ALMA Test Interferometer PROJECT BOOK

Version 1.00, Last changed **2000-02-23**

This book describes the ALMA Test Interferometer plan for the US test site at the VLA, NM. (See the ALMA Construction Project Book for ALMA Construction at the Chajnantor site)

DTE & *JWMB*

Table of Contents

Notes

++**Dates:** *The date format used here and elsewhere in this project book is based on the international ISO 8061 standard, being given as year-month-day.*

THE ALMA TEST INTERFEROMETER (TI)

Purpose, Scope and Goals

J.W.M. Baars
D.T. Emerson
Last revised 2000-Feb-18

Revision History:
First version: 2000-Feb-14

1. Introduction

When the Atacama Desert was chosen for the site of the MMA, it was decided at NRAO to build and test a prototype array element before going into the series production of the 40 or more antennas. In the context of the larger ALMA project with Europe providing a contribution comparable to that of the US, agreement has been reached to acquire two prototype antennas, one each procured and financed by NRAO and by ESO. This has the obvious advantage of putting industrial competition into the prototype phase of the project. It has also been decided to bring both antennas to the site of the VLA for the test program. Thus it will now be possible to combine the two prototype antennas into an interferometer, thereby significantly expanding the range of tests which can be undertaken, including the tests of prototype electronics for the final array.

The first priority of these activities is the thorough test of the antennas for their adherence to the specifications. The quantitative data on the antenna characteristics and behavior will enable one of the two prototypes to be selected for the eventual fabrication of up to 64 production antennas. The antennas will be subjected to a series of measurements, both as single dish antennas and connected together as an interferometer, the Test Interferometer (TI).

For the purpose of these antenna evaluation measurements, the antennas will be equipped with so-called evaluation receivers. This receiver system is not the ultimate ALMA receiver, but rather a system of available, well-proven designs of SIS and HFET frontends. This is the fastest and simplest solution to the task of evaluating the antennas. To support the receivers, a system of electronics including LOs, IF processing, accurate detectors, correlator, control communications and real-time computing is needed. To the extent that the schedule permits, these will be prototypes of the devices needed for the array. Also needed are a holography system and a nutation mechanism for the subreflector, with appropriate controls and software.

The evaluation receivers and other electronics must be delivered and proved to be working correctly before the antenna testing can proceed. This sets the initial schedule and limits the extent to which prototype electronics can be used. Thereafter, detailed tests of the antennas and of the electronics will proceed together, with the antenna tests having priority if a conflict should arise. As development and testing proceed, modified hardware and software may be installed to replace initial expedients with prototypes closer to the intended final design, or to correct design errors. The timing of such installations will be a matter of engineering judgment so as not to compromise ongoing tests.

This *ALMA Test Interferometer Project Book* (TIPB) describes the complete system and subsystems as are planned for the single dish and interferometric tests at the VLA test site. Parts of the system – notably the antenna itself, but also many electronics subsystems – will be described in the *ALMA Construction Project Book*, so this *TIPB* concentrates on those parts of the system that will be particular just to the VLA test site installation and tests.

2. Antenna and Prototype Electronics Tests

Two prototype 12-m antennas will be delivered to the VLA site in the fall of 2001. NRAO has contracted with Vertex for the delivery of the one prototype, while ESO has contracted with EIE for the other version. Each of the antennas will be tested to determine its parameters and its adherence to the specifications. In particular, *reflector surface accuracy and antenna pointing behavior will need to be determined under a wide range of operating conditions*. These tests should be done in a time span of about one year in order to meet the schedule of April 2003 for the contract of the production of the 64 antennas.

For the tests of the antennas, they will be equipped with a special holography receiver to measure and set the surface, and with a separate set of astronomy receivers at 8, 3 and 1.3 mm wavelength for establishing the pointing model and to perform further pointing and aperture efficiency measurements. The correlator for the test system will be a clone of the GBT spectrometer, capable of single-baseline cross-correlation for interferometry as well as autocorrelation for single-dish tests. This device is substantially different from the array correlator, a prototype of which will not be available until late in the test program.

