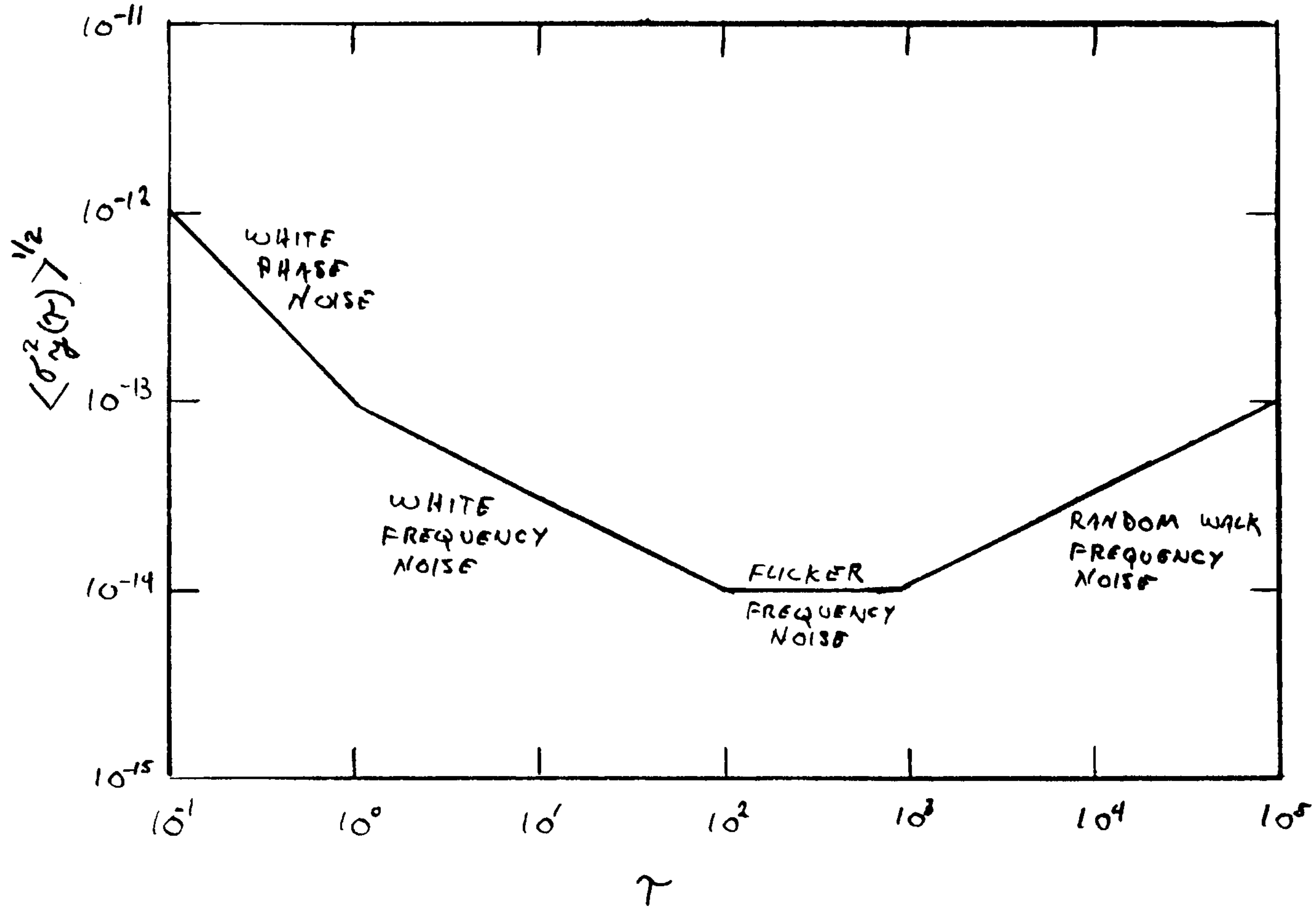


FIGURE 1 LOCAL OSC.

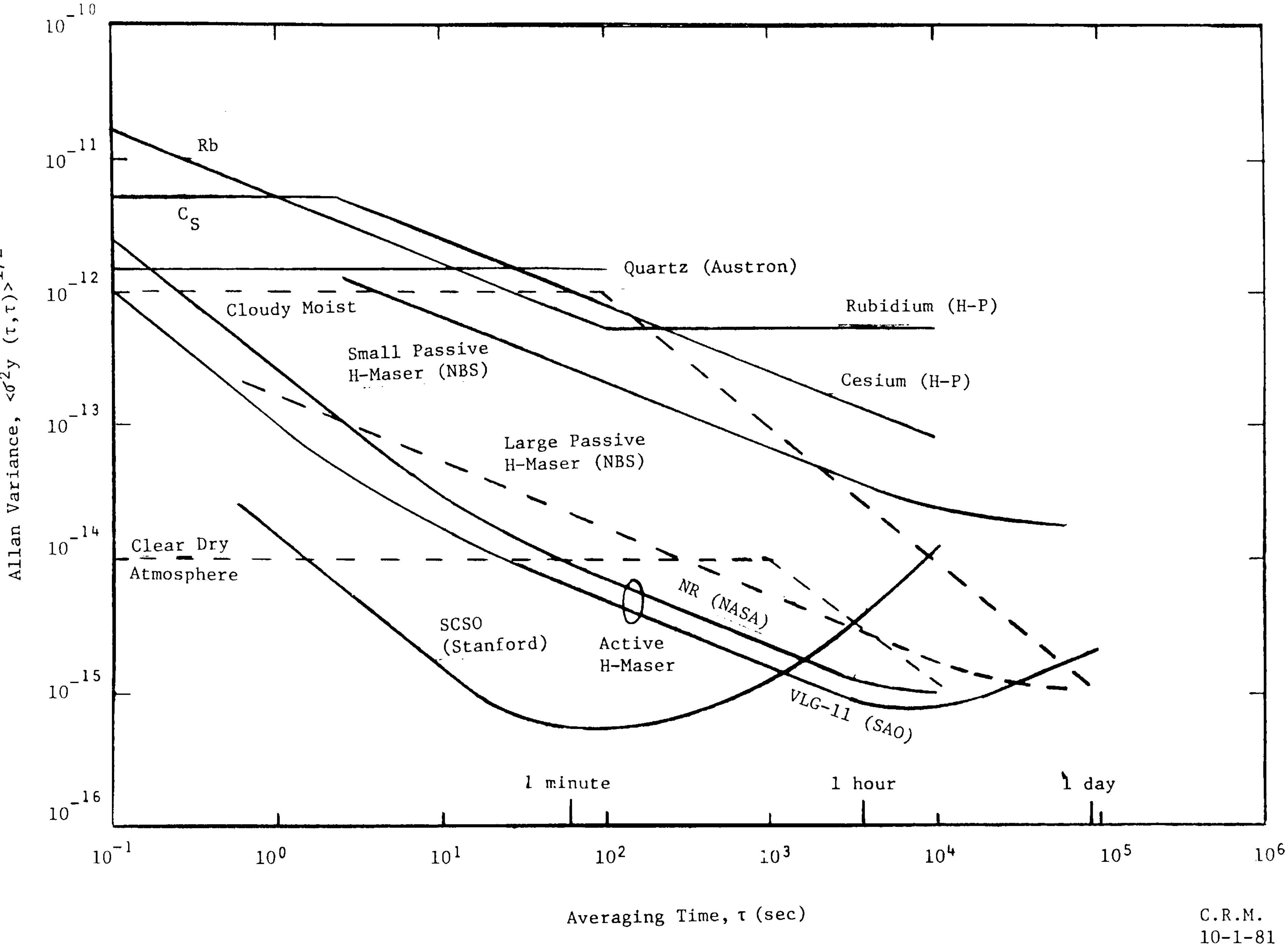


FIGURE 2 LOCAL OSC

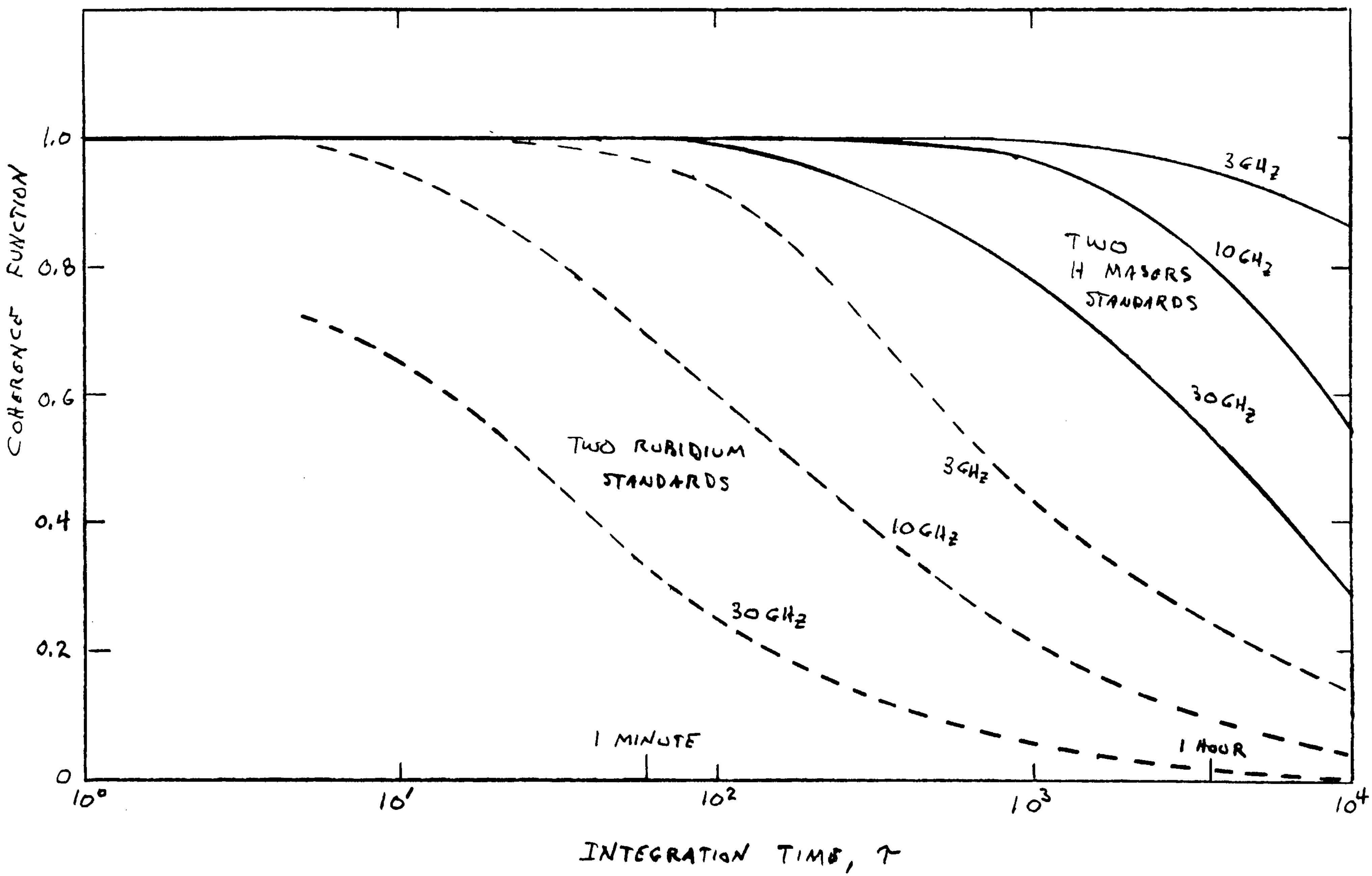


FIGURE 3 LOCAL OSC.

NATIONAL RADIO ASTRONOMY OBSERVATORY

HYDROGEN MASER COST ESTIMATE

Craig Moore

January 28, 1982

Cost estimates for acquisition of active hydrogen masers have been obtained from three sources. A detailed cost estimate was prepared for NRAO by Johns Hopkins University Applied Physics Laboratory (APL) to supply ten complete masers of the design presently being built for NASA/Goddard. APL does not wish to sell or estimate costs to supply units without the receiver/ synthesizer, i.e., the physics package only. In support of the NRAO VLBA design study, the Smithsonian Astrophysical Observatory (SAO) supplied a cost estimate via letter dated 1 July 1980 for single and lot of 10 quantities of their VLG-11 maser with and without the receiver/synthesizer. These costs were updated via a telephone conversation on 20 January 1982 to reflect the cost in 1982 dollars. Oscilloquartz S.A., a unit of Asulab S.A. of Switzerland, has offered NRAO a price (in Swiss francs) for a single hydrogen maser with or without the receiver/synthesizer. (See VLBA Memo No. 10.)

These cost estimates are summarized in Table 1. The estimated cost for NRAO to build the receiver/synthesizer is $18 K in material and 8 man-months of labor for a total unit cost of $40 K. The last column reflects this cost addition to the estimates for the physics package only. The wide spread in estimates makes it difficult to decide on a cost to use for the VLBA. The APL cost estimate is in line with current contract prices to NASA (APL to Goddard and SAO to JPL) for hydrogen masers, but NASA documentation requirements are known to be more extensive than those required by NRAO.

TABLE 1

Cost Summary for Hydrogen Maser (in 1982 dollars)

Supplier	Unit Cost				Minimum Total Cost Lot of 10 Complete Masers
	One Complete Maser	Lot of 10 Complete Masers	One Physics Package Only	Lot of 10 Physics Pkg. Only	
APL (NR)		$405 K			$4050 K
SAO (VLG-11)	∿$415 K	∿$310 K	∿$315 K	∿$210 K	∿$2500 K
Oscilloquartz	$275 K* (510 K Fr)		$170 K* (310 K Fr)		$2100 K*

* Exchange rate: U.S. $ 0.5414 = 1 Swiss franc per Wall Street Journal 22 January 1982.

VLB ARRAY MEMO No. 55

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

MEMORANDUM January 20, 1982

To: VLBA Working Group

From: R. Mauzy

Subj: Hardware Cost Estimate for Receiver Section of H-Maser Frequency Standard

Attached is a cost estimate, for hardware, for a receiver section of an H-maser frequency standard.

REM/cjd

Enclosure

H-MASER FREQUENCY STANDARD

COST ESTIMATE OF RECEIVER PARTS

Item	Cost
Crystal oscillator 5, 1, 0.1 MHz .. HP 105A	$5,000
Or basic unit, 10 MHz only .... HP 10811A	(1,000)
Synthesizer, Wavetech-Rockland 5100	3,500
Low noise amplifier, 1420	1,000
Filters, 1420, 20.4, 1400, 100	500
Mixer-preamp, 1400	1,000
IF amplifiers and 20 MHz mixer	100
Phase detector and lock circuits	100
5 MHz Buffers	100
5-100 Multiplier and amplifier	500
5-20 Multiplier	50
100-1400 Multiplier and amplifier	1,000
100 MHz Buffers	200
TIC Unit	100
Couplers and isolators	1,000
Power supplies	2,000
Batteries and charger	400
Rack, slides, hardware, etc.	1,000
Total	$17,550

This estimate is based on the receiver installed in SAO maser VLG-10A, S/N P3, and does not include any labor.

A SINGLE CARRIER SATELLITE LO SYSTEM

B. G. Clark

August, 1981

Although there are a great many schemes for round-trip LO stabilization which could be used via a satellite, they would in general use two fairly narrow carriers separated by a large frequency difference, with the LO information encoded on the phase difference between the two carriers. It is aesthetically more pleasing to use the satellite system carrier itself to be the main phase carrier. A scheme for doing so is given here.

It is presumed that the satellite is a simple transceiver - that is, a signal at frequency ω is received by the satellite, mixed with a signal $\omega_s t + \phi_s$, and retransmitted. ω_s is a moderately stable oscillator, of known frequency, such that copies can be reproduced at the master station and outstation. For convenience of notation we take ω_s to be a multiple β of ω_o, i.e. $\omega_s = \beta\omega_o$. The block diagram of the system is given in the figure. Although the diagram is drawn for a partly digital implementation, the system could be made entirely analog by encoding the phases on a low carrier frequency instead of digitizing them. There are considerable advantages to implementing the digital version. Whichever is used does not affect the analysis below. The analysis reproduces only the phase terms, the proper expression is implicitly the exponential of i times that given. Synthesizers are assumed to be perfect; that is, they simply multiply the signal frequency and phase by some factor (α for the offset synthesizer and β for the ω_s synthesizer). This causes all lobe ambiguity problems to be ignored, for the moment. All line lengths are assumed to be zero, except for the distances from the satellite to the Master station (L_o) and outstation (L_1). These two paths are assumed to be pure delays.

In the analysis below, the phase terms are numbered with numbers corresponding to those on the diagram.

Master Oscillator

$$\omega_o t \tag{1}$$

Outstation Oscillator

$$\omega_o t + \phi_1 \tag{2}$$

Master Carrier radiates

$$\omega_o t \tag{3}$$

Outstation radiates

$$(\omega_o t + \phi_1)(1 + \alpha) \equiv \omega_o t + \omega_p t + \phi_1 + \alpha\phi_1 \tag{4}$$

Master transmission received at satellite

$$\omega_o t - L_o \omega_o \tag{5}$$

Outstation transmission received at satellite

$$\omega_o t + \omega_p + \phi_1 + \alpha\phi_1 - \omega_o L_1 - \omega_p L_1 \tag{6}$$

Transceived master signal

$$\omega_o t + \omega_s t - L_o \omega_o + \phi_s \tag{7}$$

Transceived outstation signal

$$\omega_o t + \omega_p t + \omega_s t + \phi_1 + \alpha\phi_1 - \omega_o L_1 - \omega_p L_1 + \phi_s \tag{8}$$

Master signal received at master station

$$\omega_o t + \omega_s t - 2\omega_o L_o - \omega_s L_o + \phi_s \tag{9}$$

Master signal received at outstation

$$\omega_o t + \omega_s t - \omega_o L_o - \omega_o L_1 - \omega_s L_1 + \phi_s \tag{10}$$

Outstation signal received at outstation

$$\omega_o t + \omega_s t + \omega_p t + \phi_1 + \alpha\phi_1 - 2\omega_o L_o - \omega_s L_1 - 2\omega_p L_1 + \phi_s \quad (11)$$

Transmit/Receive mixer output, master station

$$\omega_s t - 2\omega_o L_o - \omega_s L_o + \phi_s \quad (12)$$

Transmit/Receive mixer output, outstation

$$\omega_s t - 2\omega_1 L_1 - \omega_s L_1 - 2\omega_p L_1 + \phi_s \quad (13)$$

ω_s synthesizer, master station

$$\beta\ \omega_o t = \omega_s t \quad (14)$$

ω_s synthesizer, outstation

$$\beta\ (\omega_o t + \phi_1) = \omega_s t + \beta\phi_1 \quad (15)$$

Phase detector output, master station

$$2\omega_o L_o + \omega_s L_o = \phi_s \quad (16)$$

Phase detector, outstation

$$2\omega_o L_1 + \omega_s L_1 + 2\omega_p L_1 - \phi_s + \beta\phi_1 \quad (17)$$

The delay is inserted so that the items presented to the subtractor represent samples of the same ϕ_s. This removes dependence on stability of the tranceiver oscillator.

Phase subtractor output, outstation

$$(2\omega_o + \omega_s)(L_o - L_1) - 2\omega_p L_1 - \beta\phi_1 \quad (18)$$

Master/Local mixer, outstation

$$\omega_p t + \phi_1 + \alpha\phi_1 + \omega_o(L_o - L_1) - 2\omega_p L_1 \quad (19)$$

Main phase detector, outstation

$$\phi_1 + \omega_o\ (L_o - L_1) - 2\omega_p L_1 \quad (20)$$

Phase multiplier, outstation

$$\omega_o\ (L_o - L_1) - \frac{1}{2+\beta}\ (2\omega_p L_1 - \beta\phi_1) \quad (21)$$

Phase difference - Servo input, outstation

$$\phi_1\ \frac{2}{2+\beta} + 2\omega_p L_1\ \frac{1+\beta}{2+\beta} \quad (22)$$

The order of magnitude component stabilities necessary to achieve an oscillator locked to 3 ps (operation at 50 GHz) are given below.

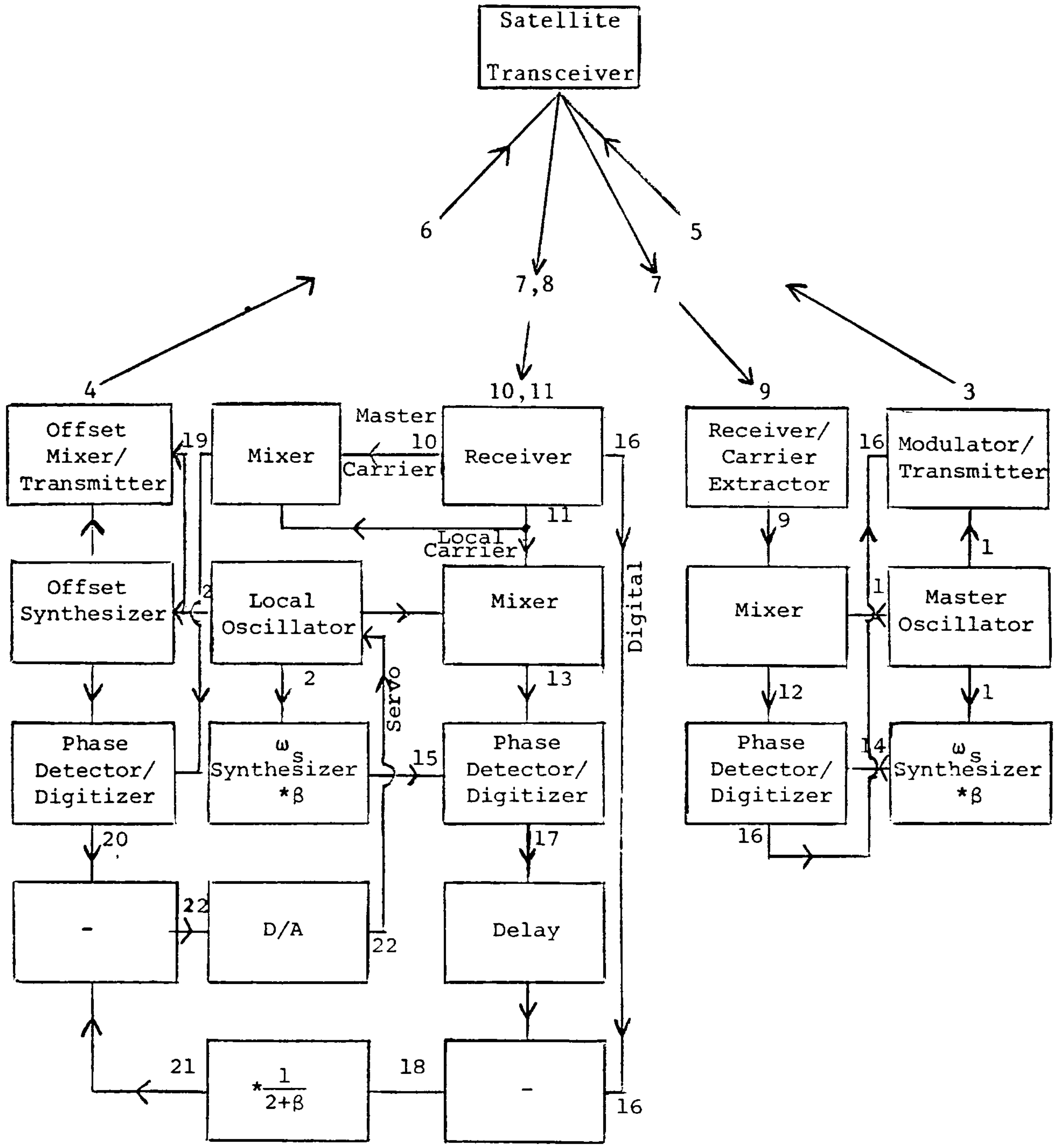
To simplify the design of the system, it would appear advantageous to have fixed frequency channels in the receiver; that is, ω_p should be large enough that the residual doppler of the satellite would not permit confusion of the signals at ω_o and $\omega_o + \omega_p$. This suggests $\alpha > 10^{-6}$. For a ten station array, spacing the ω_p (different for each station) by $10^{-6}\omega_p$ means the maximum ω_p is $10^{-5}\omega_o$. To hold the second, unwanted, term in the servo input (expression (22)) to 3 ps, requires an a priori knowledge of L_1 to 300 ns, about the state of the art in satellite orbit determination. However, the term degrades gracefully, introducing a diurnal phase term looking much like a position error, and accurate satellite astrometry need not be done except for astrometric experiments. The satellite tranceiver oscillator must be stable over the time of operation of the phase detector - a few times greater than the offset signal period - $\sim 10^{-7}$. Any old crystal oscillator should do this.

The stability of the servo loop is only assumed if it has a bandwidth several times smaller than the reciprocal of the round trip path to the satellite, say 1 Hz. The outstation oscillator must therefore have an intrinsic stability of $\sim 3\times 10^{-12}$ on a 1 second timescale. This sounds a bit too good for a simple crystal, and a rubidium or superconducting cavity controlled oscillator would be needed. The latter is especially attractive if affordable, and the removal of any requirement for stability over periods longer than one second may make it so. The servo could even be implemented as a part of the temperature controller, simplifying the design of that component.

This system has a greater dependence on remote site oscillator stability than the conventional, two-rail, system which removes the tranceiver oscillator phase by presuming it to be the same on both rails, rather than, as in this system, by feeding both the remote and local oscillator signals through it. However, an oscillator of this stability range is desireable at the remote station anyway as a back-up for the satellite link. The narrow loop bandwidths will also likely make this system "fussy" to deal with. This must be weighed against the operational advantage of needing only a single band through the satellite.

Lobe ambiguities have been steadfastly ignored throughout this document. This is fine so long as the system is in continuous operation and so long as the satellite velocity is a priori known to an accuracy of a few inches per second or so. Given this, phases may nicely be carried past one turn, and processing proceeds undisturbed. Any little glitch however - especially loss of power to the micro-processor which does the digital operations or a glitch in the satellite position predictor - will cause the system to drop one or more loops of the primary reference frequency (the satellite carrier, presumably at L or S band). The SCCO would be capable of remembering the phase of the carrier for a few seconds, but I anticipate a major effort to meet a reasonable goal of, say, having the system run for a week without a phase jump.

It is interesting to note that the total bandwidth requirements of this system (~20 KHz) are only slightly greater than one telephone channel.



Satellite Transceiver
6
7,8
7
5
4
10,11
9
3
Offset Mixer/ Transmitter
19
Mixer
Master
10
Carrier
Receiver
16
Receiver/ Carrier Extractor
16
Modulator/ Transmitter
11
Local Carrier
9
1
Offset Synthesizer
Local Oscillator
Mixer
Digital
Mixer
1
Master Oscillator
2
13
12
1
Servo
Phase Detector/ Digitizer
ω_s Synthesizer $*\beta$
15
Phase Detector/ Digitizer
Phase Detector/ Digitizer
14
ω_s Synthesizer $*\beta$
20
17
16
-
22
D/A
22
Delay
21
$*\frac{1}{2+\beta}$
18
-
16

V. RECORD SYSTEM

Tape Recording Systems for the VLB Array

K. I. Kellermann

The recording system currently planned for the VLB Array is based on the MKIII VLB system. Many of the design parameters of the MKIII system were based on the use of bandwidth synthesis necessary for the accurate measurement of group delay. This results in a very flexible, but costly system which allows different frequency bands to be independently recorded on separate narrow band tracks. It is not clear whether the MKIII design, which is now about 7 years old, is still optimum for an instrument intended primarily for radio astronomy aperture synthesis work. In particular, it may be more simple and less expensive to use broadband recordings. While the recorder itself may be more expensive than the Honeywell instrumentation recorder, the associated electronics are considerably more straightforward and less costly.

Although the broadband recirculating correlator currently being considered for the Array can be used with the multi-track MKIII system, a less complex system would have a signle high rate bit stream inputed to the high speed correlator. Multifrequency spectral line data could be multiplexed into the single bit stream.

The use of broadband recordings has the further advantage, that the whole i.f. correlator system then becomes very similar to that of the VLA, resulting in an obvious ease of simultaneously using all or parts of both instruments.

Suitable broadband recorders may soon become commercially available. One possibly suitable recorder is the AVRX (Advanced Video Recorder Experimental) system being developed by Ampex for unspecified military use. The preliminary specifications of the AVRX recorder given below are based on a presentation by Alan Schulze of Ampex, given at JPL.

Recorder:	Rotary head (6 heads)
Bit Rate:	Total -- 116 Mbits/sec Data -- 107 Mbits/sec
BER:	10^{-5} to 10^{-6} 10^{-7} to 10^{-8} with Error Correcting Code
Record time:	60 minute
Tapes:	0.8 mil x 1" x 1600 ft tape in cassette 10" x 7" x 1-5/8"
Track Spacing:	1.67 mil
Track width:	1.2 mil
Bit Density:	23×10^6/sq inch

Tape Speed: 5" ips

Rewind Speed: 150" ips

Cost: $70K
$100K with ECC

Tape Cost: $100 to $175 per cassette

The areal bit density and cost per bit of the AVRX System is comparable with the projected improved MKIII system or MKII VCR system, and a factor of 20 better than the present MKIII system. Due to the shorter tape, however, recording time is limited to 1 hour. Apparently the cassette dimensions are sufficient to hold a 2400 ft reel, so that 90 minutes playing time is possible. A further improvement of a factor of 2 may be possible if we can accept a higher BER. This would bring the recording time to within a factor of two of the improved MKIII System.

Another problem with the AVRX System is the lack of a variable speed (bandwidth) capability. This results in an inefficient use of tape for spectroscopy, and the inability to process spectroscopic data faster than real time.

The AVRX System does not have a read-after-write capability, but has what Ampex calls a CONFIDENCE HEAD. This fixed head samples data one track at a time and the resultant pulses used to continuously monitor the recording performance as well as automatically optimizing the drive level.

Ampex expects to demonstrate the AVRX system to potential customers in August 1981. Production units are expected to be available in late 1982.

Also under development at Ampex is a 750 Mbit (Super HBR) machine. This machine will write 9 to 18 simultaneous helical scans on 2 inch tape which runs at 30 ips. Projected cost is ∿ $300 K and product availability is expected in mid-1983.

7/16/81

VLB ARRAY MEMO No. 78-A

R. Escoffier
6/17/82

I. The Array Record System

The digital output of the I.F. samplers at each antenna must be stored for post observation shipment to the VLBA processor where correlation with data from all the antennas will take place. This storage will be on magnetic tape with wide band digital tape recorders required at each antenna for storage and similar units at the processor required for playback.

The maximum bit rate of 200M bps produced at each antenna and the need to observe for 24 hours a day sets the upper limit on the antenna record system data rate and storage capacity at 200M bps and 2×10^{13} bits/day. The need to record data at this high rate and in this volume with a minimum of operator intervention over 24 hours puts difficult requirements on the record system.

The two systems most investigated to meet the VLBA record system requirements are those systems already used in VLBI experiments, the MK II and MK III VLBI recorders.

The MK II system uses consumer type video cassette recorders (VCR's) modified to record digital data. These systems have proven reliability records and are inherently inexpensive.

The MK III system uses broad band instrumentation recorders that can take data at up to a 224M bps rate. This recorder is a 28-track machine which will require digital division of the four 50M bps bands into the 28 up to 8M bps recorder tracks.

Neither type recorder, however, is directly applicable to the VLBA. The MK II system suffers from low bandwidth (4M bps per recorder) while the MK III system will record only about 7.5 minutes of full bandwidth data on a 9200-ft. reel of 1 inch tape. Work at various institutions is proceeding, however, to improve both systems. A MK II recorder has been made to work at a data rate of 12M bps and NRAO is investigating recording up to 12.5M or 16M bps on these recorders and a high density moving head system is under design for upgrading the recording volume per reel of the MK III recorder.

Of these two possible recorders, NRAO proposes to use the less expensive MK II recorder in building the VLBA, keeping in mind possible improvements in the MK III recorder and other wideband recorders before actual VLBA development begins.

At a data rate of 12.5M bps, each antenna will require eight recorders to keep up with a 100M bps data rate output of the samplers. Lower sample rates can be handled by dropping recorders off line or by increasing the bits per sample. Eight recorders will produce up to 48 four-hour tape cassettes per day per antenna. To reduce the bookkeeping required to keep this many tape cassettes straight and to reduce operator intervention to a minimum, NRAO proposes to develop, for the VLB Array, a rack based recorder system using eight video cassette recorders plus one floating spare in an integrated rack assembly (see Figure 1). This rack will have a rack based automatic cassette changer plus a rack based cassette storage area, all under control of a central microprocessor. The tape storage area will be a dismountable bin which can be shipped, cassettes in place, to the correlator for processing. Two such racks will be used per antenna so that 100% redundancy is provided when operating at the normal 100M bps rate. The maximum 100 MHz bandwidth, requiring 200M bps storage, will be accommodated by using both racks simultaneously and accepting the lower reliability. A similar rack based playback system at the processor will complement the antenna record system requiring only insertion of the cassette-loaded bins to process one day's worth of observations for a given antenna. Cassette changes, recorder operations, data synchronism, automatic spare recorder replacement for a defective unit, etc. will all be done under microprocessor control requiring a minimum of operator intervention.

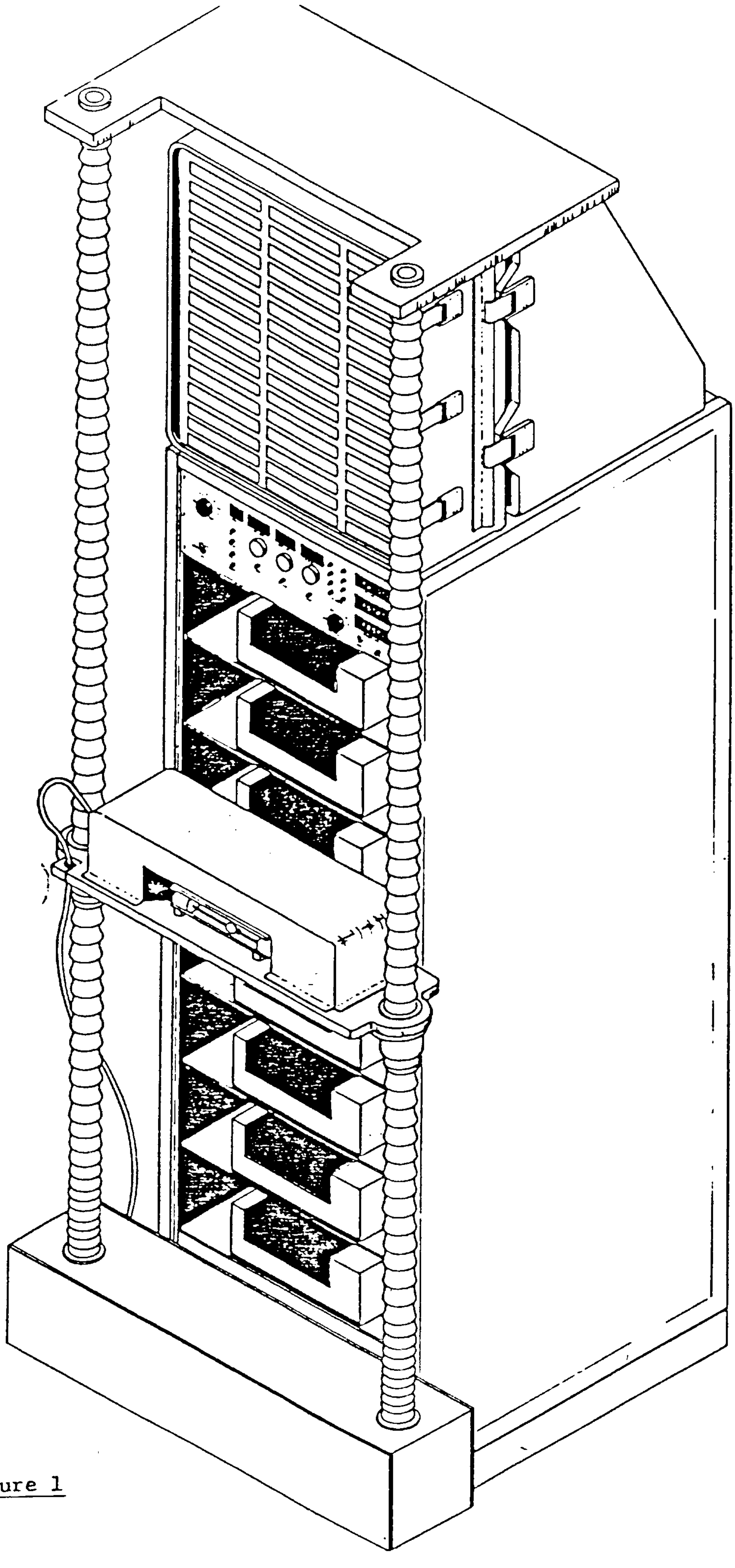


Figure 1

The sampler outputs at any antenna will be recorded on the various tape recorders in 10,000 bit swatches with each swatch having its own time code and check sum encoded. By breaking the data into such swatches, the four I.F. bands can be multiplexed between the various recorders whereby one-eighth of any I.F.'s data will be recorded on any given machine. Such an arrangement will require little digital circuitry to produce and to unscramble and yields a more graceful recorder system failure sequence, since a failure of one recorder will then result in loss of 1/8 of each I.F.'s data rather than eliminating a large percentage of one I.F.'s data.

II. Playback System

The playback system will be, like the record system, based on consumer type video cassette records. Rack based playback stations, each with 8 playback recorders plus one floating spare, a rack wide automatic cassette changer, and a central cassette storage bin will be required to service the antennas of the VLBA. The cassette bin, which holds one day's worth of observational results for one antenna at 100M bps sampling, will be loaded into a playback rack where cassette shuttling, recorder operation, recorder time synchronism, etc. will be controlled by a central microprocessor. Since the order of the cassettes in the bins will have been under software control at each antenna, little bookkeeping will be required to keep the large number of cassettes produced by the VLBA in their proper order. Twenty such racks will be provided at the processor to allow processing of 10 antennas' data at a 200M bps data rate in one pass. Fourteen of these racks will be used in supporting a 100M bps, 14-antenna observation.

