LSA / MMA

Feasibility Study

April 1998

This document, a feasibility study report for the possible merger of the Large Southern Array (LSA) and the Millimeter Array (MMA), has been prepared by the working groups of the LSA Consortium in response to ESO Council and STC discussions and recommendations at their meetings of June and October 1997 respectively, and is intended to serve as background for future discussions on the LSA/MMA.

The LSA Consortium which began in 1995 as a group of institutes interested in the next generation millimeter array (ESO, IRAM. OSO and NFRA) was joined by representatives of other ESO nations and of the UK and Australia in 1997. International working groups for the project were established at that time. The Consortium and working group members are listed in Appendix A2. We envisage that the Consortium will continue to guide the project, and that its working groups will continue to play essential roles in the technical areas.

This document was produced from contributions by the chairmen of those working groups (R.S. Booth, D. Downes, K. Jacobs, R. Lucas, F. Viallefond, P. Schilke, and S. Guilloteau, with input from their WG members), and edited by P. Shaver. Sections 4–6, showing some possible scenarios for the organizational structure and planning, were compiled by P. Shaver and R. Kurz on the basis of previous discussions of the LSA/MMA joint Management Working Group.

Summary

Advances in (sub)millimetre astronomy over the past decade – the detection of molecular and dust emission at redshifts up to 4.7 and the first hints of the formation of proto-stellar discs – make this spectral range one of the most vital for future astronomical research. It is therefore not surprising that there is great interest, worldwide, in the construction of a next generation instrument with properties to fully exploit the potential of the (sub)millimeter wavebands. In Europe, a concept for an array with very large collecting area (10,000 m^2) and high angular resolution ($< 0.1''$) working at millimetre wavelengths has been developed with special reference to studies of the early Universe and star formation: the Large Southern Array (LSA). In the U.S. a 2,000 m^2 array of many antennas working to the shortest accessible submillimeter wavelengths has been proposed: the Millimeter Array (MMA). In both cases the proposed location is northern Chile, and a merger of the two projects seems desirable for several reasons.

An agreement was reached last year to work towards a common Europe-U.S. array. Recent studies indicate that the optimum configuration, for a cost envelope of $400m, is probably one with 64 × 12m antennas giving a total collecting area of 7,000 m^2, with baselines up to 10 km and full submillimeter performance. This will be the most powerful (sub)millimeter telescope in the world – a (sub)millimeter equivalent of the VLT, HST, and NGST, capable of opening up entire new areas of science.

This document summarizes the scientific potential and outlines technical and organizational aspects of the LSA/MMA project. The feasibility in key technical areas is demonstrated: construction and operation at the high (5,000m) site, large antennas providing good submillimeter performance at reasonable cost, large numbers of reliable and sensitive receivers, signal transport over long baselines, the prospects for a sufficiently large correlator, calibration at (sub)millimeter wavelengths, and rapid data transmission and processing.

The LSA/MMA would be a 50-50 partnership between ESO and the U.S. National Radio Astronomical Observatory (NRAO) on behalf of their respective communities. In Europe, ESO would draw on its own resources for project management, and involve specialised institutes for their technical expertise. The observatory would probably be run by a Foundation incorporated in Chile and controlled by an ESO-NRAO Board. The array could be built in the period 2002–2008, and become incrementally operational over that period.

In parallel with continuing LSA/MMA technical studies, ESO with the support of the other participating European institutions will prepare a formal proposal for the European side of a common project. This proposal will be submitted to the ESO Council in June 1999 with a goal of receiving approval of the proposal and European funding by the end of 1999.

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1. Introduction

1.1 The Large Southern Array (LSA)

Discussions in Europe concerning a possible millimeter array in the southern hemisphere began in the late 1980s, and a European study group was established. At meetings in 1991, following the discovery of CO at a redshift of 2.3, it was suggested that this array should be a major step beyond any existing millimeter telescope in the world. A collecting area of 10,000 m^2 and angular resolution of < 0.1 arcsec was proposed – both fully an order of magnitude improvement on the largest existing instruments. Thus began the LSA project.

In 1994, the STC endorsed the recommendations made by an ESO millimeter working group, which described the field as moving towards large distributed arrays and recommended the establishment of a permanent mm advisory group. Later the same year, that group in turn proposed the initiation of a design study, and in April 1995 a Memorandum of Understanding concerning a study for a Large Millimeter Array in the Southern Hemisphere was signed by ESO, Institut de Radioastronomie Millimétrique, Onsala Space Observatory, and the Netherlands Foundation for Research in Astronomy. A workshop on "Science with Large Millimeter Arrays", held at ESO in December of that year, demonstrated the great enthusiasm for the LSA, in particular its very high resolution and sensitivity.

A number of studies were carried out by the LSA collaboration. Possible sites in Chile were explored and a few were selected for detailed testing. Antenna concepts were examined, the objective being the largest possible aperture consistent with good high frequency performance, reliability and low cost. Other studies concerned array configurations, phase calibration strategies, receiver, correlator, and signal transport developments. The results of the first two years of these studies were presented to STC and Council last year in the document "LSA: Large Southern Array, Combined Report".

1.2 The Millimeter Array (MMA)

The Millimeter Array project in the United States has a longer history. In 1983 a subcommittee of the National Science Foundation recommended a design study for a millimeter-wavelength synthesis array, and this was initiated at the National Radio Astronomy Observatory (NRAO) in 1984. A scientific workshop in 1985 gave a strong endorsement to the MMA, which was to have excellent imaging capabilities, 1000-2000 m^2 total collecting area, and frequency coverage up to 366 GHz. The MMA proposal was submitted to the NSF in July 1990. In the 1991 report of the Radio Astronomy Panel of the U.S. Astronomy & Astrophysics Survey Committee, the MMA was the highest-priority item, and it was also awarded the highest priority after Gemini in the Bahcall Report.

At the time of the MMA proposal, three possible sites had been identified in New Mexico and Arizona. Mauna Kea and northern Chile were also mentioned, but the U.S. continental sites were preferred. In 1994 this situation was reversed. Northern Chile was re-examined, and the 5000m Chajnantor site was selected for detailed study. In view of its very superior characteristics, especially for submillimeter observations, it is now strongly preferred as the site for the MMA.

1.3 The LSA/MMA

With the LSA and MMA projects both now concentrating on northern Chile, it became obvious that the possibility of a partnership should be explored. An agreement to this effect was signed in June 1997 by ESO and NRAO on behalf of their respective communities (Figure 1.1). Three joint working groups were immediately established to study aspects of such a partnership: a Science Working Group to consider the scientific objectives of a joint project, a Technical Working Group to study antenna and system issues, and a Management Working Group to explore possible organizational scenarios, both between ESO and NRAO, and in Chile.

The LSA and MMA concepts initially differed from each other because of different primary scientific objectives. The MMA was intended to be capable of fast imaging and mapping, and over the last few years a submillimeter capability has also become a requirement. Therefore, relatively small (8m) antennas with good submillimeter performance and large primary beams were chosen, to be located on a very high (5000m) site. The total collecting area of the 40-element array was to be 2000 m^2, with maximum baselines of a few km. The European LSA, on the other hand, was meant to have very high angular resolution and sensitivity, in order to detect and study protogalaxies at the highest redshifts and the details of star and planet formation. This requires a very large total collecting area (10,000 m^2, an order of magnitude greater than that of current arrays, and baselines up to 10 km. It would be used primarily at millimeter wavelengths, so that a reasonable number (50-60) of large (15m) antennas could be used, and the array could be located at a lower altitude (3500-4000m).

However, there is also considerable interest in submillimeter wavelengths in Europe, and in large collecting area in the U.S. community, so a compromise seemed possible. The joint working groups considered the options, and studied four antenna designs in considerable detail. The outcome was an array of 64 × 12m antennas, good to the shortest possible submillimeter wavelengths, a total collecting area of 7000 m^2, with baselines to 10 km, located on the high (5000m) Chajnantor site, within a cost envelope of $400m.

At the moment a full-scale design and development phase is proceeding in the U.S.,

RESOLUTION

Whereas the development of millimeter-wavelength astronomy has shown the potential of large millimeter interferometric arrays for revealing the origin and evolution of stars and planetary systems, of galaxies, and of the Universe itself; the communities in the United States and Europe have proposed the construction of the Millimeter Array (MMA) and the Large Southern Array (LSA), respectively; and there is an opportunity through cooperation to achieve more than either community planned; we, as the observatories responsible for these projects and with the support of our communities, resolve to organize a partnership that will explore the union of the LSA and MMA into a single, common project to be located in Chile. Specifically, this partnership will study the technical, logistical, and operational aspects of a joint project. Of particular importance, the two antenna concepts currently under consideration will be studied to identify the best antenna size and design or combination of sizes to address the scientific goals of the two research communities. In doing so we will work through our observatories, utilizing the expertise in millimeter astronomy resident in research groups and institutions in our communities. Finally, we recognize that there are similar goals for millimeter astronomy in Japan, and cooperative activities with that project will continue.

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26 June 1997

Figure 1.1: The ESO-NRAO agreement concerning the LSA/MMA.

with \$26m available for this purpose over the next three years. In Europe working groups involving some 80 scientists and engineers in several institutes continue the studies started a few years ago, and will now be collaborating closely with the groups in the U.S. on the joint project. However, design study funds remain extremely limited in Europe at present, and a significant increase will be required in order to even begin to match the U.S. effort.

A third major project of this kind is under consideration in Japan: the Large Millimeter and Submillimeter Array (LMSA). It is the highest-rated astronomy project in Japan, for the period following completion of the Subaru telescope. It would also be located near the Chajnantor site, and so discussions are taking place concerning collaboration possibilities, ranging from sharing of infrastructure to a complete merging of the projects into one "World Array".

1.4 A Feasibility Study

As agreed at STC and Council meetings last year, a Feasibility Study was to be carried out and presented in mid-1998. This report examines both the technical and organizational aspects of the LSA/MMA project, with emphasis on feasibility. In Section 2 the main scientific objectives are briefly reviewed in the context of recent developments, taking into account the enhanced capabilities of the combined LSA/MMA array. In Section 3 technical aspects are assessed in some detail: the advantages and practicalities of the site, all major components and technologies of the array, and operational aspects. In section 4 concepts for the organizational structure are outlined, and sections 5 and 6 summarize tentative cost and schedule projections. On the basis of this report it is proposed to move on to the next step, a formal proposal for the funding of the European share of the LSA/MMA.

2. Science with the LSA/MMA

(This section was written/compiled by D. Downes, chairman of the Science Working Group, with input from the WG members)

2.1 Introduction

The millimeter and sub-mm bands are unique in astronomy in having more than 1000 radio spectral lines of interstellar and circumstellar molecules as well as the thermal continuum spectrum of cold dust in space. They are the only bands in the electromagnetic spectrum where we can detect cold dust and molecules far away in young, high redshift galaxies in the early universe, and nearby in low-temperature cocoons of protostars in the Milky Way. They are the only bands that can give us the fine-scale kinematic details on young stellar disks that can potentially form planets, and on old ejected stellar envelopes that are forming dust grains and enriching the interstellar medium with carbon, oxygen, and nitrogen.

To make a major step forward in millimeter and sub-millimeter astronomy, it is intended to combine the previous European millimeter project for a Large Southern Array (LSA) with the project of the U.S. National Radio Astronomy Observatory for a large MilliMeter Array (MMA). The advantage of combining the two projects is, for Europe, the possibility to go to submillimeter wavelengths, and for NRAO, to have larger collecting area. The current concept for the LSA/MMA is an array of 64 $\times$ 12 m antennas with excellent performance over all the mm and sub-mm windows from 3 mm to 350 microns. This new array will have a collecting area of 7000 m^2 and 2000 simultaneous baselines. With its longest baselines, the array will have a beam of 0.03$''$ at 1.3 mm. The collecting area, resolving power, excellent high-altitude site, better instrumentation, and the large number of baselines will give vastly increased sensitivity and image quality, representing 2 to 3 orders of magnitude improvement over what is now available or planned, especially at the higher frequencies. This millimeter and submillimeter instrument will be particularly well suited to two domains that are major challenges in modern astrophysics:

- the formation and evolution of galaxies and quasars in the early universe, and
- the formation of stars and planets in the Milky Way and nearby galaxies.

Such an array will also open new paths in the study of molecular clouds in our Galaxy and other galaxies, the chemistry of the interstellar medium, the envelopes of all types of stars, including planetary nebulae, novae, and photospheric and chromospheric emission of normal stars. The LSA/MMA will open up the mm/submm windows to the whole

Table 2.1: Sensitivity at 230 GHz in 1^{hr}, with $T_{sys} = 70\,K$, dual polarization, and area = $7000\,m^2$.

		— Galactic —		— Extragalactic —		Continuum
max. baseline	230 GHz beam	resolution at 10 kpc	$5\,\sigma$ in δv = 0.2 km/s	resolution at 10 Mpc	$5\,\sigma$ in δv = 20 km/s	$5\,\sigma$ in $\delta\nu$ = 8 GHz
0.3 km	1″	$5.0\ 10^{-2}$ pc	0.1 K	50 pc	0.01 K	20 μJy
1.0 km	0.3″	$1.5\ 10^{-2}$ pc	1 K	15 pc	0.1 K	20 μJy
3.0 km	0.1″	$5.0\ 10^{-3}$ pc	10 K	5 pc	1 K	20 μJy
10. km	0.03″	$1.5\ 10^{-3}$ pc	100 K	1.5 pc	10 K	20 μJy

astronomical community in the same way that the VLA opened up cm-radio astronomy to many non-radio astronomers. Because optical telescopes like the HST or the ESO VLT cannot look into the obscured regions where star formation takes place, the LSA/MMA is an essential complementary tool for optical astronomers. In particular, it is a highly appropriate partner instrument to complement the current European investment in the ESO VLT for southern hemisphere optical astronomy.

Because the mm and submm bands are the parts of the electromagnetic spectrum where *cold* matter radiates, two main goals of the LSA/MMA will be the study of the origin of galaxies and the origin of stars and planets — all of which originally form in cold matter. The thermal line brightness temperatures of these objects are low, a few degrees K, so high instrumental sensitivity is required. The point-source flux sensitivity of a large array varies as

$$\Delta S = \frac{2k\,T_{sys}}{\eta\,A\,(t\,\Delta\nu)^{0.5}} \tag{1}$$

where k is Boltzmann's constant, T_{sys} is system temperature, η is a global efficiency factor of the order of 0.5, A is the total geometric collecting area, t is integration time, and $\Delta\nu$ is the bandwidth. Table 1 gives the expected sensitivities of the LSA/MMA at 1.3 mm. For comparison, current arrays (IRAM, Nobeyama, Caltech, BIMA) work only at mm wavelengths, not submm, and only on the shortest baselines listed in Table 1. Because these arrays have smaller collecting areas, their sensitivities are more than 10 times poorer than the values in the Table.

2.2 Early Universe Studies

The discovery of CO in the $z = 2.3$ galaxy IRAS F10214+4724 dramatically opened up the distant universe to mm and submm astronomy. Since then, CO has been detected in the gravitationally lensed Cloverleaf quasar at $z = 2.56$ (Fig. 2.1a), and in several other high redshift objects. The most remarkable discovery is that large amounts of dust and CO molecules are present already at $z = 4.7$ (Fig. 2.1b). This redshift corresponds to a look-back time of 92% of the age of the universe and shows that enrichment of the interstellar medium occured at very early epochs. These lines make it possible to estimate the mass, density, velocity spread, and kinetic temperature of the cold molecular gas. As

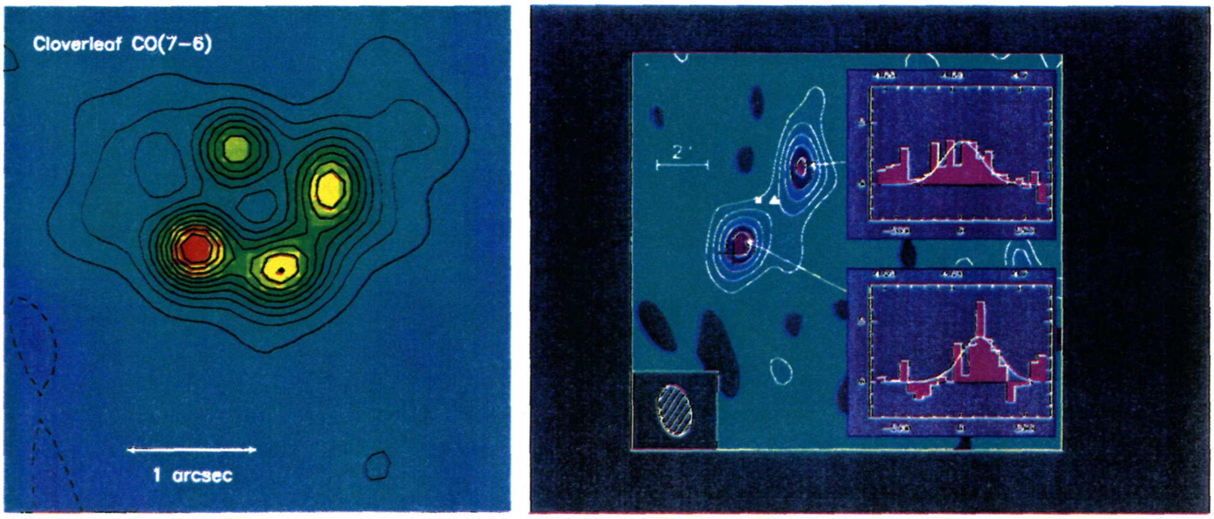

Figure 2.1: CO in high-redshift objects. *a), left:* The cloverleaf quasar, H1413+117, at $z = 2.56$, mapped in the CO(7–6) line with the IRAM interferometer with an $0.6''$ beam (Kneib et al. 1998, A&A, 329, 827). *b), right:* The quasar BR1202−07 at $z = 4.69$, mapped in the dust continuum at 1.3 mm with the IRAM interferometer. The insets show the CO(5–4) spectra (Omont et al. 1996, Nature, 382, 428).

well as the emission lines, numerous molecular lines have been detected at $z = 0.3$ to 0.9 in absorption against distant background radio sources. The absorption lines allow us to measure the temperature of the cosmic background radiation at intermediate redshifts ($z = 0.9$), and may be valuable for deriving differential time delays in gravitational lenses. In the millimeter and submm bands, we can detect not only molecular lines but potentially also the atomic fine-structure lines of carbon, oxygen, and nitrogen. These lines have rest frequencies in the far infrared, but at high-z, they are redshifted into the submm bands. An advantage of the mm and submm bands over other radio bands is that for spectral lines with the same brightness temperatures and velocity linewidths, the line power varies as $\nu^2 T_b \Delta\nu$, and hence as ν^3. A CO(3–2) line redshifted to 100 GHz emits 3 10^7 times more power than an H I line shifted to 400 MHz. Even if the H I line could be detected at $z > 2$, it is redshifted to the meter band where there is high radio noise from our Galaxy, strong ionospheric effects on interferometer phases, and much man-made radio interference. Another advantage of the mm/sub-mm bands is that most molecules have a ladder of spectral lines. If a redshift is so high that a spectral line is shifted out of a given mm window, there is a good chance the next line up the ladder will be shifted into it. It is thus imperative that the receivers cover all of the mm/submm bands.

A crucial advantage is that we can study the mm and sub-mm emission from dust, which is too weak to detect at cm or meter wavelengths. At present, the mm/sub-mm continuum from dust has been detected in quasars with redshifts as large as 4.7 (Fig. 2.1b). From the dust flux, one may estimate the mass of dust and gas in the central regions of these objects. The mm/sub-mm thermal dust continuum may be one of the best tracers for

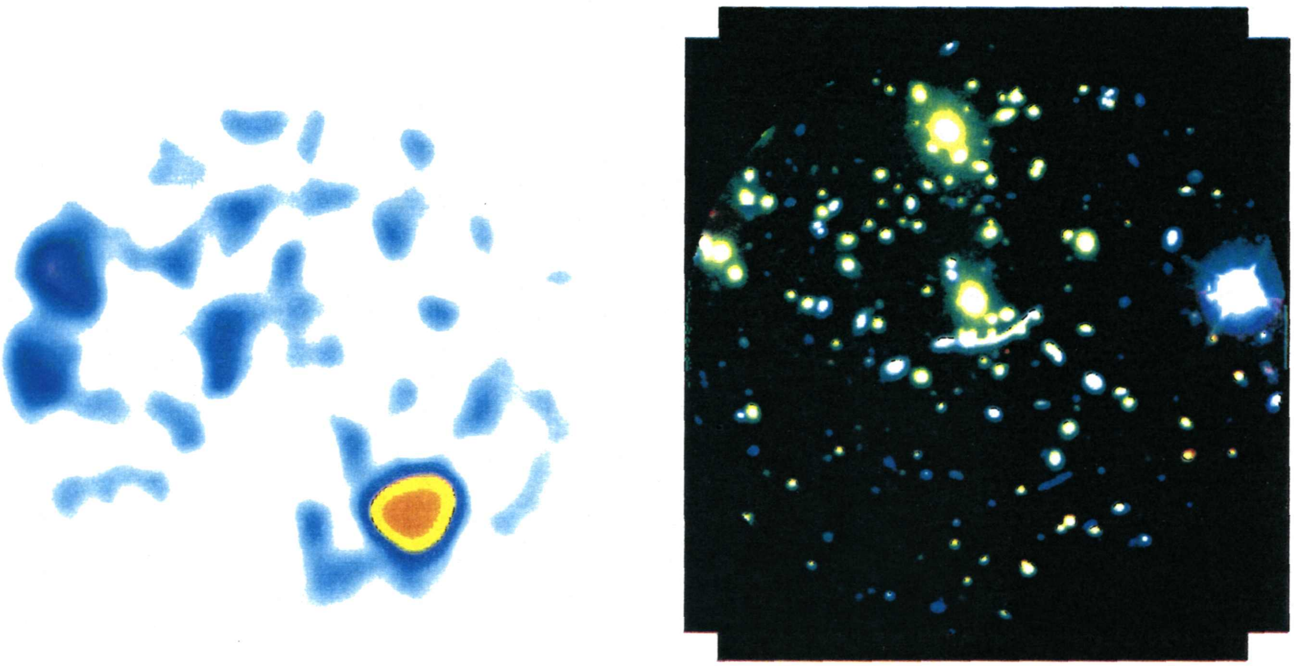

Figure 2.2: Submillimeter Sky and Optical Sky. *a), left:* Map at 850 μm of a 180″-diameter field centered on the galaxy cluster Abell 370. The map was made with the SCUBA array on the JCMT (Smail, Ivison, & Blain 1997, ApJ, 490, L5). *b), right:* The same patch of sky in a composite of blue, red, and near-IR images taken at the 3.6 m Canada France Hawaii Telescope (J.P. Kneib, in prep.). The prominent optical arc is a distant galaxy at $z = 0.73$, whose image is gravitationally distorted by the foreground galaxy cluster at $z = 0.37$. The objects on the submillimeter map are unrelated to the cluster galaxies, and are possibly dusty protogalaxies in the early universe, at much greater distances than the galaxies on the optical image (Ivison et al. 1998, MNRAS, in press). While the JCMT map took many hours to make, the LSA/MMA will be able to detect such objects with the same sensitivity in just three minutes, and will be able to map them at a resolution 5 to 10 times better than that of the *optical* image.

finding primeval galaxies at $z \geq 5$; indeed the LSA/MMA may be the only instrument that will be capable of finding such galaxies. If starbursts injected large amounts of dust into the disks of young galaxies, the resulting far IR continuum will be detectable at high z — the increasing distance is compensated by increased flux as the far IR bump is redshifted into the mm and sub-mm bands. Studies in these bands can potentially determine the redshift range in which most of the early-universe star formation and dust injection occurred. Tantalizing examples of this possibility are now being obtained with the SCUBA bolometer array on the James Clerk Maxwell Telescope. Figure 2.2 shows a map made with this instrument at 850 μm toward the galaxy cluster Abell 370 (Smail, Ivison, & Blain 1997, ApJ, 490, L5), and an optical image of the same patch of sky. The foreground cluster, seen in the optical image, has a redshift of 0.37, and acts as a gravitational lens that distorts and magnifies the images of distant galaxies well beyond the cluster. The prominent arc in the optical image is a distant galaxy at $z = 0.73$. However, the objects on the submillimeter map, from optical spectra taken so far, seem to be even farther away, and are possibly dusty young protogalaxies in the early universe. With existing facilities, we are thus able to detect distant dusty protogalaxies when their emission is amplified by gravitational lenses; with the LSA/MMA, we will be able to detect them everywhere in the sky. Because of the much greater sensitivity and much higher resolution of the LSA/MMA, such results will greatly improve our knowledge of the timescales of galaxy and structure formation in the universe, and the chemical evolution as a function of redshift. **The study of the early epochs of galaxy evolution is one of the main goals of a new mm/submm array, and it is one of the main reasons to have a huge collecting area.**

2.3 Formation of Stars and Planets

A major astronomical goal of the 21st century will be an understanding of how stars and planets form. The large collecting area and high resolution of the LSA/MMA will make it the best instrument for studying how gas and dust evolves from a collapsing cloud core into a circumstellar disk that can form planets. The array will be able to directly observe astrophysical phenomena that have until now only been conjectured in our theoretical models of the early stages of star formation. At the distance of the nearest young stars, in Taurus and Ophiuchus, the synthesised beam of the LSA/MMA — 4 AU at 1.3 mm — will allow us to constrain different models of forming stars. The data will yield new unique information on the gravitational contraction of protostellar cloud cores, with accurate kinematics and mass distributions inside the cores and their envelopes. The results will give new clues to the role of the magnetic field in the cloud cores, the circumstellar disks, and its influence on the accretion disk and the outflow jets that carry away the original angular momentum. A good example of bipolar outflow jets is shown in Fig. 2.3, which is a map of the high-velocity CO gas streaming out in two opposed jets of the source HH 211. The flow emerges from an embedded protostar surrounded by a disk of cold dust that is detected in the 1.3 mm continuum at the center of the flow. At their terminal points, the lobes of the jets produce shocks that emit in the near infrared lines of molecular hydrogen.

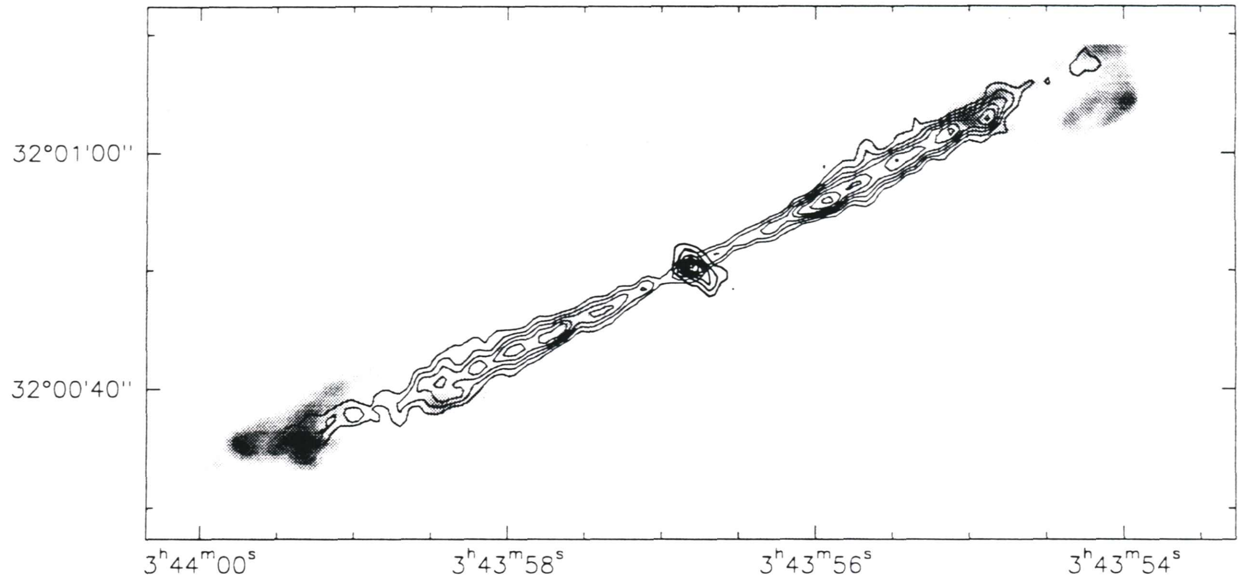

Figure 2.3: Jets from a Protostar. IRAM interferometer map of the high-velocity CO in the bipolar outflow in HH 211 (Gueth et al. 1998, in prep.). The contours at the center of the flow show the 1.3 mm thermal dust continuum from what is presumably the accretion disk. The greyscale shows the near-IR line intensity of molecular hydrogen, which is excited by shocks at the terminal points of the outflow lobes (McCaughrean, Rayner, & Zinnecker, 1998, in press).

For the later stages, when the newly-formed stars are surrounded by protoplanetary disks, imaging the gas and dust on scales of few tens of AU will be the only way to study the disk physics and chemistry in the earliest stages of planet formation. Current mm arrays do not have small enough beams to study the physics of the inner disks (inside the $\sim$ 100 central AU), and even the rotating molecular disks recently resolved by mm arrays around single T Tauri stars like DM Tau and GM Aur are actually very large structures that would be beyond the Kuiper Belt in our Solar System — well beyond the orbits of all the planets. The necessary resolution will be provided by the LSA/MMA, and maps of cold dust and optically thin molecular lines with $0.1''$ to $0.05''$ beams will provide crucial data on the chemistry, the gas/grain coupling, the reservoirs of the biogenic elements, and the timescales on which planets form. The high sensitivity of the array will allow us to make unbiased surveys of pre-main sequence stars to obtain the statistics of disk properties and frequency of protoplanetary systems in different star-forming regions.

For such studies, the LSA/MMA and the VLT will be complementary in the same sense as the current 4m optical telescopes and the IRAM mm array, examples of which are given by the recent combined imaging with the CHFT and the IRAM array of the low-mass, pre-Main Sequence binary star GG Tau. The near-IR images (Roddier et al., 1996) and mm data (Guilloteau et al., 1998, in prep.) show the circumbinary ring of GG Tau (Fig. 2.4) which is truncated by tidal effects at an inner radius of $1.2''$. These results provide a tantalizing preview of what will become possible with the next generation of telescopes, which will have 10 times better resolution in the mm/sub-mm and the near-

GG Tau

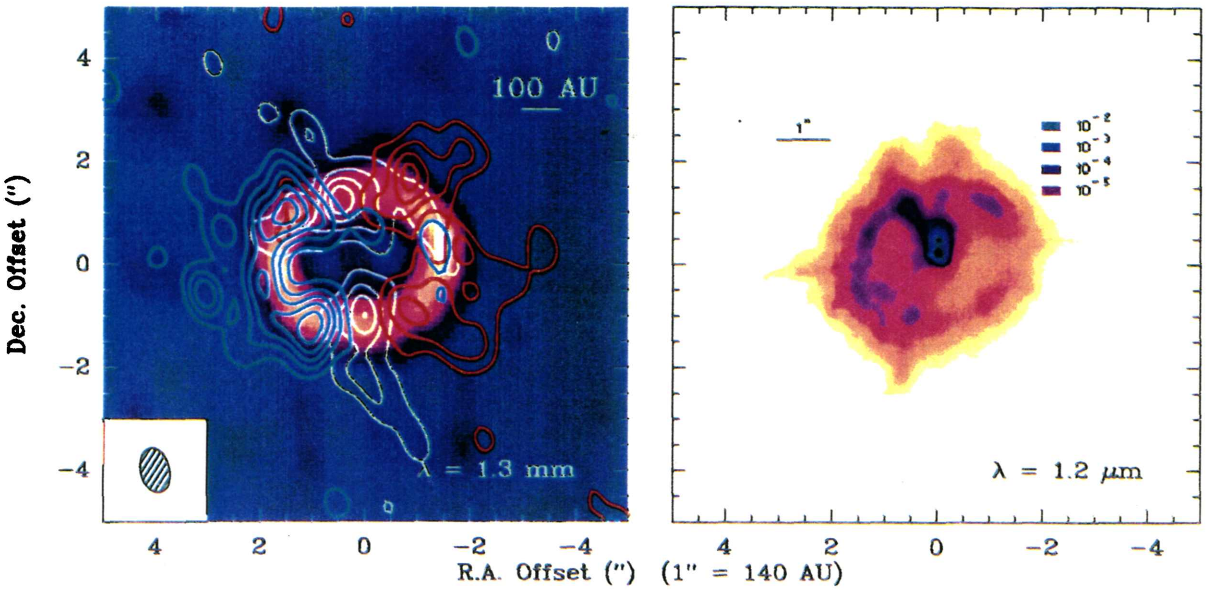

Figure 2.4: A Disk around a Young Binary Star. *Left:* IRAM interferometer map of the disk around the binary star GG Tau (Guilloteau et al. 1998, in prep.). The contours show $^{13}CO(2–1)$ in three different velocity ranges, while the false-color image shows the 1.3 mm dust emission. The beam is 0.6″ × 0.9″. The central gap of radius 1.2″ (180 AU) is a tidal effect of the binary star, separated by 0.26″. *Right:* Image of the GG Tau disk in J band (1.2 μm). The inner part of the circumbinary ring is seen in scattered light, and also shows a hole of radius 180 AU. The 20° position angle and the 37° inclination of the IR disk agree with those of the mm data (Roddier et al. 1996 ApJ, 463, 326).

IR/optical ranges. This will enable the LSA/MMA to resolve, within proto-planetary disks, the gaps that are tidally cleared by Jovian sized planets at distances of a few AU from their young, central stars. With the LSA/MMA and the VLT, multi-wavelength studies of such objects will be powerful tools for analysing the dust and gas properties on the scale of the Solar System.

The LSA/MMA will also allow us to study disks around newly-formed, higher mass stars, which has been impossible up to now, due to lack of resolving power. An example of the strong signals we can expect is shown in the VLA map of the ammonia (4,4) main line emission around the young high-mass star that is exciting the ultracompact H II region G10.47+0.03 (Fig. 2.5). The brightness temperatures of the NH_3 line in the 0.4″ beam range from 20 to 180 K. Because similar temperatures are found in optically thick 3 mm lines of molecules like methyl cyanide (CH_3CN), we expect from the sensitivities listed in Table 2.1 that the LSA/MMA will be able to image structures as small as 0.1″ without much difficulty.

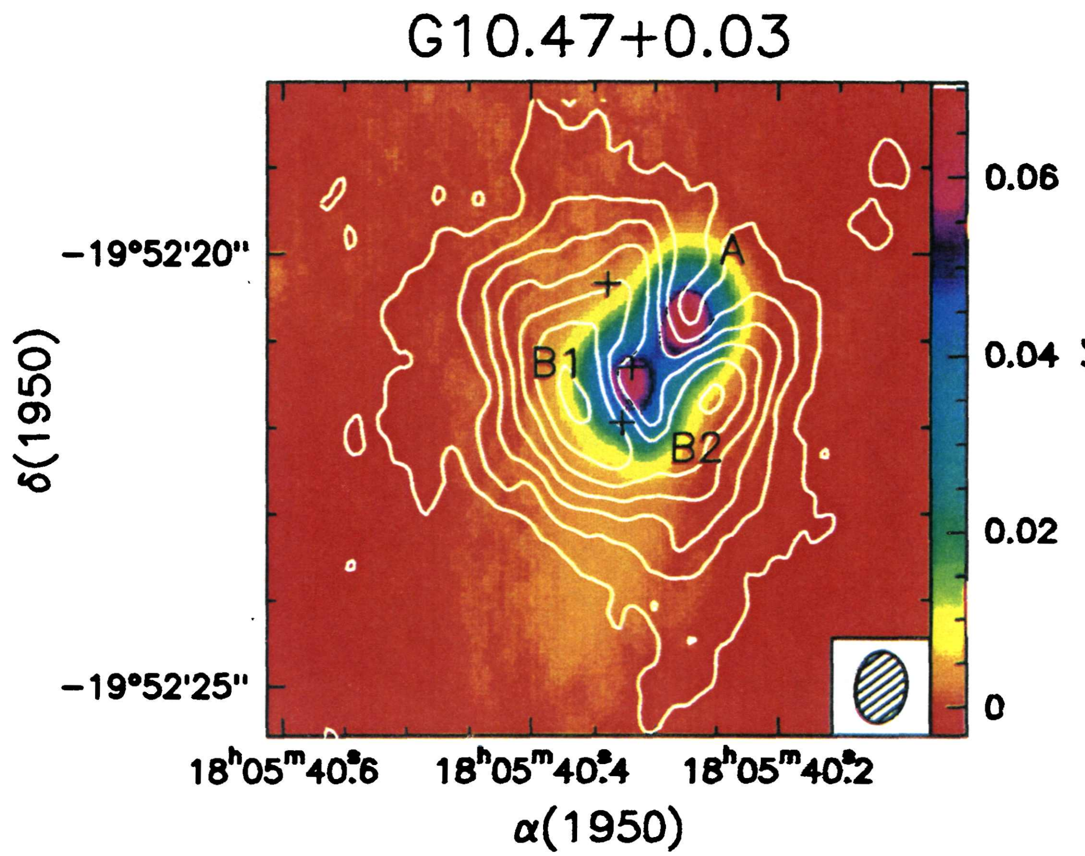

Figure 2.5: Sub-arcsecond Structure in Hot Cores of Molecular Gas around High-Mass Protostars. VLA contour map of the ammonia (4,4) emission around the young high-mass object G10.47+0.03, superposed on the 1.3 cm continuum emission from the ultracompact HII region (Cesaroni et al. 1998, A&A, 331, 709). The ellipse at bottom right shows the $\sim 0.4''$ beam for the NH_3 line map. The crosses are positions of H_2O masers (Hofner & Churchwell 1996, A&AS, 120, 283). Contours are −2.5, 2.5 to 26.5 by 4 mJy/beam.

2.4 Molecular Clouds in Galaxies

Galactic disks, with their spiral arms and Giant Molecular Clouds (GMCs), are the birthplaces of stars. Millimeter and sub-mm line and continuum data provide clues to how stars form and how they affect the interstellar medium and the chemical evolution of galactic disks. The mm and sub-mm lines of CO and its isotopic species trace both high and low density gas, HCN and CS trace high density gas, and HCO^+ traces ionization. These data yield the sites and physical properties of star-forming clouds across galactic disks, and will be a valuable complement to high-resolution ground-based IR and optical telescopes. For such studies a large new mm/sub-mm array is indispensible.