The ALMA antennas are specified to perform well at the short submillimeter wavelength of 330 µm. Thus the surface accuracy is specified at 25 µm (goal 20 µm) and the pointing accuracy, between calibrations, should be better than 1”. It is a challenging task to measure the antenna characteristics astronomically to a precision sufficient to confirm the specifications. The use of a terrestrial transmitter as the prime holographic signal source should nevertheless permit sufficiently precise measurements of the antenna surface, albeit at only one elevation angle.

The prototype antennas will also be used for the initial tests of special metrology systems, which have been included by the antenna contractors or are developed by the ALMA consortium. A preliminary program of this work is included later in the PB.

Of equal importance is the measurement of pointing stability under influence of wind and solar radiation. Obtaining a pointing model with arc-second accuracy will not be easy in view of the relative scarcity of sufficiently strong pointing sources at 3 and 1.3 mm wavelength. Separating wind induced pointing variations from atmospheric (refraction) effects may be difficult. The tests of the pointing behavior of the antennas could be a time consuming effort. For a meaningful comparison between the two antennas at this level of accuracy, it might be necessary to perform many of the tests in the domain of environmental influences with both antennas simultaneously.

The stability of the reflector surface under gravity, wind and temperature changes needs to be carefully measured to determine the submillimeter wavelength quality of the antennas. Lacking a metrology system to measure the shape of the reflector at arbitrary elevation angles in “real-time”, in single dish mode this can only be done by the measurement of aperture efficiency and beam maps. It might be feasible to obtain useful data from a series of holography surface maps, obtained under varying conditions of wind and thermal regime (both sufficiently stable over the time of the holography measurement). However, as soon as both antennas are operating in a sufficiently reliable and reproducible way, and adequately debugged and reliable electronics to support interferometric operation is available, then interferometric holographic observations on, for example, the strong SiO maser sources at ~86 GHz will become possible. Such astronomical measurements will become an important part of the antenna test procedure – the prime measurement of large scale deformations as a function of antenna elevation. Interferometric tests will contribute further, essential knowledge about the antenna behavior, such as a quantitative check on the specified 15 µm wavefront stability of the antennas when operating together as an interferometer.

The initial antenna measurements **must** be performed in single dish mode. Interferometric operation puts different demands on the electronics – such as phase stability and coherence of the local oscillator systems, and some necessary degree of confidence in the overall operation of both antennas and electronics. Some measurements can **only** be performed in interferometric mode, while some other measurements, perhaps including pointing studies, may be performed equally well in single dish or in interferometric mode. During the antenna test period, engineering judgement will be used to decide at which point to switch from predominantly single dish to interferometric testing.

There is also a need to install and test prototype ALMA instrumentation on the test interferometer before starting the mass production of this equipment. The schedule for the development of the ALMA instrumentation does not allow these tests to be delayed until the antenna test program has been completed. Thus, we need a test schedule whereby both objectives can be realized with as little mutual interference as possible. Once the antenna tests have been finished, the TI will be available fully for the further testing of prototype ALMA instrumentation and software.

3. Future Revisions to this Project Book

Finally, this *TIPB* is to be considered a living document. Inevitably, as our planning and instrumentation development for the TI continue, there will be changes; regrettably but equally inevitably, this first version of the *TIPB* (February 2000) will likely contain errors, omissions and inconsistencies. The editors (DTE & JWMB) ask readers to draw our attention to such errors. The latest and definitive version of this *TIPB* will always be that available on the WWW.

JWMB & DTE, 2000-02-17

ALMA Proto-Memo
ALMA Prototype Antenna Tests

Darrel Emerson
email: demerson@nrao.edu
and
Jeffrey G. Mangum
email: jmangum@nrao.edu
National Radio Astronomy Observatory
949 North Cherry Avenue
Tucson, AZ 85721

February 16, 2000

Abstract

This memo describes the ALMA prototype antenna tests. In formulating this plan, our basic assumptions are:

1. The primary goal of the ALMA prototype antenna tests are to evaluate the prototype antenna to determine if it meets the manufacturer specifications set forth in the antenna fabrication contract.
2. A secondary goal of these tests is to evaluate the ALMA electronics systems, such as LO, IF, etc.
3. Testing of the electronics and monitor and control software should not interfere with evaluation of the prototype antenna.