Although 126 recorders will be required at the processor to support a 14-antenna array, a more or less modular rack design as above should make the operational process at the correlator more reasonable. The inexpensive nature of the cassette recorders will also make sparing, both at the rack level and at the individual recorder level, economical.

The playback cassette units could be modified to play back at a speed 10 to 15% higher than the record speed, allowing some processing time edge over the observing time. This edge will help reduce the possibility of tape backlogs accumulating due to correlator usage delays and inefficiencies. Except for this possible modification to the cassette recorder servo electronics, there will be no difference between an antenna recorder rack and a playback rack.

III. Recorder/Playback System Cost Estimate

A) Recorders

Each antenna will require one recorder rack plus one spare rack plus 10% spares of individual video cassette recorders and electronics. The table below estimates the recorder system cost per antenna:

20	video cassette recorders	$ 16k
2	recorder racks with electronics	43k
	spare rack electronics	4k
		$ 63k

B) Playback

Twenty playback racks, plus two spares, will be required at the processor. These 20 racks will allow processing of a 10-antenna, 100 MHz bandwidth observation. To process a 14-antenna, 50 MHz observation, only 14 of these racks are used. The table below estimates the playback system cost, including a 60-day supply of tape cassettes, bins and spares:

218	video cassette recorders	$ 175k
22	playback racks with electronics	429k
	spare rack electronics	45k
	spare recorder parts (heads, etc)	45k
60-day tape supply		380k
60-day cassette bin supply		75k
		$1,321

C) Development and Construction

The tables below summarize the development cost and man-power and the construction man-power required for the VLBA record/playback system.

Development

Item	Cost	Man-Months
Home video recorder upgrade	$ 12k	12
Automatic cassette changer	8k	8
Read/write electronics	3k	4
Rack microprocessor control	4k	4
System interface	2k	4
Documentation	-	6
	$ 29k	38

Construction

Item	Man-months
Home video recorder modifications	20
Automatic cassette changer	15
Rack electronics	12
Rack integration	6
	53

IV. Recorder/Playback System Alternatives and Comparisons

Various methods were considered in investigating how to get the remote antenna data to the processor for correlation for the VLBA. The most attractive method, real time transmission via satellite or land lines, is not practical at this time because of high cost and there seems only a slight chance at this time that direct transmission of VLBA data will ever be economically practical. However, this option, possibly using NRAO's own satellite, will be kept open.

Of recording mediums presently available or projected, only magnetic storage seems to be practical because of data storage density, storage medium cost, and storage medium reusability. Thus, most of the investigation for a VLBA data transmission system centered on magnetic tape recorders.

Tape recorders studied include wide band instrumentation recorders (specifically the MK III recorder), modified consumer type video recorders (specifically the MK II recorder), analog and digital television recorders, and projected high density digital recorders.

The television recorders suffer at present from high cost, lack of specifications (for digital TV), and the universality of 90 minute reel/cassette record times.

The array construction and operational costs of 5 possible remaining systems are summarized in Table I. These five recorder systems include:

1) The Ampex AVRX wide band digital recorder.
2) A MK III instrumentation recorder using movable heads to yield a 12-times increase in tape bit density (i.e., 336 tracks across the 1" tape).
3) A MK III instrumentation recording using movable heads to yield a 36-times increase in tape bit density.
4) A MK III instrumentation recorder using movable heads to yield a 20-times increase in tape bit density.
5) Multiple consumer type video cassette recorders (VCR) modified to record 12.5M bps.

It should be noted that none of these possible record systems have been demonstrated as yet, although the Ampex AVRX recorder has been demonstrated in a breadboard stage.

The chart is based on the following:

1) The processor will have the following number of playback stations,

AVRX	16
All MK III	16
VCR	22

allowing 14-antenna, 100M bps, or 10-antenna, 200M bps operation for all approaches except the AVRX. The AVRX system was considered too expensive to extend to 200M bps. In addition, all MK III systems will require extra operator time, not shown in the chart, for additional antenna visits and for extra tape changes at the processor to support 200M bps operation. The VCR system will require additional operator time to load two tape bins per antenna per day.

2) Operational cost is based on the operation of 10 antennas at 100M bps assuming that this will be the most common mode of operation.

3) Automatic cassette changers for the AVRX and VCR recorders are assumed.

4) Multiple MK III recorders are required at each antenna to allow 12 hours between tape changes. The resulting 2 tape changes per day at each antenna and the 3 to 8 tape changes per day at the processor result in the increase in operator time shown. No redundancy in antenna recorders is provided and recorder failures will result in additional antenna visits per day.

	Ampex AVRX	Moving Head MK III (12X)	Moving Head MK III (36X)	Moving Head MK III (20X)	12.5 Bit VCR
Recorder and electronics cost/array (including spares)	$5,956 k	$3,116 k	$2,002 k	$2,556 k	$1,496 k
60-day tape supply	$1,950 k	$1,248 k	$ 415 k	$ 750 k	$ 486 k
60-day shipping container supply	$ 75 k	$ 60 k	$ 20 k	$ 30 k	$ 75 k
TOTAL CONST. COST	$7,981 k	$4,424 k	$2,437 k	$3,336 k	$2,057 k
Maintenance cost/yr.	$2,200 k	$ 103 k	$ 103 k	$ 103 k	$ 158 k
Tape cost/yr.	$ 23 k	$ 30.4 k	$ 10.1 k	$ 18 k	$ 15 k
Tape shipping cost/yr.	$ 237 k	$ 246 k	$ 82 k	$ 152 k	$ 138 k
TOTAL OPERATING COST	$2,460 k	$ 379.4 k	$ 195.1 k	$ 273 k	$ 311 k
Operator time/yr. (in man years)	2.3	5.4	4.8	4.9	2.3
Technician time/yr. (in man years)	0.1	0.1	0.1	0.1	1.5
TOTAL OPERATING MANPOWER (in man years/year)	2.4	5.5	4.9	5.0	3.8

VLB ARRAY MEMO No. 76

NORTHEAST RADIO OBSERVATORY CORPORATION

HAYSTACK OBSERVATORY

WESTFORD, MASSACHUSETTS 01886

8 February 1982

Area Code 617
692-4764

TO: K.I. Kellerman

FROM: Alan E.E. Rogers & Hans Hinteregger

SUBJECT: Comments for VLBA design group

1) Receiver block diagrams (VLB memo No. 48)

S/X system should be compatible with the NASA system covering the following frequency range:

X-band	8.1 - 8.6 GHz	RCP
S-band	2.2 - 2.3 GHz	RCP

In addition receivers should have high image rejection (>50 dB) and have delay calibration. I suggest a first L.O. frequency of 2.02 for S-band and 8.08 GHz for X-band. Or numbers in memo No. 52 which look fine.

2) Recording systems (VLB memo No. 44)

We suggest that Tables 1 and 2 be changed to include 2 MK III options. MK III (X12) which is what we have proposed to NASA and a MK III (X36) which is what we consider to be the upper range of track density for MK III. In addition we suggest that the MK II upgrade options be 8, 12 and 16 Mbit as 20 Mbit is much too optimistic. Relative feasibility should be judged on the basis of a similar transition density (37.5 Kfci for MK III A) and SNR margin for both systems (both X12 and X36 MK III seek to maintain a 23 db worstcase broadband SNR). We enclose a revised table 1 for the MK III (X12) upgrade in which we have great confidence along with projected numbers for X36.

TABLE 1

	Moving head MK III (X12)	Moving head MK III (X36)	Comments
~~limit~~ unit price	35K$	35K$	
Head price	3.5K$	3.5K$	32 track stack, same head used for record and reproduce
Tape price '82	260$	260$	
Data rate	112 Mbit (224 Mbit double speed	112 Mbit (224 Mbit double speed)	
Record time	3.0 (4.0) hr	9(12) hr	120 IPS on 9200' length reel
10^{10}bits/reel	120 (180)	360 (540)	
Pounds/10^{13}bits	81 (60)	27 (20)	10 lb/reel
10^{6} bits/sq inch	10	30	
Ave. head life	10,000 - 40,000 hrs	10,000 - 40,000 hrs	
Ave. tape life	probably no limit >500 passes	probably no limit >500 passes	

( ) 20 m thick tape = VHS samples now, available '83 (12,000' length on 14" reel)

xc: R. Escoffier NRAO
C. Moore NRAO

20208 MEM04:EC:59

VLB ARRAY MEMO No. 93

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

MEMORANDUM

June 10, 1982

To: VLB Working Group

From: R. Lacasse

Subj: Data Digitization Electronics, Draft 2

This memo supercedes VLBA memos 57 and 60.

System Description

The function of manipulating the four wideband IF signals from the Vertex Cabin into four bit streams suitable to the recorder is performed by the Data Digitization Electronics (DDE). A few miscellaneous functions, as discussed below, are also performed by the DDE. As shown in Figure 1, the DDE consists of an IF Processor, four IF to Video Converters, a Sampler, Delay Calibration, Time of Day Clock, RS232 Distributor, and 5 MHz Distributor. The design is based on the Mark III system, modified for fewer converters with wider bandwidths, and with the data formatting and quality monitoring left to the recorder electronics.

As shown in Figure 2, the IF Processor has four IF inputs in the band from 300 MHz to 1500 MHz. Each of these inputs is frequency translated, with 10 kHz resolution, such that the lower edge of the band of interest is at 500 MHz. This section of the DDE is best implemented in the Vertex Cabin, to avoid sending wideband signals through long lengths of cable and then having to deal with the resulting frequency dependent cable attenuation.

As a result of the frequency agility of the IF Processor, the Video Converters can be relatively simple. Primarily, they frequency translate the outputs of the IF Processor to baseband, using fixed 500 MHz oscillators, and single sideband networks. The Video Converters also provide IF level setting attenuators, and selectable output bandwidths of 25 MHz, 12.5 MHz, 6.25 MHz, 3.123 MHz, 1.56 MHz, 0.78 MHz, 0.39 MHz, 0.19 MHz, and 0.10 MHz. Video, IF, and LO power levels are monitorable.

The Sampler produces one-bit, 2 level samples of the filtered, baseband data at a maximum rate of 50 Mbps. The sampling clock is derived from the 5 MHz reference using phase-locked techniques; oversampling is easily accomplished for the narrow bandwidths. Both the sampled data streams and the sampling clock are transmitted to the recorder. A Time-of-Day Clock output is also transmitted to the recorder.

The Delay Calibrator in the DDE is the same as that used in the Mark III system with the exception that it also includes a self-contained counter and communicator module. The Delay Calibrator provides a 5 MHz reference to the Vertex Phase Calibrator System, and also measures the round trip delay in the 5 MHz reference cable.

Communication to the host computer is implemented as in the Mark III system: each module includes an RS232 transceiver which is assigned an address on an RS232 link. A module responds according to a well defined protocol when it is addressed. Thus, all significant functions in the DDE are remotely controllable and/or observable.

Hardware costs are broken down in Table 1, and manpower requirements in Table 2.

Comparison with Existing MKIII System

The Data Digitization Electronics (DDE) must handle up to four, 25 MHz wide, IF signals to produce data at up to 200 Mbits/sec. A system permitting unattended operation for at least 24 hours is also very desirable, to minimize operating costs.

The existing MKIII system, with a few modificaitons, would be suitable for this application. The modifications include an IF distributor upgraded to handle four IF's and automated video converter patching. They also include Video Converter and Formatter modifications appropriate for the bit rate specification. Also, the recorder must be upgraded for a factor of 10 or 20 increase in bit density. The first two modifications are technically straightforward. Work at two institutions is in progress to realize the third modification. Multiple recorders are required to accommodate 24-hour unattended operation. Using 12,000 foot reels of tape instead of the standard 9,200 foot reels, and assuming a factor of 20 improvement in density, four recorders would be required for 24-hour operation. With only a factor of 10 improvement in density, eight recorders would be required.

The DDE, as proposed, is similar to the MKIII system in basic architecture. However, a cost savings is realized by using fewer video converters (four) with broader bandwidth ($\leq$ 25 MHz). A further cost savings is realized in the IF distributor since patching to various permutations of 14 video converters is not required. The appropriate IF signals are routed directly to the video converters by the IF switching matrix in the Vertex Cabin. For purposes of comparison this system is dubbed MKIII.1.

Cost of alternative recorder implementations is covered in another section. Therefore, a cost comparison of only the electronics required to translate four IF's into four bit streams is covered here. This comparison is detailed in Table 3. The significant differences are the following. A 29 K savings is realized in Video Converters in the MKIII.1 system since four instead of fourteen are required. The MKIII.1 system includes a Formatter in the recorder, so all that is required in the DDE are a Sampler and Clock. The 13 K for the MKIII IF Distributor includes the cost of the upgrade mentioned above. Both systems require an IF Processor to switch the nineteen receiver IF's into four and to select the band of interest from the broadband receiver output. The MKIII.1 IF Processor is more expensive since it includes some of the functions of the MKIII IF Distributor. A Decoder is included in the MKIII.1 recorder, and so is not included in this cost estimate.

A fair comparison must also include manpower and spares costs. These are detailed in Tables 4 and 5, respectively. Table 4 shows that the MKIII.1 design effort time is more than compensated by the reduced assembly and test time. Spare costs are similar.

RJL/cjd

TABLE 1

Data Digitization Electronics Hardware Cost Breakdown

Item	Cost
IF Processor	$36 K
IF to Video Converters	13 K
Sampler	2 K
RS232 Distributor	1 K
Delay Calibrator	3 K
Rack, Power Supplies, Connectors, etc.	10 K
5 MHz Distributor	2 K
Total	$67 K

TABLE 2

Data Digitization Electronics Manpower Requirements

Item	Time (Man-Months)
Design and Document	15
Order	1
Assemble (1 terminal)	8
Total	24

TABLE 3

Cost Comparison of MKIII and MKIII.1 Data Digitization Electronics

MKIII	MKIII	MKIII.1
Video Converters	$ 42 K	$ 13 K
Formatter	6 K	-- *
Sampler	--**	1 K
Clock	--**	1 K
IF Distributor	13 K	--
IF Processor	28 K	36 K
Delay Calibrator	2 K	3 K
Counter	1 K	--
5 MHz Distributor	2 K	2 K
Rack, Supplies, Connectors, etc.	11 K	10 K
Decoder	4 K	-- *
TTY Distributor	1 K	1 K
Totals	$110 K	$67 K

* Part of recorder.

** Part of formatter.

TABLE 4

Comparison of Manpower Requirements for the MKIII and MKIII.1 Systems

Item	Time (Man-Months)	
	MKIII	MKIII.1
Design and Document	2	15
Procurement	1	1
Assembly and Test (per unit)	15	8
Total (one unit)	18	24
Total (ten units)	153	96

TABLE 5

Comparison of Spares Costs for MKIII and MKIII.1 System

Item	MKIII	MKIII.1
Video Converter	$ 3 K	$ 3.2 K
Formatter	6 K	--
Sampler	--	1 K
Clock	--	1 K
IF Distributor	13 K	--
IF Processor	28 K	36 K
Delay Calibrator	2 K	3 K
Counter	1 K	--
5 MHz Distributor	2 K	2 K
Supplies, Connectors, etc.	3 K	3 K
Decoder	4 K	--
TTY Distributor	1 K	1 K
Total	$63 K	$50.2 K
Assembly and Test Time (Man-Months)	22	20

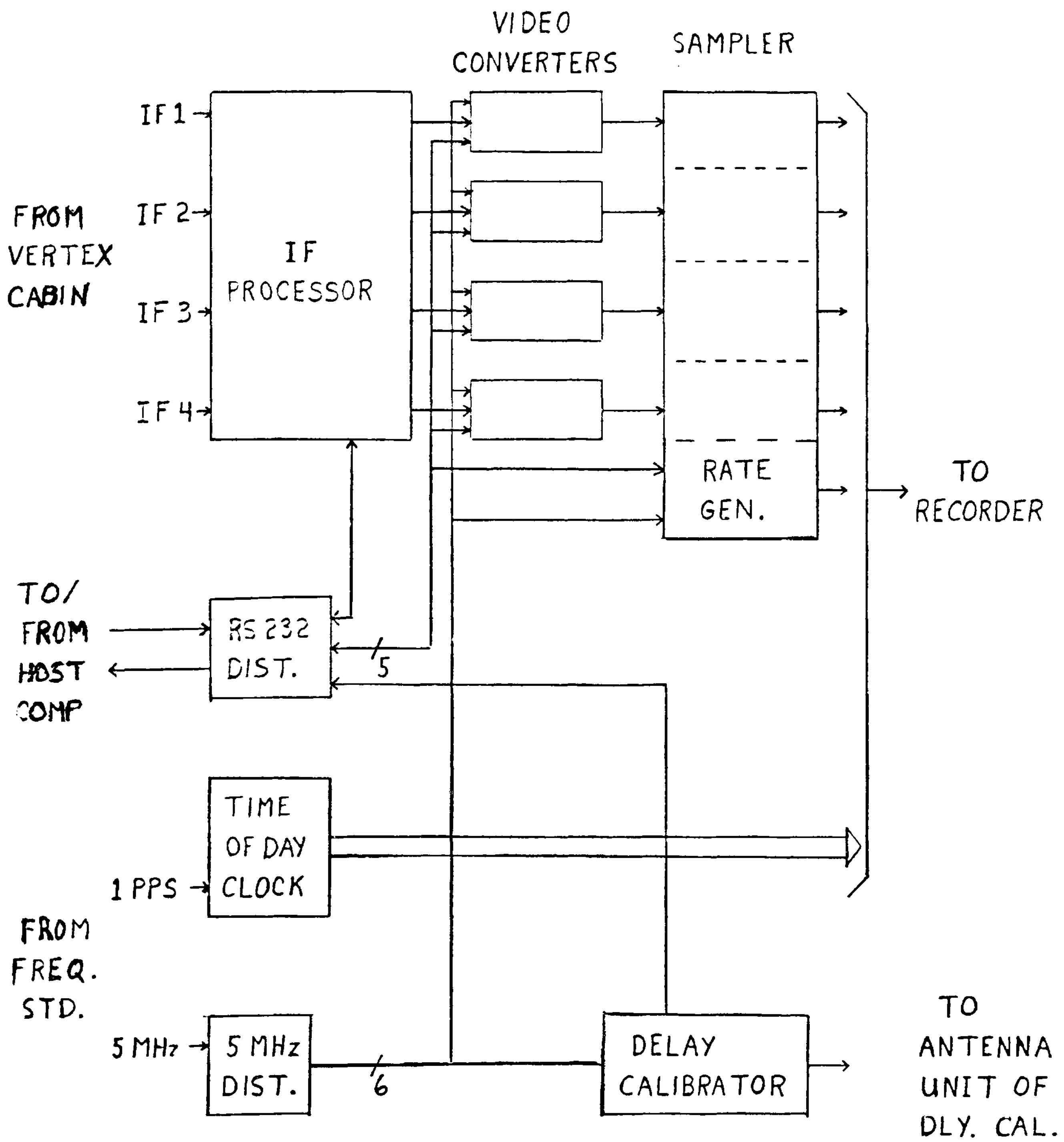
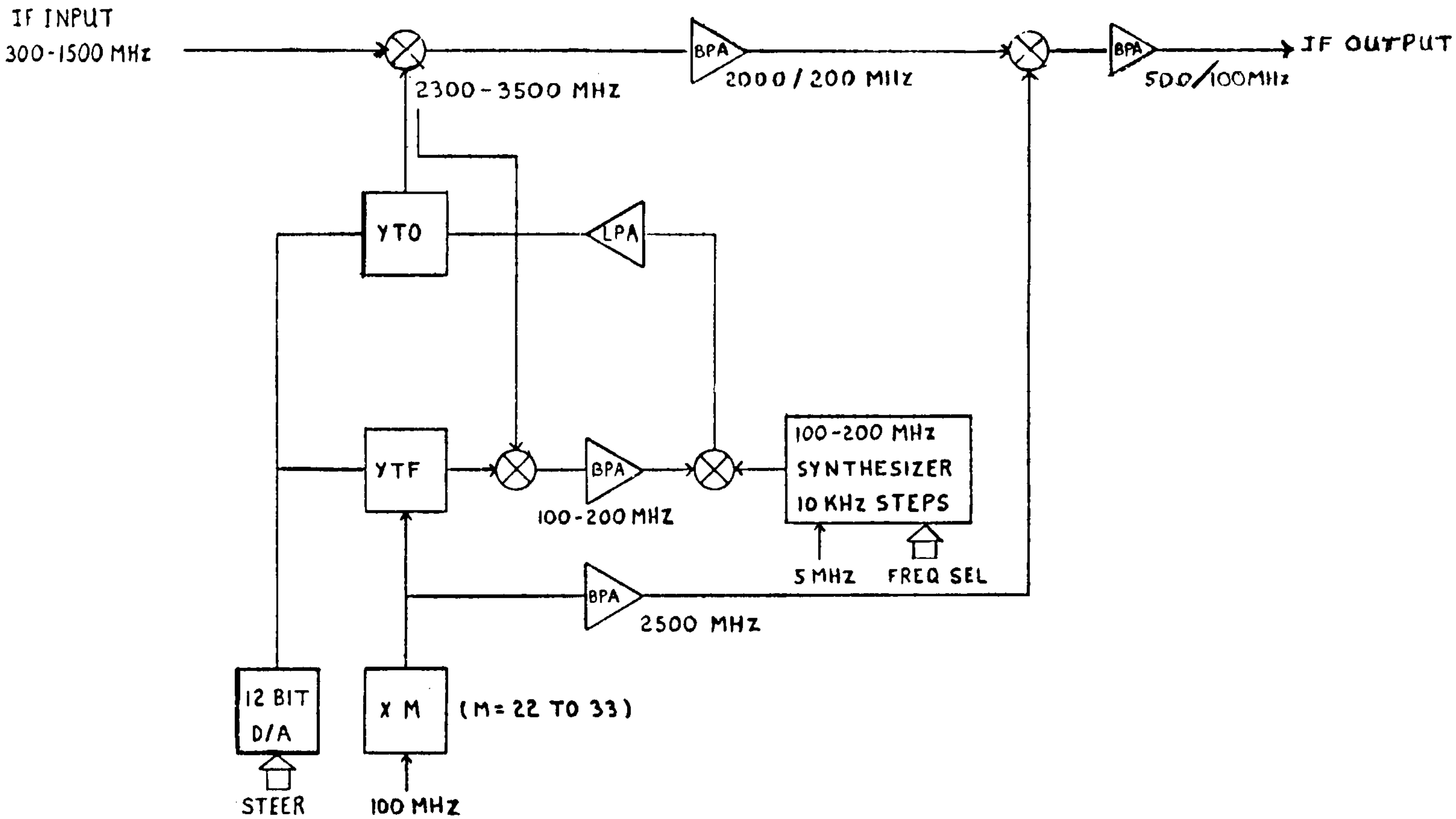


FIGURE 1

VLBA
DATA
DIGITIZATION
ELECTRONICS

1/5/82 RJL



NOTE: ONLY ONE OF FOUR IDENTICAL CHANNELS IS SHOWN.

VLBA IF PROCESSOR
1/19/82

ERM

FIGURE 2

ALTERNATIVE DATA COMMUNICATION SYSTEMS

G. W. Swenson, Jr.

All existing VLBI systems use broadband magnetic tape as the communication medium between telescopes and central data processor.

A fundamental difficulty with the tape recording system is the lack of information in real time concerning the performance of the individual telescopes and peripheral equipment. Frequently a subtle failure of a minor yet vital component will be unrecognized until after tape processing has commenced, perhaps weeks or months after the observations. Such occurrences have resulted in much wasted observing time and scientific and technical effort. Program changes during an observing session, based on preliminary examination of the correlated data, are frequently desirable; such changes are impossible with the VLBI systems currently in use.

The postobservational tape processing usually requires considerably more time than the observing itself, especially for multibaseline sessions, and so the amount of scientific labor involved in an experiment is inordinately large. Furthermore, the time interval between the observing session and the production of processed data can run to several months. Large amounts of magnetic tape are involved in a major observing program, and there are thus significant logistical problems.

Short-baseline interferometer systems, whose antennas are interconnected by guided-wave transmission systems, suffer from none of the disadvantages mentioned above. The contrast in efficiency and convenience with current VLBI systems has led to consideration of suitable long-distance, broadband communications media for VLBI use. These include dedicated microwave radio links, the continental television network, and communications satellites, all of which could permit real-time, long-baseline interferometry, although they are apparently much more expensive than the magnetic tape system.

No substantial study of a dedicated, terrestrial, microwave-link communication system for a VLBI network has been made; it seems obvious from superficial considerations of the economics, politics, and frequency-management problems involved that there is little point in considering this medium as a solution to the data communication problem. While terrestrial microwave systems well serve intermediate-baseline interferometer systems, of the order of one hundred kilometers or so, they do not provide an attractive possibility for the transcontinental or intercontinental network.

An initial inquiry into the characteristics of the network television transmission system operated by the American Telephone and Telegraph Long Lines division suggests that it would provide a technically feasible communication medium for VLBI. It is widespread throughout the country, and methods are in practice for real-time transmission from locations (such as football stadiums) other than established studios. Presumably the same services could be extended to radio observatories. It is apparent that many redundant television transmission channels are available as insurance against failure; these could conceivably be used for scientific purposes on a second-priority basis if suitable tariffs could be negotiated.

The television network has some serious disadvantages, of course. The chief one is its limited bandwidth. While the most widely-used VLBI system (Mark II) at present uses television format and bandwidth, there are strong motivations toward much broader bandwidths, and new VLBI systems are utilizing such bandwidths. There are also questions of phase and time-delay stability which are potentially troublesome. In any case, the television network has not presented an attractive-enough alternative to the magnetic-tape system to have merited intensive attention by the VLBI community, although, its potential has been recognized.

Probably the most promising communication medium for a transcontinental VLBI network is the optical fiber system, which has been developed to the point at which it offers outstanding technical advantages. Ultimately, it is possible that a national optical fiber network will be established to supplement or supplant the existing microwave, coaxial cable, and satellite communication system. At that time, adequate bandwidth at low-enough cost should be available through the commercial network to serve a national VLBI network. This situation probably will not be realized for many years, perhaps decades. In the interim, a dedicated fiber-optic system is clearly economically infeasible for scientific use.

The final possibility for real-time VLBI data transmission is the communication satellite. While the real costs of such a system are undoubtedly comparable with those of the media discussed above, particularly if space in the radio frequency spectrum is considered as an economic good, satellite communications systems are frequently subsidized by national governments for reasons of policy. Hence, from the point of view of the user the satellite often appears to be the most economical broad-band, long-distance transmission medium.

To test the feasibility of satellite VLBI, a group of U.S. and Canadian radio astronomers (Yen, Kellermann, Rayhrer, Broten, Fort, Knowles, Waltman, and Swenson, Science 198 289, 21 Oct. 1977) utilized donated time on the experimental CTS (Hermes) satellite to conduct interferometer observations on baselines between Algonquin Park, Ontario, and Green Bank, West Virginia, and Owens Valley, California, respectively. The experiment was successful. Real-time fringes were routinely obtained on both baselines, using an effective bandwidth of 10 MHz. A total of over 150 sources were observed, of which approximately 25 percent exhibited fringes in real time. No determined attempt was made to extract fringe information on the remaining sources by post-observational processing. Such an effort would have almost certainly been successful in many cases. Promising results were also obtained in the transmission of precise time signals over transcontinental baselines, a technology of central importance to VLBI. Experimenters of the U.S. Naval Research Lab and the Canadian National Research Council are continuing these time- and phase-transmission experiments with another satellite.

The CTS VLBI experiment involved transmission from the remote radio telescope to the satellite and thence to the correlator at Algonquin Park. The signal from the local telescope was sent directly to the correlator. The signal from the remote telescope was thus delayed by approximately 0.25 second in addition to the delay resulting from the geometry of baseline and source-direction. The differential delay was equalized by passing the local signal through a digital delay line, probably the most elaborate one ever built, which aligned the two bit streams to an accuracy of 0.05 microsecond before presenting them to the correlator.

In a satellite system specifically designed for multistation VLBI, all telescope signals would be transmitted to the processing station via the satellite, thus eliminating the largest part of the differential delay. The delay-line problem is thus relatively minor. Present-day satellite technology is perfectly capable of accommodating eight telescope channels of approximately 30 MHz bandwidth each (European Space Agency, Phase A Study on satellite VLBI, Document No. SC1(80)1, Paris, February 1980). Whether the attendant frequency allocation problems could be solved is an open question. The European Space Agency has planned a satellite-assisted VLBI system involving existing telescopes in eight countries, with a proposed completion date of 1985.

Should the United States wish for political reasons to provide a geostationary communication satellite for astronomical use, it is technically feasible to do so, and such a facility would greatly expedite the establishment and operation of a VLBI network. In the interim, particularly if real costs are a major consideration, magnetic tape appears to be the most practical communication medium. A satellite communication system could be added at any time in the operating life of a VLBI network without a major reconversion of existing facilities, by adding the uplink transmission facilities at the radio telescopes and the downlink reception facilities at the processing center. If such an evolution is a reasonable possiblity, it would be well to plan the processing center in such a way as to minimize retrofitting of delay lines, correlators, data buffers, etc.

VI. CORRELATOR SYSTEM

VLB ARRAY MEMO No. 61

B. Clark
1/26/82

1. The VLBA Playback Correlator System

The basic correlator system specifications are given below. This is followed by a detailed discussion of one way to meet these specifications and then by a very brief discussion of alternatives. Of particular difficulty in setting the specifications is deciding on just what the requirements are for spectral line observations. The VLB observations of the maser sources can impose as great a load of data processing requirements as anything in radio astronomy. Indeed, if one were to try to get all the information possible out of an observation, the data processing requirements quickly rise into the realm of the absurd. The correlator specifications below are a compromise, meant to cover most cases of astrophysical interest without driving the correlator costs beyond reasonable bounds. In this connection, it should be noted that it would not be unreasonable for the correlator to spend one or two percent of its time replaying line observations, if this would halve the size of the required correlator.

Unfortunately, exactly how one states the specifications depends to some small extent on how one eventually ends up implementing the device. In the specification section following, the line system specifications are stated in the form most natural for the recirculating implementation discussed following. If a non-recirculating system eventually is chosen, a slight alteration in the form of the specifications as well as in their content would result (there is no way we would build individual hardware for 4096 line channels).

1.1. Correlator Specifications

The correlator interfaces to the tape recording system. Each station of the array will have a corresponding 'station' in the playback system. That is, the playback system will have a set of recorders of identical type to those of the record system at the station to play back that station's data. The correlator specifications therefore begin with the specifications of the tape recording system.

In addition, as discussed above, the playback processor should support the desireable feature of being able to add observations from other observatories to those of the dedicated array, for better (u,v) coverage or for more sensitivity. It is sufficiently desireable to do this that we believe that a 14 station processor should be built. This would permit real-time reduction of the dedicated array and four additional observatories. In addition, for normal operation of the dedicated array alone, it allows four spare playback stations, which can be switched in in case of failures, considerably smoothing out the maintenance requirements of the playback processor. This extra capability in the playback processor increases the cost only by the station recorders and electronics; as is discussed below, the extra correlator capacity is needed to handle the spectral line case.

1.1.1. Continuum correlator specifications

The requirements on the continuum processor are primarily set by the size of the field of view to be synthesized by the array. This sets two requirements--the number of delay channels needed and the frequency with which data must be recorded for further processing. We have adopted a specification of a field of view 1" radius, 2" diameter. The diameter of the earth is approximately 42 ms. The delay range necessary to synthesize a 2" field is thus 42 ms times 2" (expressed in radians) or 0.4 microseconds. An additional allowance must be made for a possible clock error. For a dedicated array with continuing coherence checks, it would seem quite feasible to keep track of clocks to an a priori accuracy of 0.3 microseconds. Thus the total delay range needed by the processor is about 1 microsecond.

The field of view also determines the required rate of recording of the correlation function. This relationship also involves the frequency of observation. The desired relationship is

$$BFST \ll 1$$

where B is the longest baseline length in nanoseconds, F the observing frequency in GigaHertz, S the field of view in radians, and T the integration time, also in radians. In more practical units, for a 2" diameter field of view, a 42 ms baseline, and avoiding only serious effects (of order ten percent) of too long integration gives

$$T < 30/F$$

where T is now in seconds. Since we want to work to frequencies of at least 25 GHz with this field of view, and preferably 50 GHz, we must be prepared to dump the correlator at intervals of 1, or even 0.5 seconds.

We may now summarize the specifications for the continuum operation of the playback correlator as follows:

Number of bit streams per station: 4

Bit rate per stream: 25 MBits/second (100MBits aggregate rate)

Polarization processing: All four cross products of two pairs of bit streams.

Simultaneous delay range: 1 microsecond (32 channels at 40 ns/channel)

Number of stations: 14

Integrator dump rate: Selectable from 0.5 to 30 seconds.

Derived quantities

Number of baselines: 91

Number of complex quantities to be calculated per baseline and delay channel: 8

Number of complex quantities to be calculated per baseline: 256.

Length of each complex quantity: 4 bytes

Number of bytes output per correlator dump: 93184 bytes

Maximum output data rate: approx 200 kbytes/second

In the implementation discussed below we have

Number of physical complex correlators per baseline: 64

Number of simple real correlators: 11648

1.1.2. Line observation specifications

As Mentioned above, it is easily possible to think up astronomically reasonable requirements which place quite unreasonable demands on the correlator system. The specifications which are set down here are distinctly compromises--they are things which one might very often want to do, and carry no implication of being a "worst case".

Since the line system is a greater strain on the system than the continuum system, the first compromise to come to mind is to reduce the number of stations from 14 to the 10 stations of the dedicated array. Reducing the number of baselines from 91 to 45 immediately halves the number of correlations to be done.

It is necessary, or at least extremely desireable, to be able to process simultaneously full polarization information in two separate bands (for instance, two OH maser transitions).

It is necessary to process simultaneously a band at least as wide as 12.5 MHz (160 km/second for water masers).

Resolutions of 0.5 km/sec are necessary at both water vapor and at OH (40 kHz and 3 kHz respectively).

A single band (no polarization processing) should be processable with better than 1 km/sec resolution for a width exceeding 150 km/s at both water vapor and OH masers.

The correlator (and, of course, the recording systems) should be able to operate in the following modes: A) Two bands, two IFs per band, full polarization processing.

B) One band, full polarization processing (two bit streams are idle).
C) Four bands, no polarization processing
D) Two bands, no polarization processing (two bit streams are idle).
E) One band (three bit streams are idle).

It is interesting to note that surplus recorder capability is available in modes B, D, and E above. An interesting use for this capability would be to allow three level sampling. This would give a higher signal-to-noise ratio for these cases by a factor of nearly 1.3 for minimal extra cost. Using the special purpose integrated circuits developed for the VLA automatically provides this on a chip basis; the extra cost in the correlator is only the wiring to carry the second bit to the chip. The extra cost at the antenna would be the provision of a three level sampler and the switching logic to turn it on when needed.

The observation of water masers can quickly lead to requirements beyond all reasonable bounds in total data output rate. It is commonly the case that the total extent of the masing region exceeds 10" on the sky, and that the ratio of feature width to the whole velocity width of the masing region exceeds 1:500. To maintain a 10" field of view at 23 GHz would require a dump time of 0.2 seconds. 500 complex correlations per baseline gives a total data output rate of 450 kBytes/second. This output rate could be handled (barely) by a high density tape drive (6250 bytes per inch) running at an average speed of 75 inches per second. It is doubtful that the correlator computer system could sustain this data rate, and it is clear that any reasonable data processing system would take several times slower than real time to process it (even super computers can't do all that much to a byte of data in the 2.2 microseconds before the next one arrives). For this and similar practical reasons, we arbitrarily specify that the data output rate should not exceed 400 kBytes/second, and that the maximum number of channels per baseline of interest is 4096 (4096 complex numbers for each of 45 baselines will amount to 0.75 to 3 MBytes of storage, depending on how it is managed; in any case, it is a practical and manageable amount with current technology).

These specifications are summarized below.

Number of stations: 10

Number of frequency channels: Variable, 32 to 4096

Number of IF channels per station: selectable--1, 2, or 4

Maximum data rate per channel: 25 Mbits/sec

Maximum data output rate: 400 kBytes/sec

In the following section a possible correlator design will be discussed, based on the VLA correlator technology. This is a recirulating design, which runs all multipliers at their maximum rate all the time. Therefore, the number of frequency channels that can be generated is dependent on the incoming data rate. Specifically, in the 5 possible observing modes discussed above, we have the following table for number of spectral channels for the various possible sample rates.

Sample Rate MHz	Band-width each band	A numb	A res kHz	B numb	B res kHz	C numb	C res kHz	D numb	D res kHz	E numb	E res kHz
25	12.5	32	391.	64	198.	64	198.	128	98.	256	49.
12.5	6.25	64	98.	128	49.	128	49.	256	24.	512	12.
6.25	3.12	128	24.	256	12.	256	12.	512	6.	1024	3.
3.12	1.56	256	6.	512	3.	512	3.	1024	1.5	2048	0.76
1.56	0.78	512	1.5	1024	0.76	1024	0.76	2048	0.38	4096	0.19
0.78	0.39	512	0.76	1024	0.38	1024	0.38	2048	0.19	4096	0.10
0.39	0.19	512	0.38	1024	0.19	1024	0.19	2048	0.10	4096	0.05
0.19	0.10	512	0.19	1024	0.10	1024	0.10	2048	0.05	4096	0.02

1.2. Implementation

The correlator specified above is a rather large one, at least in terms of correlators currently on line, if not in terms of correlators designed. The only correlator of this size in current production work is the VLA correlator. A larger correlator was prototyped for the NASA SETI project, but it is not in current production. It therefore seems most conservative to design the correlator using the VLA technology and philosophy. Since it has been done, and works well, one can set out to design a correlator of this size with reasonable confidence that it will work when complete. Other designs have not been attempted in this size, and may require more extensive design and prototype work.