Galaxies at 30 to 200 Mpc will be prime targets for a large mm/sub-mm array. The array could image the dust and gas in galaxies at 200 Mpc with 50 pc resolution. The large collecting area of the LSA/MMA will allow us to map an enormous number of galaxies. Particularly interesting would be maps of gas and dust in a large sample of irregular galaxies. The nearest merger galaxies are at 40 to 100 Mpc; with a resolution of 50 pc, it would be possible to determine how merger-induced starbursts progress spatially in the gas.

Galaxies to 30 Mpc would be targets for which a new large array would give us the same linear resolution at 30 Mpc that we now have for the Local Group. A beam of 0.1″ will permit detailed imaging of GMCs in nearby galaxies. In fact, even clumps within GMCs could be identified to distances of 10 Mpc — a region containing hundreds of galaxies of greatly varying type. This would enable us to derive sizes, masses, temperatures, densities of star-forming clouds. With the same resolution, the statistics of the distribution of GMCs inside galaxies could be derived to distances $>$ 100 Mpc. In many nearby galaxies, a 30″ field of view is sufficient for studies of spiral arms and GMCs. To image whole galaxies (typical sizes 3′ to 15′), a mosaic is needed; this is already a familiar technique with mm interferometers.

A new large array will allow us to determine the masses and kinematics of optically obscured galactic nuclei with a resolution of a few parsecs and image the distributions of a variety of molecules and isotopic species. For nearby galaxies, current mm interferometer beams of 1″ to 2″ give a detailed look on a scale of 15 to 30 pc. This is sufficient to resolve the clumps in the central concentrations. A next-generation array with ten times more sensitivity than the IRAM interferometer could extend such studies to all the known Seyfert galaxies, and give high resolution maps of the innermost parts of the circumnuclear disks. A new large mm/sub-mm array will be able to map not only the gas but also the dust obscuring the galaxy nuclei. This will give us greatly improved possibilities of studying the connection between star formation and massive black holes in nearby active galactic nuclei (AGN), the nearest of which, Centaurus A, is a prominent radio source in the southern sky. The high resolution and the sensitivity of the LSA/MMA will allow us not only to map the dust in the nearer galaxies, but also to detect the dust in IR luminous galaxy nuclei to several Gpc. A large mm/sub-mm array with an 0.1″ beam could reveal the structure, masses, and kinematics of circumnuclear material with an accuracy equal to, or surpassing that of the Hubble Space Telescope. If these circumnuclear regions are dusty, it is of course impossible to study them in the optical range, and information from the LSA/MMA will be vital.

Local Group Galaxies are now being mapped in molecular lines with resolutions of $1''$. These studies reveal clumps within GMCs and give the clumps' mass distribution, kinematics, dynamics, and relation to ongoing star formation. With a new array's resolution of $0.1''$ or better, the clumps themselves could be mapped, and the properties of the birthplaces of stars in many low-metallicity Local Group galaxies could be compared directly with those of stars in the Milky Way. This would be highly interesting, because star formation is closely related to the ambient radiation field, dust content, and metallicity. Magellanic Cloud Studies would also benefit from a new mm/sub-mm array. Current southern mm dishes cannot resolve compact molecular sources in the Clouds. What we need are resolutions of $0.1''$ to a few arcsec. At the distance of the Magellanic Cloud, this would allow us to study objects on the same linear scales as in CO surveys with beams of several arcsec to a few arcmin in our own Milky Way.

The Galactic Center will also be a favorite target of a new, large, mm/sub-mm array. Of particular interest will be the gas dynamics of the 1-pc circumnuclear disk around the galactic center source Sgr A*, the numerous star-forming centers in the cloud Sgr B2, the environs of the various black-hole candidates detected by gamma-ray satellites, the effects of the extensive magnetic flux tubes on the molecular clouds in the arcs near Sgr A, and the hundreds of molecular clouds in the bar at the center of the galaxy.

Molecular Clouds in the Central $l = \pm 30°$ of the Milky Way make up most of the molecular clouds in our Galaxy. There is already a wealth of data on these molecular clouds from single-dish results in various lines, from maser source surveys, and from near and far IR studies. What has been lacking so far is extensive research with mm/sub-mm interferometers. Because of the great number of dense cores in the molecular clouds, and the number of spectral lines that can be mapped, this is a program which will keep a large mm/sub-mm array busy for decades.

2.5 Dynamics and Chemistry of Circumstellar Envelopes

A large mm and sub-mm array will be used to investigate all types of stars. It will be valuable for studying the winds of hot stars, novae, the photospheres of giants and supergiants, and non-thermal processes in flare stars, Be stars, and dust formation in supernovae and in the outflows of planetary nebulae. In particular, the new array will yield fundamental knowledge for our understanding of the dynamics and chemistry of the envelopes of evolved, oxygen-rich and carbon-rich stars, where important scientific goals are the understanding of dust formation and the enrichment of the interstellar medium in heavy elements. The winds of these red giant stars rapidly remove the outer layers, terminating further evolution. The winds have low outflow speeds and high densities, so

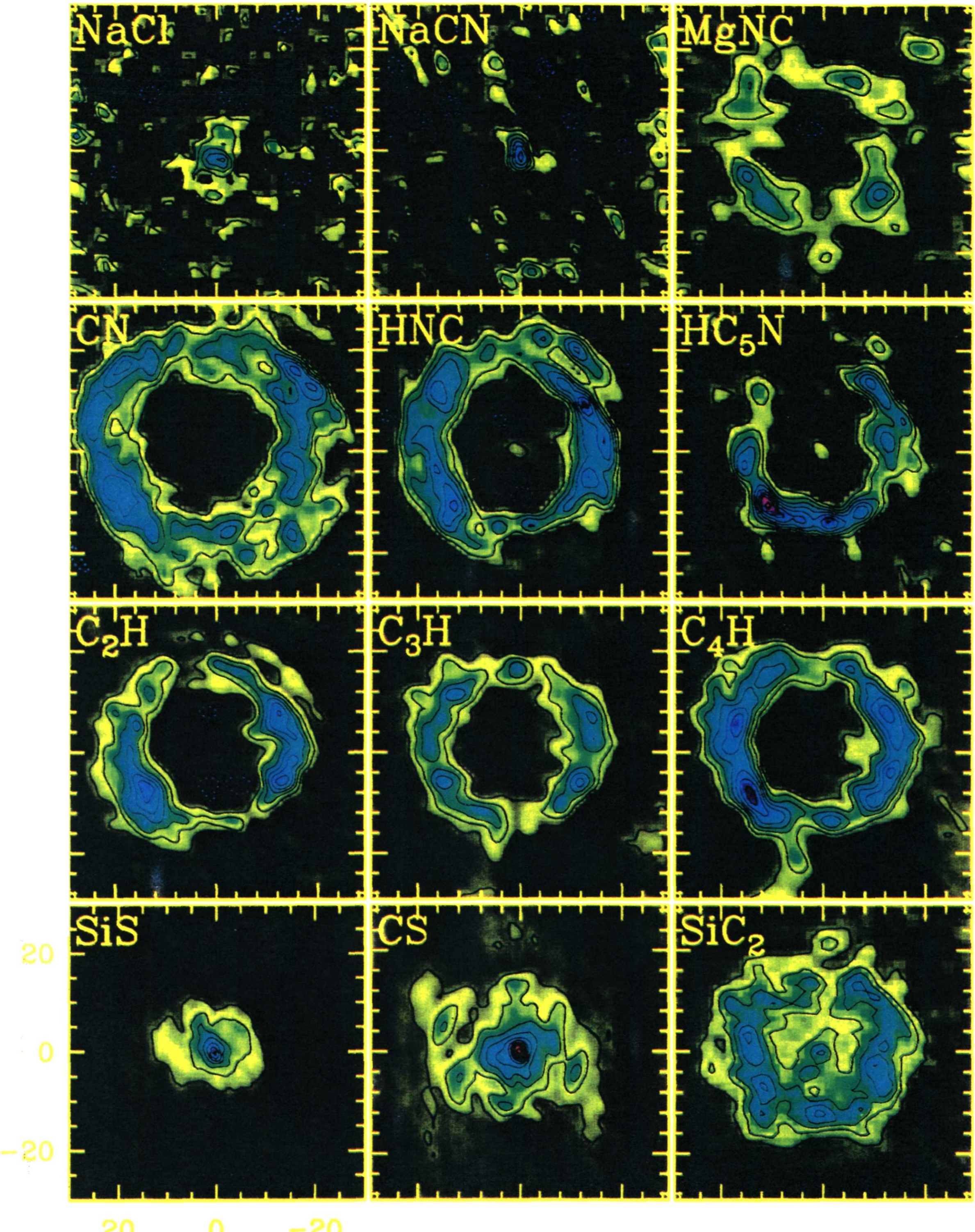

Figure 2.6: Molecules in a Circumstellar Envelope. The carbon-rich envelope ejected by the star IRC+10216, mapped in various molecular lines with the IRAM interferometer with a 3″ beam (Guélin, Lucas, & Neri, 1996, in Science with Large MM Arrays, ed. P. Shaver, Springer, 276).

that matter easily condenses into dust grains. Good examples of current capabilities in studying these envelopes are the IRAM interferometer maps of IRC+10216 (Fig. 2.6). which have enough sensitivity to show rare molecules like gaseous sodium chloride. The maps in the Figure indicate that molecules like NaCN and SiS probably form in the star's photosphere and condense rapidly on dust grains, while HC_5N and the radicals CN and C_nH form farther out in the envelope. The presence of multiple concentric envelopes on the maps of C_2H, CN, and HNC, together with the measured wind speed of 15 km s^{-1}, suggest that the outflow is discontinuous, with large impulses on time scales of 200 to 800 years. The LSA/MMA will be essential to image the distribution of matter in the outflows at distances of a few stellar radii and to solve the long-standing problem of dust formation. It will also allow us to study the interaction between stellar pulsations and wind acceleration, and will help us to understand the flattened geometry of the large, detached dust shells around stars that are evolving to become planetary nebulae. Since stars are concentrated in the Milky Way's inner disk, a southern array would allow us to study most of the large circumstellar envelopes in the Galaxy, and to use the SiO masers in red giant envelopes to trace the dynamics of the galactic bulge in the center of our galaxy. With its high sensitivity. the LSA/MMA will give us the ability to map these stars anywhere in the Galaxy with better linear resolution than we now have for stars within 500 pc of the Sun.

2.6 Solar System Research

Cometary atmospheres. Observations of comets with the LSA/MMA will directly aid our understanding of the nature and origin of comets and complement the planned space probes (in particular Rosetta) which will be able to sample only a few comets. Millimeter and submillimeter spectroscopy have by now discovered more than 20 molecules in comets, and have shown that the composition of cometary ices is highly analogous to interstellar material, indicating that comets are relics of protosolar chemistry. The large collecting area of the array will permit us to search for less abundant molecules, radicals, and new ions in bright comets coming from the Oort cloud and to investigate the composition of periodic comets born in the Kuiper belt. It will be possible to detect CO and other species in many distant comets and to study the evolution of their outgassing as they approach the Sun. CO could also be detected in giant comet-like objects such as Chiron. Such studies will provide clues to the sublimation processes and physical properties of cometary ices. The LSA/MMA will be also a key instrument for investigating isotopic ratios (such as D/H) in several species and many comets. Important information will be obtained on the origin of comets and the formation of the Solar System.

The LSA/MMA will be able to map molecules and dust continuum emission in the coma of comets, as in the maps of comet Hale-Bopp, shown in Fig. 2.7, but with much greater sensitivity and resolution. Note that with beams of $< 0.1''$ pointed at a comet at a distance of 1 AU, a new array will have a linear resolution of 70 km ! Because cometary activity varies on short time scales, the new array will be ideal for providing fast images. Such images will allow us to study structures in the inner coma, such as fans and rotating jets, and to investigate to what extent dust and chemistry in the coma are involved in the production of molecules. Maps of the distribution of rotational temperatures of different molecular species will help us study the thermodynamics, excitation processes, and physical conditions in the coma of comets.

Thermal emission of small Solar System bodies. The LSA/MMA will enable us to make sensitive studies of the thermal emission of small Solar System bodies. Asteroids and cometary nuclei of small sizes, and even distant objects such as Centaurs and trans-Neptunian objects, will be detectable in the mm and sub-mm continuum. Together with observations in the mid-infrared, centimeter, and visible bands, mm/sub-mm observations with the LSA/MMA will allow to probe the temperature of these objects at various depths and to measure their albedo and size. Imaging thermal emission from the planetary satellites, the Pluto/Charon system and the largest asteroids will provide clues to their thermal properties and the degree of heterogeneity of their surface.

Atmospheres of the Planets and their Satellites. A new large array could map CO and HDO in Mars and Venus and give data on wind, temperature, CO and water distribution, and atmospheric dynamics on spatial scales less than 100 km, which is comparable to regional weather scales. The analysis of meteorological and climatic variations in the atmosphere of Mars with the LSA/MMA will be a worthwhile complement to future space missions. Moreover, the large collecting area of the array will permit us to search for molecular trace species likely to be present in these planets, such as sulfur-bearing compounds in Venus and organic species in Mars. Wide bandwidth capabilities will allow to probe the deep atmosphere of Venus. The LSA/MMA will be the first mm interferometer that will be able to map planetary atmospheres on short timescales.

Mapping HCN and CO, and searching for other nitriles (HCN, CH_3CN) on Neptune would provide information on whether the origin of such molecules is internal or external. A long-term mapping of CO, CS and HCN in the atmosphere of Jupiter will allow us to follow the evolution of the spatial distribution of the large quantity of such molecules that were recently deposited at Southern latitudes during the impacts of comet Shoemaker-Levy. During very dry conditions at the high-altitude site proposed for the LSA/MMA, the mapping of H_2O and HDO on the four Giant Planets would provide clues as to the origin of water (interplanetary dust or ring/satellite material). A backend as broad as 8 GHz would allow us to detect and map tropospheric species such as PH_3 in the Giant Planets.

In addition, the LSA/MMA will permit us to probe with high resolution and sensitivity the atmospheres of Pluto and the satellites of the giant planets. An array with beams $<$ 0.1 arcsec could detect SO_2 and SO in the plumes of the volcanoes on Jupiter's moon Io and enable the discovery of other trace constituents. Profound advances in the general understanding of the composition and thermal structure of the plumes may be expected from such observations. Mapping the millimeter lines of CO, HCN, HC_3N, and CH_3CN

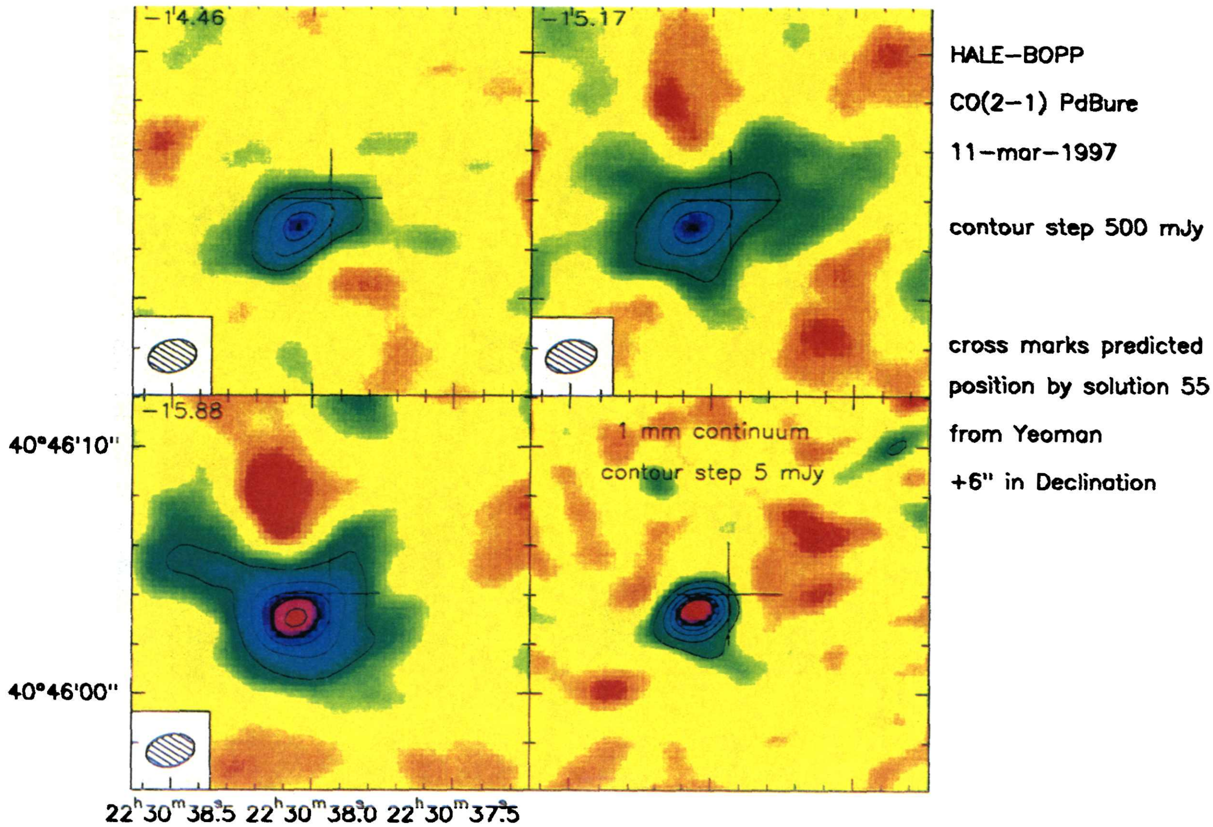

Figure 2.7: Molecules and dust in comet Hale-Bopp. The gaseous envelope around the nucleus of comet Hale-Bopp, mapped in CO(2–1) in different velocity channels with the IRAM interferometer with a 1″ beam. The lower right panel shows the dust emission around the nucleus, which appears to be more compact than the gaseous envelope traced in CO(2–1) (J. Wink, D. Bockelee-Morvan et al., in preparation).

in the stratosphere of Titan with high spectral resolution will provide the vertical and latitudinal distributions of these constituents, enabling better constraints on the photochemistry that occurs in Titan's atmosphere and its response to seasonal effects. Other nitriles, like HC_5N and C_2H_3CN, might be detected, allowing considerable advances in our knowledge of Titan's organic chemistry. Such future ground-based mm/sub-mm observations of Titan will complement in many aspects the on-the-spot measurements in a time-limited period by the Cassini/Huygens spacecraft that arrives at Saturn in 2004. The LSA/MMA will have sufficient sensitivity to detect and map CO (and perhaps other species, such as HCN) in the tenuous atmospheres of Pluto and Triton. This will provide hints on the nature of the interaction between their icy surfaces and their atmospheres. Finally, there is another object with a very tenuous atmosphere which could possibly be studied with the LSA/MMA — the Moon. If, as is currently suspected, there are icy craters present near the poles, and if water is outgassed from those places, the LSA/MMA will be able to detect it.

2.7 LSA/MMA Science in a Wider Context

We have already shown in the preceding sections examples of the potential synergy with large optical telescopes, in nearly all the possible sub-fields of astronomical research from the formation of galaxies to the formation of planetary systems. The new large optical telescopes that will be located at the same southern latitudes as the LSA/MMA include both the multi-national southern GEMINI 8 m telescope, and the European VLT with its four 8 m telescopes and smaller auxilliary telescopes capable of operating with angular resolutions comparable with those of the the LSA/MMA, whether in speckle interferometry mode, or in direct Michelson interferometry mode. There will also be considerable sky overlap with the telescopes on Hawaii, including the two Keck telescopes, the northern GEMINI telescope, and the Japanese SUBARU telescope. In addition to the telescopes in Chile and Hawaii, the LSA/MMA will overlap in sky coverage with, and be able to do projects complementary to, numerous other new-generation optical telescopes, including the projected large Spanish-international telescope in the Canary Islands, the Large Binocular Telescope in Arizona that has significant investment by European partners, as well as the new 50-m single-dish millimeter telescope that is currently in the design phase in the U.S. and Mexico.

The foregoing examples of scientific research that can be done with a new millimeter/submillimeter array should also be appreciated in the wider context of astrophysical instrumentation in the early part of the 21st century. The period just after the completion of this array will also be the period of launch and exploitation of several important scientific spacecraft. These include the Next Generation Space Telescope (NGST), the proposed successor of the current Hubble Space Telescope (HST), and the Far Infrared and Submillimetre Telescope — the FIRST mission. The LSA/MMA will complement both space missions, especially in studies of distant galaxies. Some of the FIRST mission will be dedicated to deep surveying, which with the great sensitivity of this space telescope, will lead to the discovery of many distant sources of thermal dust emission in the submillimeter range, while with the LSA/MMA, one will be able to follow up the discoveries and study the sources in detail in spectral lines and the dust continuum with high angular resolution. Although the NGST may miss distant sources that are heavily obscured by dust, it will nevertheless be able to image visible and near-IR sources with great sensitivity and with resolution comparable with that of the LSA/MMA. It is certain to make fundamental advances in optical/infrared astronomy that will surpass even those of the Hubble Space Telescope, and that will provide a wealth of new objects to investigate with a large array in the mm and sub-mm bands.

All of this new investment in large collecting area and high sensitivity guarantees that astronomy will be as exciting and as vigourous in the 21st century as it has been in the 20th century. The large effort in space astronomy and ground-based optical astronomy requires a complementary effort in the unique windows on the universe that are provided by the millimeter and sub-millimeter bands.

3. The LSA/MMA Interferometer

3.1 The Site

(This section was written/compiled by R. Booth, chairman of the Site Working Group, with input from the WG members and NRAO reports)

3.1.1 Site Selection

Site selection for the millimeter arrays has concentrated on the II region of Chile which extends between 22 and 26 degrees south and 67 to 72 degrees west (Figure 3.1.1). The very dry atmosphere in the Atacama desert, together with the availability of many high plateaux extending over some tens of kilometers, makes Northern Chile an exceptional place for high frequency radio astronomy.

From a geomorphological point of view, the II region of Chile is dominated by three mountain ranges extending N-S, the most easterly of which is the Andes with mountains as high as 6000 m. Some are volcanoes, most of which have been inactive for centuries, the exception being the volcano Lascar located 32 km south of the village of San Pedro de Atacama, which is characterised by persistent fumes and which had an explosive eruption in 1993.

The meteorology of the area is dominated by the jet stream which flows nearly continuously from west to east; the dryness of the region is explained by the fact that a very stable high pressure system in the area deflects the jet stream to the south and the high altitude of the mountain ranges ensures that the humid air from the Pacific and Atlantic oceans condenses out before reaching the central part of the Atacama region.

3.1.2 The Chajnantor Site

The site chosen for the LSA/MMA is the high (5000m) plateau of Llano de Chajnantor in Northern Chile. This is not the original site envisaged for the LSA alone (which was to operate only in the millimeter bands, down to a wavelength of 0.8 mm) since strong interest in the submillimeter regime requires the joint LSA/MMA to operate in the wavelength range 3mm to 350 microns, i.e. to the limits of atmospheric opacity. These demands require the very best site and, from initial tests conducted by the NRAO site testing team – now over two years, indicate that Chajnantor is indeed one of the very

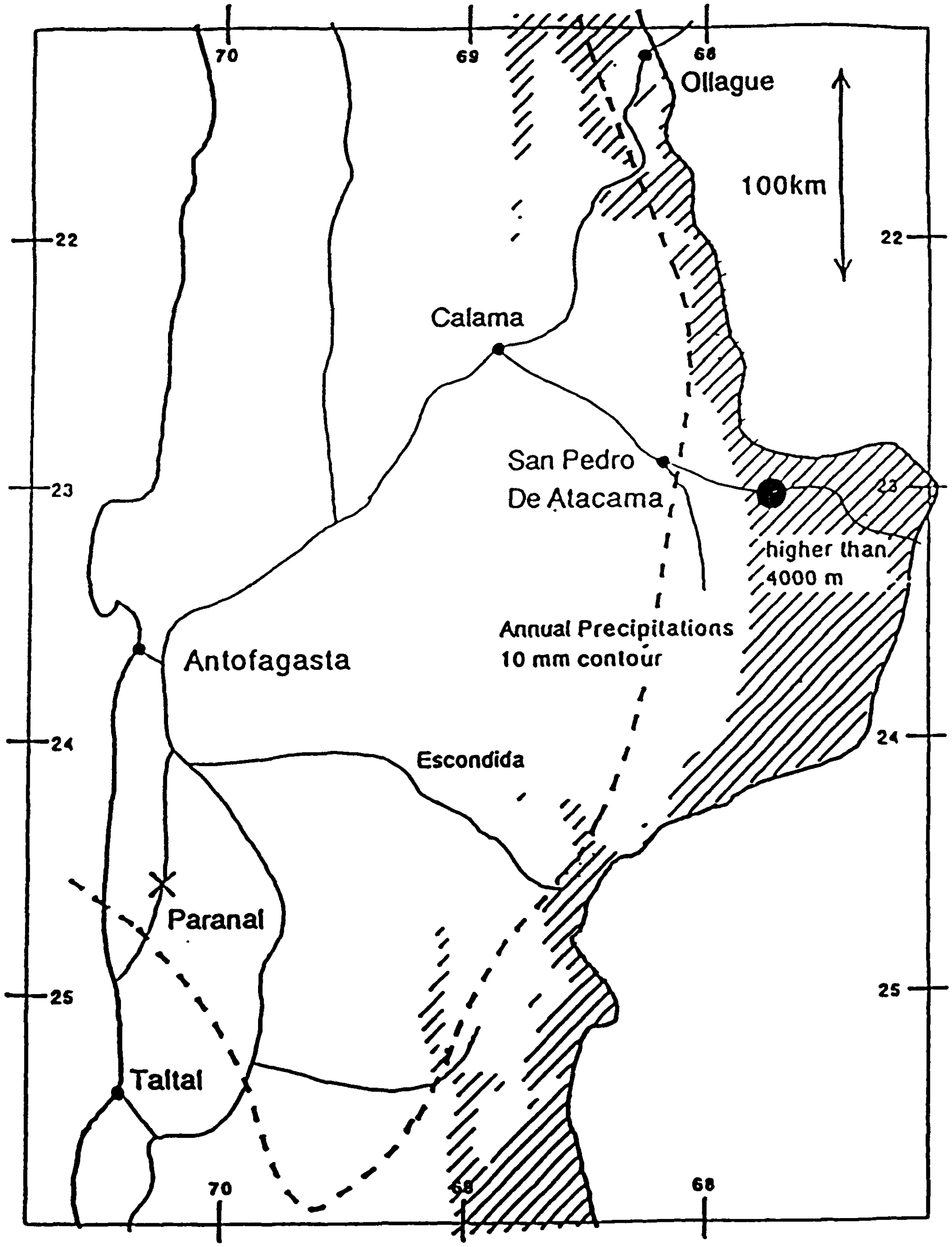

Figure 3.1.1: Map of the region of interest in northern Chile. The large filled circle shows the position of Chajnantor, the proposed site of the LSA/MMA.

best accessible submillimeter sites on Earth.

The site conditions required are most stringent for continuum imaging and these require high atmospheric transmission which is essentially determined by the total amount of atmospheric water vapour for wavelengths less than 2 mm. The plots of opacity versus wavelength as a function of the precipitable water are well known. The consequences for site selection are therefore clear cut: a precipitable water vapour content of 1mm or less for a large fraction of the time demands the highest reasonable location in an extremely arid area. For interferometry, the atmospheric turbulence is a second important factor and although much work is required before we will understand how to make maps at 350 microns, the measurements on Chajnantor indicate that the interferometer phase stability will be sufficient for the longer wavelengths at shorter baselines and that phase correction schemes applied, for example at IRAM, will facilitate longer baseline and higher frequency imaging.

Figure 3.1.2 is a 30 km scale contour image of the chosen site with 100m elevation contours. It can be seen that the maximum baselines on reasonably flat land near 5000m are measured in tens of kilometers and the site is certainly extensive enough for the 10 km baselines proposed for the array. Figure 3.1.2 shows that Llano de Chajnantor is not the highest ground in this region. Three peaks within 10 km reach 5500m. One of these, Cerro Toco, is accessible to these elevations by automobile now. Other, slightly higher, sites are reachable by road within 50 km of San Pedro de Atacama. Thus, location of the LSA/MMA on Llano de Chajnantor could provide a base for future, higher astronomical sites, and there is already considerable interest in this unique area.

3.1.3 Climate

Llano de Chajnantor is a relatively cold place as expected from its altitude. However, it does not suffer particularly extreme temperatures, so this is not seen as an issue. The estimated precipitation is 10 cm per year (SAO Submillimeter Array Memo 59).

The wind velocity statistics exemplified by Figure 3.1.3 show that the wind speed on Llano de Chajnantor goes through an afternoon peak, typically up to 10 m/s. Strong winds may hinder accurate antenna pointing, delay array reconfigurations, and potentially damage equipment. However, the normal winds are relatively gentle and should allow the highest precision pointing planned for the LSA/MMA more than half the time.

The NRAO site testing program on Llano de Chajnantor used a 225 GHz tipping radiometer. The opacity and stability measured at this frequency were combined with standard atmospheric models to give an estimate of the transparency across the millimeter and submillimeter spectrum. Wind velocity and ambient temperature also were recorded. In addition, a "seeing" interferometer with a 300m baseline was used. This interferometer

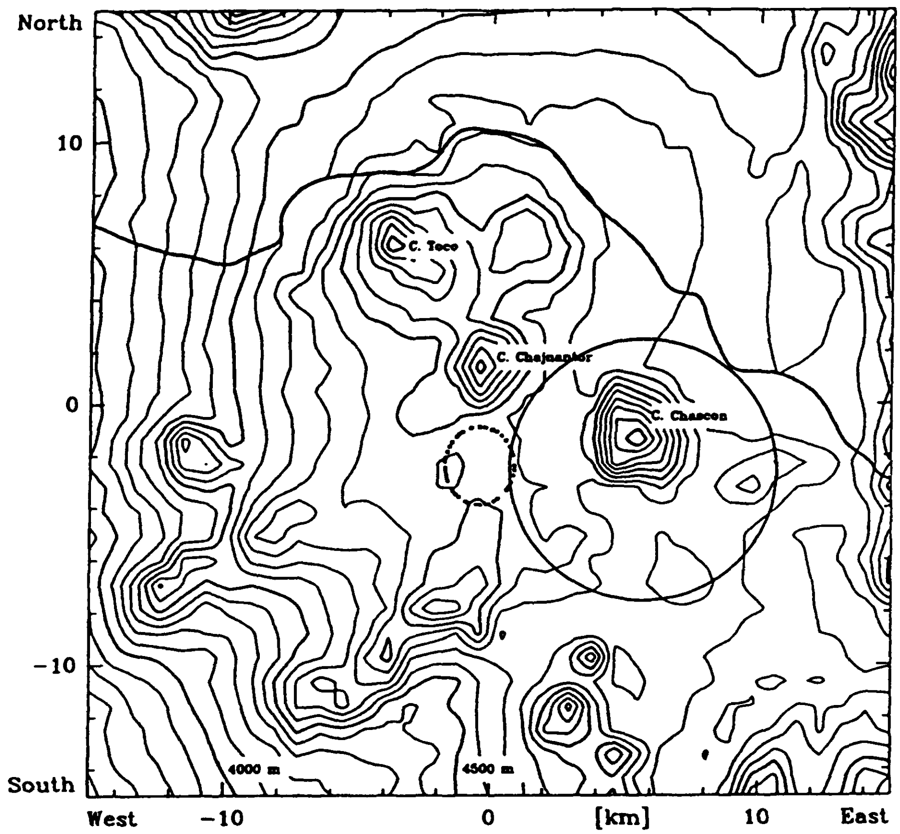

Figure 3.1.2: Environs of Cerro Chajnantor, Chile, showing approximate positions of a possible layout of a 3-km array (squares) and a 10-km array (large circle). The contour interval is 100 m. The Paso de Jama highway, shown as a dark line running north of C. Toco, runs approximately East-West just north of Cerro Toco.

was pointed continuously at a geostationary satellite and monitored the phase on this baseline at 11.5 GHz. These phase measurements, and to a lesser extent the stability measurements using the tipping radiometers, are used to assess the phase fluctuations expected at millimeter and submillimeter wavelengths.

3.1.4 Atmospheric Transparency

The cumulative distribution of opacities measured on Llano de Chajnantor are shown in Figure 3.1.4 together with similar measurements from Mauna Kea. As expected from the altitude difference, opacity quartiles on Mauna Kea are 2 to 2.5 times higher than for Llano de Chajnantor. In millimeter bands where we expect the system temperature to be dominated by the atmosphere, the measured difference corresponds to a factor of 1.5 to 2.5 improvement in sensitivity of the array in the most transparent submillimeter windows. This is an important indicator of the quality of the Chajnantor site for submillimeter observations. The lack of significant diurnal variation in the transparency suggests that

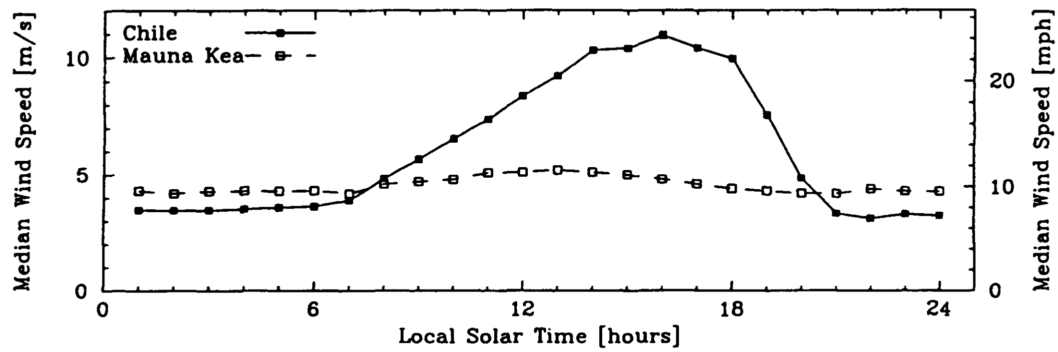

Figure 3.1.3: Diurnal variation of median wind speed on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*. Local solar time is UT minus $4^h.5$ on Llano de Chajnantor and UT minus $10^h.4$ on Mauna Kea.

the LSA/MMA would be usable 24 hours a day on Llano de Chajnantor.

The site shows a seasonal transparency variation (Figure 3.1.5) with the best conditions during the winter (April-October), when the median optical depth is 0.042. During the summer (November-March) the median optical depth, 0.087, is roughly twice as large as in the winter. In both seasons, the transparency at Chajnantor is superior to that measured on Mauna Kea in its best months.

It is, of course, difficult to say if these results are typical, or whether the period sampled was particularly good. The NRAO data set with the tipper is for 2 years only but a detailed comparison with opacities estimated during the same period using the radiosonde data from Antofagasta shows a good correlation. Thus, the radiosonde data available back to 1988 has been used to evaluate the long term trend. These data and the opacities for 1995-96 measured with the tipper on Llano de Chajnantor are shown in Figure 3.1.6. These results suggest the overall conditions on both sites are representative of the recent past and thus probably a good indication of what we can expect in the future.

One potential hazard is the effect of El Nino - Southern Oscillation (ENSO) on the seasonal and spatial variability of water vapour and cirrus cloud cover over the site. It is hoped that this will be addressed by a new study proposed by M. Sarazin of ESO in collaboration with a consulting meteorologist, in which weather satellite imagery taken at 6.7 microns will be used to derive those meteorological parameters which relate to astronomical transparency and seeing at millimeter/submillimeter wavelengths. Imagery from Meteosat-3 and GOES-8 over the period 1991 to 1998 will be used to determine the presence and thickness of high altitude cirrus cloud, and its effects on the interferometer.

3.1.5 Phase Stability

The other important issue is the atmospheric phase stability or "seeing". Because radio waves travel more slowly in wet air than in dry air, fluctuations in the water vapor

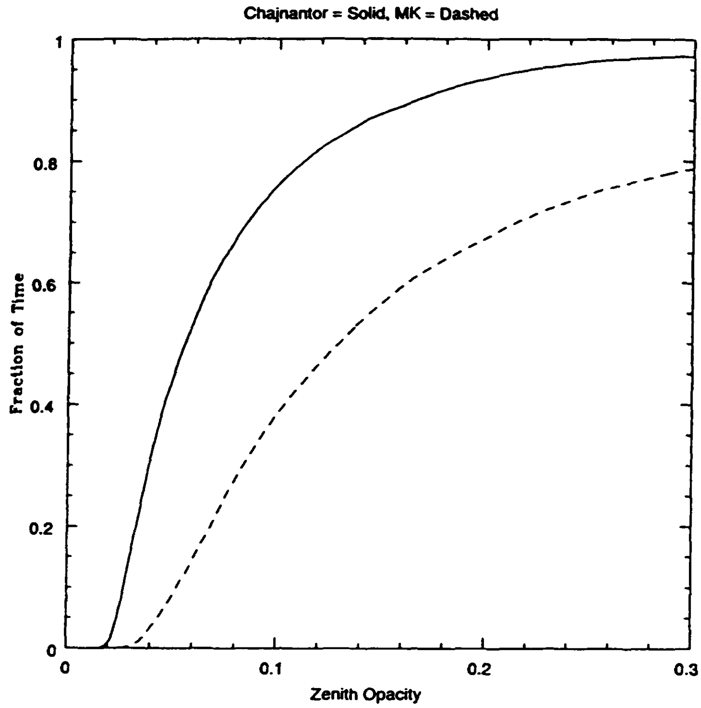

Figure 3.1.4: Cumulative distributions and quartiles of 225-GHz zenith optical depth, τ_{225}, on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*. The distributions were first averaged by month, and then the distributions for each of the twelve months were averaged to produce the final curve.

content above the array will cause variations in the electrical path length through the atmosphere. Path length variations from antenna to antenna will degrade both image quality and array sensitivity. Path length fluctuations, which are almost independent of observing frequency at millimeter wavelengths, correspond to phase fluctuations that scale linearly with frequency. Numerical simulations with a realistic model atmosphere show phase fluctuations of less than 10° rms at the observing wavelength will have little impact on most imaging. Phase errors of 30° rms will permit imaging with up to 200:1 dynamic range, at somewhat reduced sensitivity. Image reconstruction becomes all but impossible for phase errors higher than 60° rms. We expect either fast switching or phase calibration from total power or line observations to allow imaging when conditions are worse than this. The better the absolute stability is, the easier it will be to make use of these correction schemes (MMA memos 139 and 144).