Our approach to this plan is purposely conservative, emphasizing single antenna tests of the prototype antenna, which are followed by interferometric tests once interferometric capabilities can be established.

1 System Installation

It will be necessary to install a number of ancillary devices on the prototype antenna in order to complete the tests listed in §2. Most of these devices will be used to test the mechanical integrity of the telescope structure. Before installing any of these devices, the following tasks must be completed:

1. Cable outfitting for NRAO equipment
2. Installation of additional safety equipment
   - Personnel and antenna safety equipment

1.1 Install Measurement Devices

1. Thermistors
2. Tiltmeters
3. Accelerometers
4. Strain Gauges
5. On-Axis Cable Wrap
6. RF Transparent Membrane
7. Instrument Racks
8. Cryogenic Compressor
9. Telephone and Intercoms
10. Prepare Control Room and Connection Cables
11. Quadrant Detector
12. Solar Filter
13. Molecular Sieve
    (a) For oxygenation of receiver cabin
14. Nutator
15. Alignment of Receiver Optical Systems
16. Control interfaces
    (a) NRAO computer hardware/software interfaces
17. Optical pointing system
18. Calibration Systems

(a) 22/183 GHz phase calibration system
(b) Hot load vane
(c) Berkeley apex calibration system
(d) Photonic LO injection at apex

19. Evaluation Receiver

20. Prime Focus Holography Receiver

2 System Tests

1. General Mechanical Inspection

   (a) Wiring, Power, and UPS
   (b) Brakes
   (c) Interface Integrity
   (d) Slew Rate Check
   (e) Tracking Check
      i. Sidereal, fast-switching, OTF
   (f) Weather Proofing Check
   (g) AUI Equipment Installation and Removal Checks
   (h) Grounding Checks
      i. Antenna-to-ground and antenna grounding measurements
   (i) Antenna Hard-Stop Motion Tests
      i. Antenna at full velocity brake test and check
   (j) Optics Check
      i. Aperture diameter
      ii. Optics locations, alignments, travel, stability, blockage
   (k) Cable Wrap Tests
      i. Range and operation
   (l) Transporter Interface
   (m) Safety Inspection
      i. Stow, power failure, smoke detection, power faults, wind, lockouts, servo oscillation, etc.

(n) Surface Setting

2. Dynamical/Mechanical Tests

   (a) Tiltmeter Checks of AZ Rotational Stability
   (b) Resonant Frequency Measurements
   (c) Acceleration Measurements
       i. Check for AZ/EL/apex oscillations
   (d) Movement Tests
       i. Motor current, power consumption, bearing friction measurements during slewing and tracking
   (e) Apex Translations
       i. Accelerations, velocity, travel, range, stability, natural frequency, and dampening
   (f) Optical Telescope Operation and Stability
   (g) Panel Mounting Stability
       i. Stability, adjustment, and gap check
   (h) Transporter Testing of Antenna
       i. Moving, stability, repeatability
   (i) Nutator Testing
       i. Switching, throw, and duty-cycle performance
   (j) Vertex Shutter
       i. Transparency characteristics and mechanical stability
   (k) Receiver Cabin Temperature Stability and Capacity
   (l) Calibration Systems Testing
   (m) Test Antenna Transporter Survival Conditions
   (n) Verify Code Compliance of Antenna
   (o) Test Antenna RFI/EMI Characteristics
       i. To be completed in collaboration with VLA staff
   (p) Verify Antenna Alignment
   (q) Evaluate Antenna Electrical Cooling at Altitude
   (r) Check Auto Stow, Emergency Stops, and Range Limits
   (s) Evaluation of Antenna Manuals

(t) Inspect Corrosion Resistance Compliance

3. Monitoring (requires fast sampling)

   (a) Temperatures
   (b) Tiltmeters
   (c) Motor Currents and Temperatures
   (d) Weather
      i. T_{amb}, P_{amb}, V_{wind}, D_{wind}, *etc.*
   (e) Acceleration
      i. Check for flutter in the telescope servo
   (f) Strain
   (g) Quadrant Motion
   (h) General Correlations
      i. Use archived weather data to look for correlated effects on antenna.
      ii. Start this work after measurement systems have been installed.
   (i) Receiver, Rack Equipment, Cryogenics, and Safety Items