Although the correlator is a relatively straightforward design and construction project, the tape recording system is much less so. It is enevitable that modifications will be made in it based on field experience. It seems very desireable to have the correlator itself independent of such changes. A well designed interface between the tape system and the correlator system does make them quite independent. The concept of having the playback system provide four bit streams at 25 Mbit/sec each, and having validity bits with well defined properties would lead to an interface sufficiently simple for both sides to work to that the independence could be maintained. The importance of this is that the correlator can be built in its entirety from the beginning, a substancial saving in money over having to build a prototype correlator system to get the initial field experience which will surely be necessary for the recording system.

An additional impetus toward the VLA correlator philosophy is given by simple cost considerations. A look at the total costs of recently constructed correlators seems to indicate that the cost is proportional to the number of channels, and nearly independent of speed. It is therefore reasonable, for correlators large enough to justify the rather large design effort of the controllers, to run all multipliers at the maximum possible rates. This rate is, for the VLA correlator technology, 100 Mbits/sec. Even for the continuum case, a recirculating correlator running at this rate requires four times fewer hardware multipliers than a simple correlator running at 25 MHz, and is therefore expected to be substancially less expensive. The contrast in the spectral line case is even greater.

The playback correlator system consists of the following component parts: 1) The tape playback systems (one per station)
2) The bit stream handlers (one per station)
3) The baseline handlers (one per baseline)
4) The channels
5) The hardware controllers
6) The computer system

1.2.1. The tape playback systems

The tape playback system is discussed above, together with the recording systemswhich it essentially duplicates. The additional equipment required at playback time is only a buffer, to remove the mechanical variation in the playback rate, and a delay control, to that the bits are removed from the various tapes in synchronism.

1.2.2. The bit stream handlers

The interface to the correlator proper is four bit steams at a 25 Mbit/sec rate, with one or more validity bits. It might be worthwhile having several validity bits which can be handled slightly differently down-stream. For instance, it might be worth having separate bits for recorder checksum error and an antenna generated error flag (eg, antenna still slewing). On the other hand, it is possible to conceive doing with only one flag.

The bit stream handlers as part of the correlator consist of the recirculators, phase extrapolators, and delay controls. Fringe rotation is normally done in VLB interferometers by multiplying one of the two bit streams going into the correlator by a three level (-1,0,+1) signal. Two three level signals displaced by 90 degrees of phase are used. This is the equivalent of an analog mixer. The desired function is a single sideband mixer, and the sideband is selected by performing the appropriate operations on the two correlator outputs to reject the unwanted sideband of the fringe frequency. Since the single sideband mixer is not completed until after correlation, it is not practical to perform the mixing operations on the bit streams from each antenna separately. The cross frequencies of the fringe rates are not completely rejected, and a cost in signal- to-noise ratio is incurred. Therefore, fringe rotation must be done on a baseline by baseline basis. However, This can be simplified as much as possible by having an antenna based calculation of phase, which is transmitted to each baseline. The baseline equipment would then difference the two antenna phase signals to give the baseline phase. This is worthwhile because the phase calculation is a rather more complicated affair than it would be for a simple correlator. The recirculators are playing the data back at several times real time, and the fringe rotators must be speeded up by the same factor, and must be reloaded with a new initial value each time the recirculators are reinitialized.

The fringe rates encountered in VLB interferometers are at moderate rates--an earth-diameter baseline at 44 GHz gives a maximum fringe rate of 130 kHz. Simple TTL circuitry can be used in the fringe function extrapolators. Appropriate buffers for their rates and initial values can be loaded by the control microprocessor. It is probably worthwile having a hardware delay extrapolator as well as a hardware fringe function extrapolator. The maximum delay rate on an earth baseline interferometer is about three microseconds per second, or one bit (25 Mbits/sec) in 12 microseconds. This would be doable by a fast microprocessor, but there is one additional complication. Since the delay is applied in unit steps of one bit, it is not possible for a multistation processor to delay the bit streams on an antenna basis; to do so means that the maximum correlator induced delay error is one bit time, rather than the desired half bit time. Therefore, the decision one the last bit of delay must be made on a baseline basis, in the same way that fringe rotation must be done on a baseline basis.

If one has a hardware delay extrapolator, it is reasonable to add its fractional bit outputs to the fringe extrapolator. This will mean that phases track the fringes at the band center frequency when the phase rotator is initialized with parameters suitable for the signed sum of local oscillators, and that nothing further up in the system need know about the "fractional bit" of delay. Since the system is large and complicated, doing this at the hardware level will remove a likely source of error.

The recirculators themselves are simply a memory, which are filled at the 25 MBit/sec basis record system rate, and dumped at the 100 MBit/sec correlator system rate, to give maximum utilization of the correlator hardware.

There are several ways to use recirculators, and it is not clear which will be most advantageous. The one suggested here is that a separate recirculator be provided for each of the four 25 MHz bit streams. In the continuum mode, the correlator can perform four opperations in the time taken for the recirculator to refill with new data. These could be to compute the polarization parameters of the radiation. That is if there are two left hand polarized IFs, LA and LB, and two right handed, RA and RB, a single section of the correlator could compute the four products from two antennas (1 and 2) RA1*RA2, LA1*LA2, RA1*LA2, and LA1*RA2. These four products carry the intensity and polarization information at the band ("A") from which these two IFs arise.

1.2.3. The baseline equipment

As mentioned in the preceeding section, there are several devices which must occur on a once-per-baseline basis. These are: 1) The phase rotator.
2) The plus or minus one bit extra delay.
3) A correlator channel to keep track of attempted correlations.
4) Logic to OR the flags from the two antennas involved.
5) A multiplexor to achieve the reconfiguration between the basic 14 station continuum configuration and the 10 station line configuration.

The phase rotator conventionally used in VLB correlators is a three level multiplication, in which the 0 level is present 1/4 of the time, and +1 and -1 are present 3/8 of the time each. This device has a loss in signal-to-noise ratio of about 4 percent, but its simplicity recommends it. The phase rotator then consists of a subtractor of the two phase values from the two antennas in question (four bits appears to be enough), and a one-of-eight decoder. Two of the eight lines suppress correlation and three invert one of the bit streams going into the correlator.

Although it should be possible, in principle, to calculate from the initial values just what the duty cycle of the correlator is, in practice, it is not easy to get right, and it would appear that an additional channel per baseline to get this number exactly (it is needed exactly because the correlator channels are up-counters, and therefore have a large bias which must be subtracted) would save a large amount of effort elsewhere.

1.2.4. The correlator channels

The VLA correlator channels are implemented in specially designed integrated circuits. One custom circuit incorporates multipliers, the other the fast integrator. The fast integrator holds the results of the integration for one recirculator full of data. At the end of a recirculator cycle, the fast integrator adds its contents to the main correlator memory (a rather conventional semiconductor memory) and is cleared for the next recirculator buffer.

As discussed above, there are several ways to use recirculators. In the implementation suggested here, the physical correlators are used to make a complex correlation (that is, with two orthogonal fringe functions applied) on a single pair of bit streams for 32 lags. Although the correlator is running with a 100 MHz clock, the bit streams were originally sampled with a 25 MHz clock, so the spacing of the lag channels is 40 nanoseconds. The four recirculations are used to calculate the four cross products of two pairs of bit streams (that is, two bit streams from each antenna). These four cross products carry the polarization information of the correlated radiation (they are linear combinations of the four stokes parameters).

There are actually four bit streams from each antenna, so the correlator channels and baseline equipment mentioned above must be duplicated in its entirity for the second pair of bit streams.

Let us now repeat the litany of numbers. For each delay channel there is one complex physical correlator,
or two simple real physical correlators.
For each baseline and bit stream pair there are 32 delay channels,
32 complex physical correlators, 64 real physical correlators.
For each baseline there are two bit stream pairs, totalling 64
complex correlators or 128 simple correlators.
There are 91 baselines, giving a grand total of 5824 complex
correlators, or 11648 simple correlators.
In addition, there are the duty cycle correlators, two complex correlators per baseline, 182 complex or 364 simple correlators in all.

For spectral line use it is also desireable to have autocorrelation spectrometers on each of the incoming bit streams. This probably requires only 32 real correlators per antenna. Recirculation should take care of synthesising the number of needed channels and of processing all four bit streams. Thus 320 additional real correlators are necessary for the autocorrelation function for spectral processing of the 10 antenna spectral line array (in practice we would probably put them on all 14 stations to allow convenient spectral processing of the 14 station array with half the number of channels per baseline discussed above).

1.2.5. The correlator computer

The correlator proper is probably controlled most conveniently by a fast, bit slice microprocessor, as is done in the VLA correlator. This in turn must be controlled by, and pass data to, a more general purpose computer, which will do the necessary geometric calculations to provide fringe rates and starting phases, and which will format the data in convenient forms for post correlation processing.

The geometric calculations are not particularly ornerous, but must merely be done with a reasonable degree of care. To track fringes smoothly on a long baseline at 50 GHz requires an accuracy of about 34 bits. To attain this requires about 40 bits internal computation width. There is no problem in attaining this in any modern minicomputer. Again, to track fringes smoothly on a long baseline requires that the fringe phase be updated about every 0.1 seconds. Calculating the geometry of the fourteen station array will take only a few percent of this time on any modern minicomputer, if the calculation is properly organized.

The data handling is a bit more severe in its requirements. As mentioned above, Output data rates of up to 400 kBytes/second may be encountered. This carries the strong implication that input data rates will be at least as great (in a well ordered world computers perform data reduction, not data expansion). To handle this, and to resolve gracefully the inevitable bus contention problems, the computer should be specified with an agregate I/O bandwidth of at least 2 MBytes/sec.

Perhaps the most computation intensive chore of the correlator computer is to convert from lag spectrum to cross correlation spectrum in the spectral line case. The FPS AP120B array processor does longish fourier transforms at the rate of about 500,000 output points per second. However, since the fourier transform is being used to complete the quadrature mixer, half the output spectrum is empty, and thus a single FPS AP120B processor is fairly well matched to performing this chore with an output data rate of 400 kByte as discussed above.

1.3. Alternative approaches

There are many ways to design a correlator. The most obvious is to do without the complication of the recirculating design. This requires four times the number of physical correlators. It does do away with a complex part of the controller, as well as the recirculators themselves. Constructed in similar technology, one would expect the non-recirculating design for a correlator of this size to be two to four times more costly than the recirculating design discussed above. Its only chance of being economically competitive is if it can be more highly integrated. The difference between a 100 MHz clock rate and a 25 MHz clock rate, at which the non-recirculating design runs, may make the difference in being able to use Schottkey logic rather than the ECL logic, and thus enable another factor of two or four in density on a specially designed circuit. It does not seem like a profitable approach to implement with standard integrated circuits. One implementation of a three level correlator with standard circuits requires two j-k type flip-flops and three gates. Integration for 10 seconds at a 25 MHz clock requires an additional 27 stages of binary counter. With conventional MSI integrated circuits this is nine packages with a total power dissipation of approximately 0.6 watt (assuming conversion to CMOS after the first counter stage). Thus the entire correlator would amount to over 400,000 ICs drawing over 8000 amperes of power at 5 volts.

A second approach of rather more interest is that planned for the large correlator on the Nobeyama interferometer array. In this approach, the incoming bit stream is fourier transformed into individual frequency channels, and the channels are then multipied together and accumulated to give a correlated power spectrum, just what you want for the spectral line case. For use as a continuum processor, one would generate, say spectral channels of width 780 kHz which are narrow enough that the possible clock errors and delay range do not reduce the amplitude of the fringes. One can then do a fourier transform back into lag space, to be able to discard lags not of interest. A complete design of such a device has not been made, so the cost and operating properties are now well known, but some remarks on the subject are made below.

It is a property of the fourier transform that the number of points going into the transform is equal to that coming out. That is, the data rate is not changed by the fourier transform. There is a minor exception--for economy of tape bandwidth use, the incoming bit streams are two-level or three-level signals. The output cannot also be similarly truncated without the loss of significant information. It is probably sufficient to add one additional significant bit for every two levels of FFT butterfly, plus about two guard bits. Thus, an eight bit output would probably suffice for a 4096 channel spectrometer.

A second increase in the data to be handled comes from the fringe rotation. The most natural way to handle fringe rotation is to apply a phase to the incoming bit streams. This makes each sample a complex number, rather than a simple real number, doubling the amount of data to be handled thereafter, essentially the same doubling encountered in the lag domain correlator in the application of two orthogonal three level fringe functions.

The advantage of the fourier transform correlator is that the one-per-baseline equipment becomes very simple. It is simply a few high speed multibit multipliers. For instance, eight eight bit complex multipliers per baseline that run at 25 MHz will extract the four polarization parameters from two pairs of orthogonally polarized bit streams of 25 MHz each.

Because of the general usefulness of the FFT algorithm, a considerable effort has been devoted to hardware implementations. Certainly, real-time transforms of 8 bit precision and 25 MHz rates have been implemented. The question is simply whether such devices are economical for the VLB correlator, which would contain 56 of them.

Thus, the hard part of the correlator would be implemented in 56 high speed fourier transform devices and 2912 eight bit high speed multipliers. This impressively low device count suggests that this approach may be economically effective. However, these devices are relatively complex, especially considering the speed with which they must operate.A detailed design and costing must be done on such an approach. Further investigation, while obviously necessary, may disclose serious problems. Therefore, the cost information in this proposal is based on the more conservative assumption that the correlator will be based on the VLA correlator philosophy and technology.

VLB ARRAY MEMO No. 68

VLB CORRELATOR COST--NOT INCLUDING PLAYBACK TAPE SYSTEMS

ITEM	Components $K	Manpower assmb	Manpower design
Interface--tape system to correlator	3	1	1
Recirculators	39	3	2
Fringe and delay extrapolators	35	4	3
Fringe rotators/last bit delay/multiplexor	27	3	1
Multipliers	286	3	1
Autocorrelators	32	1	1
Integrators	48	2	1
Buffer memory for integrators	48	2	0
System controller and programming	15	2	36
SUBTOTAL -- CORRELATOR HARDWARE	533	20	45
PC Boards--development and fabrication	88	0	0
Power supplies	68	1	1
Racks, Cables, misc hardware	40	1	2
SUBTOTAL -- SUPPORT HARDWARE	196	2	3
Computer CPU w. 2 MByte memory, 100 MByte Winchester disk, 800/1600 BPI, 45 ips tape for software maintenance, operating software licenses	182	1	1
Magnetic tape, 2 drives 6250 BPI, 125 ips	67	0	0
Array processor, 64 kWords data memory	73	1	1
Terminals-4 text, 1 graphic	10	0	0
Cabinets, power, furniture	10	0	0
Programming			48
SUBTOTAL -- COMPUTER	342	2	38
Hardware systemwide design/checkout		4	8
Astronomical design/checkout		8	4
SUBTOTAL -- SYSTEM INTEGRATION		12	12
GRAND TOTAL	1071	36	110

Labor is distributed roughly as follows:

Technitian	2.5 man years
Advanced tech/engineer	3
Engineer	2
Programmer	4
Scientist	1

BY: B. Clark
1/29/82

VLBA CORRELATOR DESIGN

Martin Ewing, 2/4/82

The purpose of this document is to present some estimates of the size and cost of a VLBA correlator based on the JPL/Caltech Block II system.

This system uses Mark III tapes (28 tracks) and will run at 8 Mb/s. Notice, therefore, that the total bit rate (224 Mb/s) and bandwidth (112 Mhz) capability is double that of the VLA-based proposal (VLBA Memo #61). Only about 20% in cost would be saved by cutting back to 112 Mb/s, since the total number of lag channels must remain constant. We therefore keep the full Block II processing rate in most of these estimates. (Excess processor capacity is highly desireable to reduce logistical bottlenecks.)

We choose 12 stations as a reasonable compromise between redundancy, network extension capability, and cost. Cost for this design has the following station dependency:

$$\text{Cost} \sim N + 2 * N^{**}2 \qquad (N = \text{no. of stations})$$

if the number of lags per baseline is held constant, or,

$$\text{Cost} \sim N + 0.8 * N^{**}2$$

if the total number of lags is kept constant.

We analyze four cases of correlators that might be built:

- Block II, enlarged to 12 stations, 8 lags/baseline/track continuum, 112 frequency channels/baseline spectral line

- Block II, 12 stations, 32 lags/baseline/track continuum, 448 frequency channels/baseline

- Block II, 12 stations, 32 lags/baseline/track continuum, 448 frequency channels/baseline, with gate array technology

- Block II, 12 stations, 64 lags/baseline/track continuum, 448 frequency channels/baseline, with gate array technology, only 14 tracks at 8 Mbs each.

1. Enlarged Block II

We begin by estimating the parts count for a correlator using exactly the Block II design, with the following exceptions:

12 stations, 66 baselines
32 lag channels per baseline

This design is largely completed; it makes heavy use of LSI ICs that have become available in the past 1-2 years.

The following tables summarize the integrated circuit (IC) usage and power consumption of the Block II (current design).

STATION-ORIENTED ELECTRONICS

	IC count	Power (w)
"ECL" Front-end	450	160
Delay buffering	1200	500
Phase Calibrator	620	275
Station Controller	60	25
Station Phase Gen.	175	75
	=====	====
	2505	1035

BASELINE-ORIENTED ELECTRONICS (per group of 3 baselines)

Cross-corr.	2400	1050
Corr. Controller	60	25
Corr. Phase Processor	175	75
Corr. Sig. Processor	175	75
Fringe Proc. (Tensor)	500	160
	=====	=====
	3310	1385

2. Block II, Quadrupled Lags

Of the baseline-oriented components in Block II, only about 1/3 are actual lag-channels. That is, a 32-lag version would have only 4*(1/3)+2/3, or twice the number of ICs per 3-baseline group. This option is called "4 X Block II" in the table below. It provides "full" spectroscopic capability of at least 448 frequency channels per baseline.

3. Enhanced Block II Design

The economics of the Block II approach for a large correlator improve considerably with the state of the art in VLSI (very large scale integration) technology. In fact, a 30 - 50% compression of the correlator chip count has become feasible in the last months with the introduction of a larger capacity PAL (programmed array logic) chip.

In making a final, "best-guess" estimate of the cost of the real VLBA correlator following these design principles, it is necessary to estimate the level of 1985 VLSI. We feel that the following projections are conservative.

We anticipate that a custom gate array in the range 4,000 - 10,000 gates will be available and will be the optimum choice for a Block II-style implementation in the near future. One-time charges of $30,000 - $40,000 are likely for mask layouts. We assume the total IC count in the lag-dependent sections of the correlator will be reduced by a factor of 4. The gate arrays will cost about double per chip compared to the ICs currently used.

The overall effect would be to reduce chip count by 73 K and reduce parts cost by $350 K. Other cost savings due to generally falling prices of memory and other LSI components may be expected, but are not included here.

4. Gate arrays with reduced total bit rate.

(This example is most directly comparable with the VLA-based design.)

Nearly half the station-dependent circuitry is eliminated, as are parts of the baseline-dependent components. Since the total number of lag channels is constant (due to spectral-line requirements), the same savings are available from gate-array technology.

ESTIMATES

We derive the following estimates for a 12-station correlator using the Block II parallel LSI techniques. If we use a fairly conservative overall estimate of $10 per IC including printed circuit packaging, power supplies, etc., we arrive at the hardware costs indicated. (The gate array design includes an adjustment that allows for the relatively higher price expected for the gate arrays themselves.)

System	IC count	Parts $	Labor Constr.	Labor Devel.
1. Block II, 8 lags/bsl/track	103 K	$1,030 K	4 MY	1 MY
2. 4 X Block II (32 lags)	176 K	$1,760 K	7 MY	3.3 MY
3. 4 X Block II (32 lags, gate arrays)	103 K	$1,270 K	4 MY	4.3 MY
4. Block II (14 tracks, gate arrays, 64 lags/bsl/track)	68 K	$ 950 K	3 MY	4.6 MY

Development labor includes printed circuit layouts, prototyping, gate array design, microcoding, mechanical design, and documentation, as required.

Construction labor includes clerical, mechanical, integration, and test functions.

CONTROL COMPUTER

A VAX-11/780 computer operating in a general-purpose timesharing mode serves as the control computer for the Block II. This is possible because of the substantial computational power residing in the correlator itself. Geometry, phase calibration, and tape control are all performed in Block II's microprocessors. Coherent integrations, bandwidth synthesis, and first-stage fringe analysis are handled in the "Tensor" processors (one for every 3 baselines) that contain hardware FFT systems, large buffers, and M68,000 control computers.

We estimate that a single, dedicated VAX system will be adequate for the 12-station, quadrupled Block II correlator. Such a system would include 2 MByte memory, dual 6250 bpi tape units, and 600 MB disk capacity. Existing Block II software will be adequate for continuum observing. (A VAX computer is required to make use of this software.) Substantial new programming will be needed for spectral line work. Estimates are given in the following table.

COMPUTER ESTIMATES

Hardware (VAX-11/780 with peripherals): $370 K

Software:	Systems Programming	1 MY
	Spectroscopy	4 MY

CONCLUSIONS

The cost of a "conventional" VLBI correlator architecture is at least competitive with the alternative VLA-based design. The Block II/Mark III system offers 112 MHz bandwidth at record time or 56 MHz with twice-real-time playback rate. Adaptations of the Block II design could be made to work with other channelization parameters, with some parts-count savings, but with some redesign required.

In particular, correlator option 4 would be compatible with the 7-tape 16 Mb/s/tape cassette system now being proposed.

The Block II incorporates full recorder controls, deskewing and delay buffering, phase calibration, and fringe processing. Many aspects of its design derive from its principle application to geodesy and bandwidth synthesis. Relatively little, however, is to be gained by changing the design to eliminate the generality of the bandwidth synthesis capabilities.

Full spectroscopic and polarization capabilities (4 correlations per frequency) are provided in the "4 X Block II" design.

The cost attractiveness of Block II's "LSI-parallel" approach compared to the VLA recirculating technique can be expected to improve as VLSI's density grows faster than ECL's speed.

Multiple Processor Sites for the VLB Array

K. I. Kellermann

At the recent NRAO Users' Committee, the possibility of operating two Array Processing Centers was briefly discussed. The idea of having two processing centers originally arose as a result of discussions with Caltech scientists who are apparently interested in operating a "continuum only" Processing and Image construction center on the West Coast, in much the same spirit as the various proposed Regional VLA processing centers.

The advantages of operating two processor systems may be summarized as follows:

1) If the NRAO continues to operate a major VLA reduction center in Charlottesville, then Charlottesville also becomes a strong candidate for our VLBA Processing Center, and the existence of a West Coast Processing facility may be attractive to users from that area.

It is expected that the computer systems at the two Processors will be similar, although not necessarily of equivalent size. Software will be exchanged, and a real time link will facilitate transfer of computing work loads from one site to the other. A modest start to this approach has already been made with the Caltech and NRAO VAX computers.

It may be argued with some force that it would be more efficient to concentrate all of the computing facilities and personnel at one site. But science does not necessarily progress by having the most efficient organizational structure. The intangible benefits of a healthy (presumably friendly) competition and the influx of ideas from multiple concentrations of skilled scientists should not be discounted, and would diversify the scientific input, as well as allow for greater flexibility in development of software. Indeed the operation of two or more processing centers might, to some extent, reduce the concerns about concentrating VLB facilities at one institution.

2) If, as appears increasingly likely, the record-playback system is based on broad band recorders, we may lose the option of playing back spectroscopic recordings faster than real time. Then, due to inevitable Processor down time and required replays, either an infinite backlog would build up, or it would be necessary to limit the Array to part-time operation.

3) A prototype 3-station Processor is currently being built at Caltech-JPL, using a number of new innovations not present in the Haystack MK III system, whose design is already more than 6 years old. It is relatively straightforward to expand the Caltech-JPL processor to 9 or perhaps more stations. This would make available an interim Array Processor to be used with a combination of existing and new antennas, and would take the pressure off NRAO to have the final Processor, which may be of a fundamentally new design, ready before the completion of the entire array.

The construction and operation of a second Array Processing Center does not come for free. I estimate that a modest 10 station, continuum only Processor might cost 2 to 3 million dollars and would cost about 0.5 million per year to operate. Ideally, a University-operated processor would be financed through ordinary grant procedures, but more realistically, it might have to come from the Array funds, and the relative advantages would have to be weighed against other items such as reducing the number of elements to 9. At least to some extent, however, some outside processing and computing facilities are already being developed independent of the Array facility, so the additional costs necessary to upgrade to a full user operation may be less than indicated above.

7/24/81

VII. POST PROCESSING

VLBI array Computer Useage

W. COTTON AND J. BENSON

3 July 1980

I. INTRODUCTION

Both computing hardware and data analysis are developing sufficiently rapidly that accurate predictions for the computing needs of the VLB array are not possible. This report will, instead, examine the requirements of a ten antenna array on computing facilities currently available in Charlottesville.

II. POST-CORRELATION PROCESSING.

A. Continuum

1) In the current Charlottesville system the first post-correlation step is to correct the data for pecularities in the processor and to pre–average the 0.2 second integrations from the correlator to several seconds in order to reduce the volume of the data. In newer correlators such as those at Cal–Tech and Haystack much of this step is done on–line by the correlator/computer. In Charlottesville this is done in the IBM 360.

2) Following pre–averaging is the fringe fitting step which results in the estimates of the complex correlation coefficient, group delay and fringe delay rate from data coherently for several minutes. This step is also done in the IBM 360 in Charlottesville.

3) After fringe fitting the data is edited, removing bad data.

4) Current practice is to calibrate the correlation amplitudes to Janskys using measured system temperatures and antenna sensitivities. Except in certain phase referencing experiments phase calibration is considered hopeless at this stage and is ignored.

5) Finally the phases are iteratively calibrated and the map produced by a technique known as self calibration or hybrid mapping. In this technique the current model of the source (CLEAN point components or the initial guess) is used to calibrate the phases relative to an arbitrary position in the sky. This technique makes use of the fact that the number of calibration phases needed is N–1 and the number of observed phases is N(N–1)/2 where N is the number of antennas involved. Similar amplitude calibration is also possible and likely necessary for

1.3 cm observations. For VLBI observations this step is currently done on the Charlottesville VAX using the Cal–Tech VLBI package but in the future the VLA package will almost certainly be used. Thus the Fred Schwab's self–calibration program was used for timing purposes for this report.

B. Spectral Line

1) Program DECODE preaverages the correlator output.

2) Program AVERAGE corrects clock drifts, residual phase delay rates and makes instrumental phase corrections; then averages both the cross and auto correlations.

3) Program BOG transforms the auto correlations to obtain source spectra and then corrects auto and cross correlations for effects of the bandpass

4) Program CVEL corrects the data for the Earth's motion.

5) Program CAL calibrates the cross correlations using the total power spectra obtained from the autocorrelations.

6) Program PHSREF calibrates phases relative to a reference feature.

7) Program SWAMP, used in editing the data, displays coherent fits to each spectral channel; usually used several times.

8) Programs SWAMP,JANET and DUNE produce a fringe rate map prior to aperature synthesis.

After the above programs are run, the data are fully calibrated and can be analysed by VLA spectral line software.

III. COMPUTING REQUIREMENTS

A. Continuum

Computing requirements for various stages of processing were determined from timing the processing of sample data in the appropriate computer. Correction, preaveraging and fringe fitting were done in the IBM 360; the CPU time requirements for these steps are shown in Table 1.

Table 1
Continuum: pre – Mapmaking (IBM 360 CPU times)

Step	Baseline hour	Array hour (10 ant.)
correction and preaveraging	0.80 min.	36.1 min.
fringe fitting	0.45 min.	20.5 min.
Total	1.25 min.	56.6 min.

Editing and initial amplitude calibration use so little CPU time that their requirements are negligible compared to the uncertainty in the other steps and are thus ignored. However, editing and calibration are the stages which require the most user interaction and are normally repeated several times. If in the future amplitude calibration is done using VLA software initial amplitude calibration may become nontrivial in the computing budget (see the self calibration description for a crude estimate of the time requirements).

To determine the time requirements for self calibration, a VLA data set using 10 antennas with 35,763 data points was used. This is approximately tha amount of data in 12 hours of 1 minute integrations from a ten antenna array. For this test, Fred Schwab's self calibrations program was used to do both amplitude and phase self calibration. The REAL run times for the MODCOMP were recorded and the results are sumarized in Table 2. For comparison IBM 360 CPU times for the same mapping and CLEANing tasks are also shown in Table 2.

It is not clear how many iterations through the self calibration procedure will be necessary for 10 antenna data but 10 is probably a safe guess.

TABLE 2
Continuum: Mapping and CLEANing

Step	MODCOMP real time	IBM 360 CPU time
Maping 256×256 cells	5.5 min.	6.2 min.
CLEAN 127×127 500 comp.	8.3 min.	8.2 min.
Self calibration (full complex)	17.2 min.	
Total (1 pass)	31.0 min.	
Per source (10 passes)	310. min. = 5.2 hrs.	

B. Spectral Line.

The CPU time required for programs 1–8 were determined from sample data processed on the IBM 360. These results are sumarized in Table 3.

TABLE 3
Spectral Line: pre–Mapmaking (IBM 360 CPU times)

STEP	Baseline hour	Array hour
DECODE	0.80 min	36.0 min
AVERAGE	0.52 min	23.4 min
BOG	0.21 min	9.5 min
CVEL	1.64 min	73.8 min
CAL	0.48 min	21.6 min
PHSREF	0.83 min	37.4 min
SWAMP	$\geq$0.7 min	$\geq$31. min
SWAMP,JANET,DUNE	0.11 min	5.0 min
TOTAL	5.29 min	237.6 min = 4.0 hr

Since VLA spectral line software is not yet avaliable an estimate of the computing requirements must be made from the continuum test. The mapping and CLEANing could be done as for continuum maps but separately for each frequency channel. In the following estimates 256 spectral channels were assumed; Table 4 shows these estimates.

TABLE 4
Spectral line: MODCOMP real time

STEP	MODCOMP real time
Map making ($256\times256\times256$)	1408. min = 23.5 hr
CLEAN ($127\times127\times256$) 500 comp.	2125. min = 35.4 hr
Total	3533. min = 58.9 hr = 2.5 day

IV. Hardware and Software Development.

A. Continuum

If VLA software is used for editing and calibration then no independent software development past the fringe fitting stage will be necesary. The speed of the correlator correction, pre–averaging and fringe fitting could be improved up to a factor of 10 with the use of an Array Processor. In view of the large amount of CPU time required for these steps, an Array Processor would appear to be vital. In addition, the development of more sophisticated calibration and fringe fitting techniques may be able to take advantage of the large number of baselines to make substantial improvments in sensitivity over the current techniques. However, such techniques are likely to signifigantly increase the computing requirements.

The MODCOMP self-calibration programs described above make limited use of an array processor. These programs will undoubtedly be improved; for instance, an experimental version of a CLEANing program of the type designed by B. Clark did an equivalent CLEAN to the one described in Table 2 in 1.4 min. MODCOMP real time.

B. Spectral Line

Many of the programs described in Section II could be adapted to use with an array processor, reducing the enormous computing load. Past the calibration stage VLA software will be completely adequate and no independent development is necessary. Since spectral line mapping and CLEANing for VLA data produce similar problems it is likely that a more efficient method than the one discussed here will be developed.

Appendix to VLBA Memo #4 Computer Useage : or How much is that in real money?

W. COTTON AND J. BENSON

28 August 1980

The purpose of this appendix is to update VLBA memo #4 and to state the estimated post-correlation computer requirements. As in all such estimates, the numbers quoted here should be viewed with some skepticism.

I. CONTINUUM FRINGE FITTING.

The values given in VLBA memo #4 in Table 1 were based on Mk II values and are not entirely relevant to the VLBA. Estimates of Mk III fringe searching are based on values obtained from A. Rogers at Haystack from their experience with the Mk III correlator. One example:

8.5 min of data searched, 2 sec preaveraging, 14 tracks
Disk I/O = 40 sec
mostly FFT search = 120 sec.
search window = 0.8 Hz and 0.5 microsec.

The figures given above were based on a firmware FFT which does a full complex 1024 point FFT in 200 millisec.; the advertised time for the same operation on an FPS array processor is 6 millisec. A crude conversion of the above values to the useage on a machine with an array processor is 0.25 CPU–Hr / baseline hour; or 11 such systems to keep up with the processor. It should be noted that the time is 80% disk I/O. This requirement can be reduced in several ways: 1) the fringe search window can be restricted and data preaveraged for longer times. If the amount of I/O can be reduced by a factor of 10 then one computer plus array processor will be sufficient. 2) In the case of strong sources, either the amount of data recorded can be reduced and/or only a subset of the data used for the fringe search.

II. Useage Requirments.

In order to estimate the amount of computing required Table 1A uses the values given above and in VLBA memo #4. The requirements are expressed in units of a minicomputer (such as a VAX) with an array processor.

Table 1A
Total Computer Useage Requirments

Process	No. Minicomputer + AP
Cont. pre-mapping	1
Cont. mapping	0.5
Spectral pre-mapping*	1
Spectral mapping*	1
Total	3.5

* Spectral line observations assumed 20% of the time.

National Radio Astronomy Observatory

Charlottesville, Virginia

To: VLB Array Meeting - Computer Subgroup

From: R. C. Walker, B. Burns

VLB ARRAY MEMO No. 19

Subject: Computer Needs

There will be an informal discussion of the VLB Array computer needs after dinner on Monday, September 15. The time and location will be determined earlier on Monday. The discussion should be limited to 10 or 15 people actively involved in VLBI hardware and software development.

The attached documents summarize our current ideas on the magnitude of the post-processing computer needs and present a possible plan for the computer hardware for the array.

Distribution:

J. Ball
T. Clark
M. Ewing
B. Leslie
T. Pearson
M. Reid
A. Rugers
N. Vandenberg
A. Whitney
J. Benson
W. Cotton
K. Kellerman

RCW/nw

VLBI ARRAY COMPUTER NOTES

The computer effort is divided into four areas:

1) Antenna and recorder control

2) Correlator control

3) Post-processing

4) Array control

In specifying and pricing hardware we have used DEC equipment. DEC is useful for beachmarking because they carry a line of equipment from LSIs up thru VAX and because many people understand the various DEC components. If we were building the array today, DEC, ModComp and HP all would be very strong contenders. Other manufacturers equipment would be considered also.

1) Antenna and Recorder Control

Plan A - use three LSI 11/23s (128K byte memory each), one for antenna control and communications, one for the tape recorder control and one for the complete on-line back-up. This latter system may be switched in place of either of the other two.

Cost is $27K each plus some interface and communications equipment. Total cost per antenna ≈ 3 x 27 + 19 ≈ $100K.

Plan B - use single PDP 11/44 (256K byte memory) to control the telescope and recorder. Remote diagnostics via telephone are available on this machine. On-site spares at each antenna are included in price. There is no redundant system in this case. Cost is $73K plus interface and communications equipment. Total cost per antenna ≈ $100K.

For computer/telescope interface we plan to use either CAMAC or a similar serial system. An NRAO designed system like that used at the VLA is also a possibility. This will reduce the number of wires required between the computer and various parts of the antenna and electronics system. It should also make computer switching easier for the case where a redundant computer is used. Cost for the CAMAC crate controller is included in the interface equipment priced above.

It is felt a stripped down antenna/recorder system should be located in the central array control center for ongoing development and for simulation to give telescope support personnel technical support. If plan A is used this might amount to an additional LSI 11/23. If plan B is used, this support might instead come from the hardware used for either array control or post-processing.

In any case, no funds are specifically budgeted. If an additional LSI 11/23 is required there are sufficient funds in the antenna/recorder budget.

Estimated software effort = 5 man years.

2) Correlator Control

It is not clear exactly what is required here since the correlator is not yet designed. Ken has guessed $150K for control computer which is included in correlator budget. There are also trade-offs, for example: whether an external array processor or a homemade device is used.

The software estimate is 10 man years.

3) Post-Processing

Post processing estimates are in units of VAXs (each VAX assumed having an array processor). This is a strange unit but is useful because people have a feel for it. Obvious gains in technology will be made in this area over the next few years; larger VAXs, good alternatives, CPUs with built-in array processors, optical disks, etc. It is felt however, that the trend toward more sophisticated processing techniques will balance the gains in hardware technology. In capacity, we feel about 3 1/2 times the above VAX capacity is required (see attached summary of current VLB post-processing program run times and extrapolation to the needs of the array). The estimated hardware cost for a possible setup with the required capacity is as follows.

2 systems:

VAX with 2 meg memory	$210K
(basic package including disk and tape drive)	
Array processor (64K bytes)	90K
Printer	10K
Terminals	10K
2nd tape drive (high density)	35K
Extra disks (3 spindles)	60K
Misc.	20K
	$435K

1 system:

Include above	$435K
Additional 2 meg memory	33K
Video disk	40K

Optical disk	40K
Grey scale display	50K
	$598K

Add 10% for price changes effective in late 1980 ($147K). Prices should reflect Jan. '81 pricing. Total = $1600K.

Manpower estimates for the post-processing is estimated at 5 man years. This is low but it is felt much software originally developed for VLA processing can be used.

4) Array Control

The array control computer communicates with each telescope. If separate telescope and recorder control computers are used (2 LSI 11/23s) the communication is with the telescope control. If a single PDP 11/44 is used for both telescope and recorder control, it also handles the communications. For the array control computer we envisage a PDP 11/44 with 512K byte memory. No redundant system is used but this machine supports remote diagnostics and the price of spare parts is included. The system resembles pretty much a standard control system and is priced at $150K. 5 man years software effort is estimated.

Summary

Total computer budget (not including correlator control computer):

Antenna hardware	$1.0 m
Post-processing hardware	1.6 m
Array control hardware	.15m
Software (25 man years/overhead)	.8 m
Total	$3.55m

December 31, 1981

To: VLBA Study Group

From: R. C. Walker

Subject: Data storage requirements for the VLBA

The amount of storage space required for a VLBA data set is a function of several variables. Rather than trying to provide tables showing the effects of these variables, I will give the equations for the number of bytes needed for both spectral line and continuum observations as a function of all relevant parameters. A few sample cases will be evaluated.