Atmospheric phase stability was measured with a 300m baseline, 11.5 GHz interferometer observing geostationary communications satellites (Radford, Reiland, & Shillue 1996, PASP, 108, 441). Because the atmosphere is non-dispersive away from line centers, these measurements can be extrapolated to characterize the atmospheric phase stability at least up to 350 GHz. These interferometers sense atmospheric structures of about 300m and smaller scales. To compensate for the different elevation angles of the satellites observed from the two sites, the phase fluctuations were corrected to the zenith (MMA memo 127). The phase stability was characterized by the rms phase fluctuations calculated over 10 minute intervals. This interval is twenty times longer than the time it takes an atmospheric

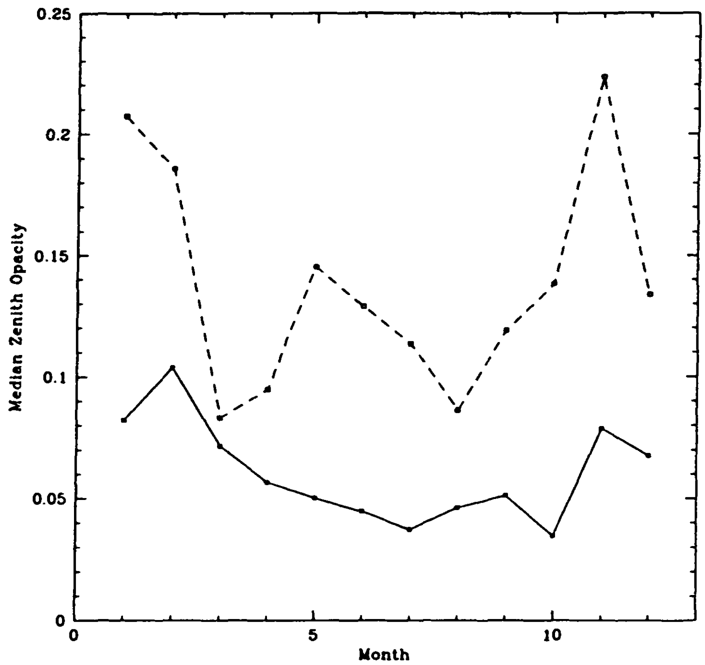

Figure 3.1.5: Seasonal variation of median 225-GHz zenith optical depth, τ_{225}, on the Mauna Kea site *(dashed)* and on Llano de Chajnantor *(solid)*.

feature to move the length of the baseline at 10 m s^{-1}, which is the median wind speed aloft. Thermal instrumental phase noise is on the order of 0°.1 rms at 11.5 GHz, while the smallest rms phase fluctuation seen to date – after correcting for instrument noise – is 0°.3 rms at 11.5 GHz (MMA memo 139).

Measurements thus far (Figure 3.1.7) show that the median phase stability on a 300m baseline at Llano de Chajnantor is about 25% better than on the other well known millimeter site of Mauna Kea. In practice, we are interested in observing on much longer baselines than 300m on which the phase stability will be worse. However, we can accurately model the use of fast switching under the power spectrum of fluctuation determined by the interferometers. This analysis shows that we can expect to be able to image coherently at 230 GHz on baselines longer than 300m about 75% of the time on Llano de Chajnantor (MMA memo 139).

There are significant diurnal variations in phase stability (Figure 3.1.8). At local noon, the median phase stability is about seven times worse than at midnight. This will limit the observations which are possible during the day, the exact details of which will depend on frequency, array configuration, and the phase calibration technique employed.

Seasonal variations in phase stability (Figure 3.1.9) are less pronounced than diurnal variations. The best conditions are in the winter when the diurnal variation in phase stability is also much less extreme than in summer. Thus, during the Chilean winter, high resolution observations are possible around the clock much of the time.

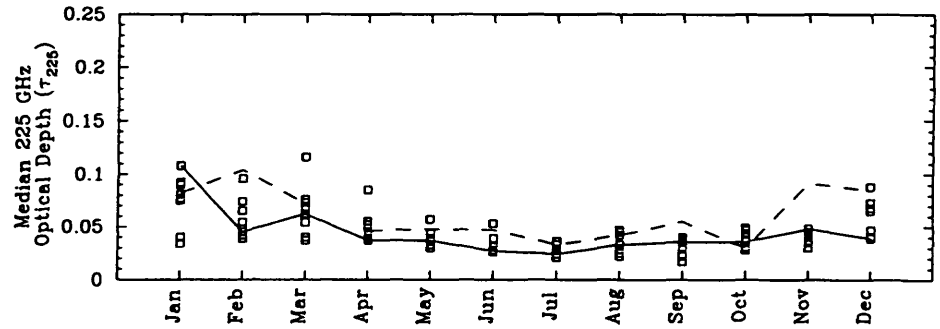

Figure 3.1.6: Seasonal variation of median 225-GHz zenith optical depth, τ_{225}, on Llano de Chajnantor for 1995–96 *(dashed)* compared with optical depth deduced from 1988–95 Antofagasta radiosonde data. The 1995 radiosonde data are connected *(solid)*.

3.1.6 Geological Considerations

Chile's geological activity is well-known. Earthquakes are a regular feature of Chilean life and Llano de Chajnantor is surrounded by volcanic cones. The engineering and logistics of the observatory are influenced by the continental and local geology: earthquakes, soil stability, water and wind erosion, electrical grounding, and other aspects. Detailed questions of civil engineering and telescope construction will require a knowledge of the geological environment as for instance provided from test drillings and laboratory soil studies.

The proposed site is located at 5000 m altitude on a large plane close to the ridge of the Andes mountains. This mountain ridge is located on the western edge of the South-American plate which moves in a western direction over the Pacific plate. At the location of the site, the depth of the Pacific plate is some 50 to 100 km. The movement and tectonic friction frequently cause earthquakes reaching a strength of 7–8 Richter. This implies horizontal accelerations of 0.2–0.35 g. There is wide experience in Chile for construction under earthquake conditions.

The material at the site (Chajnantor) is a fine grain platelike sand which may extend to a considerable depth. There is no vegetation to stabilize the top soil layer. The grainy material may easily slide and shift, and steep slopes are not observed on the site. The grainy material is volatile so that dust protection of precision equipment is required. The electrical condutivity is low and grounding needs special attention, as well as static charges. Although the amount of precipitation is small, there are washed-off roads in the same area, indicating that occasionally water erosion may be severe, in particular of the dry and sandy soil. The soil must support a telescope of about 50 tons placed on a pedestal of some 6–8 meter diameter. When evenly distributed this amounts to a load of 1.5–2 ton/m^2. The soil may need to be stabilized by concrete injection, pillaring, or extended foundations.

Although the telescopes will not frequently be moved, stable foundations are required for reproducible positioning of the telescopes. The long-term stability of the telescope stations

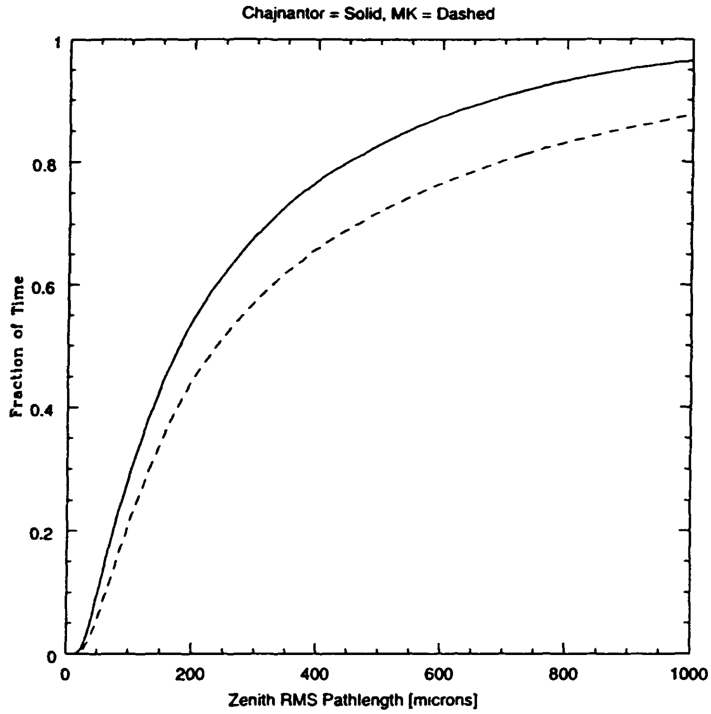

Figure 3.1.7: Cumulative distributions and quartiles of rms path-length fluctuations on a 300-m baseline on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*. The upper scale shows the equivalent phase fluctuations at 230 GHz.

should be ±0.5 mm in height and ±3 arc minutes in inclination. With respect to the high pointing precision it will be necessary to provide in the environment of each telescope a stable geodetic point, preferentially anchored to bedrock, if possible. The pointing of the telescopes may be improved significantly by the use of high precision inclinometers. It will be useful to investigate the deviation of the plumbline from astronomical zenith, as expected to occur near a massive mountain ridge.

Volcanism (based on a report by Dr. Moyra G. Gardeweg P., Department of Geology, University of Chile)

Normally, a volcano is considered active if it has erupted in historic times. However, in Chile historic time is only 400 years. Thus a volcano is considered active in Chile if it has shown outgassing or smoking during historic times. Under this definition, there are three active volcanoes within about 60 km of Llano de Chajnantor. Two of these are Putana (55 km NW) and Sairecabur (37 km NW). Neither has erupted in historic times. Putana continues to smoke but Sairecabur is considered active only on the basis of altered ground material. Lascar (40 km S), on the other hand, had a major explosive eruption in 1993 and strong activity dates back to 1848.

The risk to Llano de Chajnantor from these volcanoes is considered minimal. First, the most extreme events associated with eruptions in this part of the Andes, e.g., lava flows and ejecta from eruptions, are not known to affect areas more than 30 km from the

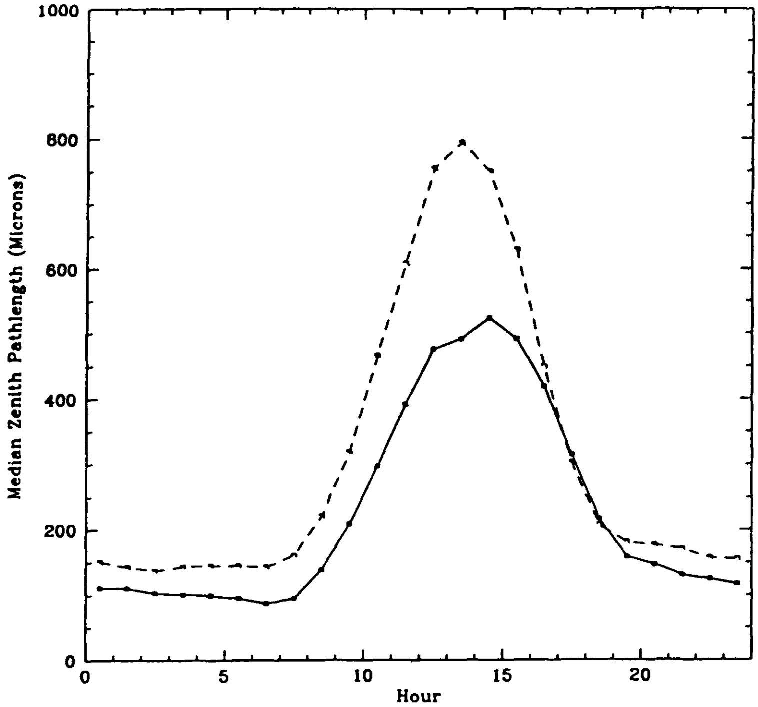

Figure 3.1.8: Diurnal variation of median rms path-length fluctuations *(left scale)* and equivalent 230-GHz phase fluctuations *(right scale)* on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*. Local solar time is UT minus $4^{h}.5$ on Llano de Chajnantor and UT minus $10^{h}.4$ on Mauna Kea.

volcano. The fine ash associated with an eruption can affect areas much further away. However, the prevailing wind pattern from Lascar has a very high probability of directing this fallout to the southeast, away from the site. The biggest risk to the site would be if Sairecabur, or to a lesser extent, Putana, had a big eruption. The prevailing winds could bring their plumes of fin ash over the site. Such an event, which has very low probability, would mainly affect unprotected machinery and possibly electrical transmission lines.

Of course, it is always possible that one of the other apparently dormant cones nearer the site could become active, but this process has a geological timescale; there is no evidence this will occur in the near future. Thus, while there is some risk due to volcanism, the greatest risk is from three volcanoes many tens of kilometers from the site, none of which is directly upwind. Should one of these volcanoes erupt, we could expect some ash fallout and some site cleanup work but no major interruption of LSA/MMA operations.

Earthquakes (based on a report by Dr. Sergio E. Barrientos, Department of Geophysics, University of Chile)

Earthquakes take place regularly all along the Chilean coast because the Nazca plate is sliding under the South American Plate. Earthquakes caused by this interaction can exceed magnitude 8. However, this interaction begins offshore about 300 km west of Llano de Chajnantor. The activity directly under the site occurs at a depth of 120 km and thus,

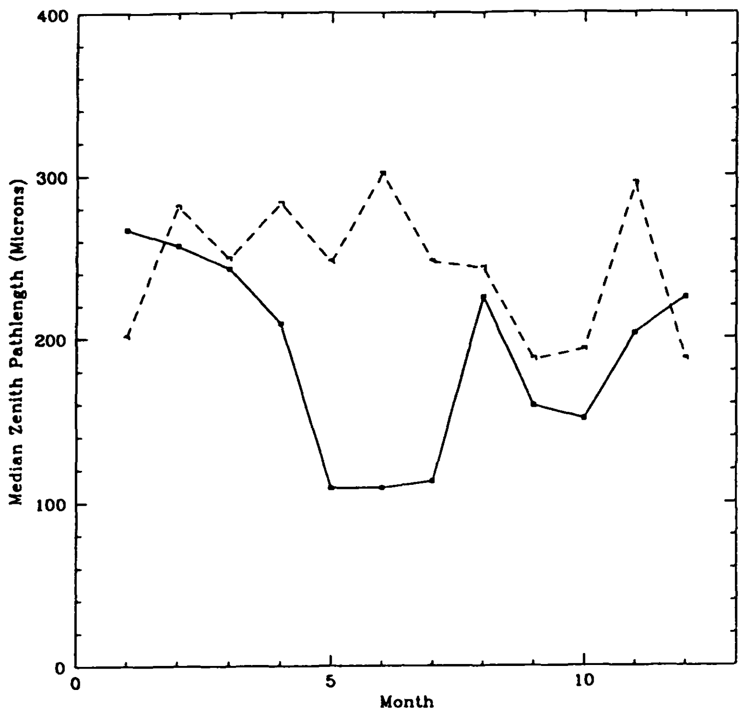

Figure 3.1.9: Seasonal variation of median rms path-length fluctuations *(left scale)* and equivalent 230-GHz phase fluctuations *(right scale)* on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*.

even though it can be quite strong at the source, the shaking on the surface is relatively mild. Both the regular thrust earthquakes offshore and the fracturing of the Nazca plate just below the site can have an important effect on the Chajnantor site. The risk of occurrence of shallow crustal earthquakes, which could cause more localized shaking is negligible.

Estimates of the earthquake risk are based on a probabilistic formalism using historical data. Even though the offshore thrust events can be stronger, the tensional events under the site have the most effect on Llano de Chajnantor. However, the attenuation and geometric spreading of seismic waves due to the depth reduces the effects greatly. The largest historical earthquake ($M_w = 8$), which took place in 1950, is estimated to have produced an acceleration of 23% g on the site. Recently, the large ($M_s = 7.3$) Antofagasta earthquake of 1995 is estimated to have produced only a 7% g acceleration. On a 100-year timescale, there is a 90% chance that the acceleration due to earthquakes will not exceed 25% g. Seismic effects should not be a problem in designing the array.

In summary, in spite of the geophysical activity in the region, Llano de Chajnantor does not appear to present an unreasonable risk. As long as we design the array with consideration for the minimal risk of some fine ash falling on the site and the accelerations which are likely due to earthquakes, this activity should represent no significant problem to location of the LSA/MMA on Llano de Chajnantor.

3.1.7 Infrastructure

The LSA/MMA site is well situated because, although it is at the very high altitude of 5000m, it is located just an hour's drive on a major international highway from a town at 2440m altitude, San Pedro de Atacama (Figure 3.1.1). The highway is an ambitious international corridor which will link Chile, Argentina, Paraguay and Brazil, opening up a major trade route to the Pacific. It is presently being paved. It runs within 10 km of the center of the array site. This makes it possible to locate most of the array operations at the lower altitude (the Operations Support Base, OSB), and only a small fraction of the workers need travel to the high site.

San Pedro is a small town with a population of 1000, but it is rapidy developing at the moment: a power link to the interconnected regional overhead line is planned, a potable water project is under consideration, a paved 2000-meter airstrip for jets is planned for 1999, and a 90-room 5-star hotel is under construction. A further hour (98 km) from San Pedro by paved road is the city of Calama. With a population of 121,000, it is the support center for the region's inland mining industry, base for the nearby Chuquicamata mine, the world's largest open-pit copper mine. It has an airport with 4-5 daily flights to Santiago, relatively well-equipped hospital facilities, and good hotel infrastructure. Calama itself is two hours (213 km) drive from Antofagasta, and there are several buses daily making this trip.

The infrastructure in the region is good and improving:

Electrical power. While San Pedro generates its own electricity, copious electric power is available at Calama and Chuquicamata, 100 km away, where it is used for the electrolytic stage of copper refining. It is expected that power transmission lines will be extended to San Pedro in the next few years. A transmission line could be built to bring electricity to the Operations Support Base in San Pedro (OSB) and the LSA/MMA site. Alternatively, electrical power could be provided for the high site by diesel generators. A third possibility is that power may be generated from gas delivered by the GasAtacama pipeline, which is presently being built from Argentina to the Chilean coast near Antofagasta (While this pipeline will run across the Llano de Chajnantor, negotiations with Gas Atacama assure minimal impact on the array or its operation.)

Water. The availability of water should not be a problem. It could be purchased from a nearby well such as Pozo Tres and trucked to the OSB and the high site. Bottled drinking water would be trucked to San Pedro from Calama as required. It is also likely that ground water will be accessible under the high site, and this possibility will be explored.

Roads. Hard-surface roads and frequent bus service connect San Pedro with Calama and the major port city of Antofagasta. The Chilean portion of the international road which runs via San Pedro and past the LSA/MMA to Argentina is presently being paved; international buses and eighteen-wheel trucks use it regularly. This easy access of the town of San Pedro at 2500m altitude from the 5000m site is one of the major advantages of the Chajnantor site.

Airports. Aside from the excellent airport facilities at Antofagasta, there are also air services to both Calama and San Pedro. Calama is served by 4-5 flights daily from Santiago. At San Pedro there is a small airfield, and a paved 2,000 meter runway for jets is planned for 1999.

Communications. Telephone service to San Pedro is good, and improvements such as fiber-optic links and E1 circuits are now being installed. For the LSA/MMA, broadband links, either fiber optic or direct microwave, will connect the Chajnantor site with the OSB in San Pedro, and direct satellite links will probably be used for communications and data transfer to Europe and the U.S.

3.1.8 High Altitude Medical Aspects

At an altitude of 5000m, the LSA/MMA will be the highest continuously operated astronomical site in the world. The barometric pressure is 56% of that at sea level, and the partial pressure of oxygen of the inspired gas in the lung is only 53% of its sea-level value. The resulting hypoxia can cause a number of physiological effects. As shown below, two key elements in the planning of the facility, proximity to a low-altitude support base and oxygen enhancement on the site, make it possible to work safely and economically at this high site.

Below 2500m the effects of altitude are minimal, and above 7500m they can be serious and permanent. Observatories have been successfully operated at altitudes near 4000m; Mauna Kea is at 4200m, the planned Large Millimeter Telescope in Mexico will operate at 4600m, and some mines in Chile, such as El Tambo and Collahuasi, successfully operate at altitudes up to 4600m with many hundreds of workers. Many workers at Mauna Kea commute between sea-level and 4200m every day. At 5000m the LSA/MMA site has 10% less oxygen than Mauna Kea. The physiological effects of high altitude are difficult to quantify precisely, because they vary from individual to individual and depend on the degree of acclimatization. The LSA/MMA staff will cycle on a daily basis between 5000m and their sleeping quarters at 2500m, and on a weekly basis between the LSA/MMA and their homes which may be at sea level. The consequences of intermittent exposure to high altitude are not as well understood as long term exposure, so the LSA/MMA planning must be flexible.

At 5000m the amount of oxygen available for use in the body (the arterial oxygen saturation) drops to about 75% of its sea-level value, and rises to about 85% after a few days (compared to 90% on Mauna Kea). The ventilation rate eventually increases to a level about 60% higher than at sea level, and the concentration of oxygen-carrying blood cells is increased by the production of new red blood cells. Heart rate and blood pressure initially increase with exposure to altitude and then slowly return towards low altitude values as acclimatization proceeds.

The ability of the body to do hard physical work is determined by the maximum rate at which it can take up oxygen. At 5000m a reduction of 25% in work ability is typical.

Mental abilities are also significantly reduced, by typically 10–30%. Again, this seems to be simply the result of a low oxygen environment, as most changes are immediately reversible with oxygen administration. To compensate for these reductions in efficiency, supplemental oxygen and oxygen enhancement will be provided where appropriate, as elaborated below.

In addition to the reduced work efficiency, there are various illnesses which can be caused by the hypoxia of high altitude. Acute Mountain Sickness (AMS) is the most common and least dangerous. The incidence is about 50% at 5000m. Most people will experience little more than a mild headache. Other symptoms can include fatigue, insomnia, loss of appetite, dizziness, palpitations and nausea. These effects typically begin a few hours after ascent and disappear after a day or two. For severe cases, rest, and eventually descent to lower altitude, are advisable. Acetazolamide (Diamox) is effective in reducing the incidence of AMS, although it is a presciption drug with some side effects, and should only be used if necessary. A small fraction of workers will not adapt well to the 5000m altitude, and they should not be used for tasks requiring ascent to the high site.

More serious, but rare, are High Altitude Pulmonary Edema (HAPE) and High Altitude Cerebral Edema (HACE). HAPE involves the accumulation of fluid in the lungs, and HACE involves increased pressure on the brain. The incidence at 5000m is in the range 0.01% to 0.1% for HAPE and much less for HACE. The primary treatment is to take the patient to lower altitude; both conditions develop sufficiently slowly that there is time to do this. As an emergency measure, in case evacuation is not immediately possible, a portable hyperbaric bag (Gamow bag) should be stored on the site. In general, a "two man rule" and a "two vehicle rule" should be observed on the site at all times.

Finally, the hypoxia of high altitude can aggravate a number of medical conditions, such as obstructive pulmonary disease or hypertension, congestive heart failure, sickle cell anemia, angina/coronary artery disease, cerebrovascular diseases, seizure disorders, etc. Such individuals should be cautious or completely abstain from visits to high altitude. All visitors to the 5000m site should first consult their physician.

The Chajnantor site is particularly well suited for coping with these problems, because it is located just an hour's drive from the Operations Support Base at 2500m altitude, in San Pedro de Atacama, where most of the LSA/MMA staff will work. Only a small fraction (20%) of the staff will go to the high site each day during routine operation, and they will return to the OSB every night to sleep. It is well known that sleep is difficult at high altitude, whereas most people can sleep well at 2500m (La Silla and Paranal are both close to this altitude). As much of the work as possible will be done at the OSB, to minimize the number of workers required on the high site. It is possible that the antennas will be built and fully equipped at the OSB, and then transported to the site on the antenna transporter. All equipment will be designed in modular form, so that modules can simply be replaced on-site and then repaired at the OSB (a "module", for example, could be a complete receiver, a correlator board, or an antenna drive motor).

Most LSA/MMA staff will work at the OSB on a week-on week-off basis. During their week off they will return to their homes in Antofagasta, Santiago, Calama, or elsewhere. During their week on they will be based at the OSB, which will have good living and recreational facilities (dormitories, cafeteria, gymnasium, etc.). There will be a medical clinic equipped to handle high altitude medical problems. As there is already a medical clinic at San Pedro de Atacama, it may be preferable to provide these facilities by enhancing this clinic rather than by providing a stand-alone operation. Those workers who have tasks to perform at the high site should spend at least one night at the OSB before ascending to altitude. There must be instructions and courses on the medical aspects of working at high altitude for all staff, particularly those who must go regularly to the high site and their supervisors.

On the 5000m LSA/MMA site itself, the key to reducing the negative effects of high altitude will be the provision of oxygen enrichment in the site buildings and other enclosures such as transporter vehicle cabins and antenna receiver cabins, and the use of lightweight portable oxygen units where appropriate. An increase in the oxygen concentration in the buildings from the natural value of 21% to 26% will provide workers with an environment equivalent to that at an altitude of 3500m, which should be acceptable. The choice of 26% is a compromise between competing requirements: improved performance would be achieved with a higher concentration, but it would reduce the degree of acclimatization for indoor workers who must also work outdoors, and it would increase the cost and fire hazard. Oxygen enrichment is now feasible and economical because of the availability of molecular seive technology - it is no longer necessary to use liquid oxygen in bottles. The effective annual cost of oxygenation in a two-man office is about $500 per worker, a small fraction of an annual salary, and it would be still more economical if used on a larger scale. Oxygen enhancement produces an increased fire risk, which is particularly dangerous at high altitude because of the increased risk of asphyxiation. Inhaled smoke decreases an already diminished oxygen supply, so the time required for evacuation is reduced. In addition, the reduced oxygen causes combustion to be less complete, increasing the levels of carbon monoxide. Thus, special care must be taken in the design of the buildings, to provide adequate smoke detection sensors and emergency exit routes. The proposed oxygen concentration of 26% is within accepted standards (including those for the Space Program), and will not cause an unacceptable fire hazard.

For outside workers, particularly those who must perform tasks which are mentally or physically particularly demanding, portable oxygen units will be available and their use should be required. A light weight, back mounted oxygen tank feeds a nasal cannulas. With an oxygen supply rate equivalent to an altitude of 3500m and by using a demand regulator which supplies oxygen only when the user breathes in, a system weighing only 4 kg will supply oxygen for more than eight hours. A nasal cannula is preferred over a mask because it makes communication easier and is less intrusive. Such portable devices are widely used by medical patients and have been used for research and mining work at high altitude.

In summary, the physiological problems associated with the high-altitude site can be successfully and economically managed. The two key elements are the existence of the low-altitude support base in close proximity to the high site, and the provision of oxygen enhancement on the site itself.

Further details concerning the medical aspects of high-altitude work can be found in MMA memo 162 ("Medical and Physiological Considerations for a High-Altitude MMA Site", P.J. Napier & J.B. West, 1996), and the LSA Combined Report p. 36 ("Site Selection: Summary of Problems Encountered in Working at High Altitudes", R. Roach, 1997), and references therein.

3.2 Antennas

(This section contains the Report of the joint LSA/MMA Antenna Study Committee (December 2, 1997))

3.2.1 Summary

Antennas in the diameter range 8 m to 15 m with a surface accuracy specification of 25 μm and a pointing requirement of 1/30 th beamwidth at a frequency of 300 GHz have been studied to determine feasibility and cost. Antennas with this desired performance are feasible over the full diameter range, although the margin with which the requirements can be met reduces as the diameter increases. For general project definition purposes an antenna production cost of $24K/sq.m of antenna collecting area can be assumed, to which an additional one-time cost of approximately $11M must be added. This production cost implies a cost scaling in which antenna cost increases as the square of the diameter, which is a slower rate of cost increase than is usually assumed. The relatively low cost of the largest diameter antennas is achieved with a number of design innovations, in particular the use of a commercial active laser metrology system which corrects for pointing errors caused by the antenna foundation and mount and allows the cost of these elements to be reduced. Such a metrology system is not yet in use on any existing telescope and needs further development.

3.2.2 Introduction

The LSA/MMA antenna study committee was formed to provide information about the cost and performance of millimeter wavelength antennas. This information is required to help define a new array to be built by the possible merging of the European LSA Project and the US MMA Project. The committee met initially in Grenoble on 19–21 August, 1997 (Napier, 1997). At this meeting it was decided that, in order to cover the range of antenna diameters of potential interest, the NRAO would study antenna designs for 8 m and 10 m diameter, ESO would study a 12 m design and IRAM would study designs for 12.8 m and 15 m diameter. The committee met for a second time in Socorro on 30 Sept. - 2 Oct., 1997. This report includes the material presented and discussed at that meeting and completed since the meeting.

3.2.3 Design and Performance Information

In this section we provide information about each of the designs studied and its predicted performance. The performance numbers are collected together in Table 3.2.1 and are discussed in more detail in the individual sections.

The principal design goals used to generate the antenna designs are as follows:

(1) Pointing Accuracy. 1/30th beamwidth rms at 300 GHz. This requirement to be met in the median wind for the 5000 m site (6 m/s) and with astronomical calibration for thermal effects allowed every 30 min during the day. Beamwidth is assumed to be 1.2*wavelength/diameter.

The pointing entry in Table 3.2.1 is the pointing error resulting from a static wind load. If the wind is sufficiently constant in time, this number could be reduced by reference pointing on a nearby astronomical source by as much as a factor of 0.25 to 0.5 (Holdaway et al., 1996). In Table 3.2.1 two pointing numbers are given, one for the basic passive structure and another, improved, number for pointing with an active metrology system turned on. For the 15 m design the active metrology system is essential to the operation of the telescope drive system and so no number for passive pointing is given. Recently, the problem of pointing errors caused by "anomalous refraction" in the atmosphere has been investigated (Holdaway, 1997; Lucas, 1997). For comparison, to indicate the relative size of antenna and anomalous refraction pointing errors, Holdaway's (1997) estimate for median pointing error due to anomalous refraction at 50 degrees elevation is included in Table 3.2.1. These values require further checks, however.

(2) Surface Accuracy. 25 μm rms in median wind and all normal daytime and nighttime thermal conditions. The number in Table 3.2.1 is for the elevation range 25 to 75 degrees.

(3) Pointing Fast Switching. 1.5 degrees in 1.5 seconds (time from beginning of move to start of data taking). This requires that the lowest resonant frequency of the antenna be greater than about 6 Hz and the predicted value for this frequency is included in Table 3.2.1.

(4) Phase Stability. 10 μm rms in median wind. Calibration allowed every few minutes during day for thermal effects. The number given in Table 3.2.1 is for a static wind load of 6 m/s.

(5) Close Packing. Minimum baseline $< 1.3\times$ (Antenna Diameter).

(6) Transportability. Road mounted transporter for terrain of high site.

(7) Direct observations of the Sun allowed. It is expected that the only consequence of this requirement for the antenna will be the need to roughen the surface of the reflector panels by a few microns to diffuse the reflection of solar energy.

(8) Low Antenna Noise. Cassegrain focus, no tertiary reflectors, minimum blockage feedlegs. The blockage number given in Table 3.2.1 is total blockage including both subreflector and support legs. Note that different designers made different assumptions about thermal and gravity loading on the feedlegs and this makes a meaningful comparison of blockage between the different designs difficult. Thus, the 8m blockage is for a feedleg width of 6 cm whilst the 12m blockage assumes a width of 3 cm. Also, antenna noise caused by ground reflections from the feedlegs is as much a function of the angle between the feedleg and the reflector axis as it is a function of the blocked area. In general, the

larger this angle. the less the antenna noise. but this effect is not quantified in Table 3.2.1. The question of the optimum size. location, number and shape of the feedlegs needs a careful study before an antenna design is completed.

(9) Single Dish (total power) Observing Mode. Possibility for subreflector nutator to be included.

It should be noted that there was not complete agreement within the group concerning the feasibility of achieving requirements 8. 9 above. More work is needed to understand the need for, and difficulty of satisfying, these requirements.

Table 3.2.1: Summary of antenna performance data.

	8 m	10 m	12 m	12.8 m	15 m
Pointing requirement, 1/30th beamwidth at 300 GHz (arc.sec)	1.0	0.83	0.69	0.64	0.55
Wind pointing without active metrology (arc.sec)	0.5	0.7	0.4	NA	NA
Wind pointing with active metrology (arc.sec)	0.3	0.3		0.3	0.4
Median anomalous refraction pointing error, 50 degrees elevation (arc sec)	0.6	0.6	0.6	0.5	0.5
Surface accuracy (μm)	16	20	25	20	25
Wind phase error (μm)	8	16		<10	10
Resonant frequency (Hz.)	9	9	8.5	12	>10
Blockage (%)	3.0	2.5	3.1	<2.4	2.4

NA=not applicable

8 m Diameter

The 8 meter antenna design uses a symmetrical reflector, a Cassegrain optical configuration, and a conventional elevation-over-azimuth mount and has several improvements compared to the design described in an earlier report (Napier et al., 1995). The subreflector is lightweight machined aluminum and the panels of the main dish are machined aluminum castings. The dish backup structure is currently slated to be entirely CFRP

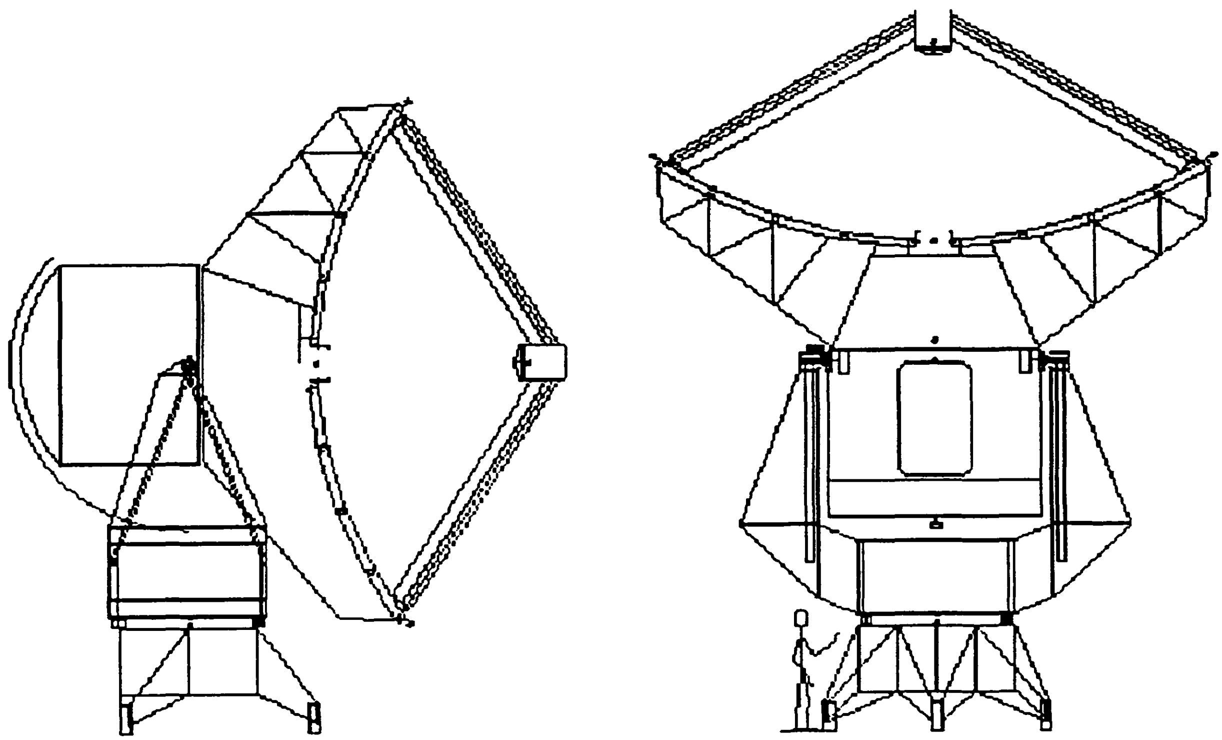

Figure 3.2.1: NRAO 8m antenna design.

(no metal nodes except for attachment of external structures), however a steel backup structure is probably acceptable at a substantial cost saving. The receivers are located at the Cassegrain focus, which has an effective focal ratio of approximately f/6.2, in a large (approximately 3m by 3m by 2.5m) temperature controlled cabin, which also houses much of the antenna electronics. The mount is constructed from welded steel plate. Elevation bearings are a pair of spherical roller bearings; the azimuth bearing is a single 2 m diameter bearing, probably the cross roller type. All bearings are sealed. The antenna base sits on the foundation at 3 points, giving a quasi-kinematic support (radially compliant feet accommodate differential thermal expansion between the steel base and the concrete foundation); each antenna and each base are pre-leveled, which allows rapid reconfiguration of the array. Choosing instead a base supported at 4 or more points may increase the antenna stiffness, but may increase the time required for array reconfiguration.

The overall geometry of the antenna is shown in Figure 3.2.1. The antenna geometry allows antenna center-to-center spacings as small as 1.27 dish diameters with no possibility of collision for elevations above 22 degrees. The diameter of the main reflector can be increased to 10 or 11 m without requiring changes to the mount geometry; the number of panels can be kept constant at 120, even for a 10 or 11 m dish diameter (the largest panel dimensions are then about 1 m). This design has some special features which are key to its excellent performance, but carry some modest risk. First, each antenna base is outfitted with a pair of tilt meters which will measure the tilt of the azimuth bearing due to deformation of the foundation and antenna base. Also, each arm of the yoke contains a CFRP A-frame structure and sensors to measure yoke deflection, which allows correction of pointing errors about the elevation and azimuth axes, and phase errors. Finally, the mount will be shaded from direct solar heating (if a steel backing structure is used, air circulation fans and sunshades are necessary). Each of these points is discussed further in the Special Features section below.