4. Optical Tracking and Pointing

   (a) Optical Pointing Model
      i. First astronomical pointing model
      ii. Study time stability of pointing model
   (b) Optical guide star tracking

5. Holography

   (a) Remove Subreflector
   (b) Pointing and Tracking System
   (c) Control System Interface
   (d) Holography Frontend/Backend
   (e) Reference Feed Measurement (should have been done in lab)
   (f) Holographic Data Acquisition

(g) Raster Scanning
(h) Holography Data Analysis System
(i) Mountain-Top Beacon (92 GHz)
(j) Mast-Top Near-Field Measurement
(k) First Holographic Maps
    i. 129×129
    ii. 10 cm spatial resolution
    iii. Day/night repeatability
    iv. Elevation dependencies
(l) Reinstall Subreflector

6. Millimeter Receiver Tests

    (a) Apex Focus, Translation, and Receiver Alignment
    (b) Radio Pointing (90/230 GHz)
    (c) Radio/Optical Pointing Comparison
    (d) Radio Tracking Tests (Moon, Jupiter etc.)
    (e) Efficiency Tests
        i. Best done at highest frequency possible
    (f) Beam Studies (Moon, planet scans)
    (g) Forward/Rear Spillover Efficiency Studies (sky tips *etc.*)
    (h) Fast Switching Tests
        i. Best done at 230 GHz
        ii. Check settling time
    (i) OTF Turn-Around Performance
    (j) Solar observation test
        i. Heating of subreflector, feedlegs, cabin, solar filter, Rx, and RF window
    (k) Nutation/Total Power Tests
        i. Pointing stability
        ii. Check beam throw on sky
    (l) Spectral Baseline Stability Tests (requires correlator)
    (m) Testing of Calibration Systems
    (n) Stability With Transportation
    (o) Verify Surface Accuracy Budget

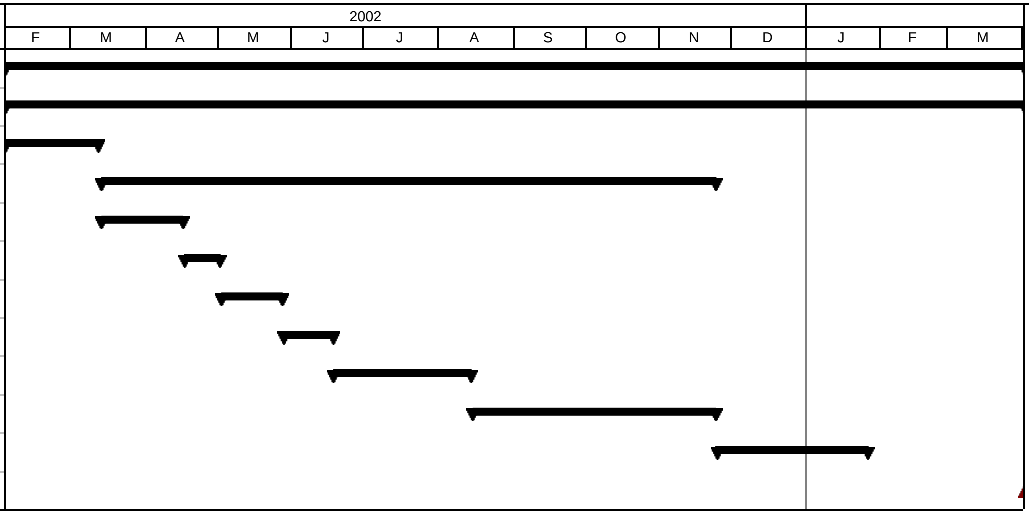
3 Interferometer Tests

1. Check Close Packing Limitations
   (a) Only need be done if two similar antennae are tested
2. Phase Stability and Electronics Tests
   (a) Lateral displacements, wind, bearing slop, differential temperature
   (b) Stability while fast switching
   (c) Includes round-trip phase correction system installation and testing
   (d) Includes path length error evaluation
3. More Extensive Radio Pointing Tests
4. Interferometric Holography:
   (a) Using 86 GHz SiO maser (needs spectral correlator) and/or planets.
   (b) Needs complete interferometric, phase stable, fringe tracking, delay tracking electronics.
   (c) Measure surface (e.g. 48×48) deformations as a function of elevation.
   (d) Might tweak surface setting with these measurements