The number of bytes in a data set is given by:

$$\# \text{Bytes} = 3600\, w\, H\, B\, C / t$$

where:
- w = Number of bytes per complex data point (Minimum 4, probably much more. VLA export format uses 48 for u,v,w,4 polarizations and bookkeeping. Fewer are needed for spectral line as u,v,w and bookkeeping can be shared.)
- H = Hours of data in observation (typical 10)
- B = Number of baselines (probably 45)
- C = Number of delay or spectral channels (see below)
- t = Integration time in seconds (see below)

The number of channels in the continuum case is determined by the delay range needed for the desired field of view and by the uncertainties in the clocks. Note that the field of view may be set by the degree of uncertainty in the a priori source position rather than the size of the source. This should not normally be a problem because accurate positions can be found very quickly with the VLA. The number of channels required by the field of view is:

$$C = 6.46\text{E}{-5}\; l\; b\; x$$

where:
- l = length of longest baseline in km (usually 8000)
- b = bandwidth in MHz (up to 50)
- x = maximum offset from phase center for good data. in arc seconds (typically 0.1 to 1.0)

The number of channels required by the uncertainty in the clocks is:

$$C = 2\, b\, T$$

where: b = bandwidth in MHz
T = clock uncertainty in microsec (usually 0.25)

The total number of channels is the sum of the above:

$$C = 6.46E-5 \; l \; b \; x \quad + \quad 2 \; b \; T$$

For spectral line data, the number of channels is determined by the desired velocity range and resolution. If the number of channels is fixed by the correlator, it probably will have a maximum value of 512. If the correlator is of a recirculating design, the number of channels could be very large although we should not attempt to support post-processing of absurd cases.

The integration time will usually be set by the need to avoid time average smearing for sources in the field of view. To give an idea of the magnitude of the problem, the fringe period for an object one arc second away from the phase center for observations at 22 GHz (reasonably common H2O maser case) can be as short as 4.8 seconds. To avoid smearing, the integration time should allow several points per fringe period. A large amount of space could be saved by making the average time a function of baseline length but that possibility is not included in the following formula. The longest safe integration time is given by:

$$t = 8.5E5 \;/\; (\; x \; f \; l \; p \;)$$

where: x = The maximum offset from the phase center for good data. This usually will be set by the a-priori's although in many spectral line sources it will be set by the separations of features.
f = Frequency (GHz)
l = Maximum baseline length in km (usually 8000)
p = The minimum number of points per fringe (5?)

The above formulae can be combined to give a composite formula for the number of bytes needed:

$$\# \text{bytes} = .00423 \; w \; l \; B \; f \; b \; H \; x \; p \; (\; 6.46E-5 \; l \; x \; + \; 2 \; T \;)$$ (continuum case)

or: $$= 4.24E-3 \; w \; l \; B \; f \; H \; x \; p \; C$$ (line case)

Note the dependence on the square of the baseline length and the field of view in the continuum case as long as the number of channels is not set by the knowledge of the clocks.

The table attached to this memo shows several cases of interest. In general, the data sets are a few times larger than full track VLA data sets with the exception of the extreme H2O spectral line case. That case is clearly too large to be reasonably supported so I suggest that we not try. Observations of sources such as H2O in ORION will have to be done with very much less than full tracks and full resolution. I suspect that most of the science in such observations can be obtained with more modest observations. The requirements for the modest H2O case are still very large but not impossible. The number of 6250 bpi tapes required is similar to the number of 1600 bpi tapes used in H2O VLBI experiments in the past and the data set is only 4 times the size of a large spectral line VLA data set that might be produced when the current channel limitations are overcome.

I am not sure how we should deal with the disk space requirements. The above information indicates that we should be prepared to deal with quantities of data somewhat larger than what the VLA generates. For continuum observations, this should not be a serious problem, especially since the tabulated data set sizes are those required before fringe fitting only. The spectral line case presents more of a problem, although it is a problem that will have to be faced for the VLA too. Mark Reid advocates storing all of the data on disk (after considerable trouble using tapes with a very large H2O VLB experiment he is now working on). This could require as much as 100 gigabytes of disk which is excessive now but may not be in a few years. I can think of several ways to be clever and reduce this requirement dramatically but history has shown that we always think of ways to increase the requirements too.

One area where I suspect that our initial impressions that the VLBA is easier than the VLA are still correct is in mapping. The coverage of the VLBA for snap-shot observations consisting of a single short integration will not be nearly as good as that of the VLA (8 times fewer baselines) so I suspect that a larger percentage of the observations will involve long tracks, or at least several scans at different hour angles, so there will be fewer maps per unit observing time. Also there will be less input data for each map which reduces the sorting and gridding which are an important part of the computing load with large data bases. This will be somewhat offset by the need for many iterations of self-calibration for continuum data. Note that, except for the reference channel, the iterative self-cal will not be needed for spectral line data.

VLBA DATA BASE SIZES

Parameters:

W	!	Bytes per visibility record. -estimate includes u,v,w,time,baseline,stokes parameters
L	!	Maximum baseline in km.
B	!	Number of baselines.
F	!	Frequency in GHz
BW	!	Bandwidth in MHz.
H	!	Hours of data per baseline.
X	!	Maximum offset from center of field.
P	!	Minimum points per fringe period.

Results to be calculated in subroutine:

C	!	Number of channels (fixed for line) - for continuum, set by delay window
CU	!	Number of channels used (allows for clock uncertainty - usually .25 microsec)
T	!	Integration time. Set by smearing. Will not exceed specified maximum.
MBYTES	!	Megabytes required.
MVIS	!	Millions of visibility records.
TAPES	!	Number of 625Ø bpi tapes (18Ø Megabytes).

Comment	W	L	B	F	BW	H	X	P	C	CU	T	MBYTES	MVIS	TAPES
Moderate continuum case	42	8ØØØ	45	1Ø.6	28.ØØ	1Ø.Ø	Ø.2Ø	5.Ø	3.	15.	1Ø.Ø3	1Ø1.Ø35	2.4Ø7	Ø.56
Extreme continuum case	24	8ØØØ	91	43.Ø	56.ØØ	1Ø.Ø	Ø.2Ø	5.Ø	6.	31.	2.47	979.5ØØ	4Ø.813	5.44
Hot spots	42	4ØØØ	35	1.6	28.ØØ	1Ø.Ø	2.ØØ	5.Ø	14.	26.	13.25	1Ø5.5Ø6	2.512	Ø.59
Fake data tests	24	8ØØØ	45	5.Ø	28.ØØ	1Ø.Ø	Ø.Ø4	5.Ø	1.	1.	121.24	Ø.321	Ø.Ø13	Ø.ØØ
Moderate H2O case	1Ø	8ØØØ	45	22.2	Ø.ØØ	1Ø.Ø	1.ØØ	5.Ø	256.	256.	Ø.96	433Ø.816	433.Ø82	24.Ø6
Extreme H2O case	1Ø	8ØØØ	45	22.2	Ø.ØØ	1Ø.Ø	15.ØØ	5.Ø	512.	512.	Ø.Ø5	129924.477	12992.447	721.8Ø
OH case	1Ø	8ØØØ	45	1.6	Ø.ØØ	1Ø.Ø	2.ØØ	5.Ø	512.	512.	6.64	1248.524	124.852	6.94
VLA continuum case - export	48	35	351	5.Ø	5Ø.ØØ	1Ø.Ø	1Ø.ØØ	5.Ø	1.	1.	2Ø.ØØ	34.3[illegible]	Ø.7[illegible]	Ø.19
VLA H2O case	1Ø	35	351	22.2	Ø.ØØ	1Ø.Ø	2.ØØ	5.Ø	256.	256.	3Ø.ØØ	1Ø78.272	1Ø7.827	5.99

(DRAFT 1)

VLBI ARRAY POST PROCESSING REQUIREMENTS

R. D. Ekers

February 3, 1982

1. Changes to Concepts in the VLBA Design Study Report Section 4B.

This is a summary of the differences which have led to an expansion of the required post processing system.

(a) Expansion over current VLBI Processing.

In the continuum the main difference is the assumption that there will be a significant amount of wide field mapping, and work on weak sources where the a priori position is not known to better than a few tenths of a second. Both of these set a similar requirement. Eg to map a half of second field of view at 5GHz would require eight channels for bandwidth synthesis and twelve seconds averaging time. The processing times given in the present report were based on one channel of continuum data with about one minute averaging time. Hence we have more than an order of magnitude increase in the post processing requirement for this particular case.

In the line case the main difference is the larger expection for the total number of channels which will be processed (see VLBA Memo #47). Such higher expectations are justified given the scope of the VLBA project compared with current practice but this can set almost impossible requirements on the post processing system. The extreme H_2O case produces a 130 G Bytes of data in a one day observation. This exceeds the maximum output ever expected from the VLA by a factor of 30, so to be realistic the proposal can't include this kind of observation. The maximum line output data rate specifical for the correlator is 400 Kbtes/sec (VLBA memo #61). This gives 14 Gbytes of data in a 10 hour observation.

The computer system changes in the following table give a maximum storage of 10 Gbytes. It can handle the moderate H_2O case and the OH case in VLBA memo #47, but it still cannot store an entire line observation at the maximum correlator output rate. This data would still have to be dumped on tape and reread for full processing.

(b) Algorithm complexity.

It is sometimes argued that the decreasing cost per unit of computer power with time will alleviate the post processing problem. However present experience indicates that this will be insufficient to offset the expansion in the complexity of algorithms which are being developed. Examples:

1) There has been two orders of magnitude increase in the complexity of problems on which the clean algorithm is being used since its introduction in the 1970's, in the same period the cost per cpu cycles has gone down by a factor______________.

2) Algorithms to provide an error analysis of CLEAN maps, (or results of other restoration algorithm) are not being implemented because of the excessive requirements on computer time.

3) Self-calibration requirements are increasing because sources of greater complexity are being analyzed, and the increased sensitivity of telescopes is making it possible to decrease the time constant for the self-calbration averaging.

4) Other restoration algorithms such as maximum entropy, optimum deconvolution method, regularization, are likely to come into use. These will require more computer power than CLEAN.

5) Completely new techniques, such as Cornwell's proposal to handle bandwidth synthesis on a source of varying spectral index, are being considered.

(c) Software

In order to minimize operating costs and to improve long term flexibility it is necessary to have an environment in which one can write high level and well structured software. This requirement can be nicely met by the VAX type systems provided they have plenty of memory space and provided we do not depend two heavily on the array processors or other special purpose hardware.

(d) Comparison with VLA post processing computers.

The estimated cost of the current VLA System excluding synchronous computers is about $7.5M. Of this $6M is hardware and $1.5M is software. As a useful comparison for the cost of software development for the VLBA it might be useful to point out that the current AIPS system has cost about $0.5M. It is unlikely that the VLBA development will be much less than that.

The proposed VLBA post processing system is then about half what we now have at the VLA which certainly does not seem excessive.

(e) Outside support.

In order to make this processing problem tractable it is necessary to assume that there will be significant use of outside post processing systems by some users. This is becoming increasingly true in the case of the VLA as there are now 6 large systems being used in the Universities to reduce VLA data.

(f) Correlator intelligence

For some types of observations, eg small continuum sources dominated by a point component, an intelligent correlator can make at least an order of magnitude reduction in the data rate by using delay and fringe rate windowing. This is important because it enables a lot of good science to be done with an insignificant post processing load but unless the majority of VLBA observing is of this type this will not change the post processing requirements.

The use of digital filtering in the processor, as suggested by Ewing, could reduce data requirements on the post processor by a factor of 2 to 3 compared with the estimates in VLBA Memo #47. This effects all observing programs so it is an important function in determining the post processing load.

2. A Proposed Post Prosessing System.

The following table lists the components of the post processing system showing the differences between the proposal in the VLBA design study and our current thinking. It is an attempt to specify a system which assumes that an observer is likely to have visibility data in the computer for about three days, that there is one moderate H_2O user, two easy line users, two wide field continuum mapping users and any number of simple continuum users. The RM05 disks with removeable packs are added to give additional cost effective mass storage on the assumption that users will not need to access all the data all the time.

RDE/er

TABLE 1. VLBA POST PROCESING SYSTEM

COMPONENT	CHANGE	COST
4 Vax-11/780 2 M byte memory	Increase from 3 to 4. (Tape drives and mass store listed separately)	1000 K
4 Additional 2 Mbyte memory	Extra memory on all systems	80
6 TU78 high density tape drives	Increase from 3 to 6 no low density drives	200
4 RP07 disks with controller (500 Mbyte non removable)		150
8 Additional RP07 disks drives	Increase total of directly accessible storage to 10 Gbytes	200
2 RM05 removable disk drives with controllers (256 Mbyte)		100
14 Additional RM05 disks drives		500
40 Disk packs	Add removable disks to provide additional 10G Bytes of mass store without tape I/O	40
4 Array processors (38 bit 64K words)	Increase from 3 to 4	300
2 Printers (600 lpm)	Decrease from 3 to 2 (Use DECNET)	30
12 CRTs (9 text, 3 graphics)	Same	30
2 I^2S image displays	Increase from 1 to 2	140
1 Video disk (Escofier design)	Instead of commercial	20
Optical disk (Mass storage)	Same	40
Misc	Same	50
Software	Same	320
		3200 K

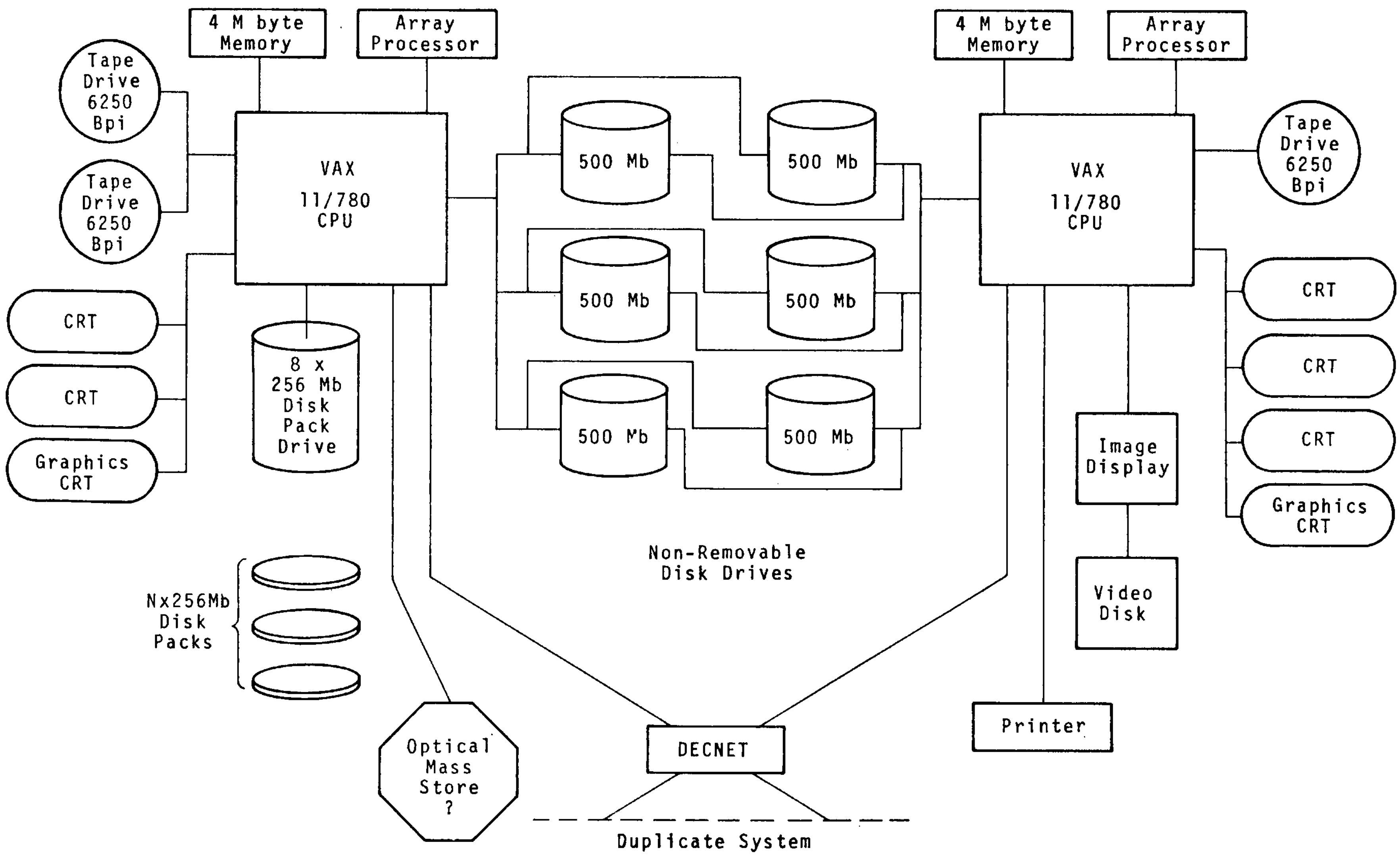
June 30, 1982

POST PROCESSING COMPUTER CONFIGURATION

R. Ekers

VLBA Memo No. 18a (Cotton and Benson) gives execution times for the various stages of data reduction. Assuming that the array is used for spectroscopy about 20 percent of the time, we estimate that a total computing power equivalent to 4 VAX-11/780's each with an array processor and 2 megabytes of additional memory will be required to handle the post-processing need. A possible post-processing computer configuration is shown in the figure. The two parallel systems are used to double throughput without increasing user interaction, and to increase overall reliability by providing two complete data processing routes. A heavy spectral line user with very large demands on capacity could be given one entire system and would not have to negotiate for resources with the astronomers sharing the other system. The DECNET link is provided to give flexible use of peripherals on either machine and to simplify the software development for both machines. The second VAX in each half of the system is essentially the same as the VAX based post-processing system (AIPS) which has been developed for the VLA. This part of the system would run software identical to the VLA software. Any VLBA specific functions would be developed in the first VAX system, without interaction with the development of other post-processing software. The use of disks which can be switched between the two halves of each system provide the extremely high data rate needed to move from the first to the second VAX without delay or additional overhead. This is also the point at which some astronomers will transfer to their own post processing systems by use of the high density tape recorders. The system provides ten GBytes of directly accessible storage on non-removable disks and an additional ten GBytes on removable disk packs without the need for tape I/O. A further increase in the mass storage may be possible using optical disks. Image display systems on each post-processing VAX are similar to those used in VLA post-processing systems. These are coupled to the image storage units (currently under development at NRAO) with the capability of storing up to 256 512^2 images.

For the VLA the total spectral line capacity will depend on the capacity of the pipeline computer system still under development. It achieves high capacity by use of AP's, pipelined processing in mini-computers, and use of low level software. Since software development costs for this type of system are very high compared with the hardware costs, and since the development time is long compared with the time scale for hardware evolution, this solution is not ideal for the VLBA. Even greater computing capacity may be eventually needed to handle the full spectral line capability of the VLBA. However, commercial development of parallel processing systems (or subsystems) should eventually provide a better route to the higher computing capacity.



4 M byte Memory
Array Processor
Tape Drive 6250 Bpi
Tape Drive 6250 Bpi
VAX 11/780 CPU
CRT
CRT
Graphics CRT
8 x 256 Mb Disk Pack Drive
500 Mb
500 Mb
500 Mb
500 Mb
500 Mb
500 Mb
4 M byte Memory
Array Processor
VAX 11/780 CPU
Tape Drive 6250 Bpi
CRT
CRT
CRT
Graphics CRT
Image Display
Video Disk
Non-Removable Disk Drives
Nx256Mb Disk Packs
Optical Mass Store ?
DECNET
Printer
Duplicate System

SOME REMARKS ABOUT THE SENSITIVITY OF A PARTIALLY COHERENT ARRAY

VLB ARRAY MEMO No. 5

I. Some simplifying assumptions.

array consists of N+1 antennas.
All LO's have constant phase for the coherence time Tc. They then take a flying leap.
The LO phases assume one of e possible values. (This assumption, although silly on the face of it, is probably not far wrong).

The sum of the fringe visibilities is Gaussian distributed. (This assumption, although reasonable on the face of it may be seriously in error.).

All antennas have equal sensitivity.

You, God, and the ApJ have an agreement that a result is to be believed if and only if its probability of arising from chance is less than ϵ .

Unproved assertion:
The best you can do is make all possible assumptions about instrumental phase, and pick the best looking one.

II. Point source sensitivity

A. Integration time =Tc.

There are N antennas whose phases may take one of e values. Therefore, there are

$$e^N \quad \text{possible assumptions.} \qquad (1)$$

Let us make them, and see if the source is detected.
What do we mean by detected? That the sum of the visibilities has a chance of less than ϵ of arising by chance. Normalizing by the rms of a coherent array under the same conditions, the distribution of the sum of the visibilities is

$$\frac{1}{\sqrt{\pi}} e^{-\frac{x^2}{2}} \qquad (2)$$

Let us make the assymtotic approximation to the error function:

$$\int_{x_0}^{\infty} \frac{1}{\sqrt{\pi}} e^{-\frac{x^2}{2}} \approx \frac{1}{x_0\sqrt{\pi}} e^{-x_0^2} \qquad (3)$$

Then the condition for detection is

$$e^N \frac{1}{x_0\sqrt{\pi}} e^{-x_0^2} = \epsilon \qquad (4)$$

Where the first factor is the number of trials, the second is the probability of an excursion of the limiting amount in each trial.
For reasonably large N it is clear that

$$X_0 \approx \sqrt{N + \log\frac{1}{\epsilon}} \qquad (5)$$

That is, that the partially coherent array is $\sqrt{N}$ times less sensitive than the coherent version of the same array.

2. Integeration time >>Tc.

Can we play the same game, making a new set of assumtions about each coherence time? First note that this is a "hard" algorithm-- it cannot be implemented in practical hardware. Second, note that if you do implement it, there are fundamental difficulties. The number of trials to be made are

$$e^{N \cdot M}$$

6

where M is the total integration time T divided by Tc. The equivalent of equation 4 above is

$$e^{N \cdot M} e^{-X_o^2} = \epsilon$$

Which is in the assymtote

$$X_o = \sqrt{NM}$$

However, the sensitivity in a single coherence interval is also

$$\sqrt{NM}$$

You have gained nothing by trying to use the whole integration time.

III. Some speculations about sensitivity to extended sources.

Mapping extended sources has an extraordinary property. Usually God employs the most effective possible strategy to keep you from finding out what you want to know. Not so in this case. He tries as hard as possible to keep you from making a map at all, as discussed in the section above, but once you have made a map, say of the strongest point in the field, then the rest of the field has the SNR of a coherent array. You can self-cal, and find out about all that interesting low level stuff.

The above remark applies nicely to the case of a field dominated by a strong point. What about the more usual case of a complex source with lots of strong points? Let us consider the case in which we have been given, perhaps by a fairy godfather, an almost correct map of the source, and we wish to improve it. Suppose we look at each coherence interval. Then we can calculate for each antenna in turn, the expected visilities with each other antenna. In cases of poor SNR, the obvious thing to do is to correlate the observed and expected visibilities.

$$\Delta\phi = ARG\left(\Sigma V_o V_e^*\right)$$

where V_e is the expected and V_o the observed visibility. It is [illegible] this number, for the extended case, which must be of order $\sqrt{N}$ SNR [illegible]. This is the output of a conceptual array consisting of the antenna [illegible] to be calibrated operating as an interferometer against all the others in the system, operating as a phased array, optimally tapered for the source distribution.

If we do not have a fairy Godfather, we shall be a bit worse off. I speculate that in the worst case, for detecting the thing in the first place, we need a detection on the conceptual array consisting of the antenna to be calibrated in an interferometer against the rest of the array, operating as a phased array. The practical case should fall somewhere in between.

The argument for inextensibility of integration beyond the coherence time developed above cannot be extended to the extended source case. There is a potential for a small increase in sensitivity after integrating longer. I off hand do not believe it to be of practical importance.

IV. A trivial remark about phase calibration.

Yes, it can, and is being done. Outside of the stupendous practical difficulties (mostly of software generation) of doing this on a regular basis, there is a fundamental limitation. The motion of the earth is known only to about one part in 4,000,000. Therefore the calibrator must be withing about 2,000,000 beamwidths of the unknown.

Global Fringe Search Techniques for VLBI

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ABSTRACT. The usual fringe search technique for VLBI is a correlator-based method. Here, more sensitive, global techniques are presented, ones yielding simultaneous solutions for all of the delay and fringe rate parameters. The number of parameters required for delay and rate compensation for an n element array is reduced from $n^2 - n$ to $3n - 3$. Two methods are given: one is based on the Fourier transform; the other is a least-squares technique. These techniques may be viewed as variants of the self-calibration/hybrid mapping techniques which already are in widespread use.

I. INTRODUCTION

Very Long Baseline Radio Interferometry (VLBI) usually involves the use of an independent time standard at each of the widely dispersed array elements, and, ordinarily, the consequent clock error is the major source of uncertainty in determining the time at which a wavefront arrives at a given antenna. Among other sources which contribute to this uncertainty are differences in the atmospheric phase path lengths over the antennas, and errors in the assumed geometric model (i.e. errors in the baseline determination). Commonly, the cumulative error is greater than the reciprocal of the recorded bandwidth, and this error, if uncorrected, may well cause complete decorrelation of the signal. In addition, the cumulative "clock error" (which now we take to include the other sources of error mentioned above) is sufficiently variable with time that it severely limits the length of the time intervals over which coherent averaging of the data can be performed. Standard practice is to correlate the signals from each pair of antennas over a range of time lags, and then to determine the difference in the "clock errors" (delay) and the difference in the first time derivative (fringe rate) — using the data from one pair of antennas, only, for each solution for these parameters. The time intervals are chosen to be short enough that the "clock error" may be assumed approximately linear.

Here we present, as an alternative to the standard correlator-based fringe search technique, a global technique which yields a simultaneous solution for all of the delay and fringe rate parameters. For each baseline, each delay or rate parameter splits into two components, ascribable to two individual antennas. Since, in an n element interferometer array, each antenna may be a part of

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$n-1$ interferometer pairs, a common component of error is present in the observations on the various baselines involving any given antenna. It is worthwhile, therefore, in cases of low signal-to-noise ratio (S/N), to solve simultaneously, using observations from all baselines, for these antenna-based effects. With a global technique of this sort, the total number of parameters necessary for delay and rate compensation can be reduced below the number required by the standard technique (the reduction is from $n^2 - n$ parameters to $3n - 3$). A global technique obviates the requirement that there be relatively strong fringes on every baseline to be processed. Also, the technique preserves the phase closure relations satisfied by the data. Conversely, the closure properties are disturbed any time that the standard technique is applied.

The global technique may be viewed as a variant of the self-calibration/hybrid mapping techniques (Readhead *et. al.* 1980, Cotton 1979, and Schwab 1980) which are in widespread use in aperture synthesis data reduction, inasmuch as the basic assumption on which this new method is based (see eq. [1], below) is the same. Other common features are that the global fringe search method requires an initial source model; and that, in combination with a Fourier synthesis program and a deconvolution algorithm (e.g. CLEAN), it may be applied iteratively to generate successive approximations to the radio source brightness distribution.

Following a description of the standard approach to fringe search, two global fringe search techniques are outlined below. The first global method that is described is a least-squares (LS) approach. The second, a Fourier transform (FT) method, is a straightforward generalization of the standard technique. The LS method requires good starting guesses but is more flexible than the FT method. In initial tests, a hybrid algorithm has been used, combining both of the global techniques. The FT method is used to generate starting guesses for the LS algorithm.

II. The Standard Approach

Assuming that the correlator responses have been transformed to the time and frequency domain (t, ν), and that n antennas comprise the interferometer array, the standard approach to fringe search can be described as follows. Visibility observations $\tilde{V}_{ij}(t_k, \nu_l)$ on the i–j baseline $(1 \leq i < j \leq n)$ at times t_k, $k = 0, \ldots, n_t$, and at frequencies ν_l, $l = 0, \ldots, n_\nu$, are related to the true source visibility $\mathcal{V}_{ij}(t, \nu)$ according to

$$\tilde{V}_{ij}(t_k, \nu_l) = g_i(t_k, \nu_l)\overline{g}_j(t_k, \nu_l)\mathcal{V}_{ij}(t_k, \nu_l) + \epsilon_{ijkl} \qquad (1)$$

where the antenna effects (clock errors, atmospheric effects, etc.) have been absorbed into complex-valued functions $g_q(t, \nu)$, and where the observational errors ϵ are sufficiently small and well-behaved. Each g can be written as $g_q(t, \nu) = a_q(t, \nu)\exp[i\psi_q(t, \nu)]$ (ψ_q is called the *antenna phase* of antenna q). Equation (1) is the model relation which is exploited by the usual self-calibration/hybrid mapping techniques. (Properly speaking, the $\tilde{V}_{ij}(t_k, \nu_l)$ are not really samples of the first term in the right-hand side of eq. [1]; rather, they are averages of this term, over some neighborhood of (t_k, ν_l). This fact may be ignored for purposes of the present discussion.) Thompson (1980) and Thompson and D'Addario (1982) present rigorous analyses of the effect of hardware electronic design considerations upon the validity of this model; further analysis is given in (Clark 1981). The so-called "phase closure" and "amplitude closure" relations follow by taking logarithms of ratios of equation (1), substituting into the relation antenna indices chosen to define a closed path among the antennas.

Although the a_q are functions of time and frequency, it is assumed that they change slowly enough that $g_q(t,\nu) = a_q \exp[i\psi_q(t,\nu)]$, with a_q constant over the (t,ν)-interval of the fringe search. Also, $|\mathcal{V}_{ij}|$ is assumed to be constant over the relevant interval. Then, to first-order,

$$\begin{aligned}\tilde{V}_{ij}(t_k,\nu_l) \simeq\ & a_i a_j \mathcal{V}_{ij}(t_0,\nu_0)\exp\{i[(\psi_i - \psi_j)(t_0,\nu_0)]\} \\ & \exp\left\{ i\left[\left.\frac{\partial(\psi_i - \psi_j + \phi_{ij})}{\partial t}\right|_{(t_0,\nu_0)} (t_k - t_0) \right.\right. \\ & \left.\left. + \left.\frac{\partial(\psi_i - \psi_j + \phi_{ij})}{\partial \nu}\right|_{(t_0,\nu_0)} (\nu_l - \nu_0) \right]\right\},\end{aligned} \tag{2}$$

where $\phi_{ij} \equiv \arg \mathcal{V}_{ij}$.

The quantities

$$r_{ij} \equiv \left.\frac{\partial(\psi_i - \psi_j + \phi_{ij})}{\partial t}\right|_{(t_0,\nu_0)} \quad \text{and} \quad \tau_{ij} \equiv \left.\frac{\partial(\psi_i - \psi_j + \phi_{ij})}{\partial \nu}\right|_{(t_0,\nu_0)}, \tag{3a, b}$$

which are called, respectively, the *fringe rate* and the *delay* for baseline i–j at (t_0, ν_0), can be estimated by searching for the location of the maximum modulus of the Fourier transform $\hat{F}_{ij}(r,\tau)$ of the distribution $F_{ij}(t,\nu)$ defined by

$$F_{ij}(t,\nu) = \sum_{\substack{0\le k\le n_t \\ 0\le l\le n_\nu}} \delta[t - (t_k - t_0), \nu - (\nu_l - \nu_0)]\tilde{V}_{ij}(t_k,\nu_l), \tag{4}$$

where δ is the two-dimensional Dirac delta function (i.e., the distribution with the property that $\hat{\delta}(r,\tau) \equiv 1$).* Furthermore,

$$\hat{F}_{ij}(r_{ij},\tau_{ij}) \simeq a_i a_j \mathcal{V}_{ij}(t_0,\nu_0)\exp\{i[(\psi_i - \psi_j)(t_0,\nu_0)]\}. \tag{5}$$

The quantities r_{ij} and τ_{ij} (actually, estimates thereof), then, are the product of the standard fringe search technique. They allow one to produce phase-corrected

*In practice, one doesn't compute $\hat{F}_{ij}$ directly, but rather a discrete approximation to it—via the FFT algorithm—, and then interpolation yields the parameter estimates.

observations

$$\tilde{V}_{ij}(t_k,\nu_l)\exp\{-i[(t_k-t_0)r_{ij}+(\nu_l-\nu_0)\tau_{ij}]\} \tag{6}$$

which, to the extent that the first-order model (eq. [2]) is valid — *and* that ϕ_{ij} is nearly constant —, can be averaged coherently over time and frequency. Note carefully, though, that the technique does not separate the $\partial\psi/\partial t$ and $\partial\phi/\partial t$ components of the rates, nor the $\partial\psi/\partial\nu$ and $\partial\phi/\partial\nu$ components of the delays, as one might wish.

Following the fringe search, the corrupting influence of the quantities $a_q^{-1}\exp[-i\psi_q(t_0,\nu_0)] = g_q^{-1}(t_0,\nu_0)$ is removed in post-processing by the self-calibration/hybrid mapping techniques.

The major disadvantage of the standard approach is that relatively high S/N (i.e., small ϵ) is required on each baseline in order to obtain reliable estimates of all the r_{ij} and τ_{ij}. The obvious approach toward a fringe processing method for the low S/N regime is to try to separate the antenna-based components $\frac{\partial\psi_q}{\partial t}|_{(t_0,\nu_0)}$ and $\frac{\partial\psi_q}{\partial\nu}|_{(t_0,\nu_0)}$ of the fringe rates and the delays by means of some simultaneous solution over all baselines. Obviously, the source phase ϕ_{ij} cannot be separated into antenna-based components — so a source model V_{ij}, approximating $\mathcal{V}_{ij}$, is required, *a la* self-calibration/hybrid mapping, in the two global fringe search methods described below.

III. A Least-Squares Approach

Here, given a source model V approximating $\mathcal{V}$, above, we consider the problem of least-squares estimation of the antenna-based components of fringe rate and delay. Simultaneously we wish to estimate the $g_q(t_0,\nu_0)$. The antenna-based parameters are the a_q, the antenna phases $\psi_{q0} \equiv \psi_q(t_0,\nu_0)$, the antenna rates $r_q \equiv \frac{\partial\psi_q}{\partial t}|_{(t_0,\nu_0)}$, and the antenna delays $\tau_q \equiv \frac{\partial\psi_q}{\partial\nu}|_{(t_0,\nu_0)}$. Define

$$E_{ijkl} = \exp\{i[(\psi_{i0}-\psi_{j0})+(r_i-r_j)(t_k-t_0)+(\tau_i-\tau_j)(\nu_l-\nu_0)]\}. \tag{7}$$

We shall fit the ensemble of observations in the (t,ν)-sample space to the model

$$\tilde{V}_{ij}(t,\nu) = a_i a_j V_{ij}(t,\nu)E_{ijkl} + \text{noise}. \tag{8}$$

Since only pairwise differences of the ψ_{q0}, the r_q, and the τ_q appear in the model, we shall settle, in the absence of other assumptions, upon estimating $4n-3$ parameters, omitting ψ_{p0}, r_p, and τ_p for some choice p of "reference antenna." Thus, if we set $\psi_{p0}=r_p=\tau_p=0$, then we estimate antenna phase, fringe rate, and delay with respect to the phase, rate, and delay at antenna p. A least-squares formulation of the problem, then, is to minimize the functional

$$S(\mathbf{x}) = \sum_{\substack{0\le k\le n_t\\ 0\le l\le n_\nu}} \sum_{1\le i<j\le n} \frac{1}{\sigma_{ijkl}^2}|\tilde{V}_{ij}(t_k,\nu_l) - a_i a_j V_{ij}(t_k,\nu_l)E_{ijkl}|^2. \tag{9}$$

Here, $\mathbf{x}$ is the (column) vector of unknown parameters, $\mathbf{x} = \mathrm{col}'(a_1, \ldots, a_n, \psi_{10}, \ldots, \psi_{n0}, r_1, \ldots, r_n, \tau_1, \ldots, \tau_n)$, the prime denoting that antenna p's parameters (except for a_p) are omitted; and σ^2_{ijkl} is an estimate of the variance of $\tilde{V}_{ij}(t_k, \nu_l)$.

One might choose to minimize, instead of S, the functional

$$S_1(\mathbf{x}) = \sum_{k,l} \sum_{i<j} \frac{1}{\sigma^2_{ijkl}} |\tilde{V}_{ij}(t_k, \nu_l)/V_{ij}(t_k, \nu_l) - a_i a_j E_{ijkl}|^2 \tag{10}$$

— with an appropriate redefinition of the weights (this form may be preferred when data storage is at a premium); or, if it were assumed that $a_q = 1$ for every q,

$$S_2(\mathbf{x}) = \sum_{k,l} \sum_{i<j} \frac{1}{\sigma^2_{ijkl}} |\tilde{V}_{ij}(t_k, \nu_l)/V_{ij}(t_k, \nu_l) - E_{ijkl}|^2, \tag{11}$$

where the a_q have been deleted from the vector $\mathbf{x}$ of unknowns; or, if there were a desire to neglect the amplitude information

$$S_3(\mathbf{x}) = \sum_{k,l} \sum_{i<j} \frac{1}{\sigma^2_{ijkl}} |\exp\{i[\tilde{\phi}_{ij}(t_k, \nu_l) - \phi_{ij}(t_k, \nu_l)]\} - E_{ijkl}|^2, \tag{12}$$

where $\tilde{\phi}_{ij} \equiv \arg \tilde{V}_{ij}$, and where, again, the a_q have been deleted from $\mathbf{x}$. Thus far, in the attempt at a practical implementation of the LS method, only the form S_3 has been employed.

Additionally, one might choose to incorporate prior knowledge of the parameters: for example, one might tabulate a running mean m_{r_q} of solutions for each antenna's fringe rate r_q, along with an empirical measure of the r.m.s. scatter σ_{r_q} about this running mean. If one were then to assume a Gaussian prior distribution $\mathcal{N}(m_{r_q}, \sigma^2_{r_q})$ for r_q, one would add to S the "penalty" term

$$\sum_{\substack{q=1 \\ q \neq p}}^{n} \frac{(r_q - m_{r_q})^2}{\sigma^2_{r_q}}. \tag{13}$$

Similar terms would be added for the other parameters. (Cornwell and Wilkinson (1981) advocate just such a Bayesian approach in ordinary self-calibration/hybrid mapping). Or, if there were simply a desire to constrain the estimates of some parameter to a given interval, one could add to S a differentiable penalty function which is small over the given interval and which rises sharply at its boundaries. Either of these techniques would serve to reduce the variance in the parameter estimates — at the expense of increased bias, over and above the bias inherent in the basic nonlinear LS approach. Preliminary tests of the method indicate that constraints are not required in cases of moderate S/N in order for the method to behave sensibly; but, since often there is good prior knowledge, the present implementation of the method does allow the use of prior distributions for the r_q and the τ_q.