Performance Summary

The pointing performance is calculated for a 6 m/s wind velocity, for the standard air density at 5000 m elevation, using the force coefficients of Levy (1996). For the dish pointing directly into the wind, the pointing error is 0.2 arcsec with the tilt meters inactive, but reduces to 0.06 arcsec with the tiltmeters activated. The pointing error is estimated to be better than 0.5 arcsec over the whole sky.

The phase change due to wind deflection of the mount is less than 4.1 microns worst case.

The surface RMS is less than 16 microns over the whole sky; the gravitational deformation of the backing structure is about 11 microns and the thermal performance of the CFRP backing structure is excellent since metal nodes are avoided.

The blockage due to the subreflector is 0.79% and the blockage due to the quadrupod is 2.21%. Because the legs extend to just inside the dish edge, all of the quadrupod blockage is blockage of the plane wave.

Special Features

Each antenna base is outfitted with a pair of tilt meters located on the non-rotating structure at the height of the azimuth bearing. These tilt meters will measure the tilt of the azimuth bearing due to deformation of the foundation and antenna base. Also, each arm of the yoke contains a CFRP A-frame structure which carries no load, but provides a stable reference for the elevation encoder, and allows measurement of yoke deflection. This CFRP reference structure automatically corrects most of the elevation pointing error which results from bending of the yoke due to either wind loading or thermal gradients. In addition, 4 displacement transducers (e.g. Schaevitz 050HR or similar) measure the lateral and vertical translation of each of the yoke arms; this completely determines the azimuth pointing error (tilt of the elevation axis and wind-up of the yoke arms) and the instrumental phase change due to deflection of the yoke arms. Thus, with the tilt meters to correct for the base and foundation tilts and the reference arms to correct for most of the yoke deflection, mount contributions to pointing error and instrumental phase are almost completely removed.

Two other notable features are that the panels of the main reflector are supported at 4 convenient points, but in a way that they cannot apply significant loads to the backing structure due to their own stiffness or thermal excursions. The antenna's elevation range is 0 degrees to 120 degrees; holographic surface measurement over this very large range

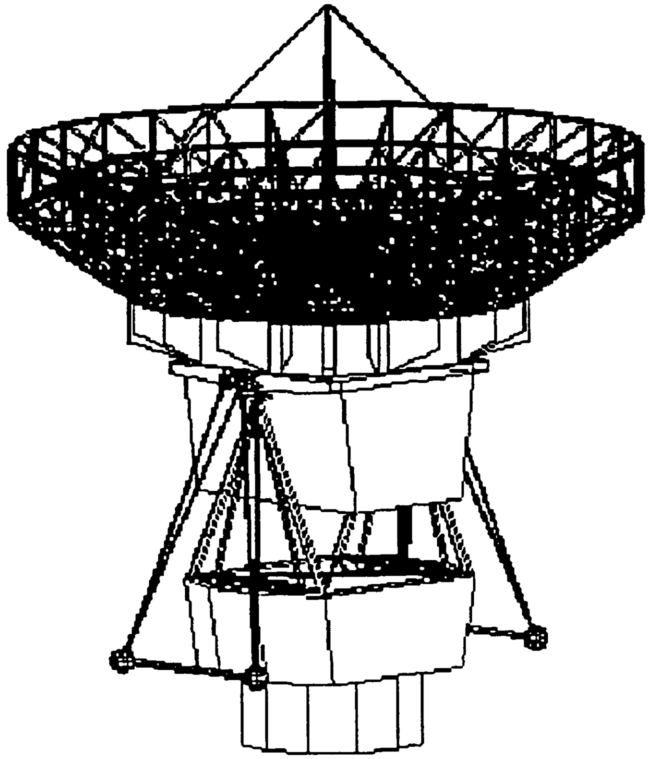

Figure 3.2.2: NRAO 10 m antenna design.

is very important for setting the surface to minimize the maximum RMS over the typical observing range, say 15 to 75 degrees.

10 m Diameter

The present 10-m antenna design is shown in Figure 3.2.2 (note: in the figure the dish depth is not to scale, the dish should be thinner). The design has the following features:

1) Cast aluminum panels with dimensions of about 1 m are used. The panels should be thin and be supported at the four corners. The expected weight of the panel is between 15 - 22 kg/m^2. The dish will have 5 rings of panels. The outer four rings will have 32 panels for each ring and the inner one has 16 panels.

2) The dish is a CFRP double-layer truss structure. The dish support ring has a radius of 3.2 m. The support ring has 16 equal softness points. For this deflection driven design, the maximum distance of the dish surface points to a nearby support point is smaller compared with a six-point supported dish.

3) Four feedlegs are supported at the same radius of 3.2 m. However these support points are separate from the 16 dish support points. It is intended that the radius of the feedleg support on the top of the dish is also 3.2 m in radius, which results in small blockage but not as low as could be achieved with the feedlegs supported at the edge of the reflector.

4) A steel sub-ring is provided to produce 16 equal softness points. The steel ring also provides torsional stiffness. The steel ring is supported by 4 points from the elevation beams. The sub-ring also provides 4 feedleg support points.

5) Between two elevation beams, a strong platform is provided to house the receivers and other equipment. Cabin space is provided. The size is 3m $\times$ 3.3m on the top and 2.4m $\times$ 3.3m on the bottom, the height is 2m. A permanent cabin box is not preferred so as to avoid any unexpected loading to the BUS structure, although provision has been made to avoid transferring any unwanted moments to the dish structure.

6) Counterweight is arranged on both sides of the elevation beams. Soft counterweight support is preferred. However, to reduce risk, a stiff counterweight support should be prepared for the first test antenna. In theory, a soft swinging counterweight($\sim$ 0.2 Hz) will not harm the antenna pointing. Damping by using polymer material is another way to solve the problem.

7) DC torque motor drives are used at both sides of the elevation axis.

8) CFRP and invar truss yoke structure is used. The invar bars are used at the bottom of the yoke for taking tension loading. This truss design will have nearly zero thermal pointing problem (for steel yoke of 1 inch wall thickness, the pointing error with 30 minutes could be 0.9 arcsec and for a thinner wall thickness (e.g. 0.5 inches) this error could double.). In the preliminary calculation, the CFRP tube has a medium modulus and the weight of the material is small. If higher modulus or more material is used, the wind pointing error of the yoke could be reduced again.

9) The bottom of the yoke is connected with a strong steel yoke base through some slot-like linear guiders. Since the total movement due to temperature change is about 1 mm, the linear guider is not complex in design. The steel structure also supplies some stiffness for the yoke in the vertical direction. On top of the yoke base, rails may be installed in helping the receiver mounting. The yoke base is thick, it may cover both the top and the bottom of the azimuth bearing. On the front and back sides of the yoke base, holes are provided for antenna lifting.

10) An enclosed azimuth bearing is used. The antenna base is cylindrical in shape. Inside the base is a cable wrap.

11) Tilt meter, laser quadrant detectors, and laser angle detectors could be used in improving the antenna performance in the future.

In summary, the 10-m design is light in weight. It is about 25 tonnes in total weight. This design, which still needs further optimization, will provide very stable pointing, phase and surface accuracy. Frequent calibration of the phase and pointing may be not so important, especially the pointing. On the windy Chile site, the open truss yoke structure and the cabin-free design will have minimum wind drag force over a wide range of sky coverage. This design is low in cost and the light weight design will also reduce the cost of other

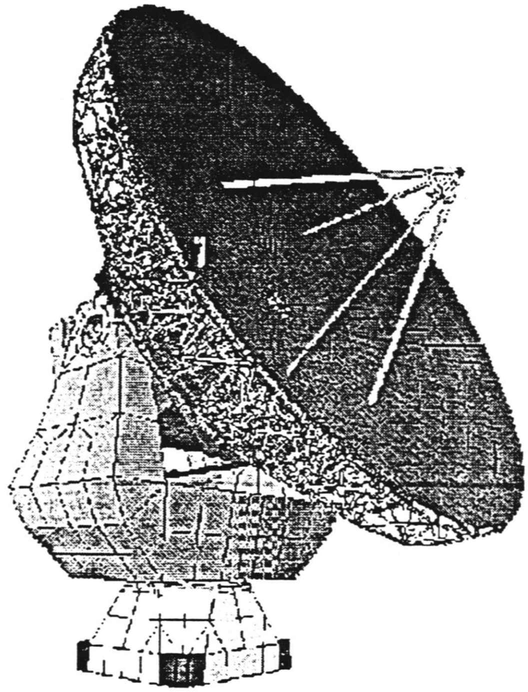

Figure 3.2.3: ESO 12m design.

parts of the system including foundation, transporter, service road, service shelters and the reconfiguration of the array.

12 m Diameter

The 12 m Submillimeter antenna studied by the European Southern Observatory has a conventional structural design that is highly optimized. Reference is made to the specifications below (Table 3.2.2), to Figures 3.2.3 and 3.2.4 and to Andersen (1997).

The antenna has a traditional alt-az mount. The dish panels are of lightweight aluminum. The truss structure of the dish is made of CFRP tubes and is prefabricated by epoxying the tubes together in the node points. Fabrication of the truss structure takes place on a full-size jig in the workshop. The base, yoke, center section, counterweight and box structure under the dish are all made of steel.

The azimuth bearing is a large ring bearing, possibly of cross roller type. The elevation bearings are double spherical bearings capable of carrying axial loads in both arms. The motors are of the direct-drive type. There is one for the azimuth movement near the azimuth ring bearing and two for elevation on the inside of each yoke arm. Use of such motors leads to an inexpensive and reliable design with highly optimized servos. The encoders are commercially available directly coupled optical disk encoders with a resolution of about 0.01″. Due to the high resolution, the encoders can also be applied as tachometers.

The antennas can be moved by means of a special transporter, which is a heavy trailer pulled by a truck. The trailer has a U-shape so that it can be attached to the antenna on both sides of the base.

It is foreseen that the telescopes are pre-assembled in Europe or the United States and transported to Chile divided into a few subassemblies. The complete truss structures for the dishes are shipped as single units to Chile. Final assembly of the telescopes takes place in San Pedro. After assembly, they are moved to the Chajnantor site using the transporters.

Table 3.2.2: Extract of Specifications

Item	Value	Comments
Antenna diameter	12 m	
Main reflector f-ratio	f/0.35	
Exit f-ratio	f/8	
Scale	0.465 mm/″	
Beam width	19.8″	10 dB tapering
Pointing precision	0.66″	Max Offset over 30 minutes
Surface errors	25 μm rms	Max
Receiver cabin	3m × 3.75 m	
No of panels	135	
Mass	50 t	

Only a tentative foundation design has been carried out. It appears that foundation cost is significant and highly design dependent. Hence it is advisable to carry out a detailed study, including soil investigations, to find a low-cost foundation solution.

Error budgets for surface precision and pointing have been set up and the performance of the antennas has been studied by finite element calculations. It has been shown that the gravity induced error of the main reflector over the typical pointing range is about 3 μm rms. It is a prerequisite that the subreflector is continuously adjusted to its optimal position during observations as in a normal homologous design.

Wind calculations have been carried out for a few representative pointing angles. More detailed wind calculations are still pending. A wind velocity of 6 m/s has been assumed as limit for full performance. Calculations show that the primary reflector deformations induced by wind (< 3 μm) are negligible and that the main influence of wind is related to

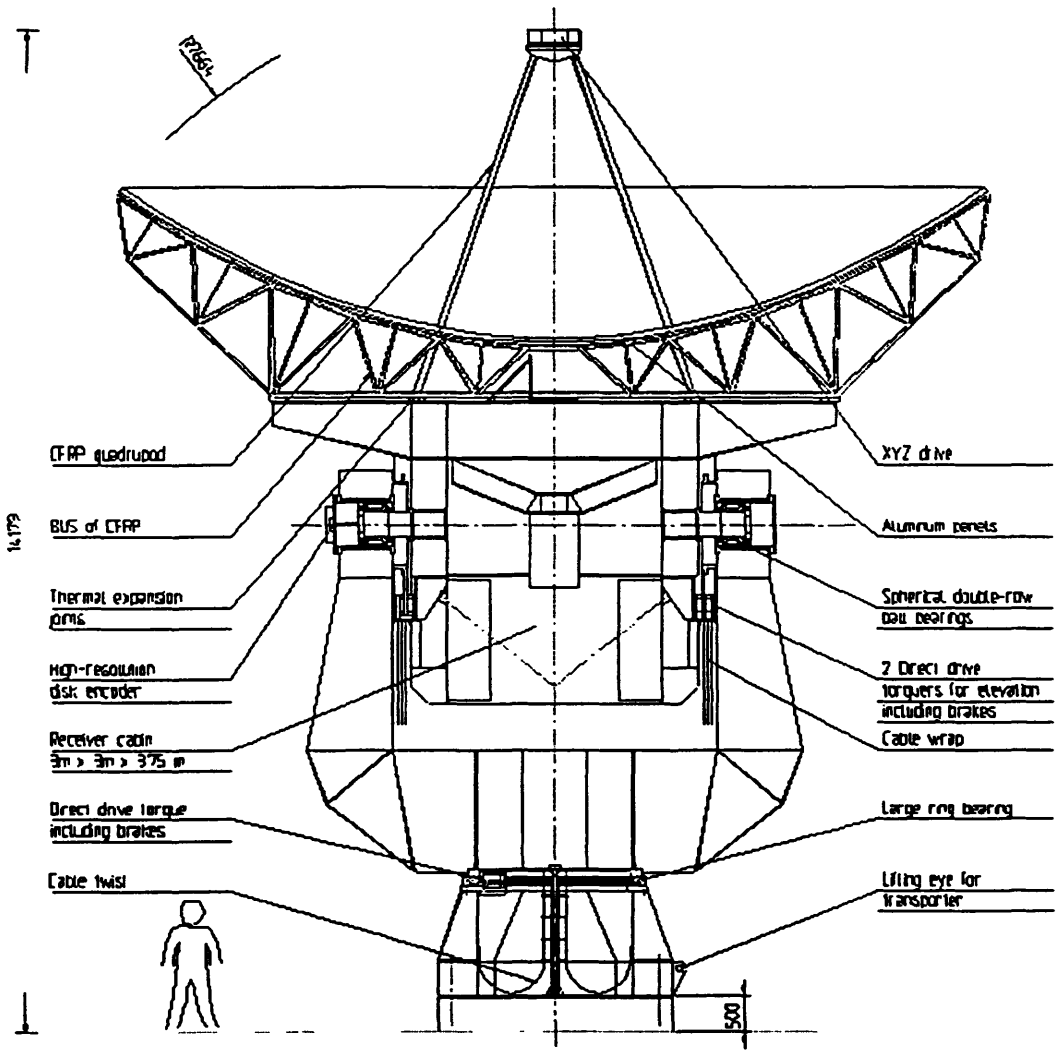

Figure 3.2.4: ESO 12m antenna design.

pointing precision. It is required that the antenna points better than 0.66″ in offset over 30 minutes. Wind induced pointing errors have been found to be less than 0.4″ and are therefore acceptable.

Thermal performance has not yet been studied. However, there is good hope that no major thermal problems will be present since the dish backup structure is made of CFRP without steel nodes. The large steel structures will be thermally insulated to reduce solar heating.

The lowest eigenfrequency of the antenna has been computed to be 8.5 Hz. This value seems entirely satisfactory.

All calculations indicate that the telescope will fulfill specifications for submillimeter operation. However, to provide larger safety margins it seems advisable to develop a laser-based optical system that measures alignment errors for the elevation axis.

It can be concluded that there is good evidence that the 12 m submillimeter telescope can be built as proposed and will fulfill specifications.

12.8 m Diameter

The 12.8m IRAM telescope is an exact copy of the proposed 15m telescope (see Section 3.5 below) except that the reflector diameter is reduced by one ring of panels. First computer calculations for gravity loads indicate an important gain in performance (see Figure 3.2.5 for comparison). The performance data of the 12.8m telescope (Table 3.2.3) can therefore only be indicated tentatively as computer verifications for all load cases are pending:

Table 3.2.3: Performance of 12.8 m telescope.

surface accuracy	pointing error	phase stability	resonant frequency	blockage (no taper)
~20 μm r.m.s.	~0.4 arc sec r.s.s.	<10 μm r.s.s.	~12 Hz	<2.4%

For detailed description, comments and further studies, see Section 3.5 below on the 15m IRAM Telescope.

15 m Diameter

The proposed 15m telescope (Plathner et al., 1997) is shown in Figure 3.2.6 as a simplified computer vision. It is an alt-az mount telescope with the elevation axis off-set to increase

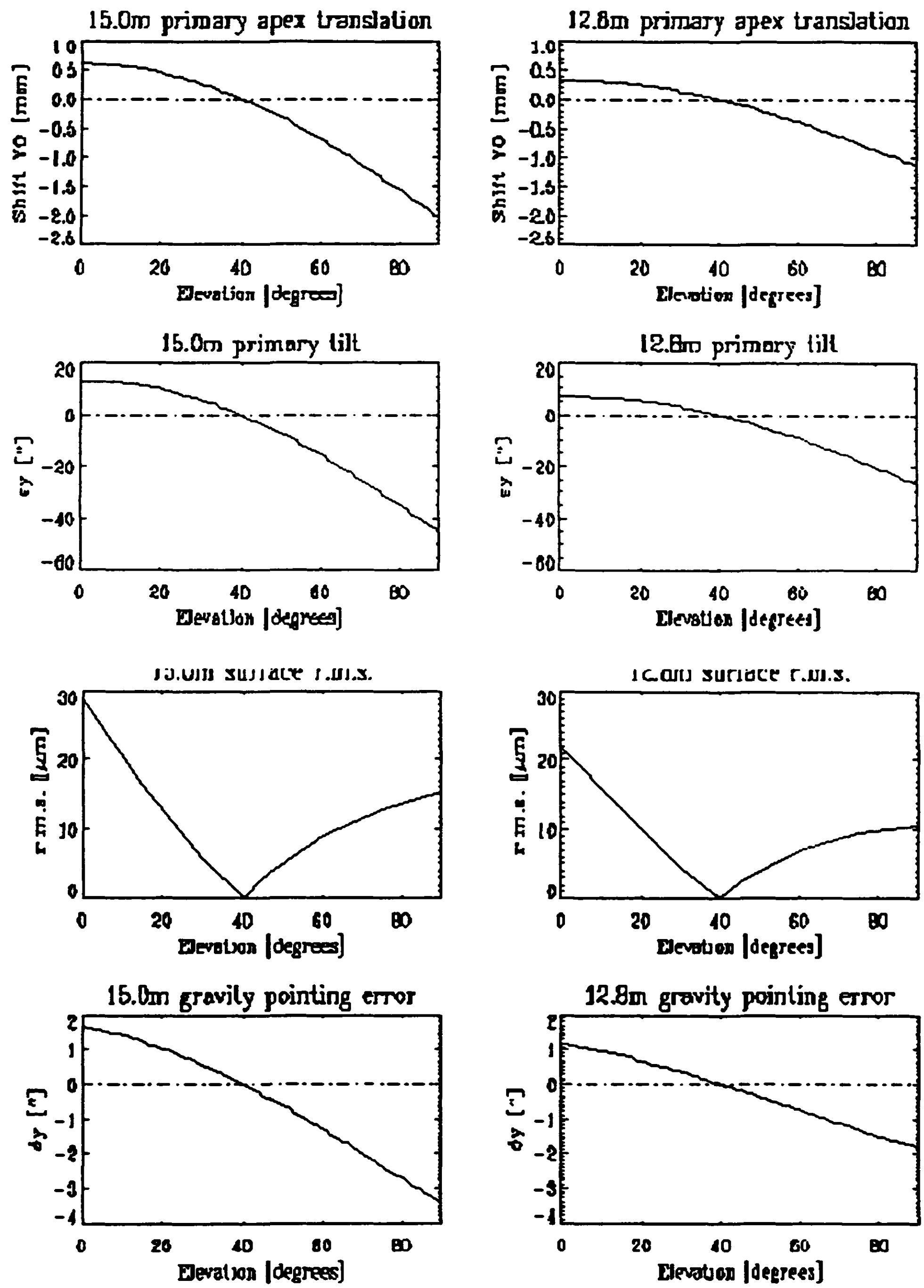

Figure 3.2.5: Comparison of gravity performance of 15.0m and 12.8m antennas.

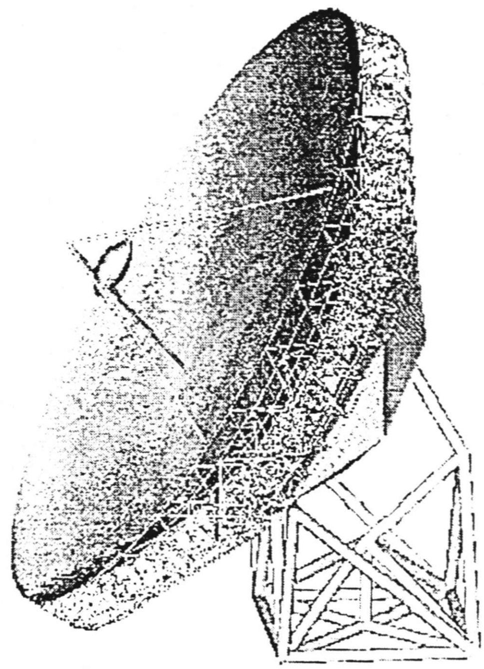

Figure 3.2.6: Computer vision of the IRAM 15m telescope.

stiffness in the reflector support system and to render the pedestal more compact. In addition, it facilitates the installation of an optically linked 2-axes encoder system which permits control of the reflector position independently of wind and temperature-induced deformations in the pedestal by a master-slave servo train.

The particular truss structure of the pedestal transfers the reflector loads directly into the ground via four bogies and a central bearing defining the az. axis position. This increases the lowest resonant frequency to values above 10 Hz and contributes to the high pointing accuracy of the whole telescope.

Fig. 3.2.6 indicates schematically the motion of the 15m telescope in elevation which is achieved by a linear drive. The reflector is composed of a carbon-fibre composite back-up structure on a large steel support box which serves also as spacious receiver cabin. The panels are extremely light weight aluminum structures of excellent thermal and mechanical performance. The secondary is also made from aluminum alloy and is supported by a carbon-fibre composite tripod.

The performance of the 15m telescope for the earlier defined elevation angles and load cases is summarized in the following table. These are for all parameters the worst case values. In addition, it must be stressed that the structural elements of the telescope have not yet been optimized for reasons of time.

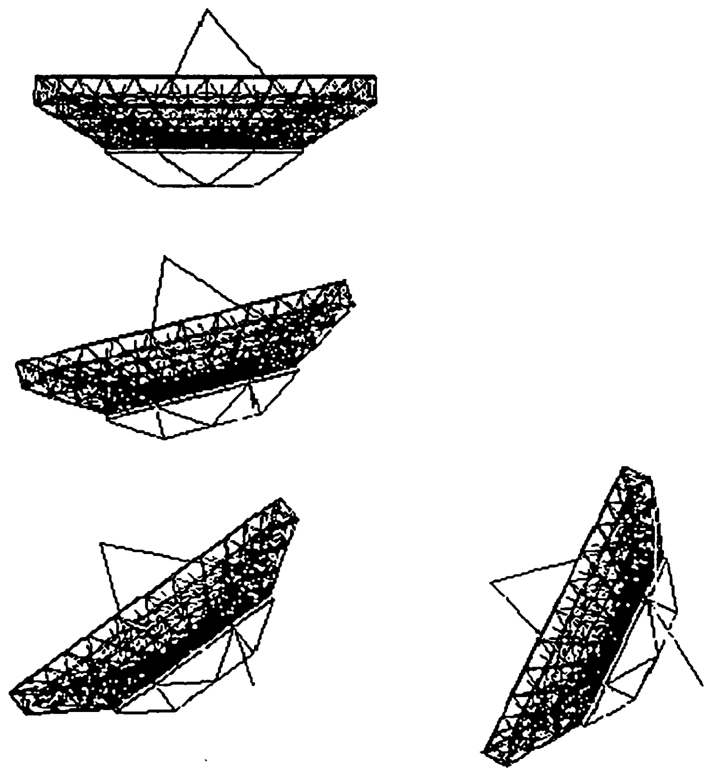

Figure 3.2.7: Motion of the 15m telescope in elevation.

Table 3.2.4: Performance of the IRAM 15 m telescope.

surface accuracy	pointing error	phase stability	resonant frequency	blockage (no taper)
25.6 μm r.m.s.	0.46 arc sec r.s.s.	~10 μm r.s.s.	>10 Hz	2.4%

The figure for phase stability includes errors resulting from the off-set elevation axis.

These outstanding results are possible because of all the experience gained from the 15m Plateau de Bure antennas that has gone into the new design. This includes the choice of structural components like carbon-fibre composite elements or aluminum panels whose excellent long-term behavior has been demonstrated under extreme conditions at high altitude.

Although the proposed encoding system is designed on the basis of industrially available components, it needs to be studied in more detail due to the extreme requirements, including the master-slave operation of the doubled servo system. The very good experience with the dual-axis photoelectric autocollimation system purchased by the NRAO for possible use on the GBT indicates the accuracy that such instrumentation can achieve,

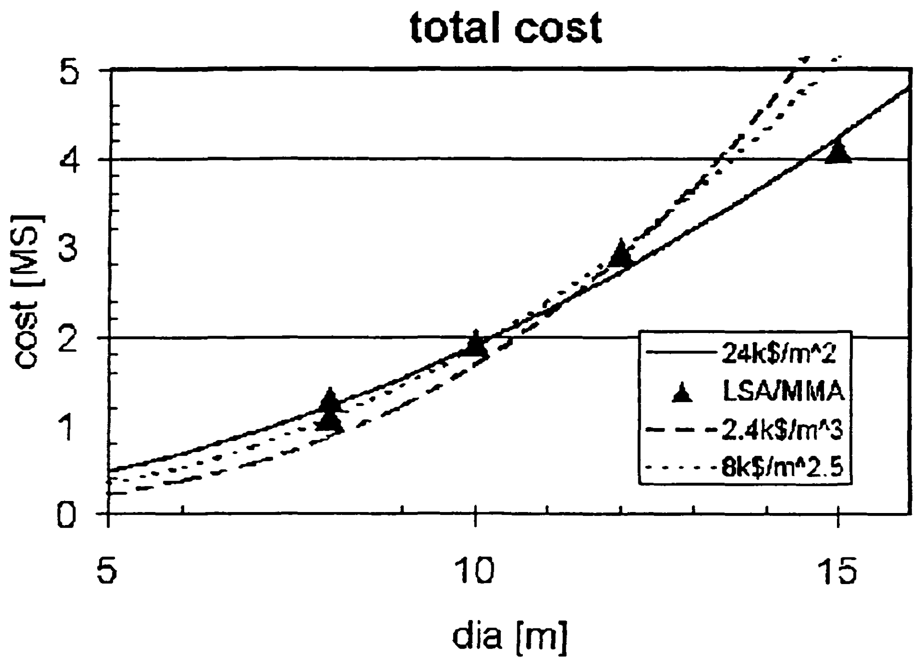

Figure 3.2.8: Total Antenna Cost.

but the system has not yet been demonstrated on a telescope. The unbalance about the main axes should not be a major servo problem under the condition that both drives are correctly designed. Also here, some development work will be necessary.

3.2.4. Cost Information

Cost Estimates

This section discusses the costs of the different telescope designs which have been studied. The costs of quantity production of the various designs have been estimated by the separate engineering groups with an attempt to break the costs down into a consistent set of subcategories. At the October meeting in Socorro the antenna working group went over the cost estimates in each subcategory and tried to rectify discrepancies by applying the same raw material costs for things like steel, concrete, etc. We also filled in various blanks where possible and used improved estimates of items such as the secondary, bearings, etc. The break down in the costs is presented in Table 3.2.6 in the Appendix. The total costs along with several cost curves are plotted in Figure 3.2.7. Note that for the 8 m diameter data points are provided for antennas using both CFRP and steel for the reflector backup structure (BUS), with the steel BUS costing about $200K less than CFRP.

The 8, 10 and 12 meter designs fall on a $D^{2.5}$ curve which has been observed for many other telescope cost studies whereas the 15 meter costs are more consistent with a D^2 curve. The uncertainties in the cost estimates are probably quite large and don't accurately determine a "cost curve". (Note that the best fit to the data is a straight line which intersects zero cost at 5 meter diameter.)

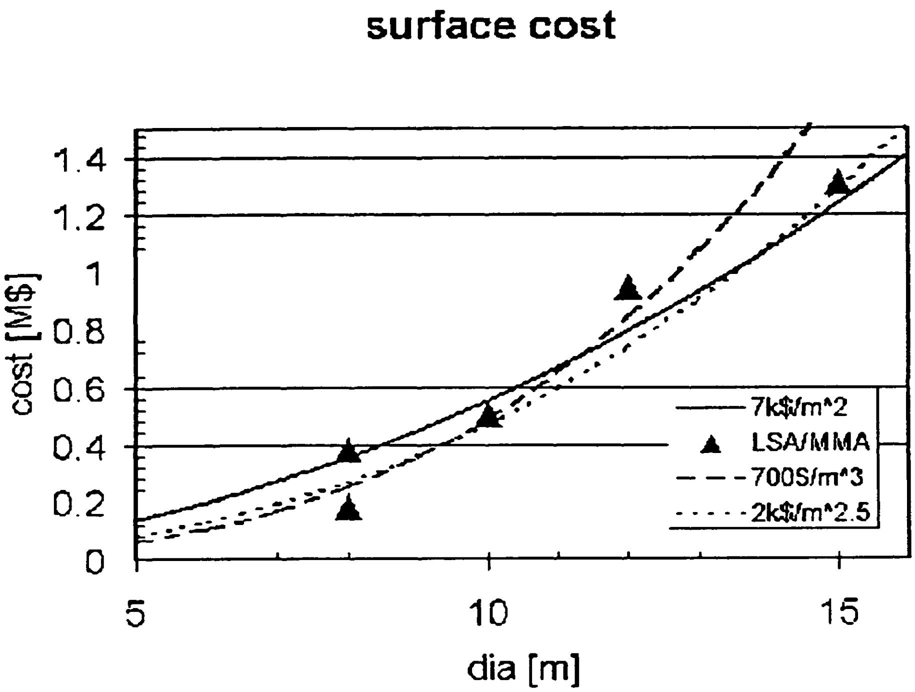

Figure 3.2.9: Reflector Cost.

Figure 3.2.9 shows the cost of just the reflectors for the various telescope designs, with costs for both a steel and CFRP BUS shown for the 8 m. These costs include all of the tipping structure except the secondary and feedlegs and don't include any of the mount costs. The three smaller designs are consistent with a cost curve steeper than D^3 while inclusion of the 15 meter cost yields $D^{2.5}$. (The straight line fit intersects zero cost at 7 meter diameter.) A separate reflector cost study was also carried out by a commercial antenna company. The data from this study was consistent with a D^2 curve over the same range of telescope diameters but with the surface and pointing specifications degrading at the larger diameters.

It should be noted that the total costs include 30% for the costs of a commercial company for administration and overhead and 15% contingency. This is 31% of the total antenna production costs. This represents a significant cost and different procurement methods, such as those used by IRAM for their 15 meter telescopes, might reduce the costs significantly.

As well as the production costs for the antennas, which have been discussed above, it is necessary to consider the one time costs for developing the final design drawings, prototyping and tooling up for the production program. Discussions with commercial antenna companies lead to the following rough estimates for the major one time costs:

Table 3.2.5: Estimate of the one-time costs

Item	Cost ($M)
Non-recurring engineering to convert final antenna concept into fully engineered design with fabrication drawings	1.0
Tooling for antenna production run	1.0
One time prototyping costs	4.5
Antenna assembly/maintenance buildings (2 @ $1.5M each)	3.0
Antenna transporters (3 @ $0.5M each)	1.5
Total	11.0

Most of these costs, except for the assembly building and one time prototype costs which are given for the larger diameter antennas, scale weakly with antenna diameter. They are rather uncertain, however, with factors of two or so difference in the estimates for some items from different commercial companies. The one time prototyping costs are intended to cover such items as additional costs for the first antenna due to small quantity production, special tests of antenna elements, costs to build some components in two different ways to determine the best design, fabrication of special alignment tools such as the surface measurer, rent of an assembly building for the first antenna and transporter prototyping costs. The cost of the first antenna should be budgeted as the production cost from Figure 3.2.8, plus the non-recurring engineering cost plus the one time prototyping cost plus the one time tooling cost.

Discussion of Cost Data

The data is remarkably consistent, considering the large differences in the design approaches used. Thus we probably know the costs for telescopes in the size range from 8 to 15 meters well enough for preliminary budget purposes. But the data do not yield a simple well characterized cost law. This means a global optimization of the array performance vs. cost will not be very definitive. Such optimizations usually produce broad peaks in the diameter range studied here and hopefully an accurate cost curve is not necessary.

The cost curve is not as steep as one might expect considering the difficulty in maintaining the precision of a structure as it is scaled up in size. Simply scaling a design up in diameter and spending more money does not necessarily get you the same performance specifications. A study by a commercial company shows this quite clearly. They scaled the same reflector design from 8 to 12 and 16 meter diameters and the costs ended up scaling as D^2 but the surface rms degraded from 15 to 17 to 25 microns. Thus the 8 meter exceeded the specification while the 16 meter just barely met the specifications.

The larger diameters require more innovative designs and this innovation does not necessarily cost a lot more. What does happen is that the phase space of specifications gets pushed around. That is the basic rms surface and pointing specifications are met but other specifications, such as elevation range, receiver room size, foundation complexity, blockage, etc. change. The innovation necessarily must increase with diameter if you are pushing the boundaries of what can be done. But what is not clear is whether you can apply the innovative ideas, once they are revealed, to smaller telescopes and save money relative to the more standard designs. The innovation is not expensive and not a way to save money but is necessitated by the design challenges as you increase the diameter.

The designs presented have probably not yet been optimized for cost. We will be building a large number of telescopes and can afford to really work on decreasing the cost. Cheaper telescopes means more of them, more collecting area and better imaging. To do this requires understanding the specification very carefully so that the system is not over designed. Exceeding specifications means that you have wasted some money somewhere. Once this is done the cost curve may steepen somewhat. Also the second order specifications (elevation range, complexity, ease of transport, etc.) and the risk or margin in meeting the surface and pointing specifications will degrade as the telescope diameter increases.

3.2.5 Future Work

It is hoped that the information provided in this report, together with consideration of the scientific issues, will allow a decision to be made concerning the diameter, or diameters, of the antennas for the LSA/MMA array. During this study a number of clever design ideas for millimeter/submillimeter antennas have been identified. Also, the different designers have chosen to emphasize the various performance requirements in different ways. The committee believes that after the final diameter is decided a period of about nine months should be spent optimizing the design before issuing an RFP for the detailed design and fabrication of prototype antennas. This optimization would be done by incorporating the best of the ideas identified during this study and by ensuring that the correct priority is given to the various, sometimes conflicting, performance requirements. This latter process of prioritizing the requirements must be carried out in close consultation with the scientists. The two primary performance requirements for the antenna are pointing accuracy and reflector surface accuracy. Secondary performance requirements which should be considered with respect to their cost and impact on the primary requirements include:

(1) For the smaller diameters, the cost/performance benefit of using CFRP for the reflector backup structure.

(2) Location and shape of the subreflector support legs.

(3) Range of elevation angles accessible to the antenna.

(4) Existence and size of the receiver cabin.

(5) Impact of array reconfiguration time on the design of the interface between the antenna and its foundation.

(6) Use of active metrology to reduce cost or improve performance.

(7) Cost/performance impact of including a subreflector nutator.

3.2.6 Conclusion

From our studies over the last two months we conclude that it is feasible to build antennas with diameters in the range 8 m to 15 m with pointing accuracy of 1/30th beamwidth at 300 GHz and surface accuracy of 25 μm. Our cost estimates for the antennas, as a function of diameter, are shown in Figure 3.2.8. A simple formula, that is a reasonable fit to this data over the diameter range 8 m to 15 m, is that antenna cost is simply proportional to collecting area at the rate \$24 K/m^2. The relatively low cost of the 15 m antenna results from a number of design innovations, in particular the use of a commercial active laser metrology system which corrects for pointing errors caused by the antenna foundation and mount and allows the cost of these elements to be reduced. Such a metrology system is not yet in use on any existing telescope and needs further development.

As the antenna diameter is increased the margin with which the pointing and surface accuracy requirements can be met is reduced. This means that, as the diameter increases, the designer has less flexibility to optimize for second order requirements such as locating the feed legs for minimum blockage and providing for full sky coverage in the range of elevation angles accessible to the telescope. On the other hand a few requirements, such as the desire for a large receiver cabin, become easier to satisfy for larger diameter antennas.

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3.2.7 Appendix

Itemization of antenna costs for each of the four designs (Table 3.2.6). These are the quantity reproduction costs and do not include the one time costs of the prototypes, fixtures, etc. Costs are given in kUS$. There are three columns for each design. The first column is the quantity with the units given with the item label such as the number of square meters of panels or the weight of CFRP. The designs which don't require an item have 0 as the quantity. Note that it has been assumed that each antenna will need four different foundations to handle the various configurations. The second column is the cost basis such as the kUS$ per square meter or kUS$ per kilogram, and the third column is the net cost for that item. The item costs are subtotaled into three categories; 1) reflector which includes the panels, backing structure and tilting structure, 2) subreflector and feedlegs, and 3) mount and foundation. Then shipping is added to give a total "material" costs to which administration and contingency are added as a per centage of the "material" cost with the grand total given on the last line. The rectification of the initial estimates provided by the designers was to use similar cost basis for items in common and to fill in blanks where needed. For the 8m antenna the costs are for a CFRP BUS. The cost for a steel BUS is about $200K less.