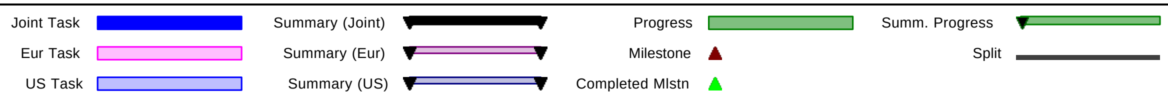
ALMA Task Scheduling

Antenna Testing selected

ID	WBS (f)	Task	Start	Finish	Duration
9	9	System Engineering & Integration	2/1/2002	4/1/2003	425d
16	9.7	Joint evaluation of prototype antennas	2/1/2002	4/1/2003	425d
17	9.7.1	System Installation	2/1/2002	3/12/2002	40d
41	9.7.2	System Tests	3/13/2002	11/24/2002	257d
42	9.7.2.1	General Mechanical Inspection	3/13/2002	4/16/2002	35d
57	9.7.2.2	Dynamical/Mechanical Tests	4/17/2002	5/2/2002	15.5d
78	9.7.2.3	Monitoring	5/2/2002	5/28/2002	26d
88	9.7.2.4	Optical Tracking and Pointing	5/28/2002	6/18/2002	21d
91	9.7.2.5	Holography	6/18/2002	8/14/2002	57.5d
104	9.7.2.6	Millimeter Receiver Tests	8/15/2002	11/24/2002	102d
120	9.7.3	Interferometer Tests	11/24/2002	1/26/2003	63d
125	**9.7.4**	**Selection of production antenna design**	**4/1/2003**	**4/1/2003**	**0d**



Milestones: **bold type**
Summary Tasks: **underline**



ALMA Task Scheduling

Antenna Testing selected

2003									2004																	
A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M

4/1/2003

Milestones: **bold type**
Summary Tasks: **underline**

Joint Task
Eur Task
US Task
Summary (Joint)
Summary (Eur)
Summary (US)
Progress
Milestone
Completed Mlstn
Summ. Progress
Split