S typically has many local minima, as well as other critical points. One can reasonably expect that a standard iterative minimization algorithm, starting with a reasonable initial guess, reliably and efficiently should be able to locate some local minimum. Locating a starting point for which a *global* minimum will be the point of attraction of the algorithm is more difficult. However, secondary minima of S ought to be spaced in fringe rate and delay roughly like the maxima of the cosine transforms of $f(t) = \sum_k w^\dagger(k)\delta(t - t_k + t_0)$ and $g(\nu) = \sum_l w^\ddagger(l)\delta(\nu - \nu_l + \nu_0)$ whenever the variance estimates are separable functions of k and l; i.e., whenever $\sigma_{ijkl} = \sigma_{ij}/\sqrt{w^\dagger(k)w^\ddagger(l)}$. In tests with model data, this observation has improved the success rate of the algorithm substantially when started with arbitrary initial guesses. But a more fruitful approach is to use a generalization of the standard method of § II in order to generate the starting guesses. This scheme is described in the next section.

A detailed description of an algorithm which has proven effective in solving the LS problem, as formulated above, is given in the Appendix.

IV. A Generalization of the Standard Approach

As in the least-squares minimization of S_3, let us discard the amplitude information but retain the phases, $\tilde{\phi}$ and ϕ. Then, to estimate the ψ_{q0}, the r_q, and the τ_q (but not the a_q), a global Fourier transform approach analogous to the standard approach is easily derived.

For simplicity of exposition, assume that antenna number 1 has been chosen as reference antenna; i.e., $p = 1$. Define the distributions

$$D_{kl}(t,\nu) = \delta[t - (t_k - t_0), \nu - (\nu_l - \nu_0)]. \tag{14}$$

Then the location of the maximum modulus of the Fourier transform of the distribution

$$F_{12}(t,\nu) = \sum_{k,l} \frac{1}{\sigma^2_{12kl}} D_{kl}(t,\nu)\exp\{i[(\tilde{\phi}_{12} - \phi_{12})(t_k,\nu_l)]\} \tag{15}$$

provides an estimate of r_2 and τ_2, and the argument there is an estimate of ψ_{20}. By the phase closure relations (cf. Readhead *et. al.* 1980), $\tilde{\phi}_{12} - \phi_{12} = \tilde{\phi}_{13} - \phi_{13} - \tilde{\phi}_{23} + \phi_{23} +$ noise. In general, for $j \neq 1,2$, define

$$F_{1j2}(t,\nu) = \sum_{k,l} \frac{1}{\sigma^2_{1jkl} + \sigma^2_{2jkl}} D_{kl}(t,\nu)\exp\{i[(\tilde{\phi}_{1j} - \phi_{1j} - \tilde{\phi}_{2j} + \phi_{2j})(t_k,\nu_l)]\}. \tag{16}$$

Since the differences $\tilde{\phi} - \phi$ occurring in F_{12} and in the F_{1j2} are all independent (apart from whatever scheme was used to derive the model) the Fourier transform of $F \equiv F_{12} + \sum_{j \neq 1,2} F_{1j2}$ yields, in general, better parameter estimates than any one of the F_{-}'s alone.

Paths like 1–3–4–2, with functions F_{1jk2} defined analogously to those above, provide further estimates of r_2, τ_2, and ψ_{20}. F_{1342} is not independent of F_{132} and F_{142}, although it incorporates new data from the 3–4 baseline. So it is not clear how to sum all of the F_{-}'s together with properly chosen weights. Nevertheless, one can adopt an *ad hoc* weighting scheme. For an arbitrary choice p of reference antenna, the paths to antenna l which incorporate at least partially independent phase differences can be enumerated as:

$$(p\text{–}l); \qquad (p\text{–}j\text{–}l), \quad j = 1, \ldots, n, \quad j \neq p, l;$$

and $(p\text{–}j\text{–}k\text{–}l), \quad j = 1, \ldots, n-1, \quad k = j+1, \ldots, n, \quad j,k \neq p, l.$

As in the standard fringe search technique, one would, in implementing this method, compute a discrete approximation to $\hat{F}$ — via the FFT algorithm —, rather than $\hat{F}$ itself. Given prior knowledge of the fringe rates and the delays, it would be straightforward to constrain the parameter estimates by doing a restricted search for the maximum modulus of $\hat{F}$. It is not readily apparent how the method could be generalized to provide estimates of the a_q.

The global FT algorithm is well-suited to implementation in a high-speed array processor.

V. Discussion

A hybrid global fringe search algorithm has been implemented within the AIPS interactive data reduction system. The FT method is used to provide starting guesses for the LS algorithm. In the LS routine, the functional S_3 is minimized. The weights $1/\sigma^2_{ijkl}$ are chosen to be proportional to the product $w_i w_j$ of two "antenna weights," times the square of the modulus of the model visibility, $|V_{ijkl}|^2$. Thus, baselines on which the source is heavily resolved are given small weight. A data editing capability based on goodness-of-fit to the model (eq. [8]) also has been incorporated. Typically, the FT method provides good enough parameter estimates for the LS algorithm to converge in 4-6 iterations. *A priori* knowledge of the fringe rates and the delays often is good enough that there is no difficulty in locating a global minimum of S.

As an alternative to the LS algorithm, one could use instead an ℓ_1 minimization method, in order to reduce the sensitivity to wild data points. This approach, whose application to ordinary self-calibration/hybrid mapping is described in (Schwab 1981), readily could be adapted to the problem at hand.

The global fringe fitting technique offers a number of substantial advantages over the standard baseline oriented fringe fitting method. Among them are:

1) By its very nature, the new method forces closure of the derived instrumental delays and rates, whereas the standard technique, in general, does not preserve delay and rate closure.

2) When, as is common, there are great differences in the sensitivity of the antennas comprising the VLBI array, the global technique allows the use of data

on baselines which by themselves are much too insensitive for baseline fringe fitting to succeed.
3) For any given array, the global technique lowers the threshold for minimum detectable point source flux density.
4) Global fringe fitting offers a simple way to process polarization observations, as the delays and rates for each I.F. in use can be determined from the parallel-polarized correlations, and then they can be applied to the cross-hand polarized correlations. This removes the requirement that the source be detectable in the cross-hand polarized channels.
5) The global fringe fitting technique allows the mapping of sources whose size is not small compared to the delay resolution on every baseline. This follows because the source structure information can be used in an iterative procedure to remove the effects of source structure before fitting for antenna delays and rates. The source then can be mapped in each frequency channel separately, and the resulting maps averaged. The larger delay beam of the narrow band frequency channels becomes the limitation, rather than the delay beam corresponding to the full bandpass. Since the frequency resolution can be set arbitrarily by changing the numbers of delays correlated, the effective delay beam can be made as large as desired.
6) The increased sensitivity of the global fringe fitting technique allows the use of shorter solution intervals than can be used for baseline fringe fitting. Hence, the actual variations of delay and rate are better approximated by the linear model (eq. [2]), than they are in the standard technique. In most cases this results in more accurate phase correction of the measured correlations.

APPENDIX

In this section, S denotes whichever functional of § III, S, S_1, S_2, or S_3, is to be minimized. $\mathbf{x}$ is the corresponding column vector of unknown parameters. With n antennas, there are $N = 4n - 3$ parameters unless S_2 or S_3 has been selected, in which case $N = 3n - 3$. Let $\nabla S(\mathbf{x})$ denote the gradient of S evaluated at $\mathbf{x}$; i.e., $\nabla S(\mathbf{x}) = \mathrm{col}(\frac{\partial S}{\partial x_1}, \ldots, \frac{\partial S}{\partial x_N})$; and let $H(\mathbf{x})$ denote the Hessian matrix of S at $\mathbf{x}$; i.e., $H(\mathbf{x}) = \left(\frac{\partial^2 S}{\partial x_i \partial x_j}\right)_{i,j=1}^{N}$. In general, S has many critical points — local minima, local maxima, and saddle points. At any critical point $\mathbf{x}^*$, $\nabla S(\mathbf{x}^*) = 0$. At a local minimum, $H(\mathbf{x}^*)$ is positive semidefinite (i.e., all of its eigenvalues are nonnegative), and at a proper local minimum (i.e., when all parameters are well-determined), $H(\mathbf{x}^*)$ is positive definite. At a local maximum, H is negative semidefinite (i.e., none of its eigenvalues is positive), and at a saddle point H is indefinite (i.e., it has some negative and some positive eigenvalues). Away from a critical point, $-\nabla S(\mathbf{x})$ points in the direction of steepest descent in the sense of the standard Euclidean metric $\sqrt{(\mathbf{x}-\mathbf{y})^{\mathrm{T}}(\mathbf{x}-\mathbf{y})}$. For any positive definite $N \times N$ matrix G, $-G\nabla S(\mathbf{x})$ is also a steepest descent direction — steepest in the sense of the metric $\sqrt{(\mathbf{x}-\mathbf{y})^{\mathrm{T}} G(\mathbf{x}-\mathbf{y})}$ derived from the inner product $\mathbf{x}^{\mathrm{T}} G \mathbf{y}$.

Clearly, because of the multitude of local maxima and saddle points, we require a descent algorithm. One would not generally choose, though, to step in the direction of steepest descent in the sense of the Euclidean metric because such a strategy can lead to arbitrarily slow convergence. But whenever $H(\mathbf{x})$ is positive definite, $-H^{-1}(\mathbf{x})\nabla S(\mathbf{x})$ is a steepest descent direction. And steps taken in this search direction will converge eventually at a *quadratic* rate in the neighborhood of any proper local minimum of S (cf. Ortega and Rheinboldt (1970) or Murray (1972)).

Because of the special structure of our problem, a simple variant of Newton's method for root-finding, applied to the equation $\nabla S(\mathbf{x}) = 0$, is practical. A variant is required because we want the algorithm to converge upon only one type of critical point — a local minimum. The reason that the structure is special and that Newton's method is practical is that, when $N = 3n - 3$, each observation, since it involves only two antennas, and, therefore, at most six unknown parameters, contributes to at most six elements of ∇S, to at most six of the diagonal elements of H, and to at most 15 subdiagonal elements of the (symmetric) matrix H. Furthermore, all of these contributions are easy to compute. When $N = 4n - 3$, the contributions are to at most 8, 8, and 28 elements, respectively. For many other problems, Newton's method is impractical because each observation may involve all of the parameters and because analytic second order derivatives of the model may be very difficult to obtain.

The raw form of Newton's algorithm is: Given an initial guess $\mathbf{x}^{(0)}$, at the k^{th} iteration form the new parameter estimate $\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} - \alpha_k H^{-1}(\mathbf{x}^{(k)})\nabla S(\mathbf{x}^{(k)})$, where $\alpha_k > 0$ is chosen so that $S(\mathbf{x}^{(k+1)}) \leq S(\mathbf{x}^{(k)})$. The difficulty is that H^{-1} (and equivalently H) must be positive definite in order for $-H^{-1}\nabla S$ to be a descent direction. Hence, any time that $H(\mathbf{x}^{(k)})$ has nonpositive eigenvalues, we shall wish to replace it by $\tilde{H}(\mathbf{x}^{(k)})$, where $\tilde{H}$ is positive definite, and in some sense close to H. One means of doing so, known as Greenstadt's modification (Murray 1975, p.59), is to compute the eigenvector expansion of H, $H = \sum_{i=1}^{N} \lambda_i \mathbf{v}_i \mathbf{v}_i^{\mathrm{T}}$, with $\mathbf{v}_i$ orthonormal, and modify it slightly so that, for some small $\epsilon > 0$,

$$\tilde{H} = \sum_{i=1}^{N} \tilde{\lambda}_i \mathbf{v}_i \mathbf{v}_i^{\mathrm{T}}, \quad \text{where } \tilde{\lambda}_i \equiv \begin{cases} \lambda_i & \text{if } \lambda_i \geq \epsilon \\ \epsilon & \text{otherwise.} \end{cases} \tag{17}$$

(On a t digit base β machine, $\epsilon \approx \beta^{-t}$ is an appropriate choice, since positive eigenvalues smaller than this cannot easily be distinguished from other eigenvalues that are close to zero). Then the search direction is given by

$$-\tilde{H}^{-1} \nabla S = -\sum_{i=1}^{N} \frac{1}{\tilde{\lambda}_i} [\mathbf{v}_i^{\mathrm{T}} \nabla S] \mathbf{v}_i. \tag{18}$$

Note that $\mathbf{v}_i^{\mathrm{T}} \nabla S$ is a scalar — the dot product of the i^{th} normalized eigenvector of H with ∇S.

A rough block diagram of an implementation of the LS algorithm is shown in Figure 1. The subroutine DSICO of the LINPACK package (Dongarra *et. al.* 1979) is used to factor H, $H = UDU^{\mathrm{T}}$, with U unit upper triangular and D a diagonal matrix. Using this factorization, DSIDI, also taken from LINPACK, tallies the number of positive, negative and zero eigenvalues of H. When H is positive definite, the subroutine DSISL of LINPACK is used to compute the search direction $\mathbf{d}_k = -H^{-1}(\mathbf{x}^{(k)}) \nabla S(\mathbf{x}^{(k)})$.

Whenever DSIDI reports that there are nonpositive eigenvalues, Greenstadt's modification is applied. The subroutine TRED2 of the EISPACK package (Smith *et. al.* 1976) is used to reduce H to tridiagonal form, via similarity transforms. Then IMTQL2, also of EISPACK, is used to compute the eigensystem by the implicit QL method. The implicit QL algorithm is quite forgiving of bad parameter scaling — say, if the parameters are defined in units in which the fringe rates are orders of magnitude different from the antenna phases — this can lead to eigenvalues of widely varying magnitude. Once the eigensystem has been computed, the search direction is given by $\mathbf{d}_k = -\tilde{H}^{-1}(\mathbf{x}^{(k)}) \nabla S(\mathbf{x}^{(k)})$.

Finally, a coarse search is made in the direction $\mathbf{d}_k$, for an α_k satisfying $S(\mathbf{x}^{(k)} + \alpha_k \mathbf{d}_k) \leq S(\mathbf{x}^{(k)})$. Close enough to a proper local minimum, the choice $\alpha_k = 1$ will do. We set $\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} + \alpha_k \mathbf{d}_k$, test for convergence, and perform another iteration, if necessary. The theoretically predicted quadratic rate of convergence near a proper local minimum frequently has been observed in the initial tests of the algorithm.

Because the first and second derivatives of the model function are entirely straightforward to compute, the expressions for ∇S and for H have been omitted here.

Preliminary results have shown this method to perform well, but other implementations of the LS algorithm would do as well or better. In particular, an alternative method of modifying indefinite H could speed up the algorithm significantly, since the eigen-decomposition is relatively expensive. The algorithm given here could be implemented in a high-speed array processor, at a moderate expenditure of human effort.

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National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22901

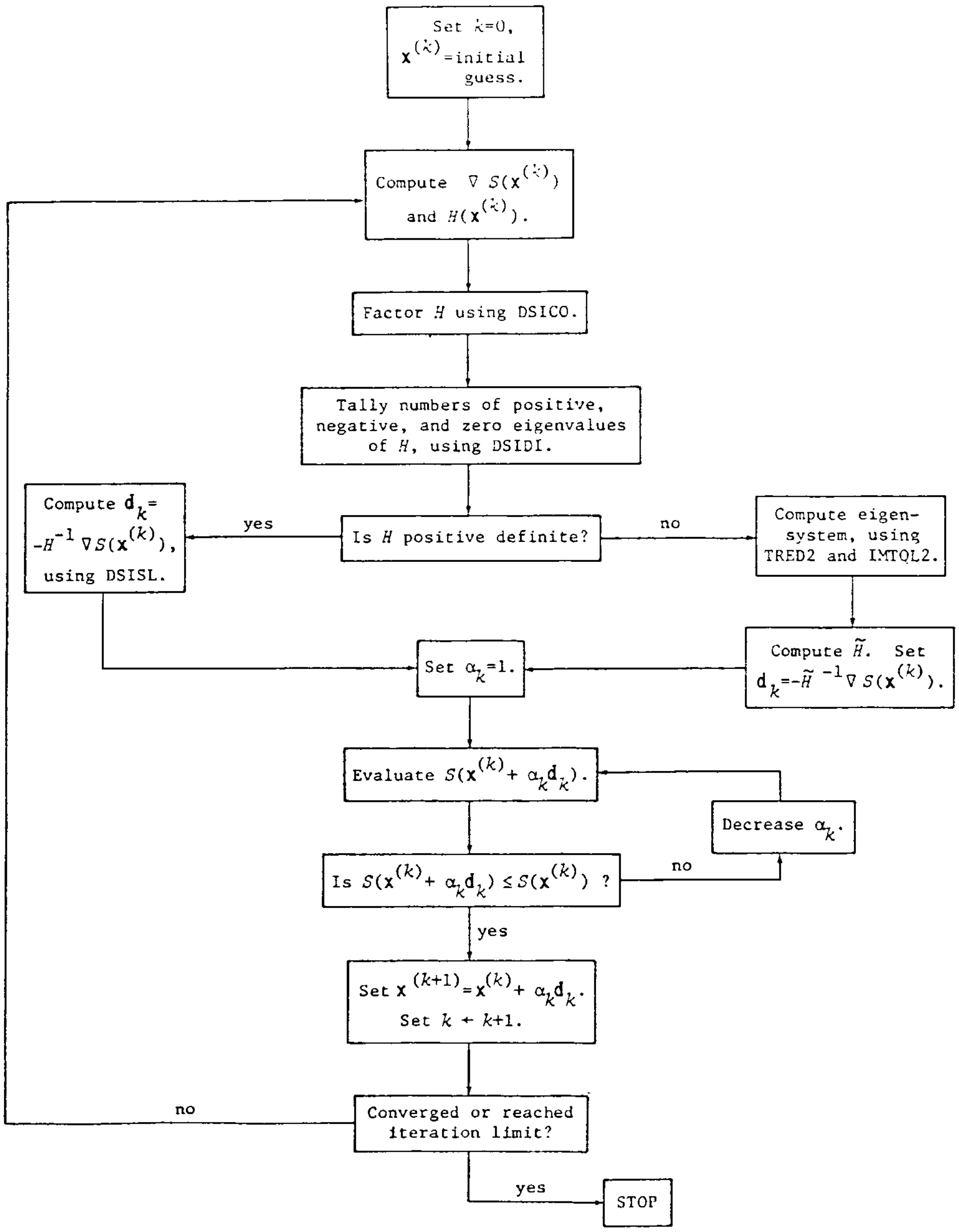


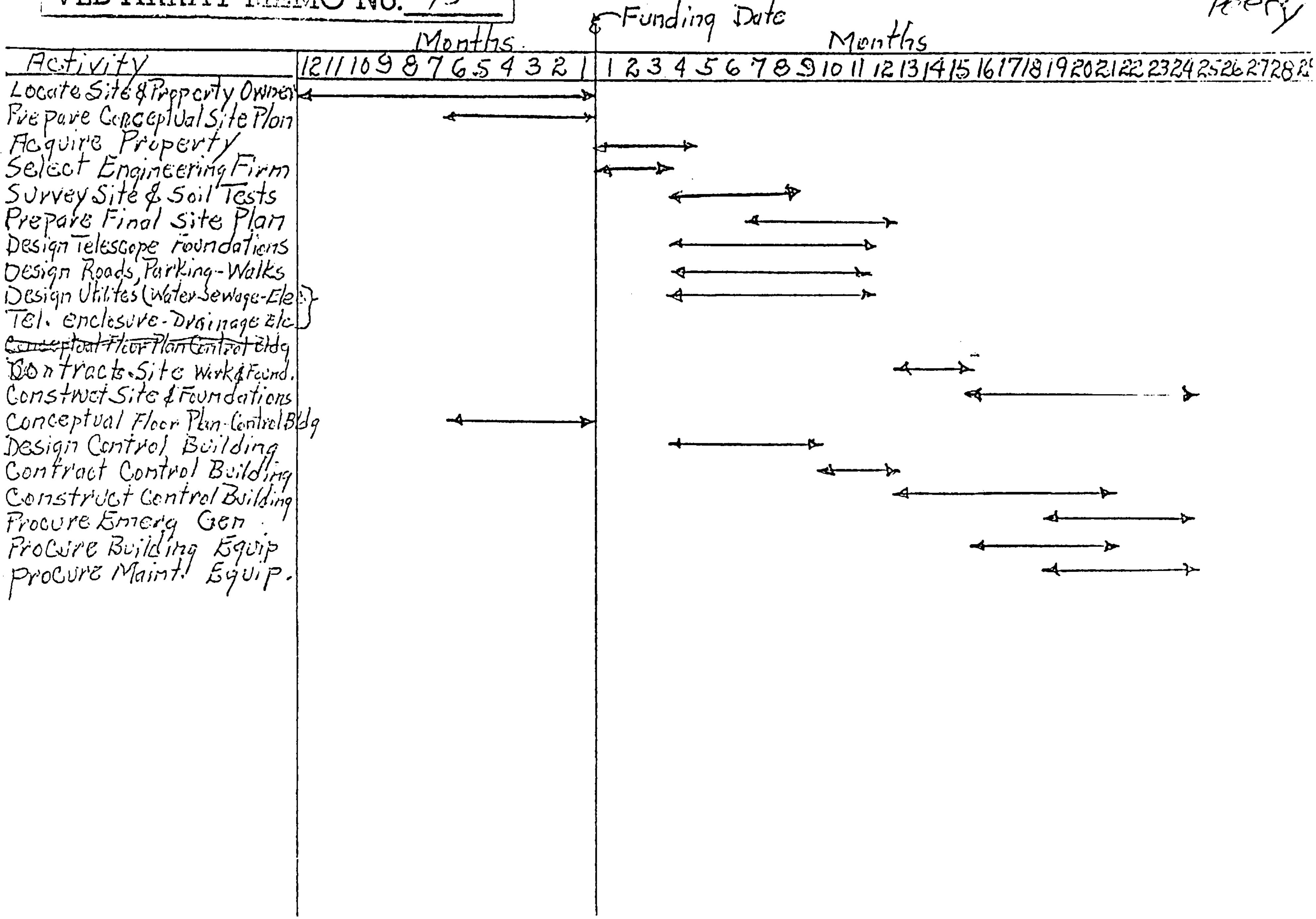
Figure 1. Rough block diagram of the LS algorithm.

VIII. G E N E R A L

VLB ARRAY MEMO No. 13

VLB ARRAY
Site Developm t Program (Typical Site)

– 8/21/80



25 M - 110' x 65' = * 7150 ft^2 (32 x 42 = 1344 ft^2) Elec Dem. 500 KW

Intf: 22 x 68 x 2 = 2992 ft^2 (21 x 31 = 651 ft^2) 8 [illegible] (Two Anten.
21 x 31 x 2 = 1302 ft^2
(Total) 4294 ft^2

300'
22 x 38 x 2 = 1672 ft^2 (33 x 30 = 990 ft^2) 55 KW
41 x 30 x 2 = 2460 ft^2
+ Storage Bldgs 4132 ft^2 (Total)

45' 7' x 20' = 140 ft^2 20 KW

Proposed 45' (Addition to Interferometer. 30 KW
15 x 10 = 150 ft^2 (Storage)
50' x 9 = 450 ft^2 Trailer (Control)

35-1 22' x 50' = 1100 ft^2 (33 x 22 = 726 ft^2) 45 KW

30 KW (VLA A[illegible]

* Does Not include living Quarters -

Road 12' wide \$15/foot to \$30.00/foot - + \$10.00 Excavat[illegible]
Bldgs - \$55.00/ft^2
Elec. U.G. \$12.00/Ft.
Elec. O.H. \$6.00
35-45 K AUI Cost / Person
EM-Gen. \$400.00 / KVA [50 KVA to start]
MG - \$200.00 / KVA
UPS - \$1750.00 / KVA uninterrupted pwr service
Service Elev. \$15,000 - \$250,000
Soil Tests 5K - foundation 50K.
Property -
Well 3K.
Septic System - 2K.
Telephone -

Grading Seeding - Planting

[illegible signature]

3/16" Cord - (800#)

ft²

(36) 1) 7' x 18 = 126 Storage
20 x 20 = 400 Control
18 x 16 = 288 Observers Lounge
10 x 12 = 120 Electronic Shop
10 x 10 = 100 Engineer
10 x 10 = 100 Shop
8 x 8 = 64 MG.
1199 ft² Total (Inside dome)

400 ft² Control Rm (Story)

116 KW Peak

66' x 37' = 3640 ft² (Lab. Bldg.)

+ { Operators Cottage
3 - Trailers
1 - Storage Building }

VLB ARRAY MEMO No. 51

NATIONAL RADIO ASTRONOMY OBSERVATORY
Charlottesville, Virginia

January 12, 1982

MEMORANDUM

TO: R. Burns
B. Clark
K. Kellermann
K. Sowinski
A. Shalloway

FROM: S. Weinreb

SUBJECT: VLBA Proposal - Monitor and Control Chapter

A draft of the Monitor and Control chapter for the VLBA proposal is attached.

Our costs are 2 or 3 times the CalTech estimate for this portion of the system. Let's have another look at our numbers and discuss this with C.I.T. people.

I believe the 350k$ for redundant site computers should be lumped into a total spares inventory. There are other portions of the system which are probably less reliable than the computer (servo, hydrogen maser focus and polarization) that will not have an on-site backup. I doubt we would lose more than a few days per year per antenna due to CPU failures. Can we arrange it so that the system will run on one disk drive if the second one fails? (Two are included in the system; two more in the redundant system.)

Attachment

DRAFT

VLBA Proposal

January 1, 1982

Control and Monitor System

The overall concept of the Control and Monitor System is a central control center linked by telephone lines to control and monitor each antenna. Typical categories of information required or supplied by an antenna along with typical data rates are given in Table I. The data rates are comfortably low, of the order of 100 bps; an antenna could be controlled and monitored with a 2400 bps dial-up telephone line with large margin for future growth and error correction. The low data rate also allows low cost buffering of data in a memory for operation during a communication failure. In addition, data processing at the antenna will further reduce data rate requirements. For example, instead of sending an antenna position every 10 seconds, a position and duration of observation can be sent to a local computer which then updates the antenna at the required rate.

The distribution of computing power between central control and antenna is an interesting but not particularly crucial question. It would be possible to give the central computer direct control and monitor capability of every bit at the antenna with minimal data processing at the antenna. This minimal data processing would include error checking, immediate action for some severe out-of-limits conditions, equatorial to azimuth-elevation coordinate conversion, and memory-buffering of the data link in the event of a communications failure. However, the system which is favored is one with a small computer at each antenna linked through commercial computer-network software to the central computer. The local computer program would be loaded via the phone link from the central control computer. This system has the advantage of great flexibility and the use of proven computer-network software.

A block diagram of a proposed remote system is shown in Figure 1. The data-sets are general purpose analog and digital input and output units which link to the local computer via a single serial-transmission twisted-pair cable. Each data-set is located close to the equipment it commands and monitors to minimize wiring. Units similar to those used on the VLA or a CAMAC adaptation will be used. The data verification buffer is a 2M bit RAM memory which is loaded with L.F. data while observing a high-flux unresolved source; the memory is then unloaded through the telephone link (taking 7 minutes at 4800 bits/sec) and correlated with similar data from another antenna to verify system coherence.

The antenna computer will be a 16-bit processor with 128k byte memory, CRT display, slow printer, keyboard, and two 10M byte disks. The communications modem will be of a advanced type which allows error checking and automatic switch-over to a dial-up line in the event of failure of the dedicated line.

A dedicated 4-wire communications line with 9600 bps capability in each direction is proposed. As many as three antennas may share one leg of the link so three 2400 bps data channels and a voice link may be simultaneously used. The line cost for such a link is $156k per year in 1982; approximately 1/2 the cost is for the Alaska and Hawaii links. A dial-up line to each site for 2.8 hours per day would cost the same amount and would not have the reliability or capacity of the 4-wire line.

The central control computer must perform the functions of communications to all antennas, presentation of CRT displays, monitoring of data, and correlation of fringe verification data. The latter inlcudes model-calculation, fringe rotation, and delay. The proposed computer includes 512k byte memory, two 122M byte disks, two 1600/6250 bpi tape drives, tele-typewriter, printer, card reader, 2 graphics and 8 text CRT's and commercial software for operating system, communications, and FORTRAN. A telescope control computer is also included at the central operations center to facilitate software development. The programming labor for control and monitor software is estimated to be 16 man-years.

TABLE I - Typical Control and Monitor Data Rates

Control

Function	Bits	Update Period	Bit Rate (bps)
Antenna Pointing	48	10 s	4.8
Local Oscillators	48	10 s	4.8
Receiver Control	24	1 s	24
Tape Control	12	10 s	1.2
Total Control Bit Rate			34.8 bps

Monitor

Function	Bits	Update Period	Bit Rate (bps)
Servo Error	16	1 s	16
Receiver Total Power - 4 channels	64	1 s	64
Monitor Data	512	100 s	5
Fringe Verification	10^6	10^4 s	100
Total Monitor Bit Rate			185 bps

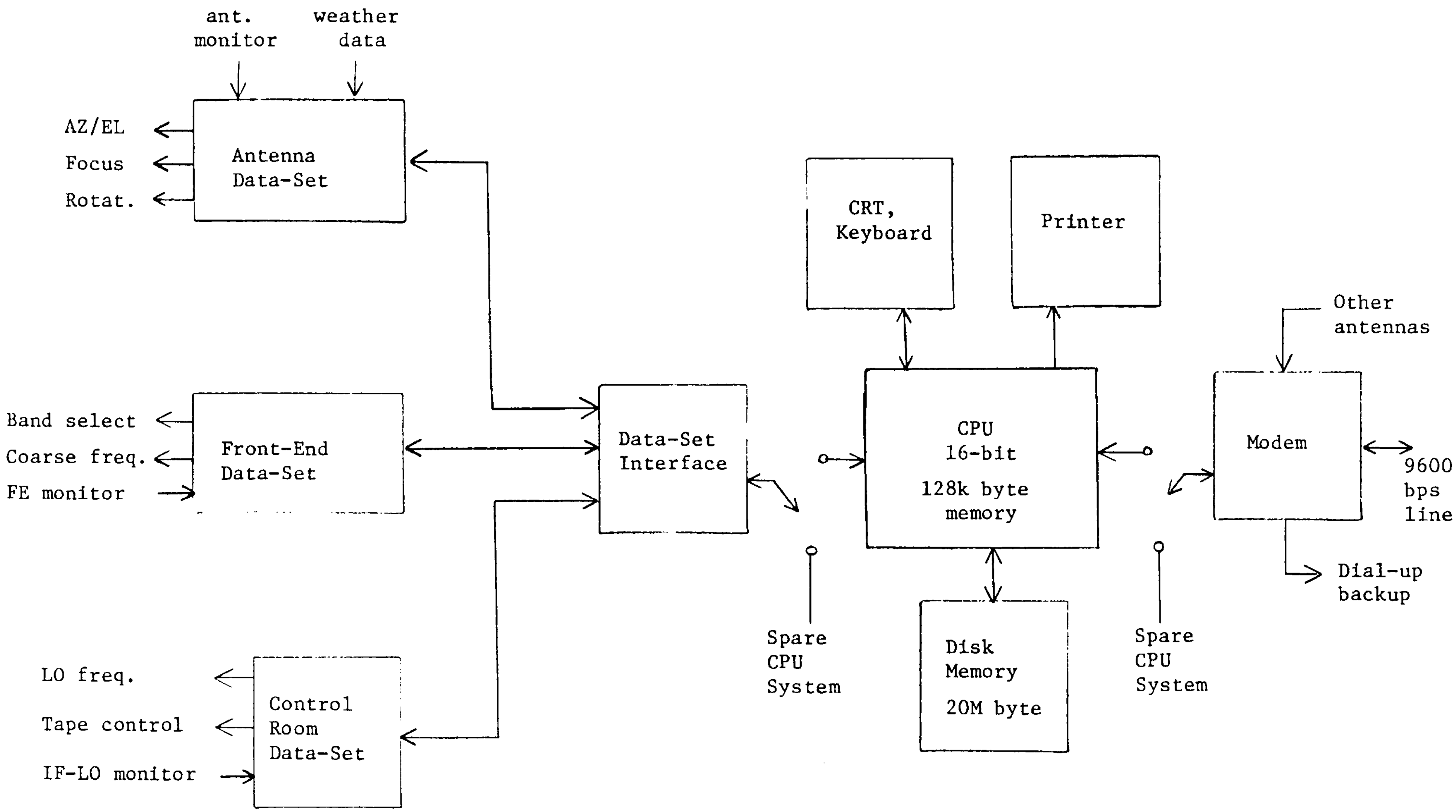


Fig. 1. Antenna Control and Monitor System

(For Cost Chapter)

Control and Monitor System Cost - Per Antenna

Telescope Control Computer	$35,000
(Includes 128k byte memory, two 10M byte disks, tele-typewriter, CRT, and manufacturer's operating system and communications software)	
Interface Equipment to Antenna and Receiver	5,000
(Three data-sets and serial interface to computer)	
Fringe Verification Buffer	3,000
(256k byte memory)	
Communication Equipment - Modems	5,400
Spare Computer	35,000
Installation Cabling ($1,000) and 1/2 man-year check-out labor	16,000
Total per Antenna	$99,400

Control and Monitor System Cost - Central Control

Array Control Computer	$ 204,000
(Includes 512k byte memory, two 1600/6250 bpi tape drives, two 122M byte disks, tele-typewriter, printer, card reader, 2 graphics and 8 text CRT's, and manufacturer's software for operating system, communications, and FORTRAN)	
Communication Equipment - Modems	15,000
Telescope Control Computer	35,000
(For software development)	
Software (16 man-years)	512,000
	$ 766,000

Total Control and Monitor System - Central Control	$ 766,000
Antenna Equipment ($99,400 x 10)	994,000
	$1,760,000

AUTOMATIC VLBI OBSERVING

G. W. Swenson, Jr.

One of the principal specifications of a dedicated VLBI array will be that it be usable by a single investigator as though it were a single instrument. It should thus be controllable from a single point, it should accept a single set of instructions applicable to all telescopes and recording systems in the array, and it should require only the barest minimum of operator intervention at individual telescope locations.

It has been determined that the most economical and practical communication medium for telescope sky signals is magnetic tape. Although it is in principle possible to program all telescope functions in advance, possibly by mailed instructions for the local control computers, in practice it will undoubtedly be necessary frequently to issue immediate, ad hoc instructions in response to unanticipated events. Thus, a real-time communication medium will be needed between the control center and all stations. This should be a narrow-band system, for economy and flexibility. Experiments at the University of Illinois' Vermilion River Observatory (VRO) over the past several years demonstrate the feasibility of the concept and illustrate a possible mode of implementation.

Almost all observations at the Vermilion River Observatory (VRO) are done automatically, with no operator in attendance at the telescope. Continuum and spectrographic single-dish observations are almost invariably conducted in this way, generally using stored programs prepared in advance, but with capability freely to make immediate changes or ad hoc observations from a keyboard terminal at any location with access to the public telephone network. The observer may interrogate the telescope at any time to determine program status or to check such parameters as receiver system temperature, local-oscillator frequency, sidereal time, telescope pointing, etc., without interrupting the observing program. The observing program is automated to the degree that, for example, the telescope can be programmed periodically to go to a strong calibrator source, do hour-angle and declination scans, fit a two-dimensional gaussian to the data, and automatically correct its internal pointing-correction table.

For VLBI observations it has not yet been possible to dispense with continual operator presence because the available tape recorder only accommodates one-hour tapes. With four- or six-hour video recorders now available at extremely low prices, it should be possible easily to automate the recording function as well, at least for bandwidths of 4 MHz or less. The VLBI observing software and interfaces provide many monitoring functions to prevent operator blunders and undetected equipment malfunctions.

The VRO automatic VLBI observing system contains the following features. The TI960A control computer is fed a list of instructions specifying source parameters and VLBI setup parameters. At appropriate times, the telescope is automatically positioned on sources and instructions are printed out for the operator concerning tape changes and special procedures. A "warning board" of lights indicates the computer's monitoring of various quantities important to proper operation of a VLBI observation; at a glance, a "green board" shows all to be well, and a red light instantly calls attention to a neglected piece of equipment. While mistakes are still possible, this system minimizes the chances of many common errors which wreck VLBI experiments. A hard-copy observing log is generated detailing start and stop times, calibrations, and other important events.

The automatic observing list consists of card images which may be entered from the terminal keyboard, paper tape, or 9-track 800 BPI magnetic tape. A program in Urbana for the campus computer permits computer files or punched cards to be converted to 9-track or paper tape. A line editor program in the telescope computer allows modification of the observing list from the terminal keyboard at any time.

An observing list consists of control cards and source cards. Control cards produce sequencing control or messages to the operator. Source cards specify scans to be performed.

Control cards contain a control character in column 1, followed sometimes by a control parameter. These are:

T output message: TAPE CHANGE (beep) followed by
(any text on the rest of the card)

S output message: STOP TAPE (beep) followed by
(text on the rest of the card)

E end of list; exit from automatic mode and await further instructions

W HHMMSS wait until the prescribed U.T. before taking further action; the telescope may be moved by the operator as desired

e.g. W 133500 waits until $13^h35^m00^s$

When a list is read into memory, an N in column 1 indicates there are no more cards to be read.

A source card has V in column 1, followed by the following:

Columns	Quantity
3-6	Start U.T., HHMM (SS in columns 7-8 optional)
9-12	Stop U.T., HHMM (SS in columns 13-14 optional)
15-22	Source name, 8 alphanumeric characters
25-30	Source right ascension (1950), HHMMSS
33-38	Source declination (1950), DDMMSS
40	Polarization: L=left, R=right, S=special (message output)
41	Bandwidth: 0=2 MHz, 1=1 MHz, . . ., 5=62.5 KHz
45-53	Local Oscillator setting in Hz

It is the observer's responsibility to convert the desired sky frequency into an L.O. setting, depending on the I.F. chain in use.