Table 3.2.6: Estimated antenna costs

LSA/MMA costing, Oct 1, 1997 — rectified pricing — labor @ 9k$/mo

item	8m quant	basis	cost	10m quant	basis	cost	12m quant	basis	cost	15m quant	basis	cost
reflector												
panels m^2	50.3	1.8	90.5	78.5	3.5	274.8	113	3.4	384.2	177	3.5	619.5
adjusters, ea	480	0.016	7.7	512	0.02	10.2	1	11	11	1	20	20
steel BUS, kg	0	0	0	2000	0.006	12	0	0	0	0	0	0
CFRP, kg	1900	.126	240	550	0.138	75.9	2280	0.222	506.2	1	115	115
tube ends	0	0	0	1400	0.04	56	0	0	0	1	250	250
nodes	0	0	0	320	0.1	32	0	0	0	1	90	90
temp. cont ea	0	0	0	0	0	0	0	0	0	0	0	0
insulat, ea	0	0	0	0	0	0	0	0	0	0	0	0
cabin, ea	1	24	24	1	8	8	1	3	3	1	140	140
assembly	2	9	18	4.4	9	39.6	4.4	9	39.6	8.8	9	79.2
subtotal			380			508			944			1314
subreflect												
quad/tripod	1	30	30	1	90	90	1	100	100	1	175	175
blower	1	1.2	1.2	1	0	0	1	0	0	1	0	0
apex, XYZ	1	15.2	15.2	1	15	15	1	15	15	1	15	15
nutator	1	36	36	1	60	60	1	100	100	1	150	150
mirror	1	10	10	1	30	30	1	30	30	1	52.5	52.5
subtotal			92			195			245			393
mount												
yoke, kg	13300	0.006	79.8	1000	0.006	6	0	0	0	0	0	0
yoke CFRP	0	0	0	1	122	122	0	0	0	0	0	0
cntr wt, kg	1630	.0044	7.2	2000	0.001	2	19	4.4	83.6	0	0	0
base, kg	5170	0.006	31	10000	0.006	60	27	6	162	8.5	6	51
bearings, set	1	30	30	1	30	30	1	35	35	1	260	260
encoder, ea	2	17	34	2	17	34	2	17	34	2	17	34
drive,mech, ea	2	20.5	41	2	22.5	45	2	27.5	55	1	160	160
control	1	20	20	1	20	20	1	20	20	1	20	20
metrology	1	20	20	1	50	50	1	50	50	1	226	226
cabling	1	30	30	1	30	30	1	30	30	1	30	30
assembly	3	9	27	2.8	9	25.2	2	9	18	1	0	0
foundation	4	20.4	81.6	4	40	160	4	67	268	4	32	128
az ring	0	0	0	0	0	0	0	0	0	1	100	100
subtotal			402			584			756			1009
misc.												
shipping	1	40	40	1	40	40	1	88	88	1	120	120
total mat'l			914			1328			2033			2835
adm,etc 30%			274			398			610			851
conting 15%			137			199			305			425
total			1325			1925			2947			4111

3.3 Receivers

(This section was written/compiled by K. Jacobs, chairman of the Receiver Working Group, with input from the WG members)

3.3.1 Introduction

The LSA/MMA project calls for equipping 64 antennas with heterodyne receivers covering the frequency range 30 GHz to 900 GHz. Due to the excellent atmospheric transparency of the 5000m site of Chajnantor in Chile, the sensitivity of the receivers is of utmost importance. Above 100 GHz, the only receivers capable of achieving noise temperatures of 2-4 times the quantum limit, $h\nu/k$, and frequency resolutions of up to 10^8, are those based on superconducting (SIS) tunnel junctions. In these instruments the extremely-sharp nonlinearity in the current-voltage characteristic of a superconducting tunnel junction is used to mix the astronomical signal from the sky together with an artificially generated local oscillator signal. The IF signal can then be amplified using cryogenically-cooled HEMT amplifiers, and conventional room temperature amplifiers, to a level where it can be applied to a digital correlator for processing. Of course the IF signal contains all of the information that was was present in the original signal, including phase.

SIS receivers with noise temperatures of a few times the quantum limit have been demonstrated at frequencies of up to 700GHz by several groups, including a number of European groups, at observatories such as IRAM, JCMT, CSO, SEST, KOSMA etc. From 30 GHz to 100 GHz, recent and steady advances in low-noise High Electron Mobility Transistor amplifiers open up the possibility of direct amplification at the frequency of the astronomical source. The subsequent mixing can then be accomplished with a much less sensitive, and much less expensive, mixer. In effect, this means that the technology required to build receivers for the LSA/MMA is largely available. To reach the ultimate sensitivity and bandwidth, however, a significant amount of development work is necessary.

To some extent this work will parallel developments and studies currently underway for air and spaceborne instruments such as SOFIA and FIRST, and there is no doubt that the LSA/MMA will benefit from the technological enhancements and innovations being considered for these projects. The overlap is, however, not complete: the LSA/MMA will not operate at the highest frequencies being considered for FIRST, and a large number of receivers must be constructed, installed and operated in the case of the LSA/MMA. Although individual receiver systems have been demonstrated, repetitive production, on what must be considered a large scale, has not yet been attempted. It might be expected, however, that the development of space-qualified mixers, local-oscillator sources, and optics, will enable large numbers of low-noise receivers to be constructed with almost identical performance.

To ensure the success of the project, both in terms of financial viability and operational security, three, to some extent related, fundamental design philosophies must be adopted: 1. simplicity—that is to say ease of construction, installation, operation and maintenance;

2. reliability:
3. cost effectiveness—for both construction and operation.

Considerable care and project control will have to be applied at all stages of the programme to ensure that the receivers operate efficiently, reliably, and with a minimum amount of operational support. Areas of concern and potential difficulty need to be addressed at an early stage and decisive management steps will need to be taken to ensure that the correct solution is adopted. Realising success in these areas will require careful receiver definition, design and management. For some components, competitive industrial tender may be the best approach: although considerable care will be needed in order to ensure that contracts are only awarded to companies that have a strong and proven capability in the appropriate area. Much of the technology and expertise are not in the domain of commercial organisations, and, in reality, it may be difficult to find companies that can provide the required level of guarantee.

LSA/MMA Receiver Requirements

The requirements for the LSA/MMA receivers are summarized in the table below.

Parameter	Specification	state-of-art
Frequency range	30-900 GHz	30-900 GHz
Noise temperature	$4h\nu/k$ SSB	$2-10h\nu/k$ DSB
Sidebands	SSB	DSB
mixer tuning	fixed tuned	DSB fixed, SSB mech. tuned
IF Bandwidth	4 (8?) GHz	1-2 GHz
Polarization	dual, linear	dual, linear
Local oscill. tuning	electrically tuned	2-6 tuners/LO
Amplitude stability	few 10^{-3} long term, 10^{-5} short term	
Phase	stable, low noise	

Receiver requirements for the LSA/MMA

Overview of Receiver Components

The receivers consist of the following subcomponents:

- an optical system which couples the horn of the mixer or amplifier to the telescope and, where relevant, to the local-oscillator source;
- an SIS mixer (above $\approx$ 100 GHz) or HEMT amplifier (30 to 100 GHz), which processes the signal from the sky;
- a cooled IF amplifier, for the SIS mixer, or a room-temperature mixer and amplifier,

for the HEMT, which amplifies the signal to a level that is suitable for further processing;

- a phase-locked local oscillator system. which in the case of the 30-100GHz channels drives the room temperature mixers. but in the case of the 100-900GHz channels drives the SIS mixers directly;
- a cryogenic cooler and vacuum system to cool the superconducting junctions and low noise HEMT amplifiers;
- support electronics in the form of mixer bias supplies. magnet current supplies. phase-locked loops, power supplies, temperature control etc.

3.3.2 Feasibility and Prospects of Receiver Components

Optics

The optics of the receiver have the primary task of efficiently matching the beams of the SIS mixers and HEMT amplifiers to the telescope. In the case of the mixers, the local-oscillator signal must also be injected. Clearly, this requirement means low loss in all senses: low ohmic loss and low diffraction loss at room temperature apertures. A conflicting requirement is that the signal beam must pass through the vacuum window of the cryostat.

With today's extremely low-noise SIS-mixers, the frontend optics can be responsible for a major fraction of the total receiver noise. Therefore, the number of optical components should be minimized. The MMA concept of distributing the frequency channels in the image plane of the telescope is an important step in this direction. From an optical design point of view, particular care must be taken to ensure that the off-axis aberrations are well understood and kept under control.

In the case of the SIS mixers, the LO signal must also be injected, and this can increase the number of optical components, and therefore loss in the signal path, significantly. There are various ways in which this can be avoided, and the inclusion of directional couplers in the mixer block is of interest. Like optical beam splitters, however, this approach throws away most of the available LO power: the precise fraction depending on how much injected noise can be tolerated. Another approach, which is starting to appear feasible, is to develop balanced mixers. This approach is much more economical in terms of LO power and has a number of other important advantages concerning stability and noise. The laser-photomixer option for the LO described below would allow us to feed in the laser power via a low-thermal conductivity optical fiber and have the photomixer in the vicinity of the SIS detector.

The design of quasioptical components and systems for millimetre-wave and submillimetre-wave receivers is well advanced. These systems have been used extensively on all of the

European submillimetre-wave observatories for a number of years. Many groups in Europe have a sound working knowledge of the concepts and design techniques used at these wavelengths, and certain groups have considerable expertise in this area. There is no doubt that quasioptical design and measurement techniques will develop significantly on the timescale of the project, and already a number of major initiatives are being planned in connection with FIRST. The ability to measure the optical performance of components and systems at these wavelengths is of particular importance.

Conclusion for feasibility of optics: The tools to design quasioptical components for millimetre-wave and submillimetre-wave receivers are well understood. The task remaining is to optimize the design of low-loss windows (antireflection coatings) and high efficiency optics (horn/lens/mirror combinations), despite the off-axis positioning. These tasks are well within the capabilities and expertise of European laboratories. Some development work will be required in this area, particularly when it comes to verifying that the receivers are working in a satisfactory and identical manner.

Mixers and mm-wave HEMT amplifiers

Introduction and state of the art

The sensitivity of the whole telescope hinges on the frontend mixers. Superconducting mixers based on Niobium/Aluminum-Oxide/Niobium SIS tunnel junctions are presently used in nearly all millimetre-wave and submillimetre-wave spectroscopic receivers. The *double sideband* noise temperature of the *mixers* is at the $2 - 4h\nu/k$ level from 80 GHz (10-20K) up to the gap frequency of Niobium of about 700 GHz (70-140K). Current practical receivers, including the optics and IF contributions are at the $6h\nu/k$ (30K) level at 100GHz, $2 - 4h\nu/k(22 - 44K)$ at 230 GHz [7] and $4h\nu/k$ (140K) DSB at 700 GHz [6]. For an overview of recent receiver results see [8].

It is important to realise that the LSA/MMA requires single-sideband operation in order to suppress the atmospheric noise in the unwanted sideband. Approximately, $T_{sys}(SSB) = 2T_{sys}(DSB)$, so that only the best receivers quoted above fulfill the requirements of the LSA/MMA. Also note that line confusion between the two sidebands of a DSB mixer does not need SSB operation but can be resolved by phase switching in case of interferometric observations.

The reasons for the high sensitivity achieved to date are the intrinsic low-noise behaviour of quantum mixers and the advances that have been made in designing and fabricating almost lossless, integrated, superconducting, impedance matching circuits. These sensitivities result, however, mostly from using a 1 GHz instantaneous IF band centred somewhere in the region 1-5 GHz. As discussed below, higher IF's can increase the noise by several $h\nu/k$. Above 700 GHz, the noise temperature of practical SIS receivers presently rises to the $6 - 10h\nu/k$ level because of the onset of RF losses in the superconducting matching circuits, and these can only be reduced, to some degree, by using normal metal films.

The hope of using Niobium Nitride with a higher gap energy for achieving the same performance as the Niobium junctions, even above 1 THz, has not been fulfilled due to the difficulties of working with the NbN material. Initial experiments with Niobium-Titanium-Nitride, however, are strong indicators that this material will allow noise temperatures as low as $4h\nu/k$ to be achieved even at frequencies as high as 900GHz and beyond.

For many years, SIS tunnel junctions have been mounted in waveguide, and one or even two movable backshorts have been used in order to provide, in a variable manner, a large range of embedding impedances. Even when integrated tuning circuits were developed to match out the capacitance of the tunnel junction, tuners were used to compensate for a lack of understanding about the behaviour of the probe. The tuners have therefore been used to compensate for unknown electromagnetic behaviour rather than immature superconducting RF circuit technology.

Over the last few years, it became possible to build fixed-tuned mixer mounts optimized to match SIS junctions with broadband integrated tuning structures. This allows the mixers to cover a complete atmospheric window without mechanical tuning, which is an important step towards reliable, easy to operate SIS receivers that are well adapted to space, imaging arrays, or large-scale interferometer applications.

There are also examples of excellent quasi-optical mixers, mostly in the submillimeter wave range, that use planar antennas on dielectric lenses instead of waveguides. Their coupling to telescopes, however, is generally not as good as the very high coupling possible with the corrugated feedhorns and waveguide mixers.

The broadband, fixed-tuned waveguide (or quasioptical) mixers are intrinsically double sideband. If the LSA/MMA could live with DSB mixers, the mixers up to 700 GHz would use existing technology, apart from the continuous efforts to gain greater instantaneous bandwidths.

A drawback of the tunerless design is, however, that a simple method of tuning the mixer to single-sideband sensitivity is lost. As we feel that both quasioptic SSB filtering as well as the re-introduction of mechanical tuners is undesirable, or at least only acceptable as a backup solution, the SSB function has to be realized with a (rather involved) integrated circuit, which has yet to be proven. The idea here is to develop image-reject mixers by using superconducting microstrip or coplanar transmission-line couplers and a pair of tunnel junctions. A joint MRAO/KOSMA project to develop a series of finline mixers is well established, and finline technology would be a particularly effective way of fabricating these components even at the shortest of wavelengths.

MM-wave HEMT-amplifiers show encouraging results up to 100 GHz and are a viable option for these frequencies. Recent results show noise temperatures of 50K SSB at around 100 GHz corresponding to $10h\nu/k$ SSB, which has to be compared to $5h\nu/k$ for an equivalent DSB SIS mixer. Yebes is intending to investigate mm-wave HEMT amplifiers over the next few years.

SIS Devices, circuits, and fabrication

Niobium SIS devices for routine use in millimetre and submillimetre-receivers are currently fabricated at a few dedicated laboratories, including several European laboratories, among them IRAM, SRON, KOSMA and (in the near future) OSO. Worldwide, they are very competitive, and it is important for the well-being of the LSA/MMA that such laboratories exist.

It is hard to conceive how this very specialized fabrication can be transferred to industry in a cost-effective way. At least, the development work necessary to achieve the goals for the LSA/MMA mixers (SSB operation, wide IF bandwidth, sensitivity) can only be done in the laboratories. The current device fabrication techniques are low volume and are aimed at specialized production runs with widely varying designs. To supply the needs of the LSA/MMA, the laboratories will have to combine their efforts, and even then, they will probably need some expansion of their current facilities to cope with the quantity and variety of devices required.

The current mixer designs at millimetre wavelengths are mostly of the simple double-sideband, single-device waveguide type without any complex integrated circuitry except for the tuning circuit to compensate the device capacitance (an exception is the integrated receiver with Flux-Flow oscillator developed at SRON/IRE). A tunerless single-sideband phase quadrature mixer will require development. As said before, a finline arrangement is an interesting approach to this problem, as well as the work done by Kerr et. al [2].

The provision of SSB mixers is an important development, which would have a large impact on the performance of the LSA/MMA as a whole. Improved sensitivity, however, is obviously only gained if it is possible to achieve the same $2 - 4h\nu/k$ noise performance as todays simple DSB waveguide mixers with the more complicated integrated SSB phase-quadrature design. An additional problem is that this performance has to be maintained over an IF bandwidth of 4 or even 8GHz, which will not be easy. There is no doubt that this development will be a challenge—especially when one realises that the two mixers needed for phase-quadrature sideband separation will be noisier than a single mixer with sideband rejection—but the underlying physics strongly suggests that it can be done with the technology that is currently at hand.

At frequencies above 700 GHz, where single-sideband operation is even more desirable, because of the lower atmospheric transmission, the necessary integrated circuits cannot be made of Niobium because of the large loss above the gap frequency. The development of Niobium-Titanium-Nitride technology would increase the frequency limit to more than 900 GHz. These developments together with the integration of the first IF amplifier are certainly some of the major development items for LSA/MMA.

A further important point is that a very large number of mixers will have to be made. Moreover there are very strong technical arguments to the effect that for the very best performance these mixers should use rectangular waveguide and corrugated horns. Even assuming, rather modestly, 5 frequency bands across the 100-900GHz range, we conclude that at least 320 mixer blocks and corrugated horns will have to be manufactured. Clearly, it is hard to see how conventional electroforming and machining techniques could meet this demand. One possibility would be to consider the bulk manufacture of split-aluminium-block corrugated horns, with parabolic mirrors at the apertures, of the type developed at MRAO. An attempt is currently been made at MRAO to fully automate the machining of submillimetre-wave corrugated horns, and if successful this technique would be of significance to the project.

Conclusion for feasibility of devices and circuit fabrication: DSB mixers with $2 - 4h\nu/k$ double sideband receiver temperatures are available using existing technology from 80 to 700 GHz. Integrated tunerless single-sideband mixers having the same sensitivity are a new technology and need to be developed. This work carries the risk of not achieving the sensitivity goals, thus negating the advantage of having an intrinsically SSB mixer—although some advantages regarding calibration would still accrue. Several European laboratories have the capability to design and manufacture such circuits, or more conservatively, conventional SIS mixer chips. For mass production, the device fabrication facilities would have to be upgraded, and also elegant and automated methods for machining mixer blocks would have to be found. Finally, it is important to emphasise that a considerable amount of mixer-development expertise exists in Europe including a significant strength in the modelling of superconducting planar structures such as waveguide probes, superconducting microstrip, finline transitions, etc.

IF Frequency and bandwidth of mixers

Intrinsically, SIS mixers can operate up to intermediate frequencies that are a substantial fraction of the signal frequency. Also, HEMT amplifier technology is advanced enough to give broad bandwidths. As mentioned in the introduction, however, the IF center frequency of most SIS receivers is in the 1-5 GHz range, with bandwidths of 1-2 GHz. This is in contrast to the plan for the LSA/MMA, where an 8-10GHz center frequency and a 4GHz or 8GHz bandwidth is preferred. A problem with the large bandwidth is that the *impedance matching* between the mixer and the IF amplifier (typically 50 Ω) becomes increasingly difficult to maintain. This happens because the capacitance of the integrated RF tuning circuit, acting as a lumped capacitance, together with the capacitance of the junction starts to short out the intermediate frequencies. An integrated sideband-separation circuit on the mixer chip will add further capacitance. Any mismatch losses multiply the noise-temperature contribution of the following IF amplifier. A detailed discussion can be found in [3].

Conventional approaches using additional matching networks could probably achieve a 4 GHz bandwidth. Presently, designs for a 8-12 GHz IF system for SIS mixers are being developed for the ESA FIRST satellite mission. Going from 1-2 GHz HEMT amplifiers to 10 GHz HEMTs amplifiers, having current performance, would result in a noise temperature increase at the amplifier from about 4K to about 10K. The difference is multiplied by the mixer losses and all other losses between mixer and amplifier, so that the impact on receiver noise can be substantial. For a 3dB loss, this would mean an increase at 100 GHz of $2.5h\nu/k$! It is very important to realize that for continuum observations, the figure of merit is $BW \cdot T_{sys}^2$, so that the price paid for higher bandwidth can be high. If the interferometer is mainly used for spectroscopy, the figure of merit is T_{sys}^2, and so it would be wiser to sacrifice the ultra-wideband IF for better noise performance.

It may be a solution to integrate the first, and possibly the second, stage of the IF amplifier into the SIS mixer block. A recent example of this approach is described in [1] and leads to a 3-4 GHz bandwidth. Also, the integrated RF tuning circuits on the SIS chip may have to use low-capacitance coplanar line technology. Perhaps one of the biggest hazards is the lack of understanding about the instability that may arise from tightly coupling two potentially unstable, wideband devices. Clearly, this is another area for development.

Conclusion on the feasibility of having a 4-8 GHz IF bandwidth: A 4 GHz IF bandwidth is feasible with some improvement in the mixer IF matching circuit. At an intermediate frequency of 8-12GHz the capacitance of the mixer circuit and its associated RF impedance matching structures become problematic. A sideband-separation circuit adds to the capacitance and could offset the tradeoff between DSB and SSB mixers. An 8 GHz IF bandwidth with the required noise performance represents a substantial development problem. The impact on the overall figure of merit of the receivers and the consequences for the backends can be considerable and will have to be carefully analyzed before any final decision is made.

IF amplifiers

The current state-of-the-art of HEMT amplifiers is a noise temperature of about 1K per GHz, for conventional GaAs based devices, and 0.5K/GHz demonstrated and 0.25K/GHz predicted for InP([4]). Amplifier development is taking place at Yebes (Spain), DEMIRM (France), MPIfR (Germany), Chalmers (Sweden), MRAO (UK), JPL/TRW (USA), NRAO (USA). New developments at eg. Chalmers, JPL/TRW and Yebes focus on InP devices, which should result in lower power dissipation and possibly lower noise temperatures at 10GHz. Most amplifiers used in SIS mixer applications are currently 1-2 GHz wide. Low-power dissipation amplifiers for 8-12 GHz, (4GHz) IF bandwidth, are being developed for FIRST with the expectation of having 10K noise temperatures with a goal of 5K. For the very high bandwidth *and* sensitivity goals of LSA/MMA the conventional approach of building and optimizing the IF amplifier separately from the mixers might not be feasible. The first or first and second IF amplifier stage would then have to be integrated with the mixer. MRAO are developing an amplifier which uses superconducting microstrip transmission lines, and a prototype amplifier is already under construction.

Conclusion for the feasibility of producing wideband IF amplifiers: HEMT IF amplifiers for a 4 GHz bandwidth are available or are under development. The main issue is matching the amplifier to the SIS mixer, rather than the performance of the amplifier or mixer itself. A substantial development effort is required if the IF amplifier is to be integrated into the mixer block. Some advantages may accrue with this approach for IF bandwidths as high as 8GHz, although, even in this case, it is still realistic to consider keeping the mixer and amplifier separate. Achieving the goal of $2 - 4h\nu/k$ over 8 GHz is not a fundamental problem but it would be a challenging technical undertaking. This development should only be considered if the impact on the whole instrument, including the backends, is fully understood.

Local Oscillators

In many ways, this part of the receiver is one of the most technically demanding and will be an instrument driver, in the same way as it is for FIRST. The use of broad-band sources without tuning mechanisms is essential. Present day millimetre and submillimetre wave sources use Gunn oscillators, in the 70-140 GHz range, together with Schottky-diode frequency multipliers. The Gunn oscillators need movable backshorts for wideband tuning. To achieve maximum bandwidth and power, existing multipliers also need movable backshorts, at least in the submillimetre-wave range. The number of backshorts increases with frequency, as the multiplication has to be achieved with only doublers and triplers. This gives rise to a multitude of tuning mechanisms, which is not acceptable for the LSA.

An alternative approach is to use a YIG-tuned microwave source, multiplied to 80-100 GHz, followed by a HEMT power amplifier, which drives fixed-tuned planar varactor frequency multipliers. The YIG oscillator is easily to tune electrically, and planar varactor circuits can be optimized to be fixed tuned over a wide bandwidth. The required millimeter-wave power amplifier is a subject of current development, and issues relating to phase noise and spurious harmonic responses of the triplers are still under consideration. FIRST is likely to use a similar system to the one described here.

As each receiver has its own set of local oscillators and multipliers, together with phase-lock electronics, the local oscillator system is is going to represent a significant fraction of the total cost. Remember that in the final stage, the receivers will have 10 frequency channels, 7 of them SIS, and the HEMT RF amplifier channels will need some kind of mixing after amplification, too.

Besides this conventional approach, there is the possibility of a laser-photonic local oscillator system, where two IR lasers are frequency locked, with the desired frequency difference in the millimetre or submillimetre-wave range, and fed to photomixers that convert the beat frequency into millimetre or submillimetre-wave power. The two powerful lasers can be in a central building and the laser power fed to each of the receivers, and photomixers, by optical fibers. This approach would probably result in a substantial reduction in cost and complexity. This possibility is currently being studied in connection with both the MMA and FIRST projects. It is, however, still in a very immature state.

All local oscillator schemes need exceptional phase stability. Except maybe for the laser-photomixer system, new technology for phase locking is not necessary, but the design has to be carefully studied at a system level.

Conclusion for the feasibility of the local oscillator system: Conventional Gunn/ multiplier oscillators are available but suffer from the need of mechanical tuning. A viable alternative is a YIG-tuned microwave oscillator with HEMT power amplifiers and Schottky planar multipliers. This technology needs development, but has been demonstrated. A very attractive solution would be the laser-photomixer approach, which is completely new but is under development both in the US and Europe for FIRST and SOFIA.

Cryogenics and Dewars

The SIS mixers will have to be cooled to about 4K, and yet it is undesirable to have to supply or handle helium at the proposed site in Chile. The baseline design is therefore to use 4K closed-cycle refrigeration. Closed-cycle refrigerators for 4K are commercially available, and a number of observatories have experience in operating them. The recent development of Gifford McMahon systems that use high capacity heat exchanges will be of particular benefit to the LSA and may enable low temperatures to be reached without the need for complicated Joule-Thompson systems.

The temperature stability requirement for stable operation, especially for continuum observations in the single-dish mode, is rather stringent and amounts to a few millikelvin. This can be achieved with a closed temperature control loop using a small amount of heating, at least for the Joule-Thomson type of cryocoolers. 4K cryocoolers operating on the Gifford-McMahon principle usually have larger temperature fluctuations and drift and may need more elaborate techniques to stabilise. Careful thermal design should be able to eliminate any potential problems. Careful thermal and mechanical design will also be required to isolate the vibrating fridge head from the mixers, but techniques that use flexible straps are well established and should be straightforward to implement. In fact, one can imagine a rather elegant and compact scheme based on this relatively new type of cooler.

Dewars for cryogenic receivers are in operation at many observatories. A task for the LSA/MMA consortium will be to simplify the design of the Dewar and make it as modular as possible, so that modules for different frequencies can be removed for maintenance or added easily as higher frequency channels come into operation. Modularity is a prerequisite to make it possible to have a multinational collaboration on receiver construction, particularly if one envisages several institutions supplying receiver channels for the different frequencies.

Conclusion for the feasibility of the cryogenic system: Commercially available coolers can be used to produce reliable receivers in large quantities. The thermal stability needs to be high and vibrations must be kept to a minimum. These requirements are well within the capabilities of existing laboratories, but careful thermal and mechanical design will be required. Modularity is needed so that the construction can be phased and distributed around a number of countries.

3.3.3 Manufacturing and Industrialization

One major feature of the LSA is that a large number of receivers will have to be constructed, and this calls for a different approach to constructing instruments than is used by almost all observatories at the present time. Below, we attempt to identify those components and tasks that could probably contracted out to industry. Included in this list are only components that have to be custom made for the LSA/MMA: not components like IF cables, warm IF amplifiers, etc., which are obviously available from commercial organisations. For some of the more advanced components, such as the laser-photonic local oscillators, the question of commercial fabrication can only be answered after the development phase.

Industrial (Mass) Fabrication of Components

All the *mechanical* parts of the receivers could be fabricated industrially; among them are the mirrors and lenses, the Dewars and Dewar modules. Manufacturing the mixer blocks requires special skills, but a number of commercial organisations may be interested in this task. Conventional local oscillator systems in the millimetre-wave range could be commercial items. The electronic systems, such as mixer bias supplies, parts of the phase-lock electronics, receiver control etc., could be manufactured commercially according to basic designs that already exist in the laboratories. As mentioned above, it is unlikely that the fabrication of the superconducting mixer devices can be commercialized at reasonable cost. There are, however, foundries like Hypres Inc. that can do at least standard processes in Niobium technology.

As far as industrialization is concerned, we feel that the best way to go would be to develop complete prototype instruments in the laboratory and then, via a small pilot series, have the majority of the instruments manufactured in industry. This approach would lessen the risk of having problems with the prototypes and would help industry to make a realistic bid.

Integration and Testing/Calibration

Of course, even though the majority of the components and subsystems can be produced commercially there is still the need to assemble and test the receivers and this is a major task. Integration, testing, and calibration has probably to be done at specialized laboratories. Maybe there should even be a centralised laboratory where integration, testing, calibration and maintenance of all the receivers takes place. As this center will need to hire non-expert personnel, automated test systems will have to be developed and extensive documentation will have to be kept. An arrangement like this would also make the collaboration with the MMA easier, because there should obviously be a common design for the receivers. The feasibility depends on the degree to which the receivers can be modularised.

3.3.4 Development Areas for Study Phase

Due to time and probable financial constraints, the study phase can only do pre-development work to assess the feasibility of the advanced performance criteria discussed above. The costing for the envisaged future LSA proposal therefore has to include substantial amounts for technology development.

One major development area is the design of sideband-separating integrated SIS mixers with wide IF capability. The broadband matching of SIS mixers and IF amplifiers with the possible integration of the first, or first two, IF amplifier stages is a second field which has important implications for the overall sensitivity of the array.

Also of great importance is the development of new local oscillator concepts. HEMT millimeter wave power amplifiers would be an important step towards high power fundamental sources for planar-circuit varactor frequency multipliers. The laser-photonic mixer is a completely new technology that would need to be studied.

Although the basic development techniques for the optical systems are well understood, a study should also begin on the development of compact, low-loss, high-efficiency, easy-to-manufacture, optical systems. The need to handle the effects of aberrations caused by the off-axis geometry of some of the pixels must be considered early, as the design of the receivers may have important implications for the design of the telescopes themselves.

The question of commercial production would need some study too. A study of low-power consumption cryocoolers and modular Dewars could be initiated.

3.3.5 Proposed Receiver Concept

Receiver concepts for the early phase of the LSA can be split into advanced and conservative options:

The advanced concept would call for a complement of four receivers at 30, 100, 230 and 345 GHz with YIG-tuned, millimetre-wave power-amplified and multiplied sources as local oscillators. It is assumed that mixer development will be rapid enough that integrated sideband-separating waveguide mixers will be available. A decision would have to be made about whether to go for the 8 or 4 GHz IF bandwidth. The room temperature IF system should support the widest bandwidth that is ever likely to be required from the beginning.

A conservative approach would use mechanically-tuned Gunn oscillators followed by fixed-tuned multipliers as the local oscillator sources and double-sideband fixed-tuned waveguide mixers with an IF of 4-8 GHz. SSB operation could be made available with mechanically-tuned mixers or optics.

The Dewar and cryosystem have to be the final designs, with preference on a highly-modularised configuration.

3.3.6 Cost Projection for LSA/MMA Receivers

The following is a cost estimate for the development phase of a receiver which has four channels at 30 GHz, 100 GHz, 230 GHz, and 345 GHz.

Budget for LSA Receiver Development
K.Schuster & B.Lazareff, IRAM, Jan-1998

Prices in kFF
Note : add 150kFF per channel for Mxr Devt if LO's must be phase locked

Task	Area	Item	*Per Channel*	*All Channels*	*Task SubTot*
Mxr Devt					
	Labor	2 my eng	1.000		
		2my tech (incl block machining)	600		
	Materials	w/g, att, couplers	50		
		HEMT amp	15		
		warm IF	30		
		LO	130		
		test signal : sweeper + harm mxr	80		
		wet cryostat + peripherals	100		
	Test Eqpt	spec analyzer	300		
		IF power meter	40		
		RF power meter	60		
		misc	50		
	Subtotal		2.455		9.820
Junctions					
	Labor	1my phys	500		
		2 my tech	600		
	Consumables	targets, maintenance, fluids	500		
		2 masksets @ 50 each	100		
	Subtotal		1.700		6.800
HEMT devt					
	Labor	4 my @ 500		2.000	
	Supplies	InP discrete chips 2 batches		400	
		InP MMIC's 2 batches		400	
	Test Eqpt		??		
	Subtotal			2.800	2.800
LO Devt					
	Labor	4 my eng		2.000	
		4my tech		1.200	
	Supplies	mm-wave power amps	??		
		planar varactors	??		
		microwave sources	??		

	Test Eqpt		??	
	Subtotal		3.200	3.200
Cryogenics				
	Labor	1my eng	500	
		2my tech	600	
	Supplies	competing cryogenerators (3)	1.500	
		test cryostats (3)	120	
		vacum, gages, etc (3 sets)	135	
	Test equipment			
		Data loggers (3)	90	
	Subtotal		2.945	2.945
Proto Rx				
	Labor			
		2my eng	1.000	
		4my tech	1.200	
	Cryogenics			
		Cryogenerator	0	
		Cryostat	200	
	Equipment			
		Control	150	
		HEMT's	60	
		Warm IF's	120	
		LO's	0	
		Optics	120	
		RF components	200	
		Mech. comp.	70	
	Test Equipment		0	
	Subtotal		3.120	3.120
Grand total				28.685

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3.3.7 Capabilities in mm- and Submm-Wave Receiver Technology

This document describes the technological capabilities of the member institutes of the LSA/MMA Receiver Working Group, compiled from input of these members. The list is by no means exhaustive – there are several other European groups active in this area – but it gives an idea of the expertise available.

IRAM

Fabrication of Superconductive Devices and Circuits. The IRAM Superconductor Device Laboratory routinely fabricates high quality SIS junctions with integrated tuning circuits in Nb technology for the IRAM telescopes and a large number of external users. The junction surfaces can be as small as 0.5 square micrometers and the current densities can be as high as $15kA/cm^2$ for high quality IV characteristics. The frequency range covered with this devices is 80 to 900 GHz. IRAM has also experience in producing high quality stacked Nb junctions.

Aside from Nb SIS junctions the lab has successfully produced devices in various other technologies: Submicron high current density NbN junctions with Nb or Al tuning structures, Large surface Nb photoncounters, submicron NbN phonon, cooled bolometric mixer elements.

Current and near-future development efforts will include: establishing a new high yield and high reproducability standard process for production of high quality Nb submicron junctions and integrated circuits. Development of new process and film characterization standards. Development of passive planar lumped elements and transmission lines for mm/submm MMIC's. Incorporation of micromechanical technologies for new integrated mm/submm device types with improved electrical properties and high reliability.

Mixer development and fabrication. IRAM has developed, for the equipment of its telescopes, receivers at frequencies up to 370GHz, with receiver noise as low as $3h\nu/k$ SSB. Ongoing development focuses on achieving wideband (typ. a waveguide band), low noise, stability, reliability, ease of tuning, and relaxing the demands on mechanical fabrication (full-height waveguide). Possible developments for the LSA/MMA project could be:
- exploring SSB mixers with inherently reliable mechanical tuning;
- integrating first stage(s) of IF amplifier for wider IF bw;
- exploring quadrature mixers.

Such developments need additional manpower.

Characterization of mm-wave devices and materials. IRAM has developed for its own needs a mm-wave VNA, allowing S-parameter measurements up to 370GHz (fully calibrated up to 270GHz) , with a dynamic range between 20 and 50dB (depending on frequency). This equipment has proven very valuable for testing prototype and production components (couplers, horns) before integration into systems. Quasi-optical components (windows, quarter-wave plates) can also be cheracterized. Measurement of components could be offered to other groups during the development/prototyping phase; testing of series production components would require to duplicate the equipment on the basis of the acquired experience. A confocal cavity under development will allow accurate measurements of the real and imaginary part of dielectrics.

Fully electronic LO's. As a first step, IRAM has started a design study for a fully electronic LO system for the 85-115GHz band, based on YIG oscillator, active and passive multipliers. This development could be extended to higher frequency bands, building upon the experience with multipliers and ongoing developments around planar varactors.

Antenna range. IRAM operates an anechoic chamber that permits the measurement of the amplitude and phase of radiation patterns of optical components and subsystems in either angular or X-Y scanning modes. This equipment currently operates up to 270GHz, but could be upgraded to higher frequencies with suitable harmonic generators and down-converters.

Water vapour radiometer. IRAM has started the design of a 22GHz radiometer system for the PdB interferometer. Although the 183GHz water line may be a better choice for the LSA/MMA site, the experience gained in the design and operation of a 22GHz radiometer will certainly be useful for the LSA/MMA.

Cryogenics. The LSA/MMA project might benefit from the experience IRAM has accumulated with various types of cryostats : wet, hybrid, and closed-cycle JT (no 4K GM, however).

DEMIRM – Paris Observatory

The Department of Millimeter and Submillimeter Radioastronomy (DEMIRM) of the Observatoire de Paris is specialized in Research and Developments of low noise receivers in the millimeter and submillimeter ranges.

DEMIRM experience : DEMIRM have been responsible for 20 years the installation of several sets of radioastronomical receivers :

- a set of two receivers at 45 and 90 GHz for the 14 meter dish antenna at Yebes (Madrid),
- a cryogenic receiver (80-120 GHz) mounted at the Observatoire de Bordeaux on a 2.5m dish,
- a cryogenic receiver (210-240 GHz) located on the Plateau de Bure at an altitude of 2500m to equip a 2.5m dish.
- a Microwave sounder radiometer breadboard (10 channels in the 110-190 GHz range) for the CNES and Meteorology,
- a 360-380 GHz and a 420-440 GHz (SIS) cryogenic receivers (balloon flight experiments) : PRONAOS SMH and PIROG 8.

The DEMIRM had close cooperation with JPL on the CSO 626 GHz SIS receiver and on the 557 GHz SIS receiver for the KAO.

To manufacture those receivers, the DEMIRM has developed several technologies : quasi-optics antenna feeds, calibration sets, filters and diplexers, cryogenic mixers, SIS junctions, varactors multipliers, very low noise cooled FET and HEMT amplifiers ; close cycle 2K and 4 K cryocoolers and pulsed gas tubes.

The DEMIRM is involved in CNES and ESA R and D contracts :

- Schottky 500 GHz receiver for MASTER
- critical technologies
- Superconductor
- supra THz receiver at 1.5 THz (ESA-SRON : STS project).

The DEMIRM is also involved on the FIRST heterodyne instrument for the HI-FI frond-end channel 1 (580-650 GHz) SIS mixers.