For example, to observe W49 at 1665.401 MHz, followed by BL LAC as a filter calibrator and fringe finder:

```
W 090000
V 0900  0920  W49 1665  190750  090100 R3    64487890
V 0920  0940  BL LAC    220039  420209 R3    64487890
V 0940  1000  BL LAC    220039  420209 R0    64487890
T
E
```

This sequence observes W49 in right circular polarization with 250 KHz bandwidth until 092000; moves to BL LAC without changing the setup; at 094000 changes the bandwidth to 2 MHz; and at 100000 outputs the messages TAPE CHANGE and AUTO LIST ENDS. Stop times are adhered to scrupulously.

All of the following functions are automatic. At the beginning of each scan, the polarization, bandwidth, and L.O. are set. If necessary, the I.F. level going into the video converter is adjusted. The computer checks the L.O. setting (by reading a frequency counter), the video converter L.O. lock, the MARK IIC formatter conditions of 4 MHz lock, data, time, and pattern, and whether the IVC video tape recorder is actually in RECORD mode. If any of these conditions is not satisfied, the appropriate light on the warning board is turned to red. When all is ready, the system temperature is measured and printed on the log, along with the source name and actual start time.

During a scan, the computer continuously monitors the following, turning on warning lights and printing messages whenever trouble develops:

1. Telescope position and status -- being blown off position by strong winds, reaching hour angle limit, and so on
2. Analog I.F. chain: oscillator settings, phase locks, levels, and so on
3. Mark IIC terminal status: formatter condition and video recorder status

The only important run-time quantity not presently monitored is the head gap position of the IVC recorder. The immediate-playback output is decoded into a data stream with BOF's and EOF's detected. A warning light indicates missing BOF, but this is not currently sent to the computer. The decoded data are sent to an oscilloscope so the operator may observe and adjust the 60 Hz head synchronization signal from the formatter. The data may also be examined for frame count, pattern, and so on. It is not clear that an automatic system can be devised which will warn of improper recorder operation without crying wolf!

Other equipment failures may, of course, ruin an experiment; but we have conquered many of the common errors so that careless mistakes by a sleepy or distracted operator will be minimized.

It should be observed that this system has been implemented on a telescope that has been consistently under-funded, with no spare or backup equipment, with an obsolete computer with very limited (8K) memory and no high-level language compiler. That it has worked so well under these circumstances suggests that it should be perfectly feasible to automate an entire network via the public telephone system, given an engineering staff who are intimately familiar with VLBI operations and given a pragmatic rather than an idealistic design philosophy.

By means of conference calls, given proper organization at the telescopes, the entire array could be controlled in real time from a single location, conceivably anywhere in the USA, or even the world. Alternatively, schedules for automatic observing could be read into the memories of all the telescopes simultaneously.

VLB ARRAY MEMO No. 48

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

MEMORANDUM — January 4, 1982

To: VLBA Working Group

From: C. Moore

Subj: Receiver Block Diagram and Test Equipment Budget

Attached are block diagrams of the RF/IF and LO portions of the array receiver as well as capital costs for test equipment to support/trouble-shoot this equipment at each array element and to repair same at a service center or operations center. I have included 1981 and 1982 H-P catalog prices as a check on the inflation factor prescribed.

Obviously, the GPS (Navstar Global Positioning Satellite) system for clock synchronization is too expensive for us at this time.

CRM/cjd

Enclosures
- Block Diagram - Receiver/LO
- Block Diagram - LO/IF
- Cost Estimates:
  - A.8.a) Test Equipment
  - B.6.a) Test Equipment
  - A.8.c) Timing Equipment

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

VLB ARRAY VI

Cost Estimates

A. Array Elements

8. Other Site Equipment

a) Test Equipment - Catalog Prices

	1982	1981
Vertical Scope Plug-In, HP 1805A	$ 2.3 K	$ 2.1 K
Time Base Plug-In, HP 1825A	2.0	1.3
Spectrum Analyzer Plug-In, HP 8559A	10.5	8.6
Main Frame, HP 182C	2.7	2.5
Power Meter, HP 436A	2.3	2.3
Power Meter Head, HP 8484A	0.7	0.7
Digital VOM, Fluke 8024A		0.3
	$20.8 K	$17.8 K

Additionally, specialized test equipment
for remote diagnostics:

Components ?
Man-hours ?

I think this specialized test equipment should
be included in item 6, Control and Monitor System.

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

VLB ARRAY VI

Cost Estimates

B. Operations Center

6. Other Service Center and Operations Center Equipment

a) Test Equipment - Catalog Prices

	1982	1981
RF Sweep Generator, HP 8350A	$ 4.3 K	$ 4.3 K
0.01-26.5 GHz Plug-In, HP 83595A	27.0	N/A
Network Analyzer, PMI 1038-D14		3.5
Horizontal and Vertical Plug-In, 1038-N/O ..		6.2
Detectors		1.5
Miscellaneous Couplers, Attenuators, etc. ..		5.0
Power Meter, HP 432A	1.0	1.0
Thermistor Mounts:		
0.01-18, 40-60, 75-110 GHz		3.0
Frequency Counter, HP 5343A	6.4	5.2
Rb Traveling Clock, HP #21-5065A	22.0	18.6
Phase Comparator, HP K34-59991A	2.0	N/A
Frequency Stability Analyzer, HP 5390A	31.7	27.3

Digital Test Equipment ?

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

VLB ARRAY VI

Cost Estimates

A. Array Elements

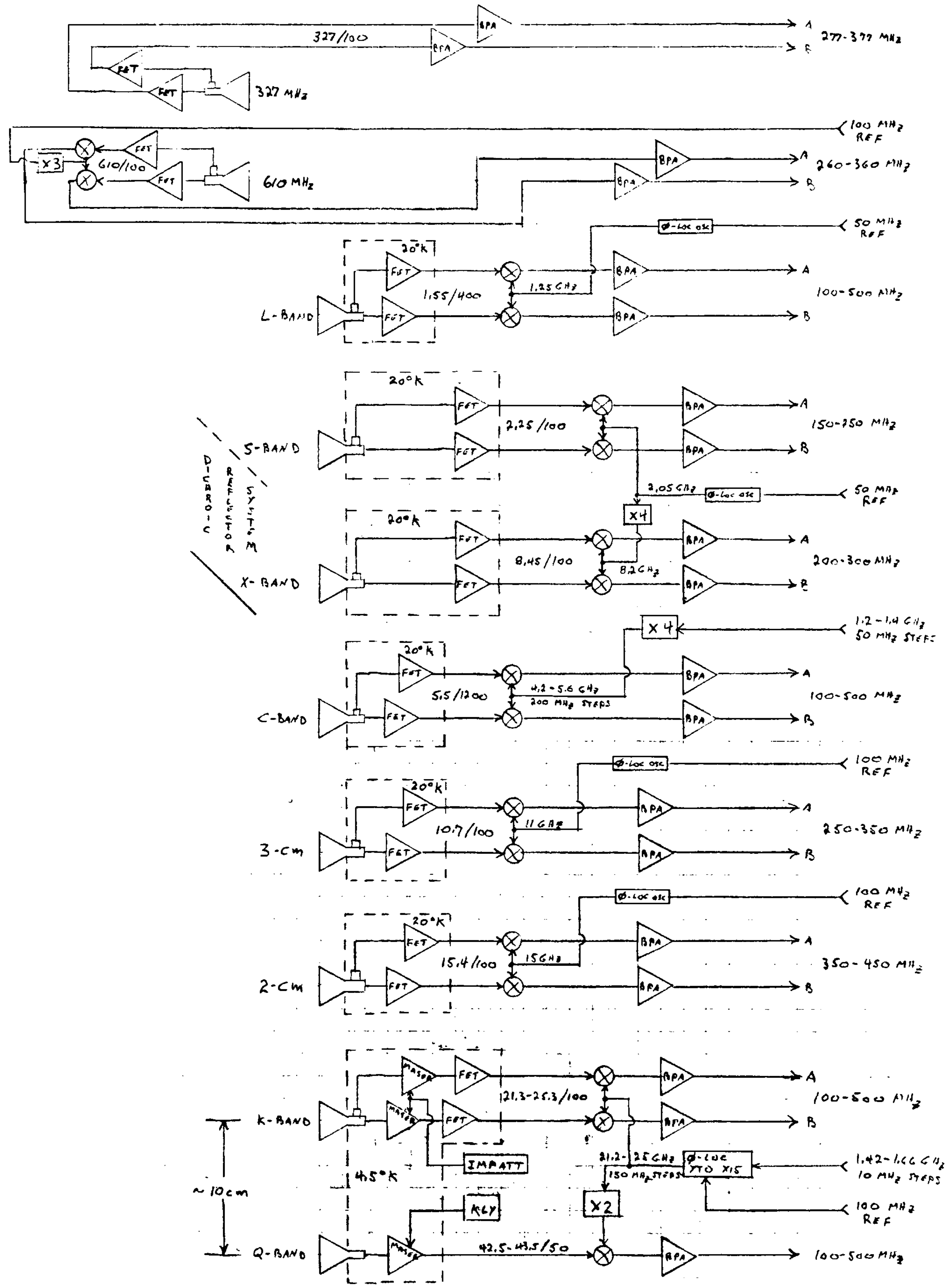
8. Other Site Equipment

c) Timing Equipment - Catalog Prices

		1982	1981
	Rubidium Clock, HP 5065A	$16.9 K	$13.5 K
one or other	→ Option 002, 10 min Standby Power	0.7	0.6
	Option 003, Digital Clock	3.0	3.2
	→ 10 Hour Standby Power, HP 5085A	5.3	4.5
	Quartz Oscillator, Austron 2010R		5.4
	16 Hour Standby Power, Austron 1290A		3.0
	WWVB Receiver, Spectracom 8160A		1.6
one or other	→ Loran-C Timing Receiver, Austron 2100		9.6
	→ GPS Receiver/Processor,		
	Stanford Telecom 502		80.0
	GPIB Option 004		4.4

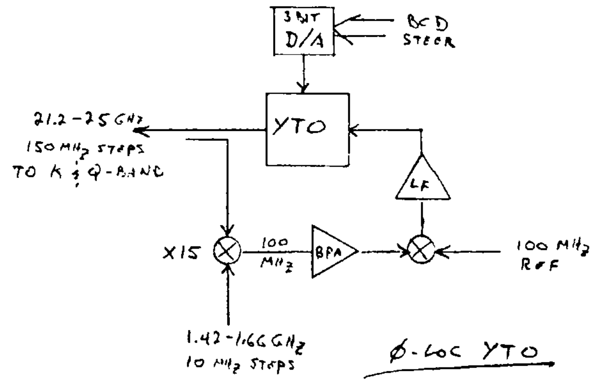
GPS receiver price will come down in future years.

I question the need for a crystal oscillator since the H-maser will have one.



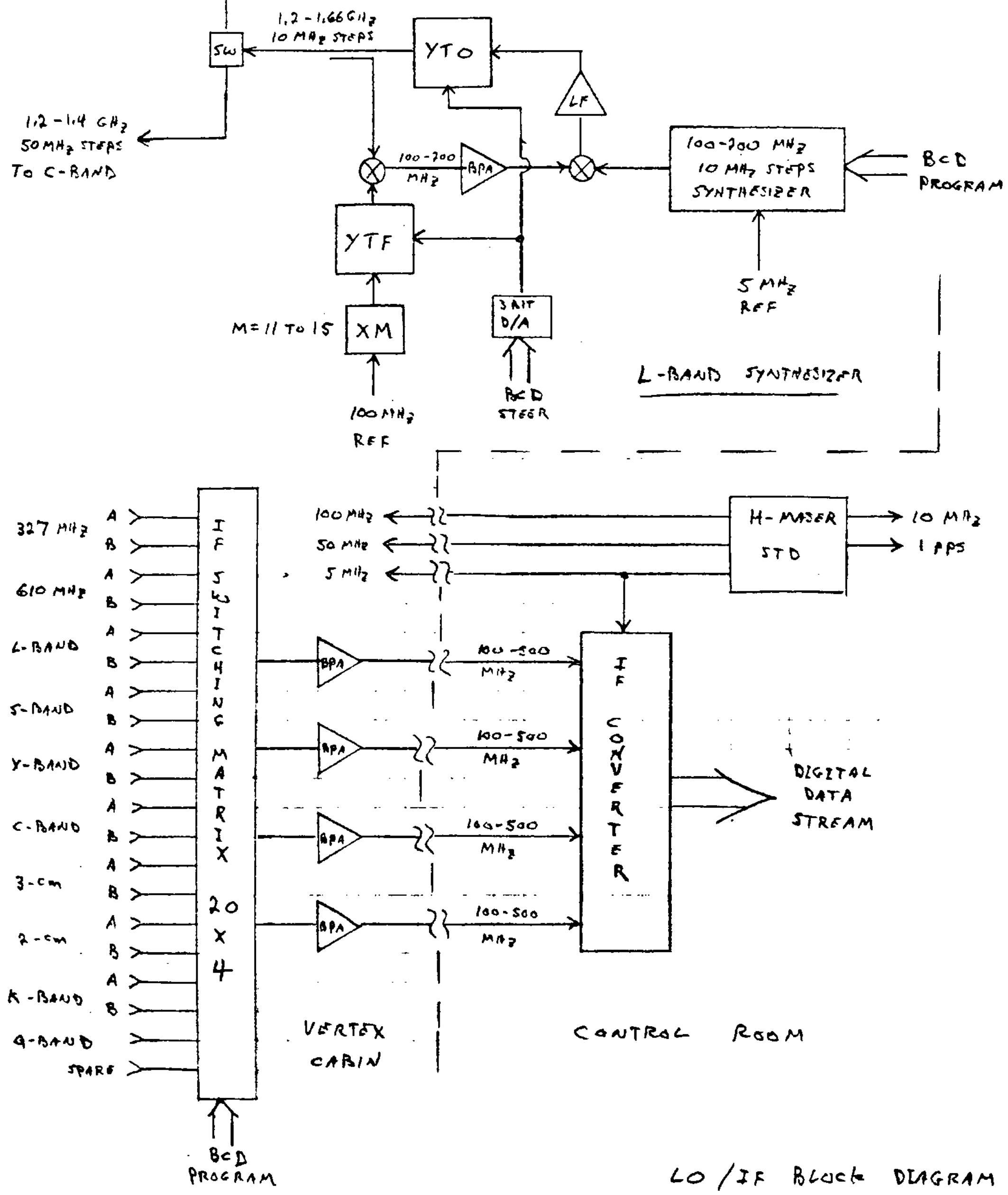
KEY: X/Y
X = CENTER FREQ. - MHz OR GHz
Y = 3 dB BW - MHz

RECEIVER/LO BLOCK DIAGRAM
VLB ARRAY PROPOSAL
BRM 12-21-81



Q-BAND FREQ. CHART

RF	LO	YTO	REF	100 MHz SIGN
42.5-42.9	42.4	21.2	1.42	−
42.9-43.3	42.8	21.4	1.42	+
42.8-43.2	42.7	21.35	1.43	−
43.2-43.6	43.1	21.55	1.43	+



LO / IF BLOCK DIAGRAM
VLB ARRAY PROPOSAL
BRM 12-21-81

VLB ARRAY MEMO No. 66

NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

MEMORANDUM

January 28, 1982

To: VLBA Working Group

From: R. Lacasse

Subj: Recommended General and Digital Test Equipment

A variety of test equipment is required at the array elements and at the operations center to maintain and service the electronic equipment. VLBA Memo 48 specifies some general purpose equipment some specific to the needs of the RF and IF electronics. This memo adds to the list of general purpose equipment and also specifies equipment specific to the needs of the digital electronics. Costs are in 1982.0 dollars. Details are shown in Tables 1 and 2.

RJL/cjd

Enclosures
- Table 1: Recommended General and Digital Test Equipment for Each Array Element.
- Table 2: Recommended General and Digital Test Equipment for the Array Operations Center.

TABLE 1

Recommended General and Digital Test Equipment for Each Array Element. This supplements VLBA Memo 48.

Item	Comments	Cost
Chart Recorder	2 pen; thermal writing HP 7130A Option 54 or equivalent...	$ 2,680
Volt-Amp-Ohm Meters ..	Portable; one analog, one digital	400
Current Probe	Hand-held 10A/V or 100A/V F.W. Bell, CG 100A or equivalent ..	330
RS 232 Bus Analyzer ..	IDS Model 60 or equivalent	240
Function Generator ...	≤ 5 MHz; sine; square, etc. HP 3310B or equivalent	1,075
Logic Analyzer	Tek 308 or equivalent	3,950
Power Supplies	0-60 V, 10A (quantity 2) .... 0-60 V, 50A (quantity 2)	1,750 3,000
Miscellaneous Tools ..	....	1,000
Total		$15,225

TABLE 2

Recommended General and Digital Test Equipment for the Array Operations Center.
This supplements VLBA Memo 48.

Item	Comments	Cost
Oscilloscope	500 MHz BW, with accessories Tek 7904 or equivalent	$19,333
Oscilloscope	250 MHz BW, with accessories Tek 475A or equivalent	5,245
Volt-Ohm Meters	Digital and Analog (quantity 3) ...	600
Pulse Generator	250 MHz, variable PW, delays, etc., HP 8082A or equivalent	4,725
Function Generator ...	General purpose HP 3310B or equivalent	1,075
Dumb Terminal	RS-232	700
Logic Analyzer	Paratronics 540 or equivalent	9,000
Counter Timer	0-100 MHz; time; time interval HP 5328A or equivalent	1,725
Power Supplies	0-60 V, 10A (quantity 2) .... 0-60 V, 50A (quantity 2)	1,750 3,100
Solder Station	....	400
Chart Recorder	2 pen; thermal writing HP 7130A Option 54 or equivalent ...	2,680
UHF Oscillator	10-500 MHz	2,950
Miscellaneous Tools ..	....	1,500
Total		$54,783

VLB ARRAY MEMO No. 53

January 7, 1982

Suggested Numbers of Spare Modules for the VLB Array

A. R. Thompson

This memorandum describes an investigation of the failure rates of VLA modules, and the use of these data to estimate the numbers of spare modules required for the VLB array. It is assumed that the electronics for the VLB array will be subdivided into modules of similar complexity and reliability to those used in the VLA.

1. VLA Reliability Data

The VLA data have been taken from the maintenance records that are on file in a computer data base and can be accessed through a program (MAINT) which sorts records and produces various statistical data. Jon Spargo has been largely responsible for the organization of this facility. The data of interest here are the mean times between failures (MTBF) for different types of modules. In this study 'failure' refers to any condition that results in the generation of a maintenance request, and includes hardware failures, cases where some adjustment was necessary, and cases where the fault could not be found when maintenance was performed. Table 1 lists the numbers of failures and the MTBF per module for 33 types of modules for the 15-month period October 1, 1980 through December 30, 1981. Data for the last six months of this period were also examined separately and did not show any significant changes. Table 1 also contains figures for ten non-modular units that are not included in the following statistics.

The distribution of MTBF values is shown in Table 2. Two main conclusions can be drawn. First, roughly equal numbers of modules fall within the four MTBF categories <1000 days, 1000-2000 days, 2000-4000 days, >4000 days. Second, there does not appear to be much correlation between the MTBF and the subsystem of the module (front-end, local oscillator, etc.). The modules with poorest reliability include the F3 (17-20 GHz L.O.) which contains a frequency-agile, phase-lock loop; the D1 (Sampler) for which adjustment is known to rather critical; the F5 (Front-End Control); and the T5 (Baseband Driver) which contains a problem that we expect to eliminate.

2. Application to the VLB Array

Those electronics modules at a VLB antenna for which a failure would put the whole antenna out of operation are in a special category and will be referred to as critical modules. For such modules a spare will have to be carried at each site. For the non-critical modules we assume the following scheme will apply. The spares will be kept at a central maintenance location, and when a module fails at an antenna the operator at that site will request shipment of a spare. The failed module will be immediately shipped back to the central location where it will be repaired and become a spare unit. It will be assumed that the time interval from shipment of the spare to the antenna to the completion of repair of the returned unit does not exceed five days. As a criterion for the number of spares to be carried, let us state that for each type of module the probability that all spares are out in the return-and-repair process must not exceed 1%.

Suppose that there are N_m of a particular type of module in each of the 10 antennas in the array. The mean failure rate for that particular type of module is 10 N_m/MTBF failures per day, where MTBF is in days. the probability, P, that one module of a particular type will be in the return-and-repair process is 50 N_m/MTBF. Thus we require

$$P^n = (50\ N_m/\text{MTBF})^n < 0.01$$

where n is the number of spares of the particular module type to be carried at the central location. Table 3 gives values of n for modules with MTBF values of 500, 1500, 2500 and >4000 days, which are representative of the four categories within which the VLA modules are roughly equally distributed. For each MTBF category values of N_m = 1, 2 and 4 are considered. For 75% of the cases in Table 3, n = 2, and the mean of n for all cases is 2.4. However, since the types of modules for which there are four units at an antenna are likely to less than 1/3 of all types, the mean value of n that is finally required may be less than 2.4. As a round figure for costing purposes 2½ spares per module type is suggested for the non-critical types. This is a fairly conservative figure, and one could argue in favor of a larger number to offset lower initial reliability, loss of modules in transit, etc.

When one of the critical modules fails it will be replaced by the on-site spare and the failed unit will be returned for repair. Two courses of action are then possible. Another spare can be sent out immediately from the central location, or else the failed unit can be repaired and returned. In the first case the mean number of spares required per critical module type is $10 + 2\frac{1}{2} = 12\frac{1}{2}$, and in the second case just 10.

Table 1 Maintenance Statistics for VLA Electronics, 80/09/01 to 81/12/30

Type of Unit	No. of Failures	MTBF (days)
Front End (Uncooled)		
F1, Bias Control	2	12,000
F4, Freq. Converter	6	4,000
F5, F.E. Control	24	500
F6, RF Splitter	4	2,200
F7, Ant. IF Filters	0	
F8, IF Offset	0	
LO (Antenna)		
F2, Upconv. Pump	16	750
F3, 17-20 GHz LO	69	170
L1, 5-50 MHz VCXO	6	2,000
L2, Harmonic Gen	1	12,000
L3, LO Tx	11	1,100
L4, LO Rx	6	2,000
L5, LO Control	6	2,000
L6, 2-4 GHz Synth.	37	650
L7, Fringe Gen.	6	4,000
L8, Timing Gen.	14	860
LO (Central)		
L9, Ant. LO Rx	6	2,000
L10, Ant. LO Tx	0	
L11, Ant. LO Control	6	6,000
L14, Ant. LO Filter	12	1,000
Transmission		
T1, Modem	17	1,400
T2, IF Combiner	12	2,000

Type of Unit	No. of Failures	MTBF (days)
IF Receiver		
T3, Baseband Conv.	2	4,500
T4, Baseband Filters	7	2,600
T5, Baseband Driver	65	280
T6, Baseband Cont.	4	2,200
Sampler		
D1, Sampler	43	560
Monitor & Control		
M1, Data Set	22	2,800
M2, Data Tap	0	
M3, Central Buffer	9	1,400
M4, Antenna Buffer	7	1,800
M7, F/R Control	7	1,700
M8, F/R Power	6	2,000
Non-Modular Units		
Refrigerator	56	214
Compressor	25	480
Vac. Pump	1	12,000
Dewar	1	12,000
Upconverter	3	8,100
Paramp	17	1,700
KU-Mixer	4	6,000
K-Mixer	17	1,400
Coax Switch	5	4,800
Paramp Pump	16	1,500

Table 2 MTBF Categories

MTBF (days)	No. of Module Types
<1000	7
1000-2000	9
2000-4000	8
>4000	9

Table 3 Calculation of Required Numbers of Spares, n.

MTBF Category (days)	Mean MTBF (days)	N_m = 1 per Ant.		N_m=2 per Ant.		N_m=4 per Ant.	
		P (%)	n	P (%)	n	P (%)	n
<1000	500	10	2	20	3	40	5
1000-2000	1500	3.3	2	6.7	2	13	3
2000-4000	3000	1.6	2	3.3	2	6.7	2
>4000	>4000	<1.3	2	<2.5	2	<5	2

ART/tr

March 5, 1982

VLBA ELEMENT OPERATING PROBABILITY USING VLA RELIABILITY DATA

Jack Campbell

This memorandum defines Optimum Reliability, and discusses the VLA reliability experience as related to the VLB array, VLBA element operating probability, and gives a Summary of results. It is assumed that the VLB array will be of modular design and its modules will be typical of modules used in the VLA. This simple analysis will provide some data to allow operating system trade-off vs the "Suggested Number of Spare Modules for the VLB Array" by A.R. Thompson in his memorandum (VLBA Number 53) date January 7, 1982.

I Optimum Reliability

Deciding what type of system provides the minimum total life cost concerns basically the following extreme design approaches:

a) A system design that requires a large number of spare units. This approach has a high maintenance and repair cost with the added cost of equipment unable to operate.

b) A highly reliable system with its high design cost and more expensive component cost.

c) These two approaches will most likely be comparable in total life cost. The minimum total life cost lies somewhere in between and therefore is the Optimum Reliability Point. This optimum reliability point reflects a moderate initial design and component cost and a reasonable (small) number of spares and reduced maintenance and repair cost. The total life cost of these two approaches is depicted graphically in Figure 1.

II VLA Reliability Experience as Related to the VLB Array

If we assume the 10 element VLB array is of similar design to the 27 element VLA design and that Critical Modules (A critical module if failed would put the whole element out of operation) can be cross shipped from the Central Maintenance Station or a secondary distribution station to a site in 24 hrs or less.

Then based on the above assumptions we can use the VLA experience to predict the VLBA reliability.

a) Probability of Failure [1] of an array element is given by

$$P = \frac{MTTR+T_A}{MTBF}$$

where

P = probability of failure

MTTR = Meantime To Repair

T_A = Access Time

MTBF = Mean Time Between Failures

For the VLA and VLBA the MTTR is small compared to T_A. Then we can simplify P to

$$P = \frac{T_A}{MTBF}$$

The average access time for the VLA is 12 hours. The average access time for the VLBA could be in the range 29 to 43 hours with an average of 36 hours as shown in Table I.

Then $P_{(VLBA)}$ becomes

$$P_{(VLBA)} = P_{(VLA)} \times \frac{T_{A\ (VLBA)}}{T_{A\ (VLA)}}$$

Using the VLA Summary of Downtime for 1981 we can predict the downtime for the VLBA. (See Appendix I). For example, for T_A(VLBA) = 24 hours.

$$\text{Critical Modules } P_{(VLBA)} = 1.54 \times \frac{24}{12} = 3.08\%$$

$$\text{Total System } P_{(VLBA)} = (1.54 + 1.69) \frac{24}{12} = 6.46\%$$

III VLBA Element Operating Probability. We can relate $P_{(VLBA)}$ to the probability of >N Antennas Operating [1] by the probability of "P_k" of "K" failures in an "N" element array. P_k is given by the binomial distribution.

$$P_K = \frac{N!}{K!\ (N-K)} \times P^K \times (1-p)^{N-K}$$

This binomial distribution for a 10 element array is shown in Figure 2 and 3. From Figure 2 and 3 we can see that for a $P_{(VLBA)}$ calculated for T_A of 0.5, 1, 2 and 3 day the operational probability will be as shown in TABLE II, and Figures 4, 5 and 6.

Access times of 1 to 2 days appear to provide a reasonable operational goal.

IV Summary

a. It is beyond the scope of this memorandum to assign costs to >N elements operating and the associated lost data and the cost trade-off for reliability vs design cost to predict the curve shown in Figure 1.

b. All critical modules do not have to be stocked at each site.

c. The shipping time of 24 hours can be reduced to 12 hours in special cases while a compromise of critical module spares kept at the site would improve the reliability at an additional total life cost.

d. A cost trade-off study of critical module size and weight Vs shipping cost should be under taken.

e. Design considerations for equipment safety vs critical modules should be considered i.e. capability of manually or automatically driving the antenna to the stow position with a defective antenna control unit.

f. System performance without a cryogenic system operating or one frequency band not operating for a short period of time should be considered. All of the above items and other considerations will determine the total life cost and therefore the optimum reliability.

JC/bg

REFERENCES

1) VLA Reliability and Maintenance

An Early Look

Balister, Fisher, Pyane and Weinreb

VLA Electronics Memorandum #165

2) VLA Summary of Downtime for 1981

Table I

Average Access Time (T_A) For Two Possible VLBA Sites

Site Location	Trouble occurs	Module Transportation Schedule* LV Socorro**	Arr Alb	Arr Airport Near Site	Installed** At Site	Access Time
Anchorage Al	0500	0900	1100	2300	1200	31
	1700	0900	1100	2300	1200	43
Bishop CA	0500	0900	1100	0800	1000	29
	1700	0900	1100	0800	1000	41

Average Access Time (T_A) = 36

* Module Transportation Schedule was arrived at using official Airline Guide - North American Edition.

** 1. Working Hours

Assume each site work 0800 to 1700 Local Standard Time

2. Times

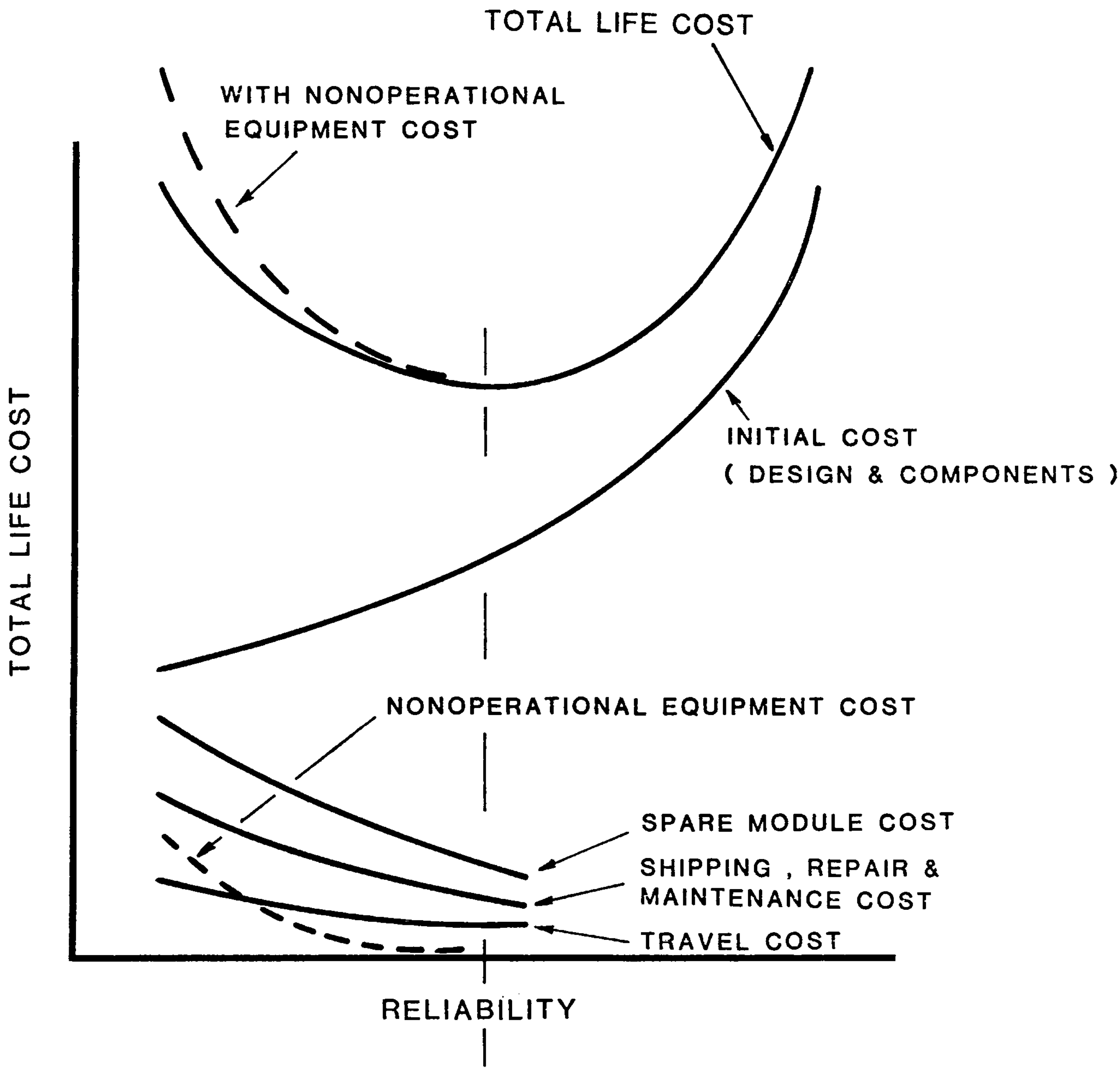
All Times listed are Mountain Standard Time for Alaska/Hawaii Standard Time Subtract 3 hours for Pacific Standard Time Subtract 1 hour.