DEMIRM Facilities:

DEMIRM is equipped with common microwave facilities:

Wiltron network analyzer. Tektronix spectrum analyzer, HP noise analyzer. microwave and millimeter/submillimeter powermeters. Some quasioptical setups are used for determining beam patterns, making beam alignments as well as a quasioptical network analyzer (ABMillimetre) which can do measurements up to 1 THz. The laboratory has some liquid helium dewar and cryocoolers for testing SIS receivers and low-noise HEMT amplifiers. The laboratory is also equipped with full clean-room facilities for UV photolithography, Reactive Ion Etching, sputtering machines and evaporation benchs for Nb, SiO, Al, Au deposition. Some facilities for micromounting using microscopes. fume hoods. microscopes and micromanipulators are also available. Finally, DEMIRM have many different software like Autocad, EEsof Libra-Touchstone, MathCad and some specific codes for SIS mixer and microwave simulations of superconducting circuits.

Onsala Space Observatory

Onsala has long time experience in SIS mixer design including submm and array applications. A new dedicated sputter machine for Nb/NbN tri-layer processing is due for installation early Autumn 1998. There is extensive experience in satellite integration. The Swedish satellite ODIN radiometer platform is being assembled at at Chalmers University. For this satellite grid technology has been developed up to 1 THz (insertion loss of the grid less than 2%). For SRON some further developments have been made for a grid up to 1.8 THz. Also, all mirrors and lenses for ODIN optics were designed and fabricated at Chalmers (118, 570 GHz).

Onsala have experience in 3-D Gaussian beam optics tracing and quasioptical design. A new facility will be built for near-field Gaussian optics testing for 400-1100 GHz frequency band dedicated for final testing and integration of the mixer assemblies for HIFI FIRST including cryogenic stand, subject to funding of participation in FIRST by the Swedish Space Board.

Equipment at Onsala includes various microwave measurement equipment for DC-20 GHz band including HP scalar 4-channel network analyzers and synthesized sources; 40 GHz, 85-119 GHz BWO sweep generator, tunable Gunn oscillators for 3 mm wavelength; Waveguide and quasioptical components for mm-wave measurements (attenuators, wave-length meters, etc.); Cryo-amplifier measuring setup based on close cycle 15 K machine with precision temperature variable load; home-developed software for data acquisition and radiometer study and measurements; precision 3D scalar beam measurement computerized system (used for ODIN); Access to vector network analyzer equipment within DC-115 GHz band; Access to HP MDS and Compact microwave design software; Access to PCB/microwave board fabrication Precision mechanical equipment with highly qualified personnel.

Max-Planck-Institut für Radioastronomie (MPIfR)

The Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn. Germany. has long-lasting experience in the design and development of new telescope facilities based on novel technologies. Since 1977, the institute operates the world's largest fully-movable radio telescope near Effelsberg. The institute initiated and supervised the construction of the 30m mm-telescope on Pico Veleta (since 1985 operated by IRAM). In a joint collaboration with Steward Observatory, University of Arizona. construction of a 10m submm-telescope on Mt. Graham, the Heinrich-Hertz-Telescope (HHT). has been completed recently.

The MPIfR operates well-equipped laboratories in support of its scientific missions. A mechanical workshop, capable of high precision mechanics, is available. The MPIfR Submillimeter Technology Division includes ~25 scientists, engineers, and technicians. Next to providing the HHT with submm heterodyne and bolometer detectors and AOS backends. the group's activity has focused on the development of large detector arrays – both for continuum (e.g., a 37-element bolometer array, working at 1.3mm wavelength at the IRAM 30m-telescope) and for heterodyne work. Later this year, first light is expected for a unique 16-element SIS heterodyne-array to better exploit the 625 μm atmospheric window. The instrument comes with a new flexible autocorrelator, built in the MPIfR Digital Electronics Laboratory, offering up to 2 GHz of bandwidth for each of the 16 pixels. In addition, waveguide and quasi-optical SIS receivers for operation in all ground-based atmospheric windows up to 800–900 GHz are built in the division. Recently, a project group has been established for the development of a dedicated 2.6 THz 2×2 pixel receiver for SOFIA (in collaboration with KOSMA, Köln), based on NbN HEB mixers (with IRAM).

Other technical groups within the MPIfR are developing state-of-the-art, low-noise HFET amplifiers covering the whole radio frequency range up to the 3-mm band and advanced digital correlator technology.

In summary, the MPIfR has a wide range of technological capabilities that are of interest for the LSA/MMA project. In addition, the institute's scientific support for the project is extremely strong. Therefore, there is great motivation to participate in LSA/MMA technical developments.

KOSMA, I. Physikalisches Institut der Universität zu Köln

KOSMA is the Kölner Observatorium für SubMillimeter-Astronomie operating a 3m diameter submillimeter telescope on Gornergrat, Zermatt, Switzerland. The telescope allows observations up to 900GHz, taking advantage of the excellent atmospheric conditions of Gornergrat (3100m elevation) during the winter months. All instrumentation for the telescope. including acousto-optical spectrometers as backends, has been built in house. SIS receivers for the 230, 345, 490, 660, and 820 GHz atmospheric windows are in operation at the telescope. Since 1990, KOSMA has a facility to fabricate Niobium-based SIS-junctions. KOSMA has played a pioneering role in extending the SIS technology to the submillimeter range, developing novel integrated tuning circuits as well as broadband fixed-tuned waveguide mixers. The lab is now also working on the design and fabrication of superconducting hot-electron bolometers for Terahertz frequencies.

For all receivers, the waveguide mixers, SIS junctions and HEMT amplifiers were developed and manufactured at KOSMA. A closed cycle 4K J-T cooler was developed and built at KOSMA and is in routine operation at the telescope. There is also experience with commercial 4K GM coolers.

Current projects of the KOSMA group are a dual frequency array receiver for the 490 and 800 GHz bands, a 1.4–1.9 THz receiver system for SOFIA (in collaboration with MPIfR Bonn) using diffusion cooled superconducting hot electron bolometers, and the development of a mixer from 640-800 GHz for the ESA satellite FIRST. The group collaborates with MRAO, Cambridge, in developing a series of finline mixers operating in the 230 and 345 GHz bands. These mixers have prospects to be scalable to submillimeter wavelengths and are very well suited to be extended to integrated single-sideband and/or balanced mixers.

SRON Groningen, Space Research Organization Netherlands

The research group Physics of Thin Films at the Materials Science Center, Applied Physics Laboratory of the University of Groningen (RuG) and the Low Energy Astrophysics (LEA) division of the Space Research Organisation (SRON) are collaborating on research and development of sensitive mixers and receivers for (sub-)millimeter waves using superconducting technology. The core of these mixers is the superconductor-insulator-superconductor junction. The SIS junctions are made at the RuG, the SIS mixers are made at SRON.

Both institutes have been pioneers in this field, and, thanks to a well coordinated and integrated approach, both are respected world-wide. SIS-products from RuG/SRON are used at institute and research groups all over the world, including the JCMT. SRON is the leader/principle investigator on a big proposal to ESA to build the heterodyne spectroscopy instrument for the FIRST satellite, which involves collaboration between 12 nations, including the US. Thus, close contacts between the various receiver groups in Europe and the US already exist.

Arcetri Observatory

Different institutions, together with Arcetri Observatory, are working in Italy on the design and construction of receivers and components for millimetre and submillimetre bands. On behalf of these institutions, namely IRA-CNR of Bologna, and Radio Group at Physics Dept-University of Milano, the available technological capabilities in the field are described here.

Arcetri Observatory, also in collaboration with Electronic Engineering Faculties of Firenze and Pisa Universities, has a large experience in designing and construction of wide-band corrugated feed horns and microwave components such as polarizers and orthomode transducers for frequencies up to 50 GHz. All horns for the Medicina radiotelescope receivers have been designed and built in Firenze.

Arcetri is involved in the design of the new 64 meter antenna (and receivers) for the band 2 - 90 GHz to be built in the next years in Sardinia. The task will be the analysis of the optical coupling, using also quasioptical methods, of millimetric receivers to the antenna.

The Milano group has experience in assembling and using absolute radiometers up to 33 GHz, is currently preparing an experiment for measurements of the CBR polarization up to 90 GHz and, in collaboration with CAISMI in Arcetri, IEN in Torino and Electronic Dept. of the Polytechnics in Torino and Milano, is developing SIS junctions and SIS based mixers for frequencies up to 350 GHz.

A 2.5 × 2 × 2.5 meter anechoic chamber is available in Firenze for horn testing.

Some relevant industries include SILO, a small firm (SILO) in Florence working in optics that could produce large quantity of high quality glass or metallic mirrors at reasonable cost; CSELT, design and construction of high quality microwave components; and MEDIALARIO, design and construction of high precision mechanical and optical components (mechanics for LBT and optics for XMM).

ETH Zurich

At the Laboratory for Electromagnetic Fields and Microwave Electronics work has been going on for 4 years on the development of integrated mm-wave (MMIC) circuits based on Indium Phosphide High Electron Mobility Transistors (InP-HEMT).

Centro Astronomico de Yebes

The Yebes Observatory can make contributions in the development and fabrication of HEMT amplifiers. During the last 10 years there has been uninterrupted activity in the design and fabrication of amplifiers to be used as IF stages of mm-wave radio-astronomy receivers equipped with Schottky or SIS mixers. The institute has built amplifiers from 0.9 GHz to 8.8 GHz with stae-of-the-art performance. The Observatory is now actively involved in the development of a prototype X-band amplifier for project FIRST. During 1998 third party InP devices will be tested. Plans for the next 5 years include the design and fabrication of mm-wave amplifiers at frequencies around 22 GHz, 45 GHz and 100 GHz.

MRAO Cambridge

MRAO has many years of experience developing and building low-noise submillimetre-wave instrumentation. Current emphasis includes SIS mixer modelling, including device physics and the electromagnetic behaviour of superconducting planar RF circuits. Mixer-block design and manufacture, including high-performance submillimetre-wave horn-reflector antennas. Submillimetre-wave optical design including aberrations in off-axis optics.

Rutherford Appleton Laboratories (RAL)

The Rutherford Laboratory has vast expertise and heritage in the development of heterodyne components (e.g. semi- or superconducting mixers, LO sources) and complete receiver systems for ground, air and spaceborne use.

Typical frequency range covered is 100 GHz to 2.5 THz Mixers and multipliers use waveguide technology. Systems have been used in atmospheric and astronomical remote sounding experiments. Available facilities and expertise include:
precision machining of mm and sub-millimetre waveguide cavities; novel device fabrication techniques e.g., planar whiskers, micro-machining;
excellent mm/submm wavelength circuit design expertise applicable to SIS and Schottky mixer and frequency multiplier technology;
substantial quasi-optical design, construction and test expertise;
substantial system integration and test expertise;
state-of-the-art performance (devices and systems);
space qualified structures.

The current programme of work is as follows:
support SIS receiver development work at the James Clerk Maxwell Telescope (800 - 900 GHz receiver (Rx E) currently under construction);
development of 820 GHz SIS Rx for the TIRGO telescope;
development of SIS and Schottky mixers and receivers for atmospheric remote sensing instruments;
instrument studies and development for ESA and the EU; and a variety of contracts with UK, European world-wide institutes and industry, for example:
development of spaceborne mixers for Matra Marconi Space Systems, UK; manufacture of feedhorns (to 700 GHz) for the Smithsonian Astrophysical Observatory; design, manufacture and test of multiplier sources for the Smithsonian Astrophysical Observatory; manufacture of large scale free-standing wire grids for IRAM; design, manufacture and test of 2.5 THz Schottky mixers for ESA and JPL; design and manufacture of receiver cryogenics systems e.g., for TIRGO and EU; manufacture of SIS mixer block for ASIAA, Taiwan; upgrade of MARSS aircraft radiometer for the UK Met. Office.

Hertzberg Institute for Astrophysics, Canada

Complete SIS receivers at 200 und 300 GHz are designed and built for the JCMT. The SIS devices currently come from U Va and SRON, Groningen but they can also be made in Canada at the AMC. The group designs the SIS device tuning structures and draws up the multilevel masks. All the mixer machining is done in house using a super-precision CNC mill and CNC lathes, and the group designs and builds all the off-axis mirrors, interferometers and other optical components. The group has software design tools such as Touchstone and Microsim, and a well equipped lab and clean room. There are various solid state LO sources including one at 700 GHz. In addition there is a group supporting a centimetre wavelength aperture synthesis telescope with a great deal of experience in correlator design and all aspects of interferometry.

3.3.8 1999 Development Plans

This section describes proposals for studies in 1999 with the goal of developing a practical European design concept for the LSA/MMA receivers. The issues to be addressed are a pre-development of SIS mixers to find out feasible ways of achieving the LSA/MMA goals, HEMT amplifier development and a development study for the front-end optics. It would be highly desirable to address the local oscillator questions in this study as well. It is not yet clear which of the members could do work in that area. The study could possibly be outsourced to industry. Below, suggestions from some of the institutes are outlined.

At SRON, Groningen, development funds would be used to set up an additional group to carry out design and development of the SIS mixers for the LSA/MMA at the higher frequencies, i.e., > 345 GHz. Specifically, they need to be tunerless, and integrated circuit mixers must be developed to achieve the necessary frequency coverage (>30 percent bandwidth) and a large IF bandwidth (> 4 GHz). A close interaction between device people and receiver designers is needed. Some aspects of this research (in particular, tunerless and the broad IF bandwidth) will also be of benefit to the parallel design and development of receivers for FIRST at SRON/RuG.

At KOSMA, work could be done on the design of integrated single-sideband mixers. Further collaboration with MRAO would extend the work on finline mixers. As in the current collaboration with MRAO, KOSMA would take responsibility for fabrication of the devices, but would also be involved in the design work and could make contributions toward integrating a first HEMT amplifier stage for 8-12GHz.

At Onsala, it is suggested that a Postdoc/Engineer position be funded to work 100 percent on the Project.

At Arcetri Observatory there is already a post-doc full time fellowship for the development of SIS mixer for frequencies up to 350 GHz, but additional funds would be needed for the development of quasioptical techniques for analysis of optical coupling of receivers to the telescope.

The Centro Astronomico de Yebes is interested in participating in the development of HEMT amplifiers for the LSA/MMA, both at the RF and IF levels. In view of the current status of the definition of the receivers for the project and of the availability of instrumentation at Yebes, the development of a prototype amplifier in the 30-48 GHz band seems a very reasonable and feasible activity for the year 1999.

As part of a development effort, MRAO could be involved in the electromagnetic design of mixers and mixer testing. The finline mixers would be a good candidate for sideband-separating mixers; although the radial probes have advantages too. The MRAO split-block horn technology is interesting, and the automation of block manufacture should receive some attention. MRAO would also be interested in looking at the design of easy-to-manufacture, high-efficiency optics for small multifrequency arrays. MRAO could make a particularly good contribution to a development study in the area of front-end optics.

For all proposed studies, the institutes would need funds for manpower of the order of a postdoc position including some overhead for travel and an amount for materials and equipment. There cannot be a decision yet how to distribute the funds among the interested groups and some discussion is still needed as there are overlapping interests.

Funding of the studies would have to be as following:
Postdoc position: DM 100.000
Overhead DM 20.000
Materials, equipment DM 80.000
Total per study area: DM 200.000

We would foresee studies in the above mentioned four areas which would amount to a total of DM 800.000.

3.4 LSA/MMA System

(This section was written/compiled by R. Lucas, chairman of the System Working Group, with input from the WG members)

3.4.1 Introduction

A large synthesis array such as the LSA/MMA has to include a large and complex electronic system, in which the signals are amplified, and down-converted in frequency using local oscillator signals with precisely controlled phases. These signals are input to a digital correlator, which, in view of the large number of baselines, and the high instantaneous bandwidth, will have to be a very powerful and flexible machine.

The detailed design of this system will be an important task for the study and development phase of the project. Much of the preliminary design for the LSA/MMA is already available for reference in MMA reports 190 (System design) and 166 (Correlator design, see also memo 194). The main challenges are the need for a high phase stability at all stages, and the need for accurate operation in total power (autocorrelation mode).

3.4.2 Specifications

- Single dish capability is required for both line and continuum mode
- Minimum integration time in line mode: about 10ms.
- Maximum bandwidth 2 times 8 GHz e.g.:
  - 8 GHz (4 times 2 GHz) times 2 polarisations from one side band of one receiver, which gives two polarizations on a contiguous 8 GHz bandwidth;
  - 4 GHz (2 times 2 GHz) times 2 polarisations times 2 side bands from one receiver. This option leads to the same sensitivity as above, but with a discontinuous band (two 4 GHz bands separated by 8 GHz). This is a limited restriction to continuum studies but is less demanding in terms of receiver performance.
- 8 independent sub-bands of up to 2 GHz each can be observed simultaneously in the 8 GHz total bandwidth, e.g.:
  - 4 sub-bands in both polarisations
  - 8 sub-bands in one polarisation only.
- Minimum number of spectral points 1024, at maximum bandwidth; e.g. 2 MHz channel separation for a single 2 GHz bandwidth (the actual resolution would be $\sim 3-4$ MHz depending on the amount of tapering used to get high dynamic range).

- 4 product pairs (RR. RL, LR. LL) possible for each polarisation. at the expense of spectral resolution channels.
- Maximum baseline length: 30 km.

3.4.3 IF Signal Transmission

We summarise here the design presented in MMA memo 190.

The signals to be processed will come from SIS receivers for the higher operating frequencies and HFET amplifiers for the lower frequencies, the limit being around 100 GHz.

Signals from SIS Receivers

Sideband separating SIS receivers are assumed to provide four outputs: two sidebands for each of the two orthogonal polarisations. The goal for those receivers is to reach 8GHz bandwidth, but it should at first be possible to use 4 GHz from each sideband, with the same sensitivity and total bandwidth.

Signals from the HFET Amplifiers

These amplifiers will operate at larger bandwidths, which will be down-converted by the first LO and second LO (26 GHz) to 4 – 12 GHz band (two polarisations).

Signals Path to the Correlator

Either two (4 – 12 GHz, two polarisation signals) or four (4 – 8GHz, two polarisations times two sidebands) IF signals will be selected from the various receivers by means of switches. In the latter case the LSB signal will be up-converted using a 16GHz LO to 8 – 12GHz and combined to the corresponding LSB signal, to obtain a single 4 – 12GHz band.

The resulting two 4 – 12 GHz signals will be fed into two optical fibres by optical transmitters, towards the central building.

In the central building, each of the 4 – 12 GHz bands will be split into 2 GHz sub-bands, to be down-converted to 2 – 4 GHz bands, by LO's at 8, 10, 12, and 14 GHz. Each of the four correlator inputs will be connected to one of these 2 – 4 GHz bands by means of a switching network (all four inputs may e.g. be connected to the same band).

Each correlator input will incorporate a baseband converter to down-convert part of the 2 – 4 GHz band to baseband. For this a tunable LO will be used ; its frequency range will be 3.2 – 5.2 GHz and it will carry the phase rotation, necessary at this stage since the delay tracking will only be applied digitally in the correlator. For the narrower bandwidths other (fixed) LO's are needed to go to baseband.

Alternate Designs

An alternate solution would be to sample the signals at the antennas and transmit the data in digital form in optical fibres. This possibility is rejected in MMA memo 142 on the basis that commercial fibre digital transmitters can handle around 1 Gbit/s; thus many would be needed to transmit large bandwidths, with high impact on the total cost. Also in the digital transmission solution all the filtering and bandwidth subdivision required for line observations would be located at the antennas; this would not ease the maintenance task. These conclusions should probably be actualised several times until a final decision is made.

An option currently under study (MMA memo 204) is the use of digital filters in the correlator inputs. A single 2GHz filter followed by a programmable digital filter based on a custom chip would replace the base-band converter, thus supressing many analog parts.

Experience with previous interferometers show that single mode fibres seem the only choice for both signal and LO transport. However there is so far no real, on-the-field experience with reconnecting these fibres. as needed for each array reconfiguration. This question clearly needs a careful study.

3.4.4 LO System

The task of this subsystem is to provide the various local oscillators for the front end receivers, but also for the frequency changes needed at several steps along the IF signal path.

In each antenna there should be one first local oscillator for each frequency band; for each band the standard solution is to use multiplier chains from a common $10 - 15$ GHz synthesiser. Because of large multiplication factors the instrumental phase stability is critical. A more innovative system would produce the local oscillators by beating of optical lasers.

Conventional Multiplier Scheme

Here each LO is obtained from the 6th or 8th harmonic of a $10 - 15$ GHz YIG oscillator, which is phase-locked to the corresponding harmonic of a $10-15$ GHz synthesiser (common to all front ends). The reference to this phase-lock loop, transmitted from the central building, carries the phase rotation and phase switches that have to be applied to the first LO's. The phase-locked output ($60 - 90$ or $80 - 120$ GHz is multiplied by the appropriate factor for each front end.

The $10 - 15$ GHz synthesiser uses a set of reference frequencies transmitted from the central building by a dedicated optical fibre. These reference frequencies are also used to obtain the 16 GHz and 26 GHz LO's needed in the signal path at the antenna.

Clearly a round trip phase measurement will be needed to monitor the path-length through the optical fibres. For instance a phase error of 4 degrees corresponds to a path length change of 11μm at 300 GHz, which may be caused by a temperature change of 0.01°C in 10m of optical fibre. Most of the fibre lengths will be buried in the ground, but a few meters will be exposed to this kind of temperature differences in the antenna structures. The round trip measurement can be achieved using two closely located fibres for the signals travelling in opposite directions, or using two optical signals at slightly different wavelengths travelling in the same fibres.

Photonic System

A photonic LO system is also investigated at NRAO as an alternative solution (MMA memo 200). The idea here is to have lasers in the central electronics building, send them through an optical fibre towards the antennas, and use a photo-diode to combine them and produce the LO frequency by beating. This system would be simpler at the antenna than the direct multiplication scheme, and the technology evolves quickly.

3.4.5 Correlator

MMA Design

The design by R. Escoffier (MMA memo 166) concerned 40 antennas, with a maximum bandwidth of 16 GHz for each antenna, obtained by as much of 8 sub-bands of maximum 2 GHz bandwidth. The total number of frequency points is 1024 if the sub-bands have 2 GHz bandwidths, and a single polarisation product (XX) is computed. If two products (XX, YY) are computed, the number of frequency points is 512, and if all four products (XX, YY, XY, YX) are needed, then the number of channels is 256. When the sub-band width is reduced from 2 GHz by a factor of up to 32, the number of channels per sub-band can be increased by a corresponding factor (see MMA memo 194 for details). The resolutions and number of products can be independently chosen for the eight sub-bands, which gives a lot of flexibility. This design has been recently upgraded to 80 antennas.

The sample rate for each of the 8 samplers is 4 Gbits/s; the samples are de-multiplexed by a factor of 32 into 2-bit digital signals at 125 MHz clock rate, and stored into RAMs large enough to accommodate delays of up to 32μs. The custom-designed correlator chips will provide 256 lag products of 4 antennas with 4 others; the chips are located on boards handling the cross-products of 32 antennas; a group of four cards thus handles all products for a fraction of the bandwidth. This setup is chosen to minimise the number of connecting wires between the RAM and the correlator boards.

Other Possible Designs

- In MMA memo 166 this lag correlator design is compared to a FX architecture. The FX correlator would require more complex custom chips, and a much higher number of cables (about 4 times).It is also less well adapted to VLSI architecture than the XF correlator.

- An alternative design for the correlator architecture is based on the idea of a system that accepts the signals from all antennas and redistributes them in a way to put all the signals for one baseline onto one output (cable or fibre) which goes to a correlator unit. The idea is that since each pair of signals to be cross correlated goes on the same line, then the location of their correlator is no longer important and more flexibility results. The one-baseline correlators would need to be realized in a great number of identical units, which could then be economically produced. This carries the difficulty onto the distribution system which would need to distribute the signals at the highest possible frequency (optical); such a system may not be feasible right now, and further technological developments should be followed.

3.4.6 Operating Modes

Phase Switching

Phase switching of the first LO by π is used to take out any offset in the system, in particular offsets due to any asymmetry in the quantisation levels in the samplers; using orthogonal waveforms for the various signals. Phase switching by $\pi/2$ is used to separate the sidebands in the first LO conversion; this is needed to reject signals in the image band by a large factor (30dB) which is useful even though sideband separating mixers will be used to reject the noise from the image side band.

Both phase switchings are to be demodulated at the latest possible stage, usually in software integrators after correlation. The switching will have to take into account the actual delay between the antennas (up to 100 μs), since it cannot be neglected in front of the short integration times (10 ms).

An alternative scheme for sideband separation has been proposed and described in MMA memo 190. Frequency offsets are added to the first and second local oscillators, in order to bring the fringe frequency of the unwanted sideband to an integral multiple of the integration time, while stopping the fringes in the desired sideband.

Total Power Observations

It is foreseen to use continuum detectors in the antennas for fast detection of the continuum total power signals. These should be used for continuum total power observations with very short integration times, in order to enable switching rates fast enough to remove atmospheric noise. It is not clear at this time whether nutating sub-reflectors will be used or if the antennas will be rapidly scanned across the sources as in on-the-fly single-dish mapping.

For line observations the correlators will be used in autocorrelation mode. The integration times will not be as short as in continuum mode but might be as short as a few 10 ms for on-the-fly maps.

Observations with Subarrays

Subarrays will be more important than for other existing interferometers. as they will allow for simultaneous multifrequency observations. or simultaneous phase calibration. Other possible uses include multibeam mapping. and using a subarray as phased array for VLBI (see the MMA memorandum "Astronomical Requirements for the Millimiter Array Correlator" for details). This adds some design constraints in in the correlator architecture.

3.4.7 Conclusion

The detailed design of the LSA/MMA system will be a rather long term effort. While the current, preliminary design leaves no doubt on the feasibility. it is expected than further progress in technology will occur in the next few years, with the consequence that still more efficient solutions could be available. The correlator itself should be built in a modular form, so that it can be delivered in a progressive way, in parallel to the assembly of the array. This will allow an early analysis and debugging of the system and software, as well as scientific operation of the array at intermediate stages.

3.5 Array Configuration

(This section was written/compiled by F. Viallefond, chairman of the Array Configuration Working Group, with input from the WG members)

3.5.1 Introduction

With a collecting area of more than 7000 m^2, the LSA/MMA will have in all cases a large number of elements, the array being either homogeneous or heterogeneous and whatever the diameter(s) of the elements. As a consequence the LSA/MMA will have an excellent instantaneous U,V coverage. At millimeter and sub-millimeter wavelengths, the elevation dependency of the atmospheric opacity implies significant effects in the Fourier plane distribution of weights when using the Earth rotation for the aperture synthesis. Those effects are not especially attractive. This is a current limitation with the existing millimeter arrays which all have a rather small number of elements. The synthesis using the Earth rotation has also drastic effects in the weights for some configuration such as the Y shape of the VLA. With the LSA/MMA the situation is radically different and this has obviously an impact for the array configuration design.

The LSA/MMA will cover a wide range of frequencies from about 70 (or possibly as low as 30) to 850 GHz. Operations in the submillimeter will be possible only a fraction of the year, mostly during the nights in winter.

These two aspects are rather new when compared with the current practice for the arrays in operations. To accomodate the weather conditions, scheduling the observing programs will require a great flexibility. There is some experience with this mode of operation for the IRAM-PdB but in a different context (small number of antennas, reconfigurations tributary of the weather conditions).

The facts that the LSA/MMA will have an excellent instantaneous U,V coverage and that dynamical scheduling will be required have a strong impact on the array configuration. The Array Configuration Working Group is undertaking studies for the LSA/MMA in this context.

3.5.2 The Specifications

The LSA/MMA must be a general purpose instrument requiring good performances for detection experiments, single pointing and wide field (mosaicing) imaging, imaging with low or with high dynamics in spatial frequencies, narrow band spectroscopy or broad band (up to 8 GHz) continuum experiments, experiments in the different atmospheric windows from 70 to 850 GHz eventually at comparable spatial resolutions. All these cannot be met with a single configuration. A set of configurations must be defined to optimize the performances (signal to noise ratio, dynamical range, image fidelity) and the array efficiency to satisfy the various goals in the observing programs.

The LSA/MMA will be an array with movable elements. It must include the most possible compact configuration to optimize the brightness sensitivity for large scale structure and the optimum capabilities for detection experiments. The minimum separation between the antenna depends on the antenna design and should be of the order of 1.3D (Holdaway and Foster, MMA memo 155). The most extended configuration will include baselines up to about 10 km. The zero spacing could be obtained either from autocorrelation measurements using the array elements themselves or with one or a few dedicated large single dishes.

3.5.3 Array Configuration Design Study

Although there is no critical aspects in the array configuration of the LSA/MMA which could compromise the feasability of the project, the array configuration design must be carefully studied, in parallel and close relation with other aspects such as the dynamical scheduling, the observing strategies, the operation efficiency, the costs in infrastructures (e.g. the number of stations required) and equipements (e.g. number of transporters required). Strictly speaking of configurations, various questions are adressed and must be studied:

- Should all configurations contain short baselines?
- What is the tolerable level of overlap between two successive configurations?
- Should all the configurations have approximately the same shape in the Fourier plane distribution of weights e.g. approximately Gaussian or should at least some of the configurations be optimized for uniform distributions (e.g. for astrometric projects).
- For single frequency projects: should the configurations be optimized such that they are essentially complementary (multi-configuration imaging) between each other?
- Should the configurations roughly scale in size with the frequencies of the different atmospheric windows such that e.g. line ratios or spectral index images can be produced over the same range of spatial frequencies?
- Observational strategies related to the U,V coverage:
  - Impact of interlacing the calibration (amplitude, phase and pointing) and the ON source for the U,V coverage. These calibrations could be very frequent, especially at high frequency. If the fast switching technique is used to correct for atmospheric phase errors, as much as 50% of the time could be spend OFF source; this has a significant effect in the U,V coverage, side lobe levels and the amount of deconvolution required.

  - Impact if the U.V plane is undersampled on the capabilities in the image restoration when interlacing different pointings for mosaicing experiments; maximum size of the mosaic; mosaic of mosaics for large surveys etc...
  - Requirements on the quality of the snapshot images to allow self-calibration of the pointing errors during the image reconstruction process
  - On-The-Fly versus pointed observations for the mosaic observations.

- How many configurations are required? This question has been adressed for the MMA (Holdaway, MMA memo 199). There is a trade-off between the operational cost in reconfiguring, the degree of overlap between configurations, the number of stations required per antenna (effect on the infrastructure cost). The number of configurations may range from at least about 4 up to infinity (case when modifying continuously the array).

- When the array is very compact, shadowing, solar illumination and wind load on the antennas must be considered. For the observations of sources far on North or South, avoiding as much as possible shadowing will require several compact configurations. North-South elongations in the distribution of the antennas will probably be conveniently obtained when reconfiguring the array (the hybrid configurations). The number of compact configurations and their characteristics needs to be determined; they depend on several parameters, in particular the antenna diameter(s), and must take into account the difficulty to move these antennas when they are closely packed on the ground.

- Submillimeter observations will probably be mostly performed when the array is not in its most extended configuration. How to best accomodate the one-year cycle for optimum submillimeter atmospheric conditions with the cycle through all the array configurations. This is tributary of the time reconfiguration which is a function of the number of transporters, the manpower etc...

Synthesized Grading Distribution in the Aperture

The properties of Fourier plane distribution are rather well controlled by available algorithms (ref. e.g. Keto, 1997 ApJ 475, 843). The desired distributions depend on the scientific goals for the wide variety of projects which are espected. The total cost of the LSA/MMA is mainly driven to obtain high sensitivity (for single pointing as well as for mosaic observations). This can only be achieved with a large collecting area. The array configurations must be such that tapering the Fourier plane distribution will be avoided and that a very large fraction of the images will be produced with natural weighting. With the LSA/MMA it is possible to almost completely avoid aperture synthesis induced by Earth rotation, at least for the compact and moderately extended configurations; this will help to avoid excessive weights in the shortest baselines for those configurations.

Sub-arrays

For sensitivity reasons operating the array as a set of smaller independent sub-arrays is not desired. However it is most likely that in some circumtances intercorrelation between all the elements will not possible. in particular during the construction phase when the antennas will not be all equiped with the receivers for all bands or. e.g.. for projects to study time variabilities of sources on short time scale at several frequencies simultaneously. The array configuration should a priori not be optimized for sub-array operations.

Short Spacings

The limitation due to missing short spacings and zero spacing has to be studied. For a homogeneous array, larger the antenna diameter larger the central hole in the U,V coverage. The response of the array to extended structure is strongly dependent of this effect. One possible solution is to consider the case of a heterogeneous array such that the original specifications on the short baselines which were set for the MMA can be preserved for the LSA/MMA. The heterogeneous array option is under investigation to determine parameters such as the fraction of the total collecting area which must be put in small antennas and the relative configurations for the small and the large antennas. For heterogeneous arrays there is an additional degree of freedom which can help in setting the desired distribution of weights. The zero spacing can be obtained with autocorrelation measurements either using focal plane arrays on a few large dedicated large single dishes or using the array elements themselves. Simulations are undertaken and will give the respective merits of the homogeneous versus the heterogeneous concept.

Inter-relation between the different types of brightness distributions to image, the different signal processing techniques and the array configuration

There is a tight link between the array configuration aspects, the observing procedures, the real-time and the post-observational error correction methods, the deconvolution procedures and the types of brightness distributions to image.

There is already significant experience with existing algorithms such as CLEAN or MEM. These algorithms have been improved during the current decade to include multi-resolutions, multi-fields and multi-frequencies characteristics. These algorithms must be extensively analysed making simulations in the specific context of the LSA/MMA. Less experimented algorithms such as WIPE (Lannes et al., Jour. of modern optics, 1994, 41 No 8 1537) will also be tested. For the LSA/MMA configurations which are not very extended and for single pointing observations Fourier components will be missing only in the central part; aliasing caused by the gridding will be less severe compared to Y or T shape arrays. This opens ways for fast and efficient algorithms to produce images. However this advantage will be counterbalanced by the complications to correct for atmospheric phase errors and pointing errors. There is only limited experience in this area and some innovating algorithms need to be developped. They may have impacts on defining the different array configurations. Although there is no conceptual difficulties to produce images with heterogeneous arrays (the mosaicing algorithm can be used with only minor modifications for some of the possible array configurations which are considered), new techniques need to be developped to fully exploit the multi-resolution aspect in the direct measurements. Those are tightly related with the properties of the array configuration. Simulations are also required in this area.

Topography and site characteristics

Obviously the array configuration study will include the constrains from the site of Chajnantor. The site is such that it is not expected to affect the feasability for the various configurations which are under consideration to meet the scientific goals of the LSA/MMA. The exact locations of the stations to be build will be studied based on the topography (MMA memo 160).

3.5.4 Conclusion

The array configuration study includes new aspcets which are specific to the LSA/MMA. A number of questions are adressed but there will be no single simple answer because the array will need to be able to image a wide variety of brightness distributions from the small compact structures to study the formation and the evolutions of galaxies and quasars to extended structures e.g. to study comets. About the extended structures, the various possible options to measure the short and zero spacings need to be investigated and compared. The array configuration design is tightly related with the observing procedures and the algorithms of deconvolution. One of the important tasks is to find methods to correct for pointing errors during the image synthesis. Most of the Array Configuration study will be performed by simulations to cover the possible designs for the locations of the antennas, the various expected instrumental errors such as the pointing errors and the different families of brightness distributions to be expected.

3.6 Calibration

(This section was written/compiled by P. Schilke, chairman of the Calibration Working Group, with input from the WG members)

3.6.1 Introduction

This section investigates the feasibility of achieving the goal of high resolution, high dynamic range imaging with the LSA/MMA interferometer for a significant fraction of the observing time. This report has benefited significantly from MMA memo 144, the report of the US Phase Calibration Working group. It emphasizes topics either not covered by MMA memo 144 (because of the more limited scope of Phase Calibration) and new developments.

Like the US report, we focus on two basic solutions for phase corrections, various variants of Radiometric Phase Correction (RPC) and Fast Phase Calibration (FPC) which are the only ones we feel are of general use. Both techniques are now being tested on various existing arrays and the results from these tests will help us decide which method (or combination of methods) is best suited for the tasks.

A proposed alternative of sub-arrays may be a good solution for dedicated problems, but is less general. One technique mentioned in the US report, the atmospheric monitoring array, can be discarded now, based on experiments in Nobeyama.

To summarize our results, we are confident that the goals are achievable. Although none of the techniques discussed here has been very thoroughly tested yet, none of them is entirely new and the preliminary results are very promising.

3.6.2 Phase and Amplitude Requirements

Description

The LSA/MMA interferometer will be a significant improvement in sensitivity and image quality with respect to current arrays. While the higher sensitivity is relatively easy to achieve (just by having a large collecting area), the high image quality does not come for free. New techniques have to be developed to get the actual performance of the array as close to the theoretical one as possible. Apart from design choices, the main problem is controlling the influence of the atmosphere. Atmospheric fluctuations decorrelate the signal, resulting in loss in flux and resolution of the image, if not corrected. Self-calibration is a highly successful technique at centimeter wavelengths, but at millimeter and sub-millimeter wavelengths it is useable only for a very limited number of sources, so other techniques have to be found.

The first problem is trying to understand the atmospheric fluctuations, their magnitude, temporal and spatial scales in order to determine on which timescale corrections are necessary on which baselines. One method (RPC) uses power differences in a receiver to determine the phase fluctuations, hence the relationship between phase fluctuations and changes in the sky brightness temperature has to be well understood. Last but not least amplitude calibration requires a good determination of the system temperature, which in turn benefits from an accurate atmospheric model.

Phase Noise Goals

Taken from MMA report 144, the following table gives the phase noise goals required at 300 GHz on timescale from 1 to 100 seconds in order to be able to image with a high dynamic range and/or at high frequencies. Atmospheric and antenna phase noises scale linearly with frequency. One expects that electronics noise would be nearly constant in phase.

Phase noise and related decorrelation at 300 GHz (MMA report 144)

Conditions	Remaining Amplitude (%)	Atmosphere rms	Antenna rms	Electronics rms
Best	98 %	6°=17 μm	5°=14 μm	3°=7 μm
Median	90 %	14°=38 μm	11°=31 μm	6°=17 μm
80th%	50 %	36°=100 μm	28°=79 μm	14°=38 μm

Note to table: values are antenna based, decorrelation is given by $\exp(-(\Sigma(\mathrm{rms})^2))$.
Column 3: required for imaging capability.
Columns 4,5: needed, instrumental noise needs to be negligible compared to the site quality.