TABLE II

PROBABILITY OF >N ANTENNAS

OPERATIONAL

>N	SYSTEM OPERATING CONDITION							
	SOME DEGRADATION				COMPLETE OPERATION			
T_A=	0.5	1	2	3	0.5	1	2	3
10	85	74	53	38	72	52	25	11
9	98.9	96.2	87	76	96.2	87	62	39
8	99.95	99.7	97.8	94	99.68	97.6	86.5	69
7	>99.99	99.8	99.7	98.9	99.98	99.7	96.8	85



TOTAL LIFE COST vs RELIABILITY

FIGURE 1

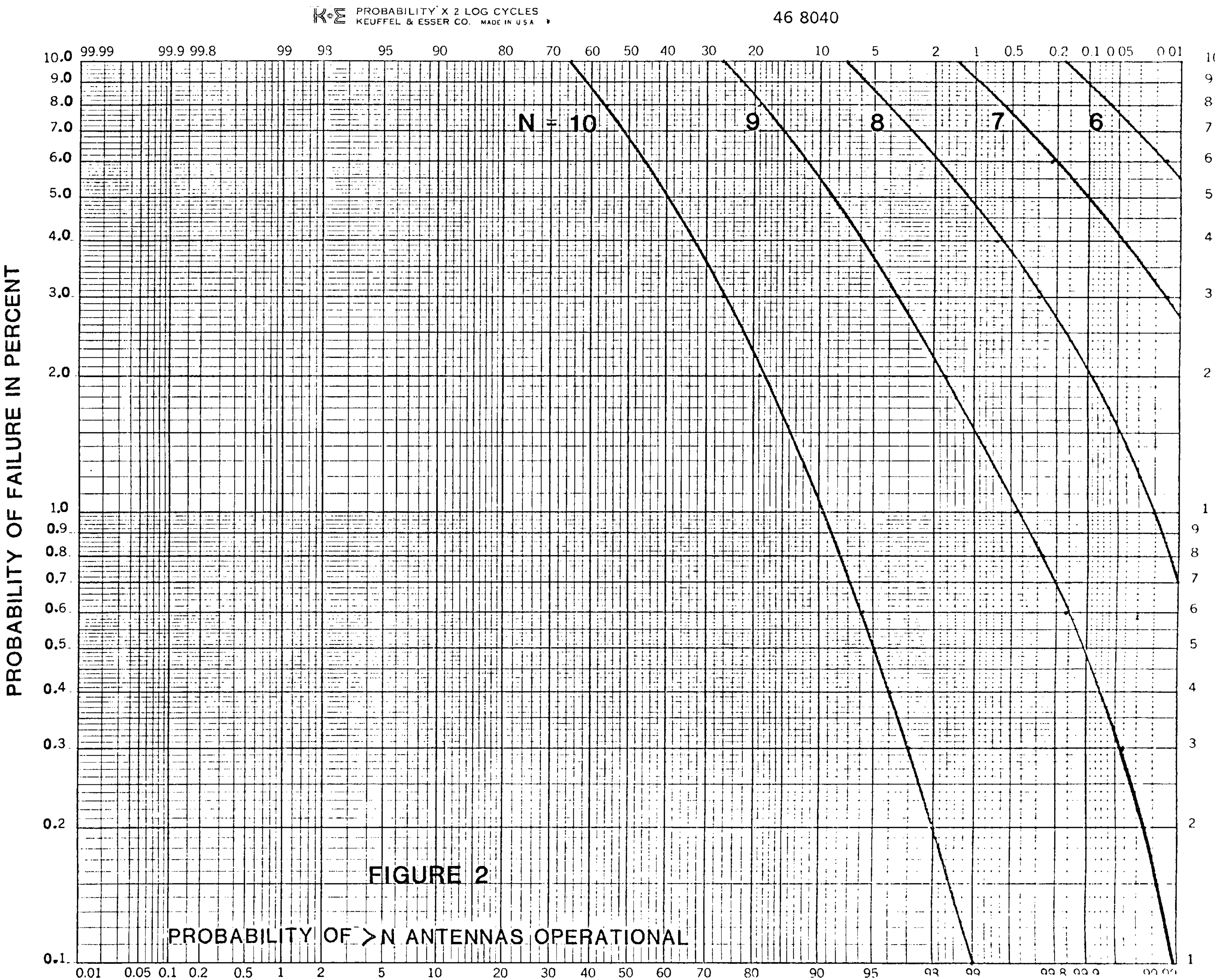


FIGURE 2

PROBABILITY OF >N ANTENNAS OPERATIONAL

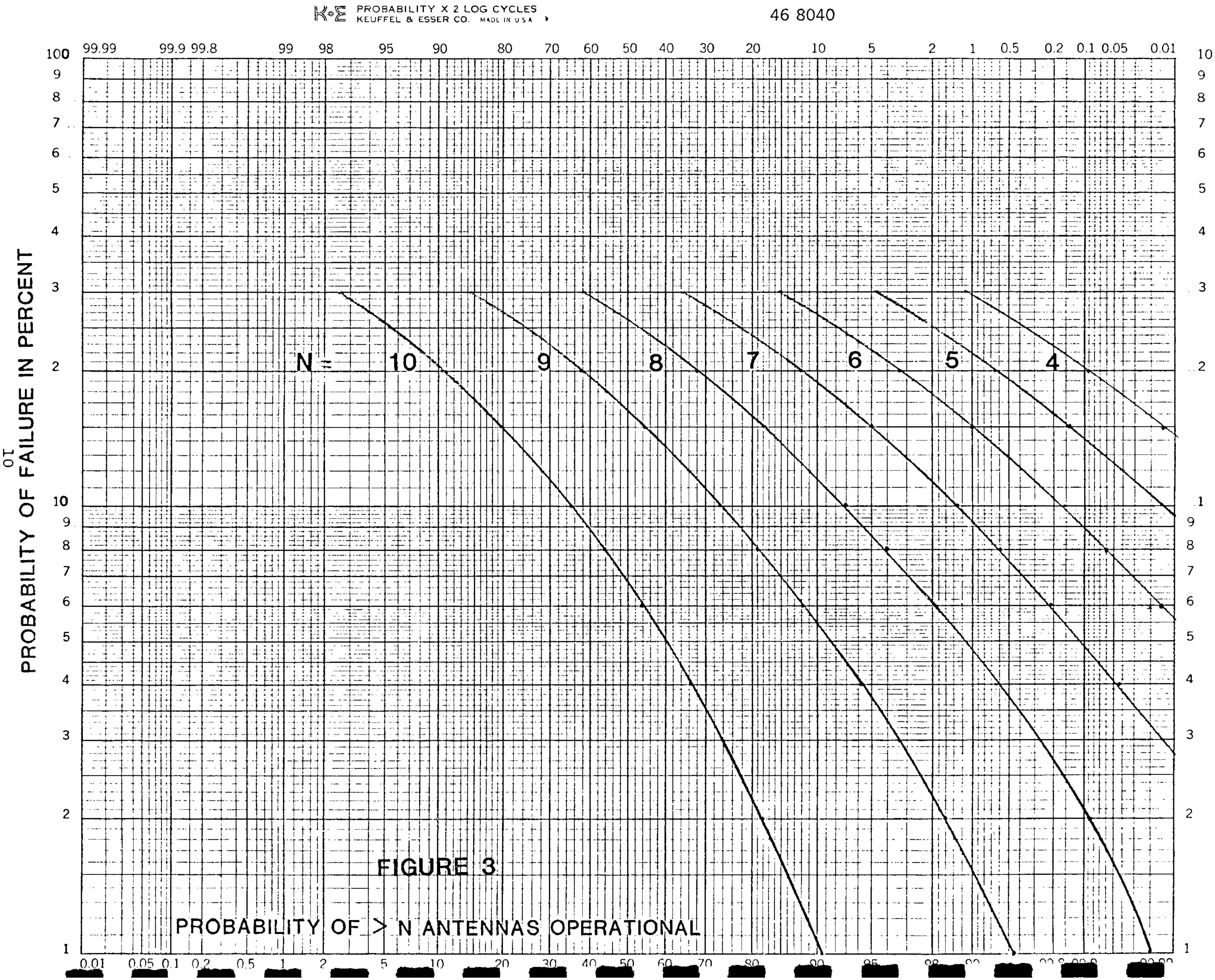
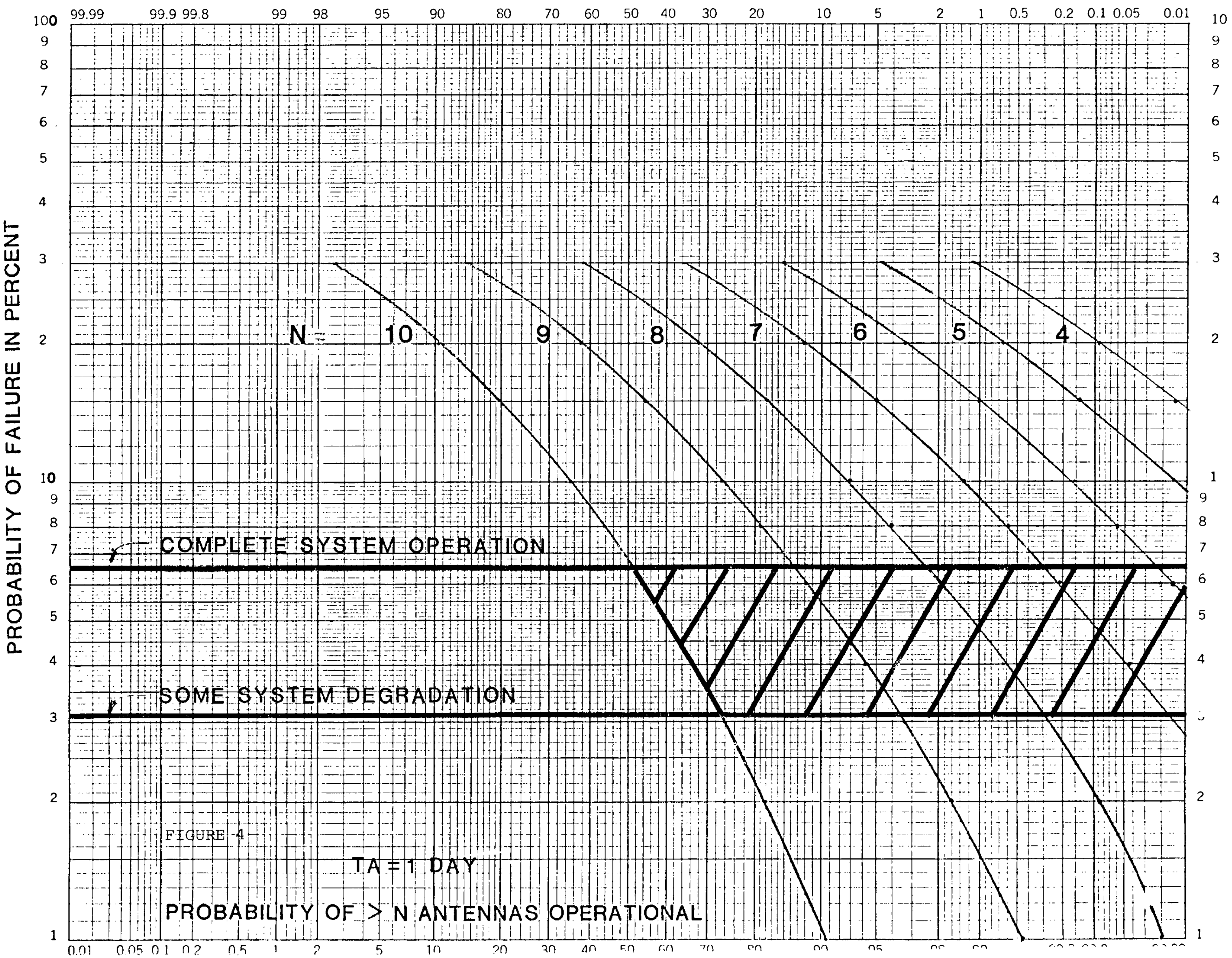


FIGURE 3

PROBABILITY OF > N ANTENNAS OPERATIONAL

PROBABILITY X 2 LOG CYCLES [redacted]
[redacted] EUFF [redacted] SSER [redacted] E IN U S [redacted]

46[redacted]0



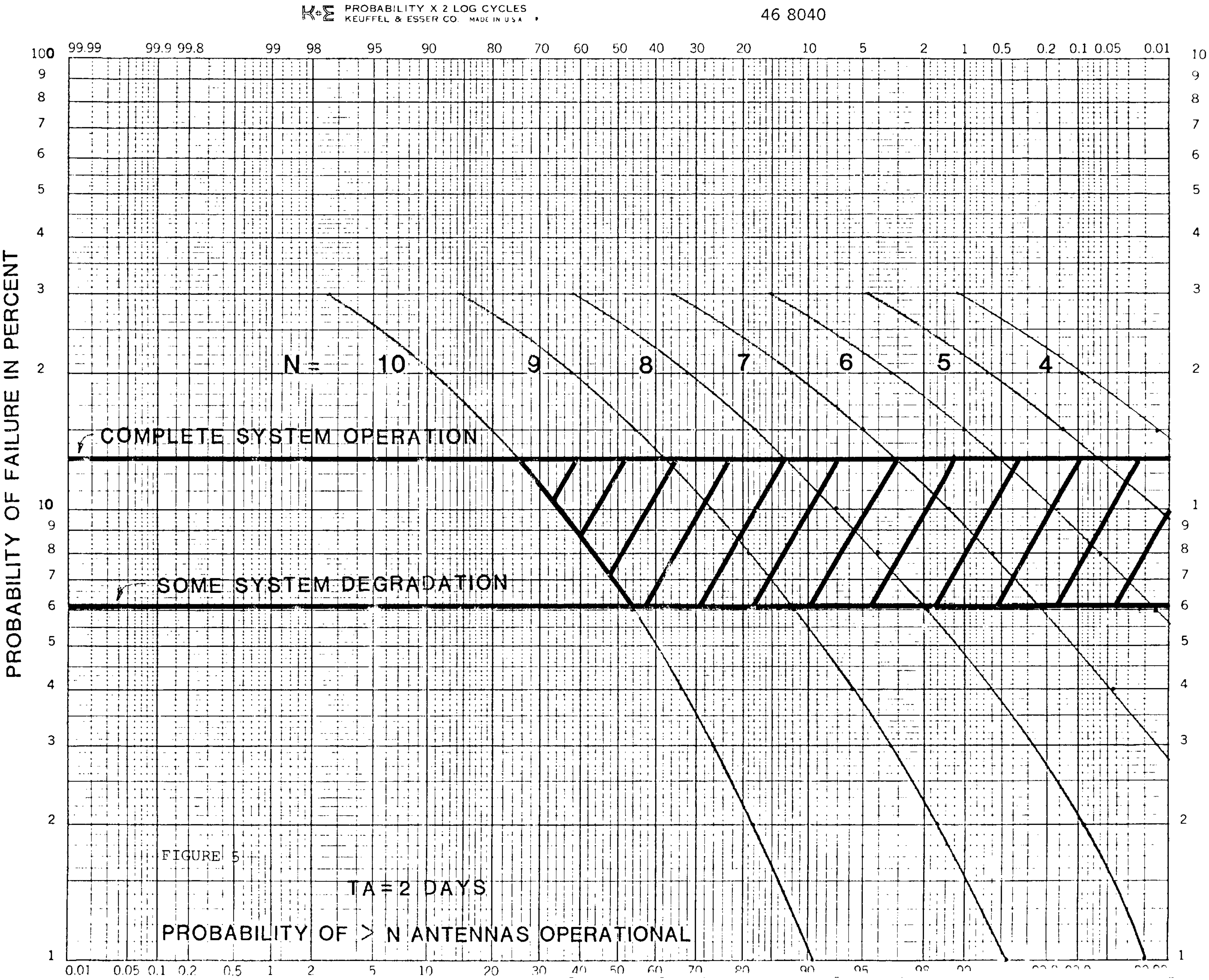
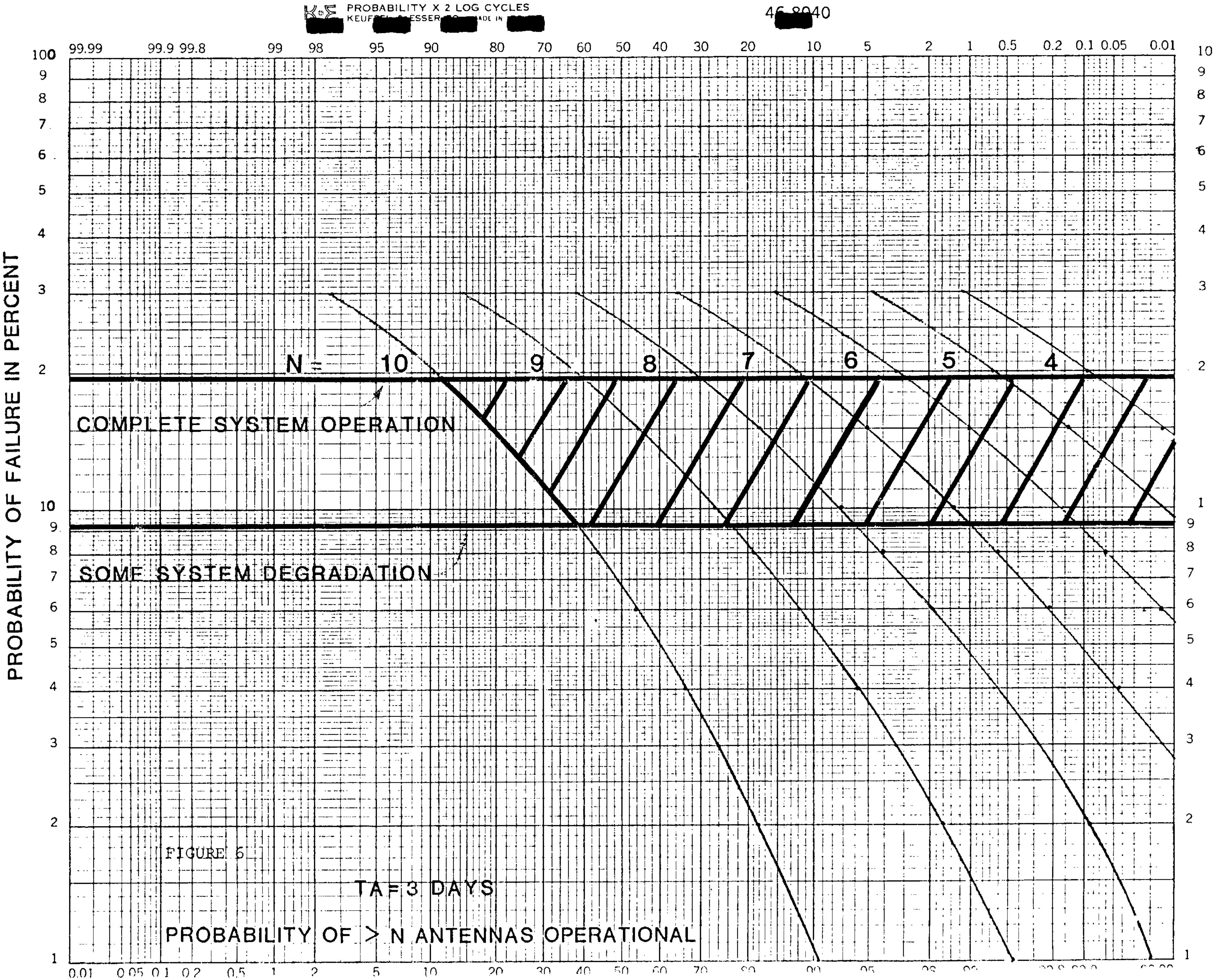


FIGURE 5

TA = 2 DAYS

PROBABILITY OF > N ANTENNAS OPERATIONAL


PROBABILITY X 2 LOG CYCLES
KEUF[redacted]ESSER[redacted]ADE IN [redacted]
46-[redacted]40
PROBABILITY OF FAILURE IN PERCENT
N = 10 9 8 7 6 5 4
COMPLETE SYSTEM OPERATION
SOME SYSTEM DEGRADATION
FIGURE 6
TA=3 DAYS
PROBABILITY OF > N ANTENNAS OPERATIONAL

Appendix I

The VLA Downtime Summary for the year 1981 was reviewed and used to define the critical and non-critical areas. The critical are defined as that area that will remove the whole element (Antenna System) from operation. The results of this review is shown in TABLE I of this Appendix.

APPENDIX I
TABLE I
DOWNTIME BREAKDOWN
BY SUB-SYSTEM OR CATEGORY

SUB-SYSTEM OR CATEGORY	TOTAL VLA %	VLBI CRITICAL	VLBI NON-CRITICAL	REMARKS
ANTENNA MECHANICAL	0.24	0.24		
ANTENNA ELECTRICAL	0.34	0.34		
FRONT END COOLED	0.46		0.46	System will operate but not on all Frequencies
FRONT END UNCOOLED	0.39		0.39	System will operate but not on all Frequencies
CRYOGENICS	0.35		0.35	System will operate but with degraded performance
MONITOR AND CONTROL	0.38	0.19	0.19	Monitor not as critical as control
FOCUS/ROTATION	0.11		0.11	Present system being redesigned.
WAVEGUIDE	0.01			Not required VLBI
L.O. ANTENNA	0.19	0.19		
L.O. CENTRAL	0.05	0.05		
IF TRANSMISSION	0.03			Not require VLBI
IF RECEIVERS & SAMPLERS	0.06		0.06	
DELAY AND MULTIPLIER	0.27			Off Line for VLBI
COMPUTER HARDWARE	0.40	0.40		
OTHER HARDWARE	0.02		0.02	
HU-ERROR	0.13	0.13		
SOFTWARE	1.41			Manpower priority can be fixed
WEATHER	0.29			Not the same at each site
POWER	0.20			Not the same at each site
UNSCHEDULED TEST	0.01		0.01	
P/M, RETRO, EXP MODULES	0.10		0.10	
TOTAL	5.44	1.54	1.69	

Interoffice

National Radio Astronomy Observatory

Charlottesville, Virginia

June 9, 1982

To: VLBA Planning Group

VLB ARRAY MEMO No. 92

From: H. Hvatum

Subject: Construction Plan/Schedule for the VLBA

VLBA memo #20 is a first attempt to design a construction plan/schedule for the VLBA. It was done sometime in 1980. Here is an updated version of that plan. It has many flaws and some of it might be outright silly, but it is a starting point. The only updating I have done is to change the date for available construction funds to January 1984 and the date to start planning and preparations for the construction to January 1982.

I believe we now should detail the plan for what we want to do between now and January 1984. In order to do so, I intend to set up working groups for the different areas such as:

Configuration

Site design/planning

Antenna design/planning

Electronics (receiver) design/planning

Data acquisition system design/planning

Processor design/planning

Computer design/planning

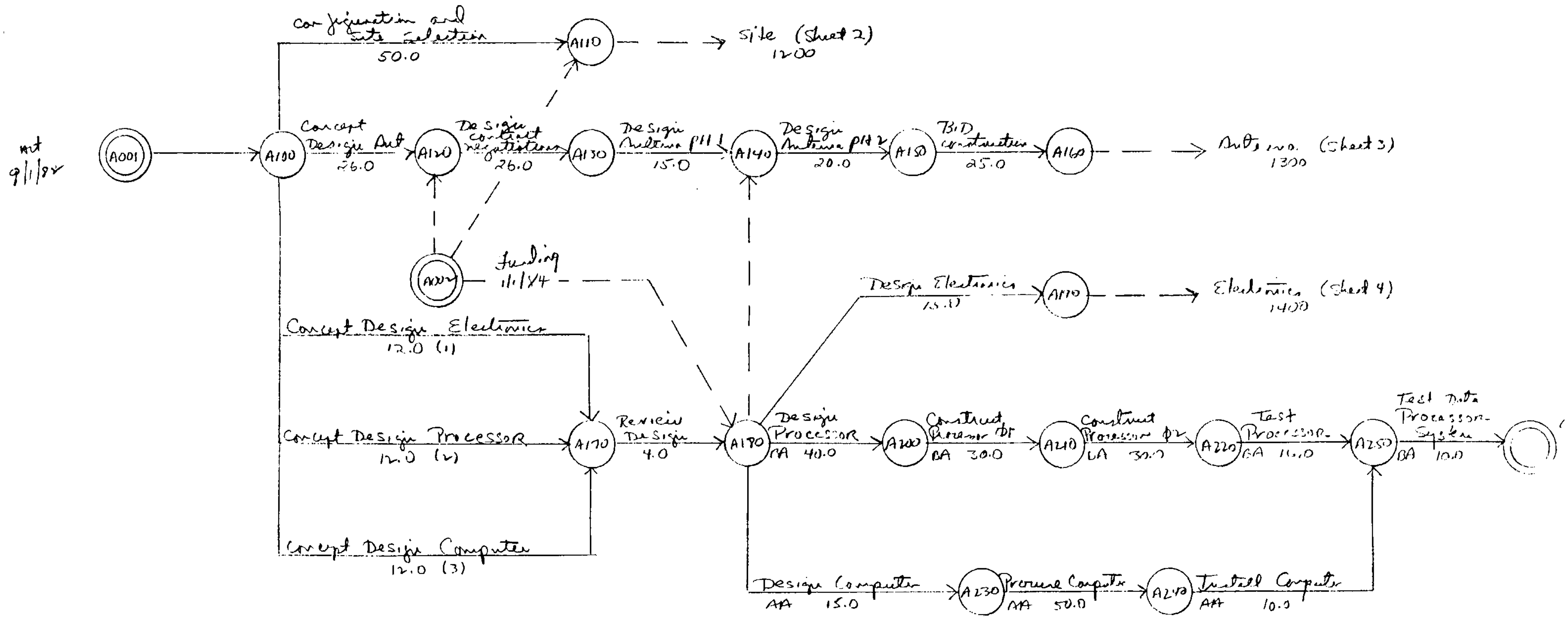
In addition I would like to establish an "overseer" group composed of the various design group leaders to work on the overall design/planning.

We shall discuss this in our meeting on Monday, 14 June 1982, 1330 EDT. The telephone number to call is 1-800-243-1055.

Attachment

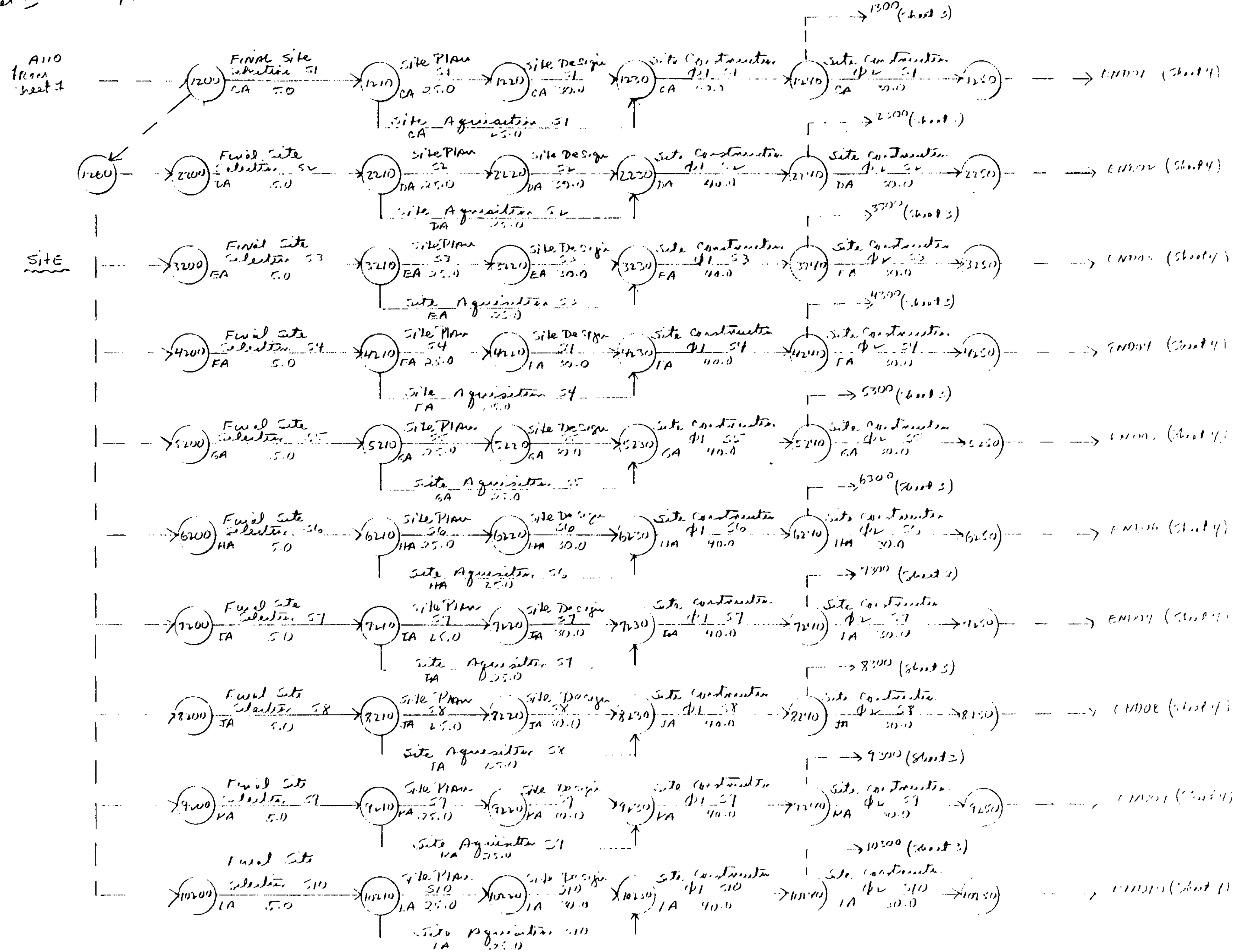
sheet 1

Array 10



VLBA
PERT
820517

Sheet 2 of 10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SITE
1200
Final Site Selection S1
CA 5.0
1210
Site Plan S1
CA 25.0
1220
Site Design S1
CA 30.0
1230
Site Construction Φ1 S1
CA 40.0
1240
Site Construction Φ2 S1
CA 30.0
1250
END01 (Sheet 4)
1300 (sheet 3)
Site Aquisition S1
CA 25.0
1260
2200
Final Site Selection S2
DA 5.0
2210
Site Plan S2
DA 25.0
2220
Site Design S2
DA 30.0
2230
Site Construction Φ1 S2
DA 40.0
2240
Site Construction Φ2 S2
DA 30.0
2250
END02 (Sheet 4)
2300 (sheet 3)
Site Aquisition S2
DA 25.0
3200
Final Site Selection S3
EA 5.0
3210
Site Plan S3
EA 25.0
3220
Site Design S3
EA 30.0
3230
Site Construction Φ1 S3
EA 40.0
3240
Site Construction Φ2 S3
EA 30.0
3250
END03 (Sheet 4)
3300 (sheet 3)
Site Aquisition S3
EA 25.0
4200
Final Site Selection S4
FA 5.0
4210
Site Plan S4
FA 25.0
4220
Site Design S4
FA 30.0
4230
Site Construction Φ1 S4
FA 40.0
4240
Site Construction Φ2 S4
FA 30.0
4250
END04 (Sheet 4)
4300 (sheet 3)
Site Aquisition S4
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5200
Final Site Selection S5
GA 5.0
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6200
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Site Plan S6
HA 25.0
6220
Site Design S6
HA 30.0
6230
Site Construction Φ1 S6
HA 40.0
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Site Construction Φ2 S6
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Site Design S7
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Site Construction Φ1 S7
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Site Construction Φ2 S7
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Site Plan S8
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Site Design S8
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Site Construction Φ2 S8
JA 30.0
8250
END08 (Sheet 4)
8300 (sheet 3)
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KA 5.0
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Site Plan S9
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Site Design S9
KA 30.0
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Site Construction Φ1 S9
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Site Construction Φ2 S9
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9300 (sheet 3)
Site Aquisition S9
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LA 5.0
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Site Plan S10
LA 25.0
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Site Design S10
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Site Construction Φ1 S10
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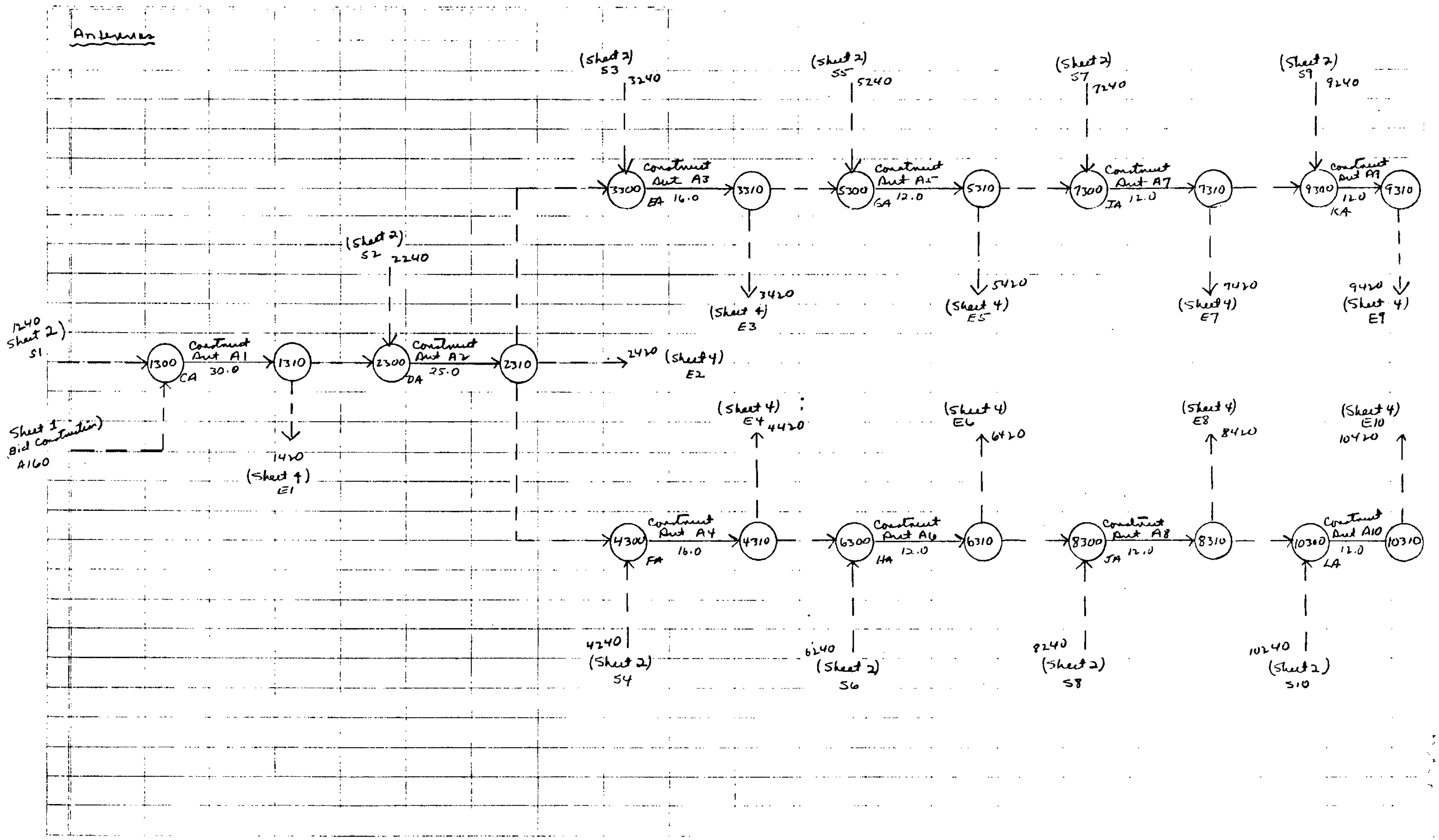
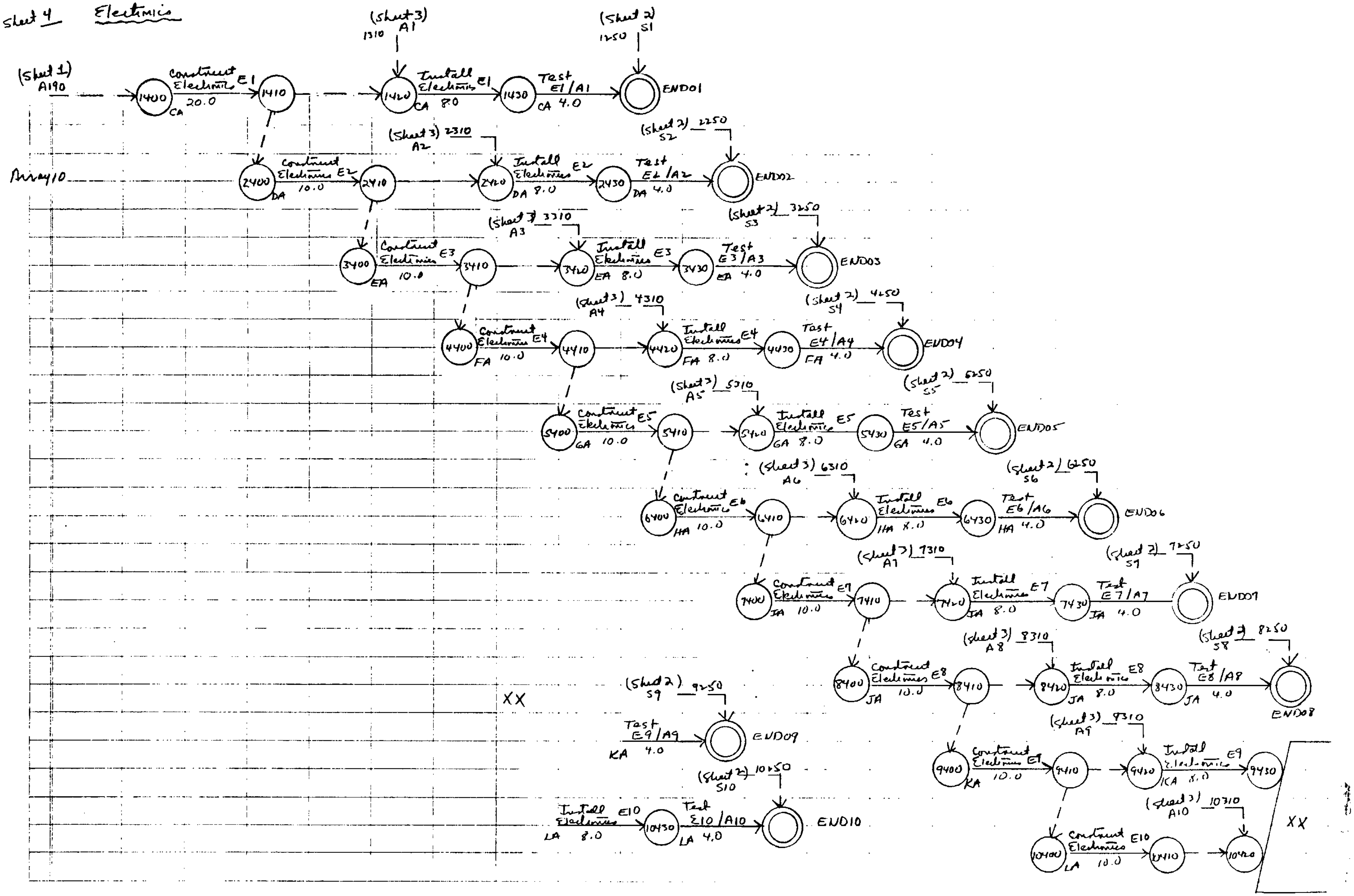
Site Construction Φ2 S10
LA 30.0
10250
10300 (sheet 3)
Site Aquisition S10
LA 25.0

Sheet 3 Array 10



Sheet 4 Electronics



NATIONAL RADIO ASTRONOMY OBSERVATORY
ACTIVITY TIME S[illegible] REPORT

PROGRAM 17MAY82 REPORT DATE. VERY LONG BASELINE ARRAY — VLB10A — RUN DATE 18M[illegible]
PROJECT CONCEPTS, DESIGN AND DEVELOPMENT — VLBA10

LEVEL DETAIL — SORTED BY PRED,SUCC

PRED EVENT	SUCC EVENT	CY. CD.	ACTIVITY DESCRIPTION	TIME EST	SLACK PRIM.	SLACK SEC.	EARLY DATES START	EARLY DATES FINISH	LATE DATES START	LATE DATES FINISH	SCHED.	DEPT
	A001 S		BEGIN ORGANIZATION		47.2		A04JAN82	A04JAN82	06DEC82	06DEC82		
	A002 S		FUNDING		.0		A02JAN84	A02JAN84	02JAN84	02JAN84		
A001	A100		GET ORGANIZED	05.0	47.2		A04JAN82	08FEB82	06DEC82	10JAN83		
A002	A110		DUMMY	0000	.0		A02JAN84	02JAN84	02JAN84	02JAN84		
A002	A120		DUMMY	0000	14.0		A02JAN84	02JAN84	10APR84	10APR84		
A002	A180		DUMMY	0000	.0		A02JAN84	02JAN84	02JAN84	02JAN84		
A100	A110		CONFIG. & SITE SELECTION	50.0	47.2		08FEB82	28JAN83	10JAN83	02JAN84		
A100	A120		CONCEPT DESIGN ANTENNA	26.0	85.2		08FEB82	11AUG82	07OCT83	10APR84		
A100	A170 3		CONCEPT DES COMPUTER	12.0	81.2		08FEB82	05MAY82	09SEP83	05DEC83		
A100	A170 2		CONCEPT DES PROCESSOR	12.0	81.2		08FEB82	05MAY82	09SEP83	05DEC83		
A100	A170 1		CONCEPT DES ELECTRONICS	12.0	81.2		08FEB82	05MAY82	09SEP83	05DEC83		
A110	1200		DUMMY	0000	.0		02JAN84	02JAN84	02JAN84	02JAN84		
A120	A130		NEGOTIATE DES CONTRACT	26.0	14.0		02JAN84	05JUL84	10APR84	12OCT84		
A130	A140		DESIGN ANTENNA PH 1	15.0	14.0		05JUL84	19OCT84	12OCT84	30JAN85		
A140	A150		DESIGN ANTENNA PH 2	20.0	14.0		19OCT84	15MAR85	30JAN85	24JUN85		
A150	A160		BID CONSTRUCTION	25.0	14.0		15MAR85	11SEP85	24JUN85	19DEC85		
A160	1300		DUMMY	0000	14.0		11SEP85	11SEP85	19DEC85	19DEC85		
A170	A180		REVIEW DESIGN	04.0	81.2		05MAY82	02JUN82	05DEC83	02JAN84		
A180	A140		DUMMY	0000	55.0		02JAN84	02JAN84	30JAN85	30JAN85		
A180	A190		DESIGN ELECTRONICS	15.0	82.0		02JAN84	17APR84	13AUG85	27NOV85		
A180	A200	BA	DESIGN PROCESSOR	40.0	.0		02JAN84	12OCT84	02JAN84	12OCT84		
A180	A230	AA	DESIGN COMPUTER	15.0	41.0		02JAN84	17APR84	19OCT84	06FEB85		
A190	1400		DUMMY	0000	82.0		17APR84	17APR84	27NOV85	27NOV85		
A200	A210	BA	CONSTRUCT PROCESSOR PH 1	30.0	.0		12OCT84	17MAY85	12OCT84	17MAY85		
A210	A220	BA	CONSTRUCT PROCESSOR PH 2	30.0	.0		17MAY85	19DEC85	17MAY85	19DEC85		
A220	A250	BA	TEST PROCESSOR	16.0	.0		19DEC85	15APR86	19DEC85	15APR86		
A230	A240	AA	PROCURE COMPUTER	50.0	41.0		17APR84	12APR85	06FEB85	03FEB86		
A240	A250	AA	INSTALL COMPUTER	10.0	41.0		12APR85	24JUN85	03FEB86	15APR86		
A250	END11	BA	TEST DATA PROCESSOR SYS	10.0	.0		15APR86	25JUN86	15APR86	25JUN86		
1200	1210	CA	FINAL SITE SELECTION S1	05.0	.0		02JAN84	06FEB84	02JAN84	06FEB84		
1200	1260		DUMMY	0000	30.0		02JAN84	02JAN84	02AUG84	02AUG84		
1210	1220	CA	SITE PLAN S1	25.0	.0		06FEB84	02AUG84	06FEB84	02AUG84		
1210	1230	CA	SITE ACUISITION S1	25.0	30.0		06FEB84	02AUG84	07SEP84	08MAR85		
1220	1230	CA	SITE DESIGN S1	30.0	.0		02AUG84	08MAR85	02AUG84	08MAR85		
1230	1240	CA	SITE CONSTR. PH 1 S1	40.0	.0		08MAR85	19DEC85	08MAR85	19DEC85		
1240	1250	CA	SITE CONSTR. PH 2 S1	30.0	12.0		19DEC85	24JUL86	18MAR86	17OCT86		
1240	1300		DUMMY	0000	.0		19DEC85	19DEC85	19DEC85	19DEC85		
1250	END01		DUMMY	0000	12.0		24JUL86	24JUL86	17OCT86	17OCT86		
1260	2200		DUMMY	0000	30.0		02JAN84	02JAN84	02AUG84	02AUG84		
1260	3200		DUMMY	0000	53.0		02JAN84	02JAN84	16JAN85	16JAN85		
1260	4200		DUMMY	0000	53.0		02JAN84	02JAN84	16JAN85	16JAN85		
1260	5200		DUMMY	0000	65.0		02JAN84	02JAN84	12APR85	12APR85		
1260	6200		DUMMY	0000	65.0		02JAN84	02JAN84	12APR85	12APR85		
1260	7200		DUMMY	0000	77.0		02JAN84	02JAN84	09JUL85	09JUL85		
1260	8200		DUMMY	0000	77.0		02JAN84	02JAN84	09JUL85	09JUL85		
1260	9200		DUMMY	0000	89.0		02JAN84	02JAN84	02OCT85	02OCT85		
1260	10200		DUMMY	0000	89.0		02JAN84	02JAN84	02OCT85	02OCT85		
1300	1310	CA	CONSTRUCT, ANTENNA A1	30.0	.0		19DEC85	24JUL86	19DEC85	24JUL86		
1310	1420		DUMMY	0000	.0		24JUL86	24JUL86	24JUL86	24JUL86		
1310	2300		DUMMY	0000	.0		24JUL86	24JUL86	24JUL86	24JUL86		