Without atmospheric phase correction or improved mapping algorithms the projected fraction of time available for 0.1″ imaging is only 4% at Cerro Chajnantor (5000 m), Chile.

The instrumental phase goals are quite realistic, since many of them are already achieved in current mm arrays at 230 GHz (*e.g.* the IRAM interferometer). The atmospheric phase goals will be adressed in the sections 3.6.4 to 3.6.7.

Amplitude Goals

High dynamic range imaging also requires accurate amplitude information. On the timescale of a cycle of integrations (a few minutes), the total stability required on the system temperature $\Delta T_{\rm sys}/\langle T_{\rm sys}\rangle$ and antenna gain is about 2%. This stability should not be limited by the receiver gain stability ($\ll 1\%$). Accurate pointing and focus stability should ensure that the antenna gain remains constant within that level. The most difficult part may be predicting the system temperature to the required accuracy, despite the elevation dependence. Current instruments reach such values at the lowest frequencies

(100 to 250 GHz). Improvement in atmospheric modelling (see next section) give some confidence that such an accuracy can be reached at submm wavelengths as well.

3.6.3 Atmospheric Models

Description

To simultaneously study atmospheric gas absorption, refraction and phase delay we need the refractive index as a function of frequency [$n(\nu)=n^r(\nu)+i\ n^i(\nu)$]. We can define a complex refractivity in units of parts per million: $N=(n-1)\cdot 10^6=N^r+iN^i$. Its real part N^r is responsible for slowing the speed of light (refraction effect) and rotating the wave's phase. The imaginary part accounts for absorption.

Imaginary part of the refractivity: absorption. For frequencies up to 1 THz the atmospheric absorption spectrum in clear sky conditions is mostly due to $H_2^{16}O$ (resonant part due to E1 transitions) and $^{16}O_2$ (resonnant part due to M1 transitions). Other minor atmospheric gases have rotational lines that show a not negligeable effect on millimetric and submillimetric atmospheric transmission for high altitude sites. FTS measurements confirm that $^{16}O_3$, HDO, $H_2^{18}O$, $^{16}O^{18}O$. and ν_2-$H_2^{16}O$ should be taken into account. The resonant absorption by $H_2^{16}O$ does not account for all the absorption of a (to some degree) humid atmosphere. This excess of absorption is usually called the water vapor continuum (N^i_{cont,H_2O}). One explanation for it is the contribution of the far wings of many far infrared water vapor lines, but usually an empirical description is introduced in the models. There is also a dry air nonresonant absorption (N^i_{dry}) due to the Debye spectrum of O_2 below 10 GHz and pressure-induced nitrogen absorption.

Real part of the refractivity: Phase dispersion. The real part of the refractivity has nondispersive (independent of frequency) and nonresonant but frequency dependent contributions due to dry air and water vapor. The most important part is however resonant dispersion by $H_2^{16}O$ and $^{16}O_2$.

State of the Art

The recent results described below are very promising. Even if more tests and studies are needed, they show that the current knowledge of the atmosphere (even for the high frequency windows) will allow proper calibration of sub-mm data.

Software. A software package called ATM (Atmospheric Transmission at Microwaves) has been already developed by J.R. Pardo and J. Cernicharo. It contains the most updated models for resonant absorption and phase dispersion by $H_2^{16}O$ and $^{16}O_2$ as well as continuum terms. All important minor atmospheric gases for ground-based submillimeter astronomy have been included and an extensive set of standard atmospheres has been taken into account. It is also possible to introduce other atmospheric profiles easily (useful for analysis of site-testing data). Details are given in the Ph.D. thesis of J.Pardo.

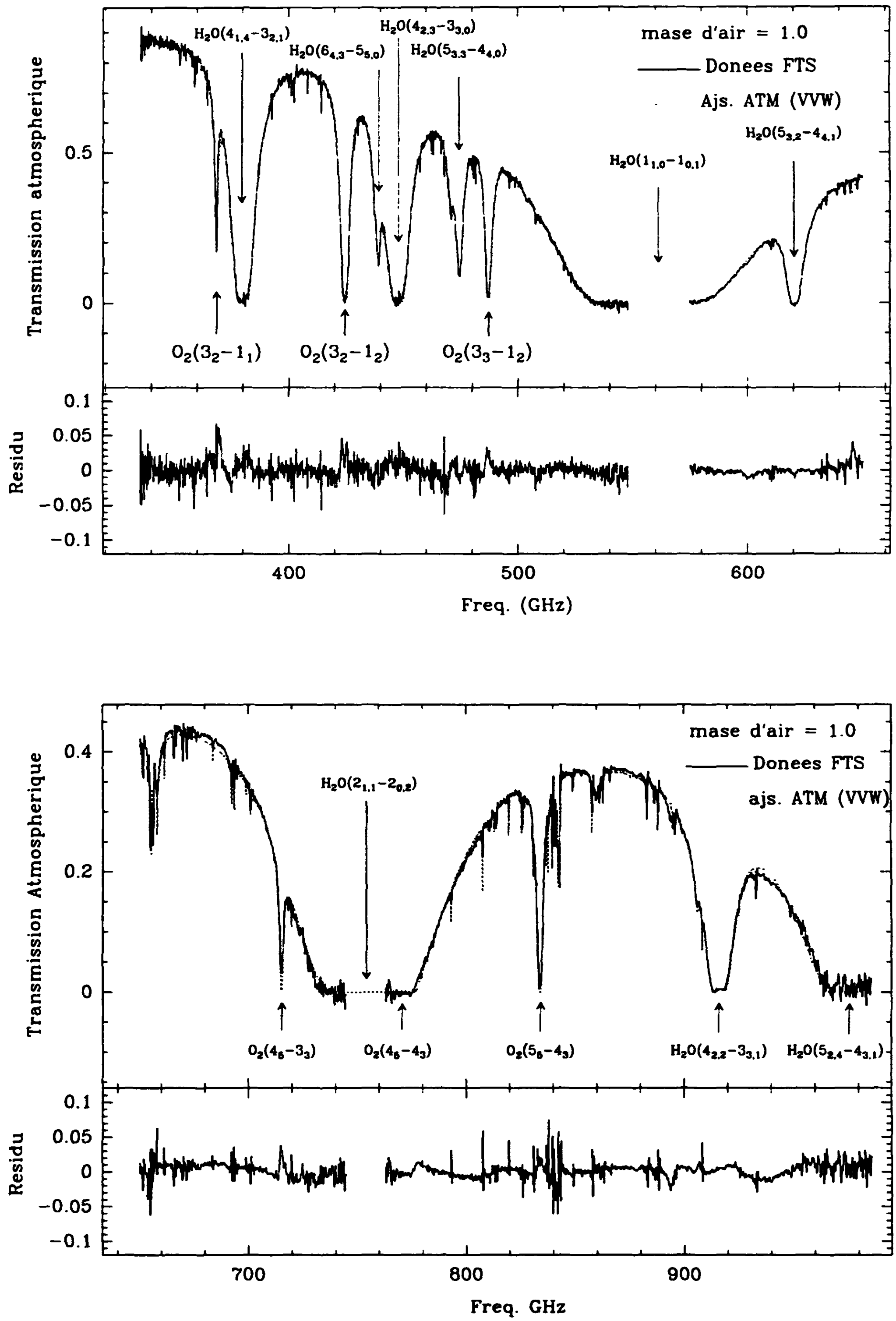

Figure 3.6.1: Results of FTS measurements on Mauna Kea, with atmospheric fits (Serabyn & Pardo, in prep.). Note the small residuals.

Validation. J.R. Pardo is working in collaboration with Gene Serabyn (CSO) on the CSO-FTS experiment. Fitting of the first data show promising results on the understanding of atmospheric transmission at the submillimeter windows. Fit accuracy of about 1% over the whole submillimeter windows has already been obtained with few fit parameters (see Fig. 3.6.1).

Japanese FTS measurements have been conducted on Pampa la Bola, adjacent to the Chajnantor site. They cover the range from 100-1000 GHz with 10 GHz resolution. The measurements have been performed in September 1997 and seem to agree well with atmospheric models, although there appear to be some differences to Mauna Kea. More measurements are planned in summer and a more sophisticated data analysis is warranted, which will lead to a better understanding of the atmospheric conditions in Chile.

The results from the atmospheric models indicate that the output from three tipper meters (instead of a single 225 GHz radiometer as used in many observatories) should be used to determine the atmospheric opacities, but that then the results will be very accurate.

The Chajnantor site's altitude and low humidity do not exclude the passage of clouds. In June 1997, a surveillance camera was installed by the NRAO team on their test container. From June 1997 to March 1998, about 145 out of 200 days show traces of clouds on at least one of the photos (mostly cirrus, but also cumulus, especially on summer afternoons. A closed cloud cover is rare). This indicates that an atmospheric phase correction method should be able to correct for thin water-bearing clouds. Ice clouds do not hinder the observations up to 1 THz.

Analysis of Chajnantor phase monitor data. NRAO site testing equipment at Cerro Chajnantor includes an interferometer with 300 m baseline observing an 11.198 GHz satellite beacon since May 1995. Compared to the 8 km distant Pampa la Bola site monitored by NRO since July 1996, Chajnantor's median phase seems to be slightly more stable due to an unimpeded western direction but basically the sites are comparable. The 50% quartile of the path r.m.s. over 10 minutes shows diurnal and seasonal (winter $\approx$ 150μm r.m.s., summer $\approx$ 350μm r.m.s.) variations, and depends also on the wind direction due to the turbulent wakes of the surrounding montains. Simultaneously recorded phase fluctuations on both sites, however, can vary by as much as a factor of 10 between the sites (MMA memo 176). It is therefore likely that phase stability will vary notably over the extent of the future LSA/MMA due to topological effects.

3.6.4 Radiometric Phase Correction (RPC)

RPC uses continuous monitoring of the atmospheric emission at one or several wavelengths along, or nearly along, the line of sight to determine the changes of the atmospheric path delay. The method is based on the well founded assumption that the source of phase fluctuations in the atmosphere is the fluctuating amount of water vapor in the troposphere, and that the fluctuations can be monitored as fluctuations of the atmospheric emission line. There are two variants of this method: total power monitoring at some frequency, and monitoring of water emission lines at either 22 GHz or 183 GHz. The emission line methods observe several (typically three) bands and can therefore both subtract baselines (in this context total power fluctuations arising from varing ground pickup etc.) and circumvent the potential saturation problems arising in the 183 GHz lines. The 22 GHz method is better suited for dealing with the effects of clouds. However, since we don't expect cloud coverage to be an major issue at Chajnantor, this advantage does not have a heavy weight.

All of these methods are currently being used or being developed, so that it can be hoped that on the timescale of one or a few years the usefulness of each method will be demonstrated. We felt that the emission line methods are intrinsically superior to the total power methods, because one can hope to achieve a continuity between calibrator and astronomical source. This is not possible using total power methods, mostly because of varying ground pickup between calibrator and source, which are typically at different elevations. The ultimate choice between 22 or 183 GHz line for the LSA/MMA remains to be decided by the tests. However, in view of the limitations of the 22 GHz sounding (sensitivity and potential interference), we recommend to actively pursue the developments of the 183 GHz technique.

Note that the RPC accuracy is limited by two factors: a constant term due to the receiver stability, and a term proportional to the initial phase noise, due to the accuracy of the prediction method. The stability of current systems is already close to the design goal for the LSA/MMA, but further improvements in the prediction techniques are required.

230 GHz Total Power Monitoring

Since 1996, IRAM uses the total power signal of the 210-240 GHz receivers for clear sky atmospheric phase correction on the Plateau de Bure Interferometer (PdBI). Using an atmospheric model, the phase shifts are calculated from the calibrated total power fluctuations and applied every second with a precision varying between 7 and 30% (depending on weather conditions). Spectral data are typically integrated over 60 seconds and stored in two versions for more security, one with phase correction applied, one without. This is necessary to avoid data loss in the presence of wet clouds along the line of sight, which cause an overestimation of the modelled phase. During data reduction, it is possible to choose freely between the two sets.

Typical baseline-based corrected optical path rms values are $\approx 100\mu$m, with best results of order 70μm, i.e. already close to the LSA/MMA goals. Drawbacks of the current system are total power jumps during elevation changes due to ground pickup, receiver gain fluctuations and instabilities of the calibration loads. This makes it impossible to track the corrected phase reliably during source changes, so that one uses the improvements in decorrelation time for the integrated amplitude but keeps the uncorrected phase for mapping.

Similar experiments are now starting at NRO, using dedicated 220 GHz radiometers. Differential outputs of the radiometers installed on two antennas (distance = about 100 m) were compared with phase fluctuations measured with the NMA (frequency = 86 GHz). Initial results show a decrease from 70 degrees phase noise down to 35 degrees, or about 300 μm path length).

22 GHz Radiometer

Tests of the 22 GHz radiometer system are under way at OVRO and the first results are very promising: the phase noise could be reduced by $\approx$ 50%, even under cloudy conditions (Woody et al., in prep.). ATCA also plans to use this system. The most interesting aspect of 22 GHz sounding is the possibility to reject cloud contribution, but as already mentioned, this is probably not very important for the Chajnantor site.

At IRAM, a 22 GHz radiometer is still in the planning phase. Simulations indicate that three bands will be necessary to reject clouds, receiver noise and ground pickup. For the design goal of phase correction with 70 μm path rms (for a maximum observing frequency of 350 GHz), it seems not feasible to stay within the protected bands at 21.2-21.4, 22.21-22.5 and 23.6-24.0 GHz (WRC-95). Most of the commercial allocations are not in use yet, but include terrestial radio links, satellite-earth and inter-satellite communication. IRAM hopes to avoid contamination most of the time due to the small beam of the 15m reflectors. Significant improvements in accuracy would be difficult, and the threat of interference is increasing every day.

183 GHz Radiometers

Two uncooled radiometers (T_{sys} = 2500 K) measuring the rotational transition of water vapor at 183 GHz have been build for the CSO-JCMT interferometer. The main advantage of this line is that it is very strong: the brightness temperature changes by approximately 20 K for each millimeter of extra optical path (c.f. at 22 GHz 0.4 K/mm, at 220 GHz 2 K/mm). Disadvantages are that the center of the line saturates at 2 mm of water vapour, a drawback for most current arrays but not for the LSA/MMA site, and that the conversion factor is a function of the amount of underlying water vapor, i.e. more complicated computation is needed.

The radiometers measure the emission in 3 channels 1.2 GHz, 4.2 GHz and 7.8 GHz away from the line center, at least the outer two channels will always be unsaturated at a site such as Cerro Chajnantor. Some test data have been taken with the 183 GHz radiometers on the JCMT-CSO interferometer. Preliminary data analysis shows that the rms phase of the interferometer at 340 GHz could be reduced from 47° to 27° in a 36 minute time interval, which eliminates 60% of the phase noise. The stability is thus already sufficient for the LSA/MMA goals, but the accuracy of the correction is not yet established. More advanced data analysis using Pardo's atmospheric models should lead to even better results.

Use of Astronomical Receivers Instead of Dedicated Radiometers

Alternatively to building dedicated radiometers one could also use the astronomical receivers of the LSA/MMA – it has been suggested that two receivers cover the frequency of the 183 GHz line, so that one of them is always available for sounding. This has the advantage that the system temperature will be much lower and integration times could be even shorter. However, the astronomical receivers would need to be adapted for this task. In particular, it would be necessary to operate the LSA/MMA with two receivers simultaneously (although the pointing directions can be different). This thereby implies two local oscillators working simultaneously, in the same dewar. The sounding receiver would also need to be connected to a special backend, and may require a specific calibration system for very frequent calibration. In view of these inconveniences, our feeling is that dedicated radiometers are the simpler and cheaper solution.

Possible Tests

It is envisaged to test the 183 GHz radiometers further in order to rigorously evaluate their performance and also to compare them to other calibration methods. At the moment there are three different suggestions for further test. Firstly, two 183 GHz radiometers could be installed at the IRAM interferometer. This would yield much more test data. (The CSO and JCMT are only operated in interferometric mode for about 12 nights each year, while the IRAM site offers low (< 1.5 mm) water vapor more frequently during the winter period). It will also allow comparison between the performance of the 183 GHz radiometers and the 220 GHz total power method at IRAM. Secondly, the two existing radiometers could temporarily be set up next to the 12 GHz phase monitors on Mauna Kea. This experiment would show to what accuracy the radiometers could predict the phase at 12 GHz. A similar experiment could be conducted at Cerro Chajnantor. In this case power supplies, a computer system and some weather protection would need to be added to the 183 GHz radiometer. In this case no extrapolation of the performance under different weather conditions would be needed.

3.6.5 Fast Phase Calibration

The basic idea of Fast Phase Calibration (FPC) is to "freeze" the atmospheric turbulence by using a short enough calibration cycle (10 to 20 sec). In the simple concept of a frozen phase screen moving in front of the array, the phase noise residual after calibration correspond to the phase structure function on spatial scales less than $vt/2 + d$ where v is the wind velocity aloft, t the cycle time scale, and d the distance between the source and calibrators at the height of the phase screen. FPC corrects the phase for baseline lengths longer than $vt/2 + d$. With median wind speeds 6 m/s, mean distance between source and calibrator 2°, an atmospheric scale height of 2 km for the water vapor, and a cycle time of 20 sec, this scale length is 120 m.

FPC is a very simple method, requiring no special computations. The Nobeyama group has evaluated the performance of FPC using numerical simulations for various switching cycle time (Asaki et al, in preparation). The preliminary results showed that the switching cycle time of 10 - 20 sec is desirable in order to obtain rms path error less than 0.1 mm after the correction. The efficiency of FPC has also been demonstrated using the VLA at lower frequencies, using baselines longer than 400 m with a cycle time of 80 sec.

It has however some serious drawbacks. First. the need for short calibration cycles requires very fast switching times for the antennas for distances of a few degrees (< 3 sec). Second. the distance between source and calibrator should not exceed 2 to 3 degrees. Third. the system sensitivity in $\simeq$ 3 sec (for a cycle time of 12 sec) should be high enough to measure the calibrator phase with sufficient accuracy. This requires good sensitivity. Fourth, FPC requires to be able to switch from one receiver to another in $\approx$ 2 sec. This has some direct consequences in the design of the local oscillator system and correlator. Last, but not least, FPC strongly reduces the observing efficiency, since the true observing time could be as low as 1/4 of the elapsed time.

Given that calibrator flux densities decreases with frequency, FPC will require calibration at the lower frequencies, e.g. 90 GHz. The rms path error due to thermal noise is given by

$$\frac{S/KT_{sys}}{\sqrt{2B\tau}}\frac{\sqrt{N-1}}{N}\frac{c}{S_\nu 2\pi\nu} \tag{2}$$

Using $T_{sys} = 60$ K at $\nu = 90$ GHz, B = 4 GHz. $\tau = 3$ sec and $N = 64$ antennas of 12 m ($S/K = 30$ Jy/K), we obtain 8 μm for a calibrator flux $S_\nu = 100$ mJy.

Since the mean distance between sources and a 100 mJy calibrator at 90 GHz is about 2 degrees (see Sec. 3.6.8), FPC will be sufficient to match the median goal for most sources. Better results could be obtained for sources closer to a calibrator.

One of the most interesting aspect is combining FPC with RPC. RPC is inherently more accurate on timescales of e.g. 30 sec to 1 min than on longer timescales. A calibration cycle with 30 sec integration on the calibrator, 3 sec slew time, 60 sec on source and 3 sec slew time, would "freeze" the atmosphere between source and calibrator, allow the use of weaker (and thus closer) calibrators, while bringing the observing efficiency to a higher value.

3.6.6 Sub-arrays

In this calibration scheme, the antennas are distributed in clusters of two or more antennas. One of the antennas observes the calibrator, the other(s) observe the astronomical source. The calibrator antenna supplies the phase correction for the others in the cluster. This method shares some of the problems of FPC: depending on the offset between calibrator and source, there may be a time delay for fluctuations to arise along the line of sight to each object. The requirements for finding a calibrator within a given distance become even more stringent than for FPC, because only a sub-array of the antenna (with correspondingly less sensitivity) is observing the calibrator, hence it needs to be stronger. There is also a loss of collecting area for the science and, if the clusters are large, the number of effective baselines. The advantage over FPC is that the antennas don't have to be moved so rapidly and so often. We feel that, although this may be the method of choice for some special projects, it does not have the generality of RPC and FPC.

3.6.7 Atmospheric Monitoring Array

This proposal wanted to use a dedicated array to measure the atmospheric phase screen over the whole sky and apply the phase correction to the LSA/MMA antennas. The phase screen would be monitored by observing a strong astronomical point source or a satellite transmitter. Tests in Nobeyama have shown that phase correlation between two sources vanishes rapidly if the distance is larger than 5° or so, so this method does not work and can be discarded from the discussion (Asaki et al. 1996, 1997).

3.6.8 Finding and Monitoring Calibrators

Calibrators are needed to monitor the amplitude and the phase. FPC requires a relatively strong calibrator as close as possible from the source. Standard amplitude and phase calibrations also need a nearby calibrator. Regular monitoring of a few strong calibrators is necessary to determine the absolute flux scale.

Recently, the catalogue of Patnaik et al. was surveyed at 3mm with the IRAM interferometer (Neri and Wink 1998, LSA report, in prep.). At 3mm, the mean distance between source and calibrator stronger than 100 mJy is about $\sim 2°$. This result is more pessimistic than previous work (MMA memo 124) which predicts that the MMA will have a 100 mJy calibrator within 2° 70% of the time. Estimates of the calibrator density available at high frequencies need to be performed. Patnaik and collaborators have started a deep bolometric survey at 1.3mm with the IRAM 30-m telescope. Surveys performed with SCUBA (JCMT) in the submillimeter range would help to extrapolate spectral indexes of calibrators. Searching for southern sources would also be useful using instruments like ATCA or SEST. Finally a non negligible part of this work can be achieved by the LSA/MMA itself. The full array (64 antennas working) will take at least 5 or 6 years to be fully operating. Surveys of calibrators (including blind surveys) can be achieved during this construction period to accurately measure the coordinates and estimate flux densities. For the LSA/MMA, the time spent to find calibrators at the beginning of each run should be negligible compared to the total integration time which will be of order 1-2 hours or less for many projects. Based on the information available now, it is conceivable that the spatial density of available of calibrators is high enough to use standard calibration methods. In the few cases where usage of the FPC may require blind searches near the source location, sensitivity will not be an issue, but short integration times (25–50 msec) are required to keep the searching time reasonable.

3.6.9 Single-dish Observations

Single-dish observations are required in the calibration process to bootstrap flux densities from primary calibrators (mostly planets, specially at the sub-mm wavelengths) to secondary calibrators (strong quasars. or other compact enough sources such as giant stars). Such a mode will also be needed to recover short spacings. It will be necessary to remove atmospheric total power fluctuations to detect the continuum sources in total power mode. This imposes either a chopping secondary, or a fast drift mode (with accurate tracking). Drift speed of order 10 to 20 arcmin/sec are required in the latter case. For calibration needs only, the choice can be left to the antenna design group. However, astronomical continuum observations may impose more severe constraints. Experts assert that, although it may in principle be possible to do without a chopping secondary if the atmosphere is under control. this is completely untested and current methods do require a chopping secondary (R. Zylka, priv. comm.).

3.6.10 Conclusion

The current results from radiometers and atmospheric models clearly show that the phase and amplitude specification required for LSA/MMA can be achieved. We are confident that the goals are achievable. It is likely that a combination of RPC and FPC methods will be required to reach the full potential. Further tests performed in the coming years will help selecting the final strategies. Based on our current understanding, we recommend to investigate strong efforts in the RPC technique at 183 GHz. The antenna, receiver, LO and correlator design should preserve the capability of switching quickly ($\sim$ 3 sec) from source to calibrator, but there are no special sensitivity requirements imposed by FPC.

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3.7 LSA/MMA Software

(This section was written/compiled by S. Guilloteau, chairman of the Software Working Group, with input from the WG members)

3.7.1 Real Time Software

The real time software includes a number of components: 1) antenna control, 2) receiver tuning and LO settings, 3) correlator control, and 4) general synchronisation and 5) data transfer from the correlator to a general computer system. Europe has been operating a number of cm and mm wave interferometers since many years, providing sufficient experience for each of theses aspects. The LSA/MMA specification introduces a number of novelties, however. The two most stringent ones are the very short setup times required by Fast Phase Calibration (FPC) and the much higher data rates.

FPC requires very short setup times for the whole system. Ideally, one would like the whole array to switch from a source to a calibrator, reset the correlator modes, switch the LO system from one receiver to another in less than 3 sec. The main difficulty certainly resides in the antenna tracking system, but the whole array timing should consider this problem from the beginning. In all mm-arrays, antenna pointing & tracking, and sometimes even receiver control, is performed locally by a micro-computer on board the antenna, connected through a network to a central computer. Extension of this technique to large number of antennas is relatively straightforward, even though the short setup times will require a more stringent timing control.

Because of the large number of spectral channels (of order 4000 per baseline) and baselines (2016), each visibility data point is equivalent to 63 MBytes of data. FPC requires cycle times of 10 to 20 sec, during which at least 2 visibilities are produced. Hence, without any specific processing, each hour of observation would yield about 25 Gbytes of data. Such large data sets could already be handled with current computers, though not conveniently, but on-going progress in computer technologies in the next 10 years will help considerably. Significantly larger data sets could in principle be produced in special observing modes, such as mosaics, or for the longest baselines.

However, the astronomically useful information is only a small fraction of the raw data set. For example, spectral line observations hardly ever have more than 100 significant channels. Continuum observations only represent one. Similarly, the whole calibrator data can be reduced to one complex gain per antenna per calibration cycle. The correlator software should be build to provide such data compression whenever possible. It may however be difficult for the standard user to specify *a priori* the correlator output. A good example is line contamination in the continuum emission from dust in circumstellar envelopes or star formation regions like Orion. The construction of a flexible "data compression" tool appears to be a necessary step in the LSA/MMA software. This software package should operate as a pipeline between the real-time data acquisition system and the archiving system. In the peculiar cases when the parameters for the compression are not known. it is unclear whether "raw" data should be archived.

Real-time software development should be done in close coupling with the associated hardware components (antennas, correlators, system aspects), but with tight interactions with astronomers.

3.7.2 Array Scheduling and Monitoring

Contrary to cm arrays, the high frequency bands observed with the LSA/MMA will require weather dependent scheduling. The IRAM interferometer has been scheduled according to weather circumstances since 1990. This relied on operator and on-duty astronomer expertise. However, the LSA/MMA will be a much faster instrument, handling many more projects than the current IRAM array. An efficient scheduling software should thus be build-in the array operation. The necessary weather informations (wind speed, atmospheric transparency, phase stability and equivalent seeing) should be provided by a dedicated monitoring sub-system, plus by feedback from the latest (or even on-going) observations.

ESO is currently developing such a system for the VLT. The peculiarities of the mm versus optical domains will have to be adressed, but similar software tools could probably be applied.

3.7.3 Data Archiving

The evolution of mm interferometers has been so important in the last 10 years, and the data throughput so small, that data archiving never was a serious issue. Because it will not be superseded for decades, the LSA/MMA will present a major change in this respect. Archiving of the LSA/MMA data should thus be considered as an integral part of the project. ESO has strong experience in data archiving. The concepts developed for the VLT project could certainly be expanded for the LSA/MMA. The volume of "raw" data in the LSA/MMA will be extremely large: a clear definition of the LSA/MMA data product will thus be necessary to avoid duplicating data analysis after archiving. The transfer of the data from the LSA/MMA to a central archive will most likely involve tape handling, because transferring through a telecommunication system would be too expensive.

Investigation in cheap computer technologies for the archiving and real time processing are important to minimize the cost of the LSA/MMA project. However, it should be kept in mind that the LSA/MMA will need several years to reach its full capacities. The computer technology will keep improving during these years. To minimize the final costs, it will be important to design the LSA/MMA computer system in a modular, expendable, way and to avoid over-specifications in the initial startup phase.

A further problem to be adressed is the data format for the archive. FITS has been the traditional format for astronomical data in the last years. However, the lack of hierarchical keywords in FITS may become a problem for a large and complex archive like needed for the LSA/MMA. This problem, if real, is certainly not insuperable, but should be adressed relatively early in the LSA/MMA software development, given the rather long time scales involved in the FITS standard. ESO is currently using hierarchical keywords, and will continue using them for the VLT Science archive.

3.7.4 Data Reduction and Analysis

Aperture synthesis is now a standard technique, even at millimeter wavelengths. Appropriate data reduction packages with particular emphasis on the spectral line aspects have been developed in Grenoble (GILDAS software, Obs. Grenoble & IRAM) and in the Netherlands (GIPSY software). Netherlands is participating to the AIPS++ consortium, which is currently developing a new software for aperture synthesis and single-dish data processing. The first release of the AIPS++ software suite is scheduled for 1998. Although not directly related to aperture synthesis, ESO also has strong experience with a large processing package with the MIDAS system.

Accordingly, preparing a data reduction software for the LSA/MMA is a feasible task. However, one of the important goals of the LSA/MMA is to be accessible and usable by the whole astronomy community, regardless of its experience in mm astronomy and/or aperture synthesis. A second measure of success is the possibility to perform observations at the limit of the instrument. This may require a two-level software organisation, with "black-box" tools for standard processing, and a more flexible "tool-box" system for advanced users. To further simplify the use of the LSA/MMA, it could be desirable that the "black-box" tools share a common user interface with that of other ESO instruments.

To reach the ultimate capabilities of the LSA/MMA, the advanced "tool-box" requires a number of new imaging techniques which are either poorly developped or even totally inexistant so far. Among these, mosaic processing is probably the domain in which further progress is most desirable. Basic algorithms do exist, but a number of improvements is still possible, e.g. by using multi-resolution techniques (either for speed of better dynamic range), in the handling of pointing errors (removal of linear drifts, possible self-calibration), etc... Another domain will be high fidelity imaging. While current arrays are mostly signal to noise limited, the LSA should be able to produce high dynamic range images. New methods such as the WIPE algorithm (Obs. Toulouse) are promising steps, but need further development. Another major area where further developments are required is the general problem of short spacings, i.e. total power measurements to be combined with interferometric data.

3.7.5 Manpower and Organisation

A strong deviation from existing arrays and even from current ESO experience will be the multi-national aspect of the project. While software for most existing telescopes have usually been developed within a single institute, the LSA/MMA software will have to be developed in a distributed manner. This will add some management layers, but is unavoidable considering the amount of software required.

Experience with distributed software development has been obtained in the AIPS++ project. A thorough analysis of the AIPS++ experience would certainly be beneficial in defining the organisation for the LSA/MMA software. Object oriented programming has also been used by ESO the the VLT data flow system, providing further experience in large, distributed software projects.

In view of the partnership with NRAO, it will also be an urgent task to define the global software management, and to setup proper standards for the developments. For example, in real-time software, the choice of the real-time operating system and development platform may have a significant impact on costs and maintainability. ESO has so far been using VXWorks, while IRAM uses OS-9, but the recent progress on real-time Linux may be worth investigating in view of the large number of licenses required (> 300). Similarly, although VME has been bus of choice for most recent instruments, one should investigate more widely distributed PC-based buses. Although this is at variant from the current experience, the potential savings are worth investigating.

3.7.6 Conclusion

Europe has long experience in successfully operating synthesis arrays. Although the LSA/MMA represents a large step in e.g. number of antennas and data throughput, the basic principles remains identical, and techniques applied for Westerbork or the IRAM arrays can be expanded.

Progress in computer technology will allow management of the huge data rate of the LSA/MMA at a reasonable price: extrapolation of the computer power evolution in the next ten years (64 bit processors, cheap data storage, network performances) bring the analysis of a standard project into the desktop computer class, while larger projects could be managed through a fast network.

The major costs in the LSA/MMA software will actually be manpower, but the large number of micro-processors involved in the array operation may justify economic approaches in the selection of the real-time systems.

3.8 Facilities and Operations

The LSA/MMA infrastructure in Chile will include limited facilities on the 5000m array site, an Operations Support Base (OSB) in San Pedro de Atacama, and a small business office near the port facilities in Antofagasta. Of course, it will also make use of the ESO guesthouse and Vitacura office in Santiago.

3.8.1 On-Site Facilities

Only essential facilities will be located at the 5000m telescope site. These will include buildings to house the electronics systems common to the array, such as the local oscillator system, the IF control circuitry, the correlator, and a small laboratory with test equipment. There will be a basic control building, to be used especially during the construction and testing phase, and a small lounge and kitchenette. There will be storage for emergency medical supplies. There will also be an antenna erection and maintenance building, a garage for transporter storage and repairs, a small warehouse, and a mechanical shop.

3.8.2 The Operations Support Base

The Operations Support Base in San Pedro de Atacama will be the major base for the LSA/MMA. From here the telescope will be operated remotely via fiber-optic and/or microwave links. This center will consist of the main control building, laboratories and offices, computing facilities, a library, dormitories, dining facilities, recreational facilities, and mechanical, electrical and automotive shops. Extra buildings to accommodate the installation crews during the construction phase will be removed after completion of the telescope. It is also possible that the antennas will be assembled at this center, to be transported as complete units to the telescope site, and appropriate assembly facilities will be required.

It is important that this center does not disturb the unique character of the town. San Pedro is the oldest continuously inhabited site in Chile, and of great ethnological and archeological importance. It is a principal tourist center because of the nearby pre-Columbian sites, the fine archaeological museum, its majestic vistas of the Andes mountains and the Atacama desert, the rustic nature of its sixteenth- and seventeenth-century adobe buildings and narrow streets, and its proximity to tourist attractions such as the Tatio Geyser fields. The OSB must be close enough to use the logistics, but far enough to preserve the character of the town.

3.8.3 Operations

As described below, the LSA/MMA Observatory will be operated for ESO and NRAO by a Foundation incorporated in Chile. This Foundation will hire all local staff and enter into all contracts with Chilean enterprises. It will be controlled by an ESO-NRAO Board.

Most of the LSA/MMA staff will work at the OSB in San Pedro on a Turno system. They will spend a week at the OSB and a week off at their homes, likely in Antofagasta or Santiago, providing eighty-eight work hours in a two-week period. Some overlap will be provided in the schedule to provide continuity from one turno to another. The dormitories and living facilities will be sized to allow this overlap, and also to provide accommodation for astronomers and engineers visiting the OSB on a non-scheduled, temporary basis. Some staff may choose to live in Calama and commute daily from there, and still others may choose to live in San Pedro itself.

A crew will commute daily from the OSB to the LSA/MMA site. The trip takes just an hour, and as described above it is highly advantageous for these "high-altitude workers" to sleep at low altitude. When necessary, staff will also commute from the OSB to the telescope site for after-hours support. No personnel will sleep or live at the high site itself. The main roles of the site crew will be regular maintenance and the transport of antennas from one configuration to another. As much as possible, a modular approach will be used for the construction of the LSA/MMA, so that "repair" will generally involve replacement and transport of a faulty component (module) to the OSB for repair. For example, 2-3 complete receiver units could be available at all times at the OSB, running and ready to go, as replacements.

The LSA/MMA will, of course, generally be used in "service mode", as is common with other radio telescope arrays such as the Westerbork radiotelescope, the VLA, and the VLBA. This is even more appropriate for the LSA/MMA, because of the greater sensitivity to changing atmospheric conditions. Observations requiring more than one array configuration will be interleaved with other programs for maximum efficiency, and snapshot observations will be made under the optimal conditions.

4. Organizational Structure

(Sections 4, 5 and 6, showing a possible scenario for the organizational structure and planning, were compiled by P. Shaver and R. Kurz on the basis of previous discussions of the LSA/MMA joint Management Working Group.)

4.1 The LSA/MMA Project in Europe

4.1.1 European Experience in Millimeter Astronomy

Any new development in European millimeter astronomy builds upon a strong base established over the past 20 years through a number of important, world class instruments and research groups. European institutes have not only built up a commanding scientific reputation in millimeter wavelength astronomy; they have also built up strong research/development groups in the field of millimeter/submillimeter receiver technology. Furthermore, European industry is responsible for the world's most sensitive millimeter telescopes, including the IRAM 30m antenna on Pico Valeta in Spain, and it is to European industry that the Mexican/US consortium has turned for its proposed 50m millimeter telescope.

The first millimeter telescope in Europe, the Onsala 20m telescope, has been operational for more than 20 years, and the experience of the Onsala group has certainly helped to make the Swedish-ESO Submillimeter Telescope (SEST) such a success. The IRAM interferometer array of 5 (soon to be 6) × 15m antennas on Plateau de Bure (SEST was modelled on the IRAM 15m telescope design) is the most sensitive interferometric instrument for millimeter astronomy and is producing impressive images of high quality. In fact the wealth of experience amassed by the IRAM group in the field of millimeter imaging will be invaluable in the operation of the LSA/MMA. At submillimeter wavelengths, Europe again has important instruments and experience from the JCMT on Mauna Kea and the 10m HHT on Mount Graham to the 3m Cologne instrument in Switzerland. The ESA FIRST project has also driven European technical development and today there is, overall, a vast experience in submillimeter technology in Europe.

A full list of European institutes involved in operating millimeter/submillimeter facilities or developing and building millimeter receivers and other technology is impressive. These institutes include IRAM, the MPI für Radioastronomie in Bonn, Onsala Space

Observatory, Chalmers University of Technology, the Observatoire de Paris/Meudon, the Netherlands Foundation for Research in Astronomy in Dwingeloo, SRON and the University of Groningen, the University of Cologne, Bordeaux University, ESTEC Noordwijk, Arcetri Observatory, the Centro Astronomico de Yebes, ETH Zurich, ESO, the University of Cambridge, Rutherford and Appleton Labs., the Royal Observatory Edinburgh. One can be sure that all of the technologies required for the construction and operation of a large millimeter array are well developed in Europe.

It is interesting to look at the spread of interest in millimeter astronomy across Europe as defined by the numbers and geographical distribution of the users of the current instruments. A look at the use of the SEST telescope which, because of its location on La Silla, has encouraged rather many otherwise optical astronomers to make use of millimeter data, and the IRAM facilities shows that many scientists from more than 60 institutes across the ESO nations are already involved in millimeter astronomy. Add to these numbers millimeter astronomers from the non ESO states in Europe and totally some 75 European groups are already using millimeter facilities. These numbers will increase considerably with the advent of the LSA/MMA because of its importance to just about all astronomical research. Both technically and scientifically, Europe plays a leading role in millimeter astronomy, so it is natural that a European collaboration should be looking to the future in the development of a next generation instrument: the LSA/MMA.

4.1.2 The Role of ESO in the LSA/MMA Project

ESO's has a major role to play in European astronomy especially in large projects which cannot easily be undertaken by individual countries. At $US 400m, the LSA/MMA project certainly fits into this category.

The LSA/MMA project is a major new project in millimeter/submillimeter wavelength astronomy which promises high scientific rewards. Its synergy with the VLT and its technological readiness make it highly appropriate for ESO as the next project after the VLT. The design phase is expected to begin in the year 2000, just as the engineering work for the VLT reaches completion.

Many of the resources necessary to undertake this project already exist in ESO, as there is much in common with the VLT: project management, system engineering, control electronics, software development and data management, contracts and procurement, infrastructure and engineering capabilities in Chile, well-established interfaces with the European astronomical community, general administration. Many staff positions in Garching that have been associated with the VLT will become available for the LSA/MMA in two or three years. Thus, it will be possible to house the LSA/MMA project activities in the Garching headquarters without the need for any increase in offices and infrastructure.

The LSA/MMA project would of course require the creation of a new Project Office, and the hiring of several new staff members with special expertise. These staff members would be involved mainly in engineering and contract management at a reasonably high level. While it is essential that ESO develop some in-house expertise in millimeter wave technology to appropriately place and monitor industrial contracts, it is anticipated that most of the technical work will be contracted out to existing institutes around Europe, as discussed in the next section.

Technical oversight of the European side of the project will be provided by a science advisory group and technical advisory groups with a broad representation from the community, in addition to the STC and its newly established "LSA Technical Advisory Board".

4.1.3 Participation of Other European Institutes

From the outset the LSA studies have involved a number of European institutes working in close collaboration. The Memorandum of Understanding for the first phase of LSA studies was signed in 1995 by IRAM, ESO, the Onsala Space Observatory, and the Netherlands Foundation for Research in Astronomy. Several other European institutes have also now become involved, and all ESO member states plus the U.K. and Australia are now represented on the LSA Board. In addition, scientists from Spain and Canada are members of working groups.

During development of the LSA/MMA it is anticipated that a large amount of the technical work will be done at the participating institutes which have the required expertise in millimeter/submillimeter technology. The role of the Institut de Radio Astronomie Millimetrique (IRAM) is clearly very important here – their experience in millimetre interferometry through the successful operation of the Plateau de Bure interferometer will be invaluable to the project. (Experience with longer wavelength systems also exists in Holland and the UK). ESO will have responsibility for all major programmatic decisions (representing the European community within the context of the ESO/NRAO collaboration), for system engineering and for placing all major industrial contracts. While ESO will not attempt to duplicate the specialized millimeter/submillimeter laboratories that already exist in these other institutes, it may have to play a significant role in the translation of laboratory prototypes to industrial production. Therefore, ESO would have to develop sufficient in-house expertise to properly supervise the industrial projects.

Such co-operative arrangements have worked effectively in the past. The SEST is a collaboration between Sweden and ESO in which Sweden has responsibility for the specialized millimeter technology. A more appropriate example, perhaps, is the case of the VLT where 10 of the 12 instruments have been contracted out to institutes around Europe, and this has been highly successful. In this way ESO provides for the needs of the astronomical community, while at the same time promoting the development of the relevant technologies in the various institutes around Europe.

In the case of receivers, for example, this distribution of effort is essential. While many components of the receivers can be manufactured by industry, the state-of-the-art SIS junctions can presently only be made by specialists in research institutes. The large number needed for the LSA/MMA may require a different approach and an effort to industrialization in which ESO would be involved. In some technical areas, specific institutes may act as prime contractors. If the need arises, ESO-supplied personnel could be co-located at one or more of the existing laboratories in member states for the duration of the development and construction phase.

In the operational phase the array will be continually upgraded - particularly the receivers. The active involvement of these institutes will therefore be essential for the long term.

4.1.4 A European Option

Throughout this document it is assumed that the array will be a joint Europe-U.S. project, and the organization of this collaboration is elaborated below. However, in the unlikely event that the project is not funded in the U.S., Europe has all the necessary technology and experience to proceed on its own, as shown above. Indeed, the LSA was originally conceived as a purely European project.

As a purely European project, the objectives, specifications, and design would have to be re-assessed. The LSA was originally intended to be a millimeter-wavelength array of 10,000 m^2 collecting area. There is now a widespread interest in Europe to include submillimeter wavelengths. The compromise between these objectives and the overall scale of the project would have to re-examined in the purely European context. However, of course, it is hoped and expected that this situation will not arise, and that the project will proceed as a collaboration with the U.S.

4.2 The Partnership with NRAO

4.2.1 Basic Principles Governing the Partnership

The partnership has been discussed as a 50-50 ESO/NRAO partnership. There will be just two full and equal partners, with no junior partners. Any other parties wishing to join the project would do so under the umbrella of one or the other of these two partners. All arrangements concerning the establishment and operation of the LSA/MMA must be agreed to jointly by the two partners.

4.2.2 Overall Management Structure

Possible management schemes for the two phases, construction and operation, are shown in Figures 4.1 and 4.2. In both cases the highest level of coordination is between the ESO Council and the National Science Foundation. Overall policy will be set here.

During the construction phase, at the next level is the executive coordination of the project between ESO and NRAO. At this level the input from both communities is represented

Fig. 4.1
LSA/MMA Management Structure Construction Phase

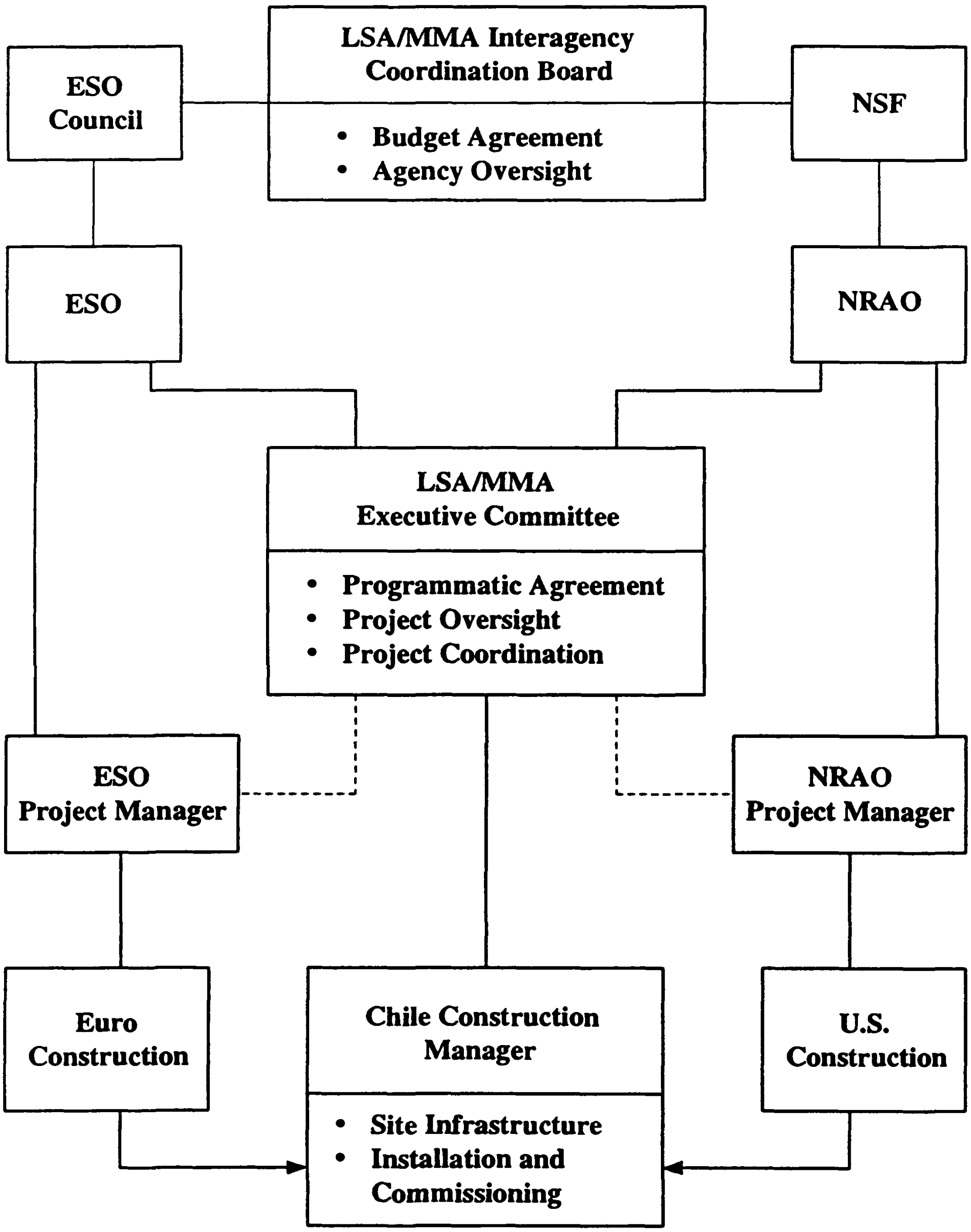
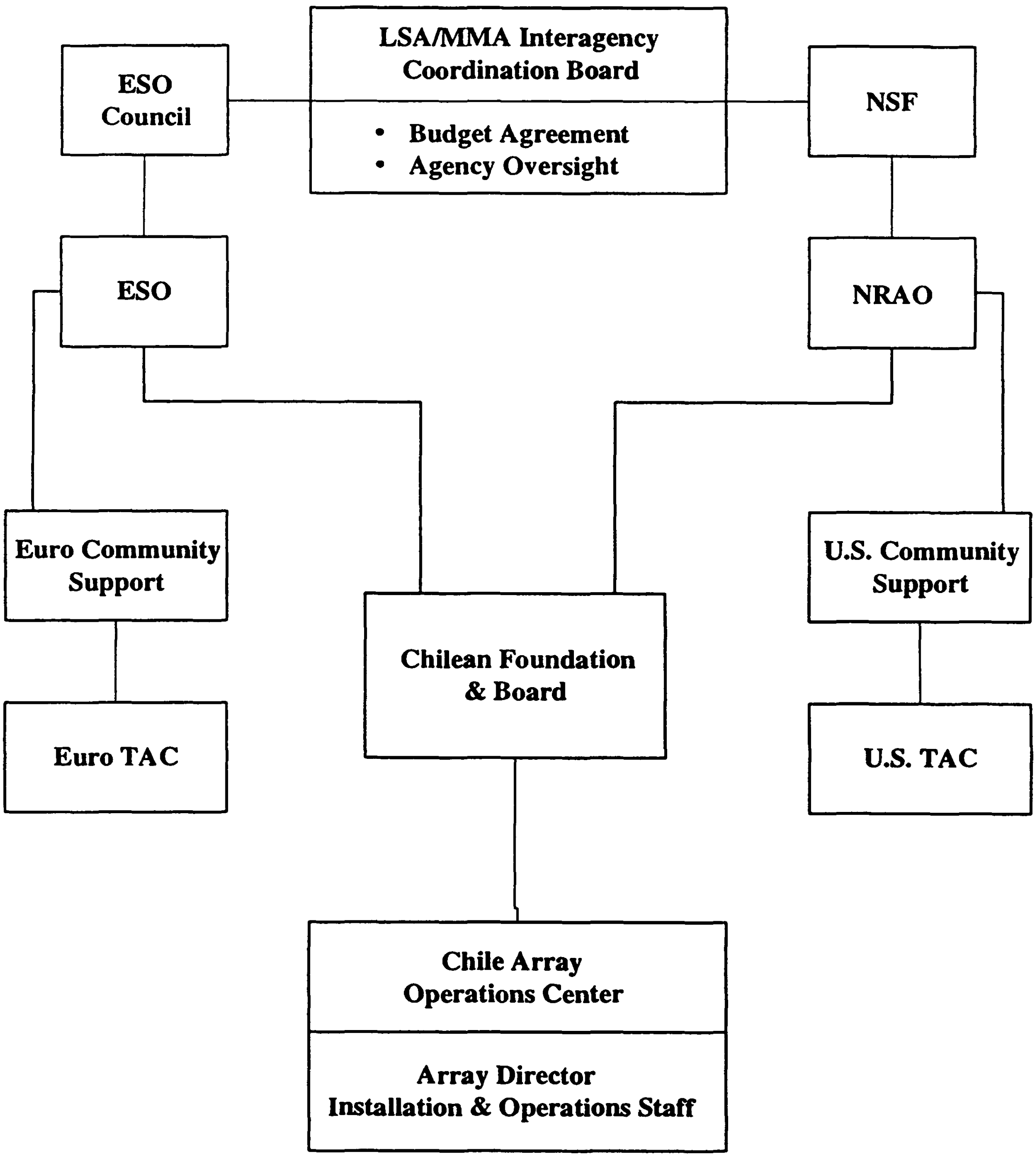


Fig. 4.2
LSA/MMA Management Structure
Operations Phase



through a small, joint Executive Committee as well as the relevant committees on each side. The Executive Committee sets scientific and technical policy and provides project oversight and coordination.

Contracts and construction activities in Europe and the U.S. are managed by the ESO and NRAO Project Managers, respectively. They work closely with each other and the Executive Committee, which sets policy and priorities. Once a contract is established, in Europe or the U.S., it is the responsibility of the relevant Project Manager. For contracts and construction in Chile, there will be a Chile Construction Manager, who, under the direct guidance of the Executive Committee, is responsible for the project funds provided equally by ESO and NRAO.

In the operations phase (Figure 4.2) the observatory will be run by a Chilean Corporation or Foundation to be established for this purpose by ESO and NRAO. ESO and NRAO will control this entity through a Board of Directors, share equally in the cost, and assign to it staff members for particular tasks. Those staff members so assigned will retain their affiliation with ESO or NRAO. The Corporation or Foundation will also have its own local staff.

4.2.3 Overall Funding Structure

Project funds will not cross the Atlantic, except those going to Chile itself. The European funds will stay in Europe and be managed by the ESO Project Manager, and the same applies in the U.S. Overall project coordination is provided by the Executive Committee, but the funds are controlled by the ESO and NRAO Project Managers.

The allocation of contracts and work must ultimately reflect the fact that this is a 50-50 partnership. Major contracts may be open for tender on both sides of the Atlantic to assure quality and economy, but for most of the work the contracting procedures in Europe and the U.S. need not be in any way similar.

The cost of the Chilean operational entity will be shared on a 50-50 basis. However, related activities in Europe and the U.S. (interfaces with the community, data transmission and archiving, etc.) will be funded separately.

4.3 Relationship with Chile

4.3.1 Use of the Land

The site, described in section 3, is owned by the Chilean Government and would be given in concession to CONICYT. CONICYT would make it available to an observatory for use under the conditions outlined in the proposed new Chilean law for astronomy. The use of the land would be negotiated in a new agreement. Among the various provisions is the requirement of 10% observing time for Chile, representation on boards, and that Chilean workers should be employed under Chilean labor law. Exemptions from duties, taxes, etc. would remain in principle the same as currently agreed with ESO, but conflicts would have to be settled by Chilean courts.

4.3.2 The Observatory in Chile

The Observatory will be a Chilean non-profit Corporation or Foundation having legal capacity in Chile to assure applicability of the Chilean Law on Astronomy, in particular tax-free operations, with a President and a Site Director to run the combined array. ESO and NRAO will control the Foundation and Observatory through the LSA/MMA Board.

The LSA/MMA Chile Foundation will be established as soon as possible once the joint project has been approved in Europe and the U.S. It will conclude the agreement with CONICYT for use of the site, and provide a Chilean base for the project during the construction phase. It will enter into all contracts with Chilean Corporations. It will develop the site and provide logistic support. It will hire all local staff, with liability under local laws. Scientists from Europe or the U.S. working at the Observatory will be either ESO or NRAO employees, or under contract to one of those two organizations.

The Observatory will begin to operate as soon as the necessary infrastructure is in place and a reasonable number of antennas are available for interferometry. The Foundation will operate the Observatory for ESO and NRAO, and provide 10% of the observing time to Chile through CONICYT.

4.4 Design and Construction Phase

4.4.1 Coordination, Control and Review

As mentioned above and illustrated in Figure 4.1, the project will be coordinated at two levels: overall policy decided by ESO Council and the NSF, and project definition, oversight, and coordination provided by ESO and NRAO. Input from the astronomical communities in Europe and the U.S. will come from the relevant scientific and technical advisory committees on each side.

At the top level, the Interagency Board will be made up of an equal number of representatives from Europe and the U.S. Members will be appointed by the ESO Council and the NSF, respectively. Procedures are still to be agreed, but the Interagency Board would probably meet formally once or twice per year with the chair alternating between the two sides.

At the next level the Executive Committee will be made up of a small number of representatives from ESO and NRAO, most likely the Project Directors, Project Scientists, and

Project Managers from each side. Frequent meetings will take place, either face-to-face or by video or teleconference. The ESO and NRAO Project Managers will work under the overall coordination of the Executive Committee, but they ultimately control the funds for their respective organizations and manage the actual contracts and work. The Chile Construction Manager also works under the guidance of the Executive Committee and controls and allocates the funds sent to Chile from Europe and the U.S.

Any disputes concerning the distribution of work and allocation of funds will be resolved by the Executive Committee, which, together with ESO and NRAO management, will assure the smooth coordination of the project. In the unlikely event that an issue cannot be resolved at this level, it will go to the Interagency Board level for resolution.

4.4.2 Construction and Contracts

During construction ESO and NRAO will carry out all design, development, and production using their normal channels for project development. Each organization responds to its governing bodies and follows its normal rules and procedures. Upon completion of the hardware and software development and production, the products will be sent to Chile for installation and commissioning.

For some of the major contracts, calls for tender may be open to both sides of the Atlantic, to ensure the best product at the lowest cost.

4.5 Operations Phase

4.5.1 Management and Control Structure

The overall organization of the project during the operations phase is illustrated in Figure 4.2. The Interagency Board will continue at the top level, but the Executive Committee will be replaced by the LSA/MMA Observatory to be established as a corporation or foundation under Chilean law. It will be funded 50-50 by ESO and NRAO, and will be directed by a Board representing the two organizations. It will have a Director, who will report to the Board. The annual budget and global allocations will be set by the Board, following approval by the governing bodies of ESO and NRAO. The Director will be responsible for contracts in Chile and day-to-day allocations of funds within the approved envelope.

The scientific communities, ESO, NRAO, and their governing bodies will determine the policies and activities of the Observatory through the Board. The Observatory Director will be responsible for implementing these policies and regular reporting to these groups through the Board.

4.5.2 Continuing Technical Development

During the lifetime of the LSA/MMA, there will be a continual upgrading of the array and its receivers. Priorities will be set by the Board, on the basis of input from the user communities, ESO, NRAO, and their governing bodies. As usual, funding will be on a 50-50 basis.

The upgrade projects will be allocated by the Board, and carried out by the Project Offices at ESO and NRAO, which will continue to exist (in reduced form) for this purpose following completion of the array. As in the construction phase, ESO and NRAO will be free to follow their own contracting rules and procedures. The upgrade products will be delivered to the Observatory when completed, and installed jointly by the Observatory and the Project Office involved. Both Project Offices will act as conduits to the originating institutes or companies in case of problems with equipment or services provided.

4.6 Involvement of Other Countries

4.6.1 The Japanese LMSA

The LMSA is the proposed Japanese Large Millimeter and Submillimeter Array. The present concept is a 4000 m^2 array of 10m antennas with a maximum baseline of 10 km. A decision has recently been made in Japan to locate the LMSA also in the Chajnantor area - at Pampa la Bola, less than 10 km away from the center of the LSA/MMA. The reasons include the excellent submillimeter properties of the site, the superior infrastructure, and the possibility of sharing facilities with the LSA/MMA project. Two possible ideas have been discussed:

(a) A "handshake" arrangement, in which the two arrays, although independent, can sometimes be used together in a large combined array. This possibility has been discussed over the last two years by Japan and the U.S. in the context of the LMSA and MMA, and could equally well apply to the LMSA and LSA/MMA. A large number of compatibility issues would have to be agreed upon for this to work - not a trivial task if the two arrays are designed independently. The combined array could be optimised, in the extreme case by moving all antennas of both arrays. It has been referred to as the "Atacama Array". This does not seem to be a viable option.

(b) The two projects could be combined into one large "World Array", in which case there would be three equal partners instead of two. The symmetrical organizational structure outlined above for the LSA/MMA lends itself to a natural extension to three partners. In this case the design would be optimized from the outset, economies would be maximized, the array would be the most powerful possible, and there would be no later compatibility problems. Discussions concerning these possibilities are taking place between Europe, the US, and Japan.

4.6.2 Participation of Other Countries

There are several other countries interested in taking part in the LSA/MMA project, such as the UK and Spain. Discussion is still required in this area, but ESO and NRAO would prefer that other partners should join under the umbrella of either ESO or NRAO, so the project would remain an equal partnership between these two organizations.

If such countries chose to enter the project on the European side, they could do so without becoming full members of ESO. Their participation, financial and otherwise, would extend only as far as the LSA/MMA project itself. Their contributions would be negotiated in accordance with the guidelines set out in ESO/Cou-619 and approved by Council as reported in ESO/Cou-622. Their role in the committees and bodies overseeing the LSA/MMA project would be the same as that of any full member of ESO. The detailed arrangements are open to negotiation in individual cases.

5. Schedule and Costs

5.1 Project Schedule

Figure 5.1 shows a proposed top-level schedule for the LSA/MMA project. The European consortium (ESO-IRAM-NFRA-Onsala) conducted the LSA study starting in 1995 and culminating in the April 1997 Combined Report. In June 1997 ESO and NRAO resolved to form a partnership to study the union of LSA and MMA into a single, common project. The ongoing LSA/MMA study is a result of this resolution and this Feasibility Report is an important output from this study. In parallel with the LSA/MMA study, which will continue through 1999, ESO with the support of the other participating European institutions will prepare a formal proposal for the European side of a common project. This proposal will be submitted to the ESO Council in June 1999 with a goal of receiving approval of the proposal and European funding by the end of 1999. Authorization to proceed with preparation of the proposal will be requested from the ESO Council in June 1998.

Assuming a favorable ESO Council decision in June 1998 on proceeding with the joint studies and preparation of a formal proposal, negotiations between ESO and the U.S. National Science Foundation (NSF) should begin immediately. The goal of these negotiations should be to reach agreement in principle on the joint project as rapidly as possible and to conclude an Agreement formalizing the joint project by the end of 1999. Following execution of this Agreement, formation of the LSA/MMA Observatory in Chile as a corporation or foundation under Chilean law can proceed with the goal of having the Observatory established by the beginning of 2001.

Once the project is fully approved, detailed design and development will start on the European side at the beginning of 2000 and proceed for three years until the end of 2002. Construction at the site and limited production of long-lead elements will start at the beginning of 2002 with production moving into full swing in 2003 after conclusion of the design phase. Operations at the site in Chile should start on a limited basis in 2004, but significant operational activities and funding are not expected to be required until the 2006–7 timeframe.

The current NRAO schedule for the MMA is shown at the bottom of Figure 5.1. It should be noted that this is the schedule for the MMA as a stand-alone U.S. project and does not reflect the possibility of a single, common project with Europe. NRAO has approval and funding ($26M) for a three-year design and development phase that is just starting. The major objective of this activity is to produce a complete, auditable cost and schedule for

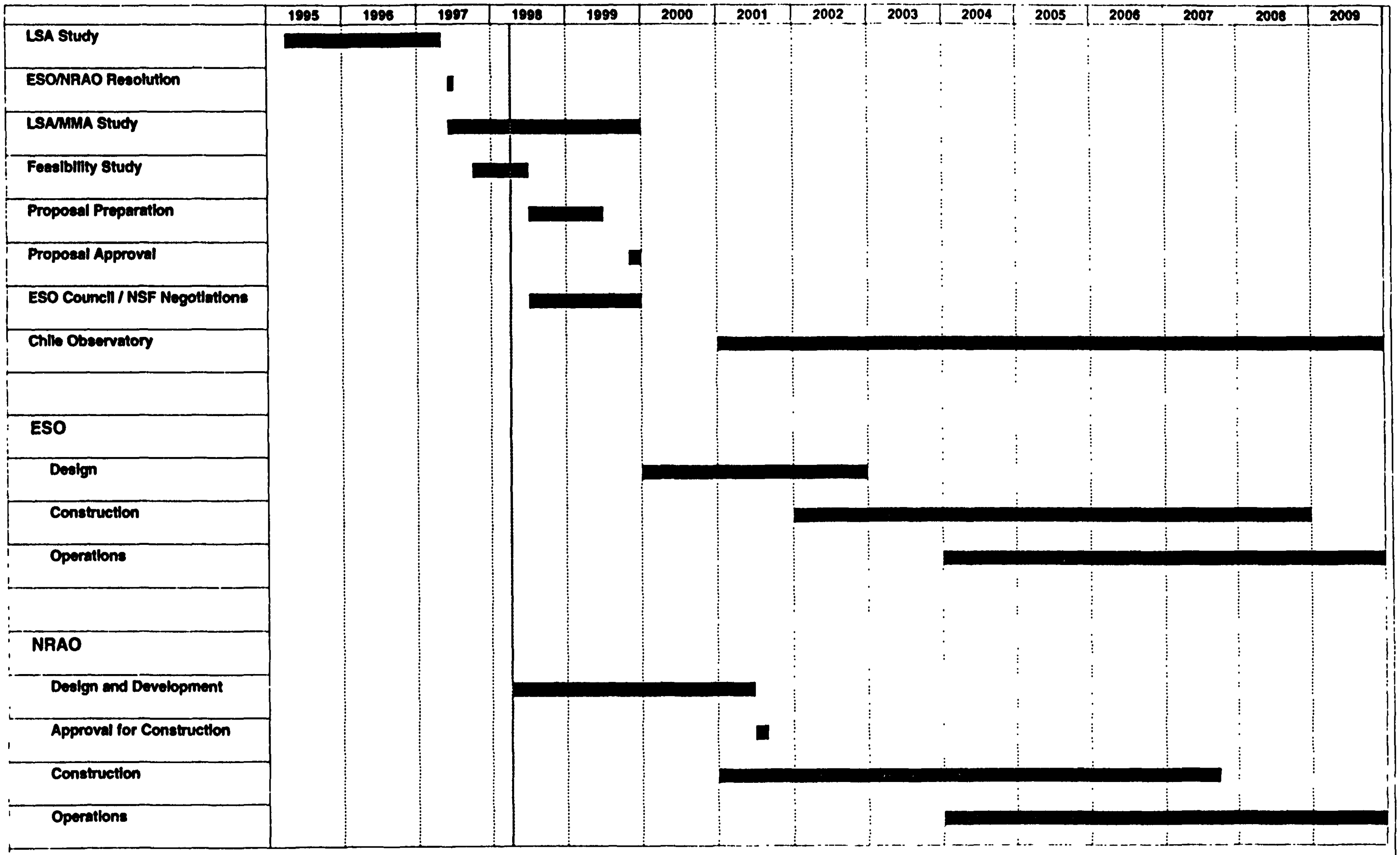


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Figure 5.1 LSA/MMA Schedule

construction of the MMA based on demonstrated technology. Successful completion of this phase will result in approval to proceed with full-scale construction. The NRAO schedule calls for limited construction and production activities to start early in 2001. Full-scale construction will start following approval to proceed and continue through September 2007 (the end of U.S. fiscal year 2007). Although planning and development for operations at the Chile site will occur starting in 2001, significant operations of a partial MMA are planned to begin in 2004.

While we believe the common LSA/MMA project may be feasible without major changes to the current MMA schedule, an optimum schedule must consider the joint project. For this reason it is important that ESO and NSF reach the agreement in principal on a single, common project referred to above at the earliest possible date. Planning on both sides should then be able to proceed realistically on the basis of the joint project.

5.2 Construction Cost

A variety of cost estimates have been developed independently for the LSA and MMA, and more recently for a common LSA/MMA. Although there are differences between the various estimated costs of individual elements of the system, there is a consensus that an LSA/MMA consisting of 64 12-meter antennas with receivers spanning the millimeter and submillimeter bands will have a total cost of about $400 million (1997 U.S.$). Table 5.1 gives a representative breakdown of this total LSA/MMA estimated cost.

Table 5.1: Estimated LSA/MMA Cost (in millions of 1997 U.S.$)

Site Development (including antenna pads and long baselines)	48
Antennas (including transporters)	200
Antenna Electronics (including receivers and local oscillators)	84
Central Electronics	8
Correlator	18
Monitoring and Control Systems	10
Post-processing and Computers	7
Systems Engineering	7
Project Management and Control	8
Spares	10
Total	$ 400 M

The precision of this estimated cost will certainly be improved as a result of the on-going joint LSA/MMA studies, the NRAO design and development work, and the European proposal preparation activity. However, only after the design and development phases in the U.S. and Europe are completed will a high confidence estimate of the project total cost, or more likely, a detailed definition of the LSA/MMA that can be delivered for $400M be available.

6. Planning for 1998/1999

Work is planned in two general areas for 1998/1999 – preparation of the proposal for the European side of the common LSA/MMA project and design studies on specific topics both in collaboration with the U.S. and independently in Europe. As discussed in Section 5.1, the proposal preparation will occur during the first half of 1999 and the design studies will continue through the entire year.

Proposal preparation will draw on previous as well as on-going studies to formulate a complete plan for European participation in LSA/MMA. In addition to a technical baseline, a management plan will be developed defining what work will be carried out in Europe and what the responsibilities of participating institutions will be. We expect to work with NRAO during the later half of 1998 to come to an agreement on the division of responsibilities and tasks between Europe and the U.S. Cost estimates of the entire project will be refined, including detailed estimates of the work to be carried out in Europe. All of the technical, management, and cost information will be compiled into a comprehensive proposal to be submitted to ESO Council for consideration in June 1999.

Parallel working groups have been established in Europe and the U.S. to guide the work in the technical areas comprising LSA/MMA. The independent and joint study activities were defined at meetings held at Charlottesville and Tucson in March 1998 to coordinate the efforts in Europe and the U.S.. Tasks were categorized as either common, U.S., or European studies. Common studies include both collaborative efforts and those pursued in parallel on both sides. Table 6.1 summarizes the recommendations of these meetings.

The working groups are envisioned as bodies that guide and review the work performed by individual institutions. Design studies in Europe requiring significant resources beyond those needed for participation in the working groups are proposed in six areas: site testing and meteorological studies, antenna design, receiver development including local oscillators, study of alternative approaches to transmission of data from individual antennas to the central processing facilities, correlator design, and data flow analysis/design.

Testing of the Chajnantor site will be continued and expanded. In addition to characterization of the atmosphere above the site, geotechnical studies will be conducted to characterize the properties of the soil and further data on the power spectral density of the wind will be collected. These later data are critical to design of the antenna foundations and prediction of antenna pointing performance. Data obtained on the atmosphere from site testing will be compared with meteorological data to determine the correlation with satellite measurements and potentially greatly expand the time span of characterization.

Table 6.1: March 1998 LSA/MMA Technical Workshop Recommendations

Area	Common	U.S.	European
Array System	Analog vs. digital signal transmission	4 GHz sampler design	Alternative correlator designs
		Digital filter design	
Antenna	Laser metrology	10-m antenna design	12-m antenna design
	Drive system design		
	Panel fabrication		
	All CFRP backup structure		
Receivers	HFET/SIS comparison at > 115 GHz	Photonic local oscillator design	Conventional sub-mm local oscillator design
	Bandwith vs. Receiver temperature		
	High volume manufacturing		
	Impact of 30 GHz inclusion		
Science	Array configuration		
	Phase and amplitude calibration comparison		
Software	Specification of requirements and goals		Data flow design and prototyping
	Existing software survey		Data compression analysis
	Data flow analysis		
Site	Upgrade of weather stations		move equipment to Chajnantor
	Radiosonde experiments (with Cornell)		Meteosat image analysis
	Physiology study		
	Sodar measurements		
	Soil properties		

Multiple antenna design studies will investigate critical areas identified in the 12-meter conceptual designs performed to date. Finite element analyses and performance predictions will be refined. Metrology systems identified as essential to achievement of the required pointing accuracy will be studied. Alternative drive systems will be analyzed. Fabrication techniques for all carbon fibre reinforced plastic (CFRP) structures without metal nodes will developed and tested.

Receiver development at multiple locations will investigate essentially all elements of millimeter and submillimeter systems. Low noise, broadband mixers and amplifiers; local oscillator systems, both conventional and photonic; phase compensation receivers; as well as cryostat and optics design are among the topics to be pursued. Emphasis will be on development of systems that are reliable, require no mechanical tuning, and manufacturable in the quantities needed for LSA/MMA.

Digital versus analog transmission of data from the antenna locations to the central processing facilities will be evaluated. A global IF system and frequency plan will be designed, modelled, and breadboard hardware built to demonstrate the feasibility and performance of the design.

Alternative correlator architectures and designs will be investigated to evaluate different approaches with respect to performance, cost, and producibility.

Comprehensive analysis of the complete data flow for arrays will be performed and a system data flow designed that goes from observation planning through to data archiving, including calibration techniques. The potential benefits of data compression and alternative techniques will be investigated.

In addition to these subsystem design activities, significant systems engineering work will be conducted to guide the overall technical effort. Performance requirements derived from top-level scientific requirements will be developed at the system and subsystem levels. Error budgets will be established and the development of end-to-end performance models and simulations will be initiated. Reliability analyses will be done to identify components whose reliability will be critical to achieving acceptable system availability. Critical interfaces will be identified, particularly those between areas of U.S. and European responsibility, and preliminary definition of these interfaces established.

ESO will be overall manager of the design studies in Europe responsible for coordination and oversight of the various activities. Systems engineering will be focused at ESO, but most of the subsystem work will be performed at other institutions. The Consortium and its technical working groups will continue to play an active role in reviewing all aspects of the design activities and providing advice and guidance to ESO and the teams performing the work. Contracts to fund the design work will be issued and administered by ESO.

7. Conclusion

The LSA/MMA appears to be feasible in all respects. The remarkable site provides excellent observing conditions, possibly the best available anywhere in the world. The low opacity makes the submillimeter wavebands accessible with high efficiency, and, with appropriate calibration strategies, good phase stability can be achieved for the longest baselines foreseen.

Several antenna designs have already been studied in considerable detail. The various groups involved agree that 12 meter diameter antennas can be built at reasonable cost which will perform well at the shortest submillimeter wavelengths with high efficiency and good pointing, even exposed to the elements in the Chajnantor region. A goal for the surface accuracy of these antennas should be better than $20\,\mu$. The problem of providing and maintaining large numbers of receivers, with their associated cryogenics, can be solved in such a way that maintenance problems are minimized. A correlator to handle so many baselines is a challenge, but within the range of present-day technology. The calibration goals are achievable. Techniques for phase calibration have been developed that give very good results. The processing and distribution of the vast data flow from the LSA/MMA is manageable even with present technology, and will become even more so as a result of rapid progress in this area.

The basis approach proposed to implement a single, common LSA/MMA project is a 50-50 partnership led by NRAO on the U.S. side and ESO on the European side. The management structure envisioned takes advantage of the existing ESO and NRAO organizations and capabilities without creating a large, new international entity with attendant infrastructure and overhead. Mechanisms are provided to oversee and coordinate the activities on both sides while allowing each side to retain control of their funds and to use their existing methods and procedures. Common tasks in Chile such as site development and system installation and commissioning will be managed by a jointly funded and staffed element. In the operations era, the LSA/MMA Observatory will be formed as a single entity under Chilean law. This entity will be funded and controlled jointly by ESO and NRAO. The partnership arrangement also provides for the eventual entry of Japan and the participation via ESO by European countries that are not members of ESO, such as the U.K. and Spain.

Although NRAO is currently somewhat ahead with an approved $26 million, three-year design and development phase just starting, a joint schedule for a common project is feasible if we move ahead expeditiously on the European side. Sufficient design and development can be completed on both sides to allow construction to start in 2002 and be completed in 2008. Operation with a partial array could start as early as 2004 ramping up to full-scale operation in 2009.

Maintaining this schedule on the European side requires continuation of the on-going LSA/MMA design studies through 1999 with an increased level of effort. In parallel, a formal proposal completely spelling out the European participation must be prepared by June 1999 leading to approval to proceed by the end of 1999.

Current estimates on both the European and U.S. sides are in general agreement that a LSA/MMA comprised of 64 12-meter antennas can be built for $400 million. Much more work is needed over the next two to three years, however, to determine exactly what the system configuration and capabilities are that can be confidently delivered for $400 million.

Appendix A1

List of Documents

- "(Sub)Millimeter Astronomy at ESO", ESO/STC-148, April 1994
- "Memorandum of Understanding concerning a Study for a Large Millimetre Array in the Southern Hemisphere", between IRAM, ESO, Onsala Space Observatory, and the Netherlands Foundation for Research in Astronomy, April 1995
- "LSA: Large Southern Array - A 21st-Century Millimeter Array with 10000 m^2 Collecting Area" (ed. D. Downes), October, 1995
- "Science with Large Millimetre Arrays", Proceedings of the ESO-IRAM-NFRA-Onsala Workshop, ESO Astrophysics Symposia Series (ed. P. Shaver), September, 1996
- "LSA: Large Southern Array, Combined Report", ESO/Cou-611, April 1997
- ESO-NRAO Agreement on the LSA/MMA partnership, June 1997
- "Report of the LSA/MMA Antenna Study Committee", December 1997

Appendix A2

LSA Board and European Working Group Members

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Michel Mayor	Obs. de Genève, Switzerland
Karl Menten	MPIfR, Bonn, Germany
Peter Shaver	ESO, Garching, Germany
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François Viallefond	Observatoire de Paris, France
John Whiteoak	ATNF, Sydney, Australia

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