PROGRAM 17MAY82 REPORT DATE. VERY LONG BASELINE ARRAY VLBIOA RUN DATE 18M.
PROJECT CONCEPTS, DESIGN AND DEVELOPMENT VLBA10

LEVEL DETAIL SORTED BY PRED,SUCC

PRED EVENT	SUCC EVENT	CY. CD.	ACTIVITY DESCRIPTION	TIME EST	SLACK PRIM.	SEC.	EARLY START	DATES FINISH	LATE START	DATES FINISH	SCHED.	DEPT
1400	1410	CA	CONSTR. ELECTRONICS E1	20.0	82.0		17APR84	07SEP84	27NOV85	22APR86		
1410	1420		DUMMY	0000	95.0		07SEP84	07SEP84	24JUL86	24JUL86		
1410	2400		DUMMY	0000	82.0		07SEP84	07SEP84	22APR86	22APR86		
1420	1430	CA	INSTALL ELECTRONICS E1	08.0	.0		24JUL86	19SEP86	24JUL86	19SEP86		
1430	END01	CA	TEST E1/A1	04.0	.0		19SEP86	17OCT86	19SEP86	17OCT86		
2200	2210	DA	FINAL SITE SELECTION S2	05.0	30.0		02JAN84	06FEB84	02AUG84	07SEP84		
2210	2220	DA	SITE PLAN S2	25.0	30.0		06FEB84	02AUG84	07SEP84	08MAR85		
2210	2230	DA	SITE AQUISITION S2	25.0	60.0		06FEB84	02AUG84	12APR85	09OCT85		
2220	2230	DA	SITE DESIGN S2	30.0	30.0		02AUG84	08MAR85	08MAR85	09OCT85		
2230	2240	DA	SITE CONSTR. PH 1 S2	40.0	30.0		08MAR85	19DEC85	09OCT85	24JUL86		
2240	2250	DA	SITE CONSTR. PH 2 S2	30.0	37.0		19DEC85	24JUL86	12SEP86	16APR87		
2240	2300		DUMMY	0000	30.0		19DEC85	19DEC85	24JUL86	24JUL86		
2250	END02		DUMMY	0000	37.0		24JUL86	24JUL86	16APR87	16APR87		
2300	2310	DA	CONSTRUCT ANTENNA A2	25.0	.0		24JUL86	21JAN87	24JUL86	21JAN87		
2310	2420		DUMMY	0000	.0		21JAN87	21JAN87	21JAN87	21JAN87		
2310	3300		DUMMY	0000	.0		21JAN87	21JAN87	21JAN87	21JAN87		
2310	4300		DUMMY	0000	.0		21JAN87	21JAN87	21JAN87	21JAN87		
2400	2410	DA	CONSTR. ELECTRONICS E2	10.0	82.0		07SEP84	16NOV84	22APR86	02JUL86		
2410	2420		DUMMY	0000	110.0		16NOV84	16NOV84	21JAN87	21JAN87		
2410	3400		DUMMY	0000	82.0		16NOV84	16NOV84	02JUL86	02JUL86		
2420	2430	DA	INSTALL ELECTRONICS E2	08.0	.0		21JAN87	19MAR87	21JAN87	19MAR87		
2430	END02	DA	TEST E2/A2	04.0	.0		19MAR87	16APR87	19MAR87	16APR87		
3200	3210	EA	FINAL SITE SELECTION S3	05.0	53.0		02JAN84	06FEB84	16JAN85	21FEB85		
3210	3220	EA	SITE PLAN S3	25.0	53.0		06FEB84	02AUG84	21FEB85	20AUG85		
3210	3230	EA	SITE AQUISITION S3	25.0	83.0		06FEB84	02AUG84	25SEP85	25MAR86		
3220	3230	EA	SITE DESIGN S3	30.0	53.0		02AUG84	08MAR85	20AUG85	25MAR86		
3230	3240	EA	SITE CONSTR. PH 1 S3	40.0	53.0		08MAR85	19DEC85	25MAR86	07JAN87		
3240	3250	EA	SITE CONSTR. PH 2 S3	30.0	53.0		19DEC85	24JUL86	07JAN87	06AUG87		
3240	3300		DUMMY	0000	55.0		19DEC85	19DEC85	21JAN87	21JAN87		
3250	END03		DUMMY	0000	53.0		24JUL86	24JUL86	06AUG87	06AUG87		
3300	3310	EA	CONSTRUCT ANTENNA A3	16.0	.0		21JAN87	14MAY87	21JAN87	14MAY87		
3310	3420		DUMMY	0000	.0		14MAY87	14MAY87	14MAY87	14MAY87		
3310	5300		DUMMY	0000	.0		14MAY87	14MAY87	14MAY87	14MAY87		
3400	3410	EA	CONSTR. ELECTRONICS E3	10.0	82.0		16NOV84	30JAN85	02JUL86	12SEP86		
3410	3420		DUMMY	0000	116.0		30JAN85	30JAN85	14MAY87	14MAY87		
3410	4400		DUMMY	0000	82.0		30JAN85	30JAN85	12SEP86	12SEP86		
3420	3430	EA	INSTALL ELECTRONICS E3	08.0	.0		14MAY87	09JUL87	14MAY87	09JUL87		
3430	END03	EA	TEST E3/A3	04.0	.0		09JUL87	06AUG87	09JUL87	06AUG87		
4200	4210	FA	FINAL SITE SELECTION S4	05.0	53.0		02JAN84	06FEB84	16JAN85	21FEB85		
4210	4220	FA	SITE PLAN S4	25.0	53.0		06FEB84	02AUG84	21FEB85	20AUG85		
4210	4230	FA	SITE AQUISITION S4	25.0	83.0		06FEB84	02AUG84	25SEP85	25MAR86		
4220	4230	FA	SITE DESIGN S4	30.0	53.0		02AUG84	08MAR85	20AUG85	25MAR86		
4230	4240	FA	SITE CONSTR. PH 1 S4	40.0	53.0		08MAR85	19DEC85	25MAR86	07JAN87		
4240	4250	FA	SITE CONSTR. PH 2 S4	30.0	53.0		19DEC85	24JUL86	07JAN87	06AUG87		
4240	4300		DUMMY	0000	55.0		19DEC85	19DEC85	21JAN87	21JAN87		
4250	END04		DUMMY	0000	53.0		24JUL86	24JUL86	06AUG87	06AUG87		
4300	4310	FA	CONSTRUCT ANTENNA A4	16.0	.0		21JAN87	14MAY87	21JAN87	14MAY87		
4310	4420		DUMMY	0000	.0		14MAY87	14MAY87	14MAY87	14MAY87		
4310	6300		DUMMY	0000	.0		14MAY87	14MAY87	14MAY87	14MAY87		
4400	4410	FA	CONSTR. ELECTRONICS E4	10.0	82.0		30JAN85	12APR85	12SEP86	21NOV86		

PROGRAM 17MAY82 REPORT DATE. VERY LONG BASELINE ARRAY VLB10A RUN DATE 18M.
PROJECT CONCEPTS, DESIGN AND DEVELOPMENT VLBA10

LEVEL DETAIL SORTED BY PRED,SUCC

PRED EVENT	SUCC EVENT	CY. CD.	ACTIVITY DESCRIPTION	TIME EST	SLACK PRIM.	SLACK SEC.	EARLY DATES START	EARLY DATES FINISH	LATE DATES START	LATE DATES FINISH	SCHED.	DEPT
4410	4420		DUMMY	0000	106.0		12APR85	12APR85	14MAY87	14MAY87		
4410	5400		DUMMY	0000	82.0		12APR85	12APR85	21NOV86	21NOV86		
4420	4430	FA	INSTALL ELECTRONICS E4	08.0	.0		14MAY87	09JUL87	14MAY87	09JUL87		
4430	END04	FA	TEST E4/A4	04.0	.0		09JUL87	06AUG87	09JUL87	06AUG87		
5200	5210	GA	FINAL SITE SELECTION S5	05.0	65.0		02JAN84	06FEB84	12APR85	17MAY85		
5210	5220	GA	SITE PLAN S5	25.0	65.0		06FEB84	02AUG84	17MAY85	13NOV85		
5210	5230	GA	SITE AQUISITION S5	25.0	95.0		06FEB84	02AUG84	19DEC85	18JUN86		
5220	5230	GA	SITE DESIGN S5	30.0	65.0		02AUG84	08MAR85	13NOV85	18JUN86		
5230	5240	GA	SITE CONSTR. PH 1 S5	40.0	65.0		08MAR85	19DEC85	18JUN86	02APR87		
5240	5250	GA	SITE CONSTR. PH 2 S5	30.0	65.0		19DEC85	24JUL86	02APR87	30OCT87		
5240	5300		DUMMY	0000	71.0		19DEC85	19DEC85	14MAY87	14MAY87		
5250	END05		DUMMY	0000	65.0		24JUL86	24JUL86	30OCT87	30OCT87		
5300	5310	GA	CONSTRUCT ANTENNA A5	12.0	.0		14MAY87	06AUG87	14MAY87	06AUG87		
5310	5420		DUMMY	0000	.0		06AUG87	06AUG87	06AUG87	06AUG87		
5310	7300		DUMMY	0000	.0		06AUG87	06AUG87	06AUG87	06AUG87		
5400	5410	GA	CONSTR. ELECTRONICS E5	10.0	82.0		12APR85	24JUN85	21NOV86	04FEB87		
5410	5420		DUMMY	0000	108.0		24JUN85	24JUN85	06AUG87	06AUG87		
5410	6400		DUMMY	0000	82.0		24JUN85	24JUN85	04FEB87	04FEB87		
5420	5430	GA	INSTALL ELECTRONICS E5	08.0	.0		06AUG87	02OCT87	06AUG87	02OCT87		
5430	END05	GA	TEST E5/A5	04.0	.0		02OCT87	30OCT87	02OCT87	30OCT87		
6200	6210	HA	FINAL SITE SELECTION S6	05.0	65.0		02JAN84	06FEB84	12APR85	17MAY85		
6210	6220	HA	SITE PLAN S6	25.0	65.0		06FEB84	02AUG84	17MAY85	13NOV85		
6210	6230	HA	SITE AQUISITION S6	25.0	95.0		06FEB84	02AUG84	19DEC85	18JUN86		
6220	6230	HA	SITE DESIGN S6	30.0	65.0		02AUG84	08MAR85	13NOV85	18JUN86		
6230	6240	HA	SITE CONSTR. PH 1 S6	40.0	65.0		08MAR85	19DEC85	18JUN86	02APR87		
6240	6250	HA	SITE CONSTR. PH 2 S6	30.0	65.0		19DEC85	24JUL86	02APR87	30OCT87		
6240	6300		DUMMY	0000	71.0		19DEC85	19DEC85	14MAY87	14MAY87		
6250	END06		DUMMY	0000	65.0		24JUL86	24JUL86	30OCT87	30OCT87		
6300	6310	HA	CONSTRUCT ANTENNA A6	12.0	.0		14MAY87	06AUG87	14MAY87	06AUG87		
6310	6420		DUMMY	0000	.0		06AUG87	06AUG87	06AUG87	06AUG87		
6310	8300		DUMMY	0000	.0		06AUG87	06AUG87	06AUG87	06AUG87		
6400	6410	HA	CONSTR. ELECTRONICS E6	10.0	82.0		24JUN85	04SEP85	04FEB87	16APR87		
6410	6420		DUMMY	0000	98.0		04SEP85	04SEP85	06AUG87	06AUG87		
6410	7400		DUMMY	0000	82.0		04SEP85	04SEP85	16APR87	16APR87		
6420	6430	HA	INSTALL ELECTRONICS E6	08.0	.0		06AUG87	02OCT87	06AUG87	02OCT87		
6430	END06	HA	TEST E6/A6	04.0	.0		02OCT87	30OCT87	02OCT87	30OCT87		
7200	7210	IA	FINAL SITE SELECTION S7	05.0	77.0		02JAN84	06FEB84	09JUL85	13AUG85		
7210	7220	IA	SITE PLAN S7	25.0	77.0		06FEB84	02AUG84	13AUG85	10FEB86		
7210	7230	IA	SITE AQUISITION S7	25.0	107.0		06FEB84	02AUG84	18MAR86	12SEP86		
7220	7230	IA	SITE DESIGN S7	30.0	77.0		02AUG84	08MAR85	10FEB86	12SEP86		
7230	7240	IA	SITE CONSTR. PH 1 S7	40.0	77.0		08MAR85	19DEC85	12SEP86	25JUN87		
7240	7250	IA	SITE CONSTR. PH 2 S7	30.0	77.0		19DEC85	24JUL86	25JUN87	27JAN88		
7240	7300		DUMMY	0000	83.0		19DEC85	19DEC85	06AUG87	06AUG87		
7250	END07		DUMMY	0000	77.0		24JUL86	24JUL86	27JAN88	27JAN88		
7300	7310	IA	CONSTRUCT ANTENNA A7	12.0	.0		06AUG87	30OCT87	06AUG87	30OCT87		
7310	7420		DUMMY	0000	.0		30OCT87	30OCT87	30OCT87	30OCT87		
7310	9300		DUMMY	0000	.0		30OCT87	30OCT87	30OCT87	30OCT87		
7400	7410	IA	CONSTR. ELECTRONICS E7	10.0	82.0		04SEP85	13NOV85	16APR87	25JUN87		
7410	7420		DUMMY	0000	100.0		13NOV85	13NOV85	30OCT87	30OCT87		
7410	8400		DUMMY	0000	82.0		13NOV85	13NOV85	25JUN87	25JUN87		

PROGRAM 17MAY82 REPORT CATE. VERY LONG BASELINE ARRAY VLB10A RUN DATE 18MA...
PROJECT CCNCEPTS, DESIGN AND DEVELCPMENT VLBA10

LEVEL DETAIL SORTED BY PRED,SUCC

PRED EVENT	SUCC EVENT	CY. CD.	ACTIVITY DESCRIPTION	TIME EST	SLACK PRIM.	SEC.	EARLY DATES START	FINISH	LATE DATES START	FINISH	SCHED.	DEPT
7420	7430	IA	INSTALL ELECTRCNICS E7	08.0	.0		30OCT87	29DEC87	30OCT87	29DEC87		
7430	END07	IA	TEST E7/A7	04.0	.0		29DEC87	27JAN88	29DEC87	27JAN88		
8200	8210	JA	FINAL SITE SELECTICN S8	05.0	77.0		02JAN84	06FEB84	09JUL85	13AUG85		
8210	8220	JA	SITE PLAN S8	25.0	77.0		06FEB84	02AUG84	13AUG85	10FEB86		
8210	8230	JA	SITE AQUISITICN S8	25.0	107.0		06FEB84	02AUG84	18MAR86	12SEP86		
8220	8230	JA	SITE DESIGN S8	30.0	77.0		02AUG84	08MAR85	10FEB86	12SEP86		
8230	8240	JA	SITE CCNSTR. PH 1 S8	40.0	77.0		08MAR85	19DEC85	12SEP86	25JUN87		
8240	8250	JA	SITE CCNSTR. PH 2 S8	30.0	77.0		19DEC85	24JUL86	25JUN87	27JAN88		
8240	8300		DUMMY	0000	83.0		19DEC85	19DEC85	06AUG87	06AUG87		
8250	END08		DUMMY	0000	77.0		24JUL86	24JUL86	27JAN88	27JAN88		
8300	8310	JA	CCNSTRUCT ANTENNA A8	12.0	.0		06AUG87	30OCT87	06AUG87	30OCT87		
8310	8420		DUMMY	0000	.0		30OCT87	30OCT87	30OCT87	30OCT87		
8310	10300		DUMMY	0000	.0		30OCT87	30OCT87	30OCT87	30OCT87		
8400	8410	JA	CONSTR. ELECTRCNICS E8	10.0	82.0		13NOV85	27JAN86	25JUN87	03SEP87		
8410	8420		DUMMY	0000	90.0		27JAN86	27JAN86	30OCT87	30OCT87		
8410	9400		DUMMY	0000	82.0		27JAN86	27JAN86	03SEP87	03SEP87		
8420	8430	JA	INSTALL ELECTRONICS E8	08.0	.0		30OCT87	29DEC87	30OCT87	29DEC87		
8430	END08	JA	TEST E8/A8	04.0	.0		29DEC87	27JAN88	29DEC87	27JAN88		
9200	9210	KA	FINAL SITE SELECTICN S9	05.0	89.0		02JAN84	06FEB84	02OCT85	06NOV85		
9210	9220	KA	SITE PLAN S9	25.0	89.0		06FEB84	02AUG84	06NOV85	06MAY86		
9210	9230	KA	SITE AQUISITICN S9	25.0	119.0		06FEB84	02AUG84	11JUN86	08DEC86		
9220	9230	KA	SITE DESIGN S9	30.0	89.0		02AUG84	08MAR85	06MAY86	08DEC86		
9230	9240	KA	SITE CCNSTR. PH 1 S9	40.0	89.0		08MAR85	19DEC85	08DEC86	18SEP87		
9240	9250	KA	SITE CCNSTR. PH 2 S9	30.0	89.0		19DEC85	24JUL86	18SEP87	22APR88		
9240	9300		DUMMY	0000	95.0		19DEC85	19DEC85	30OCT87	30OCT87		
9250	END09		DUMMY	0000	89.0		24JUL86	24JUL86	22APR88	22APR88		
9300	9310	KA	CONSTRUCT ANTENNA A9	12.0	.0		30OCT87	27JAN88	30OCT87	27JAN88		
9310	9420		DUMMY	0000	.0		27JAN88	27JAN88	27JAN88	27JAN88		
9400	9410	KA	CCNSTR. ELECTRCNICS E9	10.0	82.0		27JAN86	08APR86	03SEP87	13NOV87		
9410	9420		DUMMY	0000	92.0		08APR86	08APR86	27JAN88	27JAN88		
9410	10400		DUMMY	0000	82.0		08APR86	08APR86	13NOV87	13NOV87		
9420	9430	KA	INSTALL ELECTRCNICS E9	08.0	.0		27JAN88	25MAR88	27JAN88	25MAR88		
9430	END09	KA	TEST E9/A9	04.0	.0		25MAR88	22APR88	25MAR88	22APR88		
END01		E			.0		17OCT86	17OCT86	17OCT86	17OCT86		
END02		E			.0		16APR87	16APR87	16APR87	16APR87		
END03		E			.0		06AUG87	06AUG87	06AUG87	06AUG87		
END04		E			.0		06AUG87	06AUG87	06AUG87	06AUG87		
END05		E			.0		30OCT87	30OCT87	30OCT87	30OCT87		
END06		E			.0		30OCT87	30OCT87	30OCT87	30OCT87		
END07		E			.0		27JAN88	27JAN88	27JAN88	27JAN88		
END08		E			.0		27JAN88	27JAN88	27JAN88	27JAN88		
END09		E			.0		22APR88	22APR88	22APR88	22APR88		
END10		E			.0		22APR88	22APR88	22APR88	22APR88		
END11		E			.0		25JUN86	25JUN86	25JUN86	25JUN86		
10200	10210	LA	FINAL SITE SELECTICN S10	05.0	89.0		02JAN84	06FEB84	02OCT85	06NOV85		
10210	10220	LA	SITE PLAN S10	25.0	89.0		06FEB84	02AUG84	06NOV85	06MAY86		
10210	10230	LA	SITE ACUISITICN S10	25.0	119.0		06FEB84	02AUG84	11JUN86	08DEC86		
10220	10230	LA	SITE DESIGN S10	30.0	89.0		02AUG84	08MAR85	06MAY86	08DEC86		
10230	10240	LA	SITE CCNSTR. PH 1 S10	40.0	89.0		08MAR85	19DEC85	08DEC86	18SEP87		
10240	10250	LA	SITE CCNSTR. PH 2 S10	30.0	89.0		19DEC85	24JUL86	18SEP87	22APR88		

PROGRAM 17MAY82 REPORT DATE. VERY LONG BASELINE ARRAY VLB10A RUN DATE 18MA..
PROJECT CONCEPTS, DESIGN AND DEVELOPMENT VLBA10

LEVEL DETAIL SORTED BY PRED,SUCC

PRED EVENT	SUCC EVENT	CY. CD.	ACTIVITY DESCRIPTION	TIME EST	SLACK PRIM.	SEC.	EARLY START	DATES FINISH	LATE START	DATES FINISH	SCHED.	DEPT
10240	10300		DUMMY	0000	95.0		19DEC85	19DEC85	30OCT87	30OCT87		
10250	END10		DUMMY	0000	89.0		24JUL86	24JUL86	22APR88	22APR88		
10300	10310	LA	CONSTRUCT ANTENNA A10	12.0	.0		30OCT87	27JAN88	30OCT87	27JAN88		
10310	10420		DUMMY	0000	.0		27JAN88	27JAN88	27JAN88	27JAN88		
10400	10410	LA	CONSTR. ELECTRONICS E10	10.0	82.0		08APR86	18JUN86	13NOV87	27JAN88		
10410	10420		DUMMY	0000	82.0		18JUN86	18JUN86	27JAN88	27JAN88		
10420	10430	LA	INSTALL ELECTRONICS E10	08.0	.0		27JAN88	25MAR88	27JAN88	25MAR88		
10430	END10	LA	TEST E10/A10	04.0	.0		25MAR88	22APR88	25MAR88	22APR88		

NATIONAL RADIO ASTRONOMY OBSERVATORY
CYCLE CODE BAR CH

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PROGRAM      17MAY82   REPORT DATE.  VERY LONG BASELINE ARRAY                      VLB10A                       RUN DATE  1_ _AY82
PROJECT                CONCEPTS, DESIGN AND DEVELOPMENT                            VLBA10
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       CYCLE CODE           .                                                                                        . FINAL
CODE   DESCRIPTION          .      A ALL ACTIVITIES COMPLETE                              * ALL ACTIVITIES NOT COMPLETE  . DATE
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                            .                                                                                        .
                            *************          ******************** ***  * **  *  *  **  * *  *  *        .      . 22APR88
AA  COMPUTER                .   :       .          ******************          .          .           .         .      . 24JUN85
BA  PROCESSOR               .   :       .          ******************************         .           .         .      . 25JUN86
CA  STATION 1               .   :       .          **********************************     .           .         .      . 17OCT86
DA  STATION 2               .   :       .          ****************************************           .         .      . 16APR87
EA  STATION 3               .   :       .          *******************************     ********       .         .      . 06AUG87
FA  STATION 4               .   :       .          *******************************     ********       .         .      . 06AUG87
GA  STATION 5               .   :       .          *******************************    .    ******     .         .      . 30OCT87
HA  STATION 6               .   :       .          *******************************    .    ******     .         .      . 30OCT87
IA  STATION 7               .   :       .          *******************************    .       ******            .      . 27JAN88
JA  STATION 8               .   :       .          *******************************    .       ******            .      . 27JAN88
KA  STATION 9               .   :       .          *******************************    .         *******         .      . 22APR88
LA  STATION 10              .   :       .          *******************************    .         *******         .      . 22APR88
                                 01JAN83    01JAN84    01JAN85    01JAN86    01JAN87    01JAN88    01JAN89
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NATIONAL RADIO ASTRONOMY OBSERVATORY
ACTIVITY BAR CH/

PROGRAM 17MAY82 REPORT DATE. VERY LONG BASELINE ARRAY VLB10A RUN DATE . /82
PROJECT CONCEPTS, DESIGN AND DEVELOPMENT VLBA10

PRED EVENT	SUCC EVENT	CY CD	DESCRIPTION	A - ACTIVITY COMPLETE / * - ACTIVITY DURATION / P - PACING ITEM / - - ACTIVITY FLOAT	FINAL DATE	DEPT
A001	A100		GET ORGANIZED	**-----------	08FEB82	
A100	A110		CONFIG. & SITE SELECTION	************------------	28JAN83	
A100	A120		CONCEPT DESIGN ANTENNA	*******-------------------	11AUG82	
A100	A170	3	CONCEPT DES COMPUTER	****-------------------	05MAY82	
A100	A170	2	CONCEPT DES PROCESSOR	****-------------------	05MAY82	
A100	A170	1	CONCEPT DES ELECTRONICS	****-------------------	05MAY82	
A120	A130		NEGOTIATE DES CONTRACT	*******---	05JUL84	
A130	A140		DESIGN ANTENNA PH 1	****---	19OCT84	
A140	A150		DESIGN ANTENNA PH 2	******---	15MAR85	
A150	A160		BID CONSTRUCTION	*******---	11SEP85	
A170	A180		REVIEW DESIGN	**------------------	02JUN82	
A180	A190		DESIGN ELECTRONICS	****------------------	17APR84	
A180	A230	AA	DESIGN COMPUTER	****----------	17APR84	
A230	A240	AA	PROCURE COMPUTER	*************----------	12APR85	
A240	A250	AA	INSTALL COMPUTER	***----------	24JUN85	
A180	A200	BA	DESIGN PROCESSOR	PPPPPPPPPP	12OCT84	
A200	A210	BA	CONSTRUCT PROCESSOR PH 1	PPPPPPPP	17MAY85	
A210	A220	BA	CONSTRUCT PROCESSOR PH 2	PPPPPPPP	19DEC85	
A220	A250	BA	TEST PROCESSOR	PPPPP	15APR86	
A250	END11	BA	TEST DATA PROCESSOR SYS	PPP	25JUN86	
1200	1210	CA	FINAL SITE SELECTION S1	PP	06FEB84	
1210	1220	CA	SITE PLAN S1	PPPPPPP	02AUG84	
1210	1230	CA	SITE AQUISITION S1	*******-------	02AUG84	
1220	1230	CA	SITE DESIGN S1	PPPPPPPP	08MAR85	
1230	1240	CA	SITE CONSTR. PH 1 S1	PPPPPPPPPP	19DEC85	
1240	1250	CA	SITE CONSTR. PH 2 S1	*********---	24JUL86	
1300	1310	CA	CONSTRUCT ANTENNA A1	PPPPPPPP	24JUL86	
1400	1410	CA	CONSTR. ELECTRONICS E1	******------------------	07SEP84	
1420	1430	CA	INSTALL ELECTRONICS E1	PPP	19SEP86	
1430	END01	CA	TEST E1/A1	PP	17OCT86	
2200	2210	DA	FINAL SITE SELECTION S2	**-------	06FEB84	
2210	2220	DA	SITE PLAN S2	*******-------	02AUG84	
2210	2230	DA	SITE AQUISITION S2	*******---------------	02AUG84	
2220	2230	DA	SITE DESIGN S2	********-------	08MAR85	
2230	2240	DA	SITE CONSTR. PH 1 S2	**********-------	19DEC85	
2240	2250	DA	SITE CONSTR. PH 2 S2	********---------	24JUL86	
2300	2310	DA	CONSTRUCT ANTENNA A2	PPPPPPP	21JAN87	
2400	2410	DA	CONSTR. ELECTRONICS E2	***--------------------	16NOV84	
2420	2430	DA	INSTALL ELECTRONICS E2	PPP	19MAR87	
2430	END02	DA	TEST E2/A2	PP	16APR87	
3200	3210	EA	FINAL SITE SELECTION S3	**------------	06FEB84	
3210	3220	EA	SITE PLAN S3	*******------------	02AUG84	
3210	3230	EA	SITE ACUISITION S3	*******------------------	02AUG84	
3220	3230	EA	SITE DESIGN S3	********------------	08MAR85	
3230	3240	EA	SITE CONSTR. PH 1 S3	**********-------------	19DEC85	
3240	3250	EA	SITE CONSTR. PH 2 S3	********-------------	24JUL86	

01JAN83 01JAN84 01JAN85 01JAN86 01JAN87 01JAN88

NATIONAL RADIO ASTRONOMY OBSERVATORY
ACTIVITY BAR CH

PAG

PROGRAM 17MAY82 REPORT DATE. VERY LONG BASELINE ARRAY — VLB10A — RUN DATE 1[illegible]MAY82
PROJECT CONCEPTS, DESIGN AND DEVELOPMENT — VLBA10

A - ACTIVITY COMPLETE · * - ACTIVITY DURATION · P - PACING ITEM · - - ACTIVITY FLOAT

PRED EVENT	SUCC EVENT	CY CD	DESCRIPTION	BAR	FINAL DATE	DEPT
3300	3310	EA	CONSTRUCT ANTENNA A3	PPPPP	14MAY87	
3400	3410	EA	CONSTR. ELECTRONICS E3	***--------------------	30JAN85	
3420	3430	EA	INSTALL ELECTRONICS E3	PPP	09JUL87	
3430	END03	EA	TEST E3/A3	PP	06AUG87	
4200	4210	FA	FINAL SITE SELECTION S4	**------------	06FEB84	
4210	4220	FA	SITE PLAN S4	*******------------	02AUG84	
4210	4230	FA	SITE AQUISITION S4	*******------------------	02AUG84	
4220	4230	FA	SITE DESIGN S4	********------------	08MAR85	
4230	4240	FA	SITE CONSTR. PH 1 S4	**********-------------	19DEC85	
4240	4250	FA	SITE CONSTR. PH 2 S4	********-------------	24JUL86	
4300	4310	FA	CONSTRUCT ANTENNA A4	PPPPP	14MAY87	
4400	4410	FA	CONSTR. ELECTRONICS E4	****--------------------	12APR85	
4420	4430	FA	INSTALL ELECTRONICS E4	PPP	09JUL87	
4430	END04	FA	TEST E4/A4	PP	06AUG87	
5200	5210	GA	FINAL SITE SELECTION S5	**---------------	06FEB84	
5210	5220	GA	SITE PLAN S5	*******---------------	02AUG84	
5210	5230	GA	SITE AQUISITION S5	*******----------------------	02AUG84	
5220	5230	GA	SITE DESIGN S5	********---------------	08MAR85	
5230	5240	GA	SITE CONSTR. PH 1 S5	**********---------------	19DEC85	
5240	5250	GA	SITE CONSTR. PH 2 S5	********---------------	24JUL86	
5300	5310	GA	CONSTRUCT ANTENNA A5	PPPP	06AUG87	
5400	5410	GA	CONSTR. ELECTRONICS E5	***--------------------	24JUN85	
5420	5430	GA	INSTALL ELECTRONICS E5	PPP	02OCT87	
5430	END05	GA	TEST E5/A5	P	30OCT87	
6200	6210	HA	FINAL SITE SELECTION S6	**--------------	06FEB84	
6210	6220	HA	SITE PLAN S6	*******---------------	02AUG84	
6210	6230	HA	SITE AQUISITION S6	*******----------------------	02AUG84	
6220	6230	HA	SITE DESIGN S6	********---------------	08MAR85	
6230	6240	HA	SITE CONSTR. PH 1 S6	**********---------------	19DEC85	
6240	6250	HA	SITE CONSTR. PH 2 S6	********---------------	24JUL86	
6300	6310	HA	CONSTRUCT ANTENNA A6	PPPP	06AUG87	
6400	6410	HA	CONSTR. ELECTRONICS E6	****------------------	04SEP85	
6420	6430	HA	INSTALL ELECTRONICS E6	PPP	02OCT87	
6430	END06	HA	TEST E6/A6	P	30OCT87	
7200	7210	IA	FINAL SITE SELECTION S7	**-----------------	06FEB84	
7210	7220	IA	SITE PLAN S7	*******-----------------	02AUG84	
7210	7230	IA	SITE AQUISITION S7	*******------------------------	02AUG84	
7220	7230	IA	SITE DESIGN S7	********-----------------	08MAR85	
7230	7240	IA	SITE CONSTR. PH 1 S7	**********-----------------	19DEC85	
7240	7250	IA	SITE CONSTR. PH 2 S7	********-----------------	24JUL86	
7300	7310	IA	CONSTRUCT ANTENNA A7	PPP	30OCT87	
7400	7410	IA	CONSTR. ELECTRONICS E7	***-------------------	13NOV85	
7420	7430	IA	INSTALL ELECTRONICS E7	PPP	29DEC87	
7430	END07	IA	TEST E7/A7	PP	27JAN88	
8200	8210	JA	FINAL SITE SELECTION S8	**-----------------	06FEB84	
8210	8220	JA	SITE PLAN S8	*******-----------------	02AUG84	

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NATIONAL RADIO ASTRONOMY OBSERVATORY
ACTIVITY BAR CH'

PROGRAM 17MAY82 REPORT DATE. VERY LONG BASELINE ARRAY VLB10A RUN DATE . Y82
PROJECT CONCEPTS, DESIGN AND DEVELOPMENT VLBA10

A - ACTIVITY COMPLETE; * - ACTIVITY DURATION; P - PACING ITEM; - - ACTIVITY FLOAT

PRED EVENT	SUCC EVENT	CY CD	DESCRIPTION	BAR	FINAL DATE	DEPT
8210	8230	JA	SITE ACUISITICN S8	.*******------------------------	02AUG84	
8220	8230	JA	SITE DESIGN S8	********------------------	08MAR85	
8230	8240	JA	SITE CONSTR. PH 1 S8	**********-----------------	19DEC85	
8240	8250	JA	SITE CONSTR. PH 2 S8	********-------------------	24JUL86	
8300	8310	JA	CONSTRUCT ANTENNA A8	PPP	30OCT87	
8400	8410	JA	CONSTR. ELECTRONICS E8	***--------------------	27JAN86	
8420	8430	JA	INSTALL ELECTRONICS E8	PPP.	29DEC87	
8430	END08	JA	TEST E8/A8	PP	27JAN88	
9200	9210	KA	FINAL SITE SELECTION S9	**----------------------	06FEB84	
9210	9220	KA	SITE PLAN S9	.*******---------------------	02AUG84	
9210	9230	KA	SITE AQUISITION S9	.*******--------------------------.	02AUG84	
9220	9230	KA	SITE DESIGN S9	********---------------------.	08MAR85	
9230	9240	KA	SITE CONSTR. PH 1 S9	**********--------------------	19DEC85	
9240	9250	KA	SITE CONSTR. PH 2 S9	********---------------------	24JUL86	
9300	9310	KA	CONSTRUCT ANTENNA A9	PPPP	27JAN88	
9400	9410	KA	CONSTR. ELECTRONICS E9	****-------------------	08APR86	
9420	9430	KA	INSTALL ELECTRONICS E9	PPP	25MAR88	
9430	END09	KA	TEST E9/A9	. PP	22APR88	
10200	10210	LA	FINAL SITE SELECTION S10	**----------------------	06FEB84	
10210	10220	LA	SITE PLAN S10	.*******---------------------	02AUG84	
10210	10230	LA	SITE AQUISITION S10	.*******--------------------------.	02AUG84	
10220	10230	LA	SITE DESIGN S10	********---------------------.	08MAR85	
10230	10240	LA	SITE CONSTR. PH 1 S10	**********--------------------	19DEC85	
10240	10250	LA	SITE CONSTR. PH 2 S10	********---------------------	24JUL86	
10300	10310	LA	CONSTRUCT ANTENNA A10	PPPP	27JAN88	
10400	10410	LA	CONSTR. ELECTRONICS E10	***------------------	18JUN86	
10420	10430	LA	INSTALL ELECTRONICS E10	PPP	25MAR88	
10430	END10	LA	TEST E10/A10	. PP	22APR88	

01JAN83 01JAN84 01JAN85 01JAN86 01JAN87 01JAN88