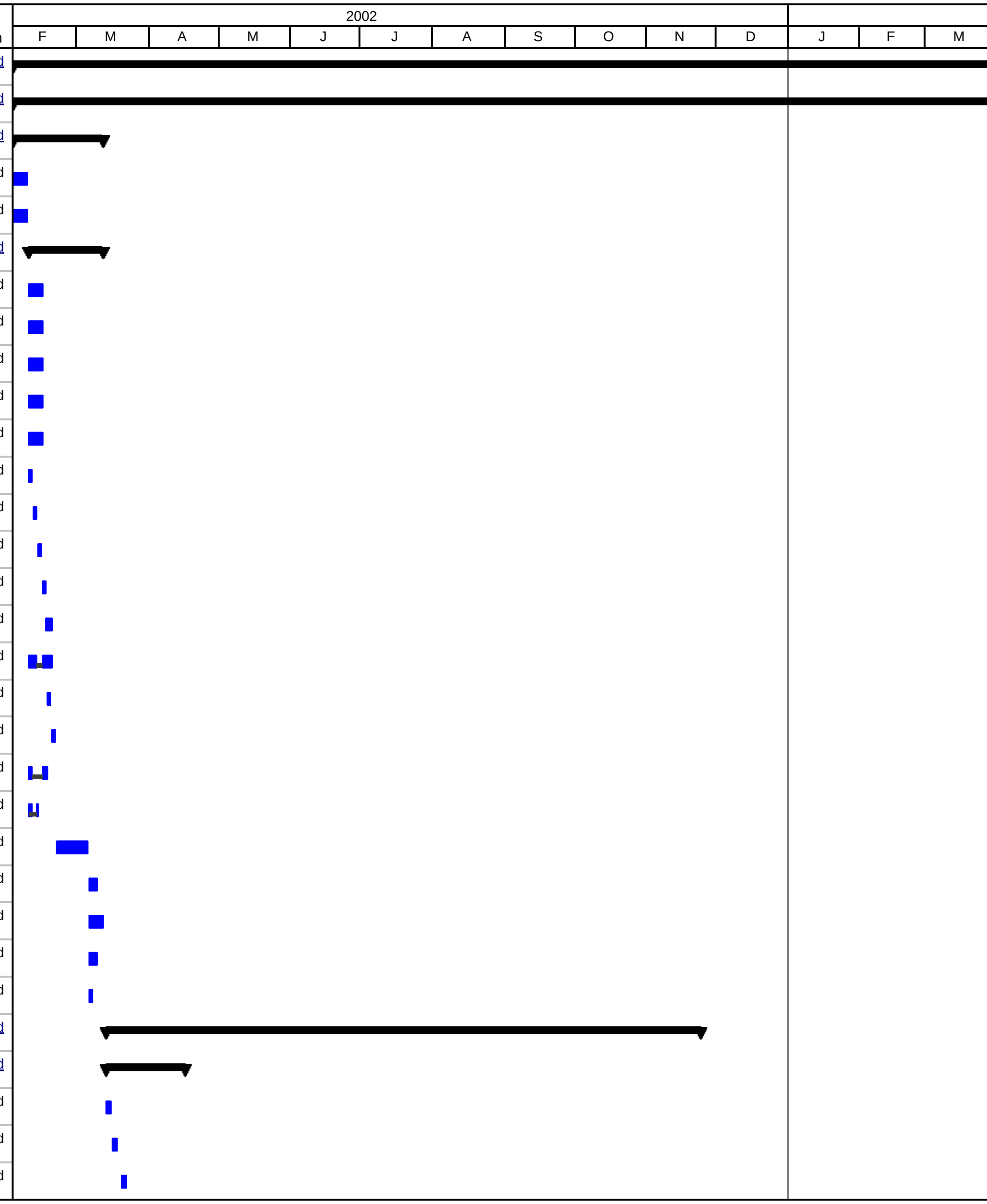
Atacama
Large
Millimeter
Array

ALMA Task Scheduling

Antenna Testing selected

File: almaantennaprototypingtestsrev01.mpp
View: Clean Gantt View
Printed: 9:28 AM Wed 2/16/00

ID	WBS (f)	Task	Start	Finish	Duration
9	9	System Engineering & Integration	2/1/2002	4/1/2003	425d
16	9.7	Joint evaluation of prototype antennas	2/1/2002	4/1/2003	425d
17	9.7.1	System Installation	2/1/2002	3/12/2002	40d
18	9.7.1.1	Outfitting with Cables for NRAO Equipment	2/1/2002	2/7/2002	7d
19	9.7.1.2	Additional Safety Equipment	2/1/2002	2/7/2002	7d
20	9.7.1.3	Install Measurement Devices	2/8/2002	3/12/2002	33d
21	9.7.1.3.1	Thermistors	2/8/2002	2/14/2002	7d
22	9.7.1.3.2	Tiltmeters	2/8/2002	2/14/2002	7d
23	9.7.1.3.3	Accelerometers	2/8/2002	2/14/2002	7d
24	9.7.1.3.4	Strain Gauges	2/8/2002	2/14/2002	7d
25	9.7.1.3.5	On-Axis Cable Wrap	2/8/2002	2/14/2002	7d
26	9.7.1.3.6	RF Transparent Membrane	2/8/2002	2/9/2002	2d
27	9.7.1.3.7	Instrument Racks	2/10/2002	2/11/2002	2d
28	9.7.1.3.8	Cryogenic Compressor and Helium Lines	2/12/2002	2/13/2002	2d
29	9.7.1.3.9	Telephone and Intercoms	2/14/2002	2/15/2002	2d
30	9.7.1.3.10	Prepare Control Room and Connection Cables	2/15/2002	2/18/2002	4d
31	9.7.1.3.11	Quadrant Detector	2/8/2002	2/18/2002	7d
32	9.7.1.3.12	Solar Filter	2/16/2002	2/17/2002	2d
33	9.7.1.3.13	Molecular Sieve	2/18/2002	2/19/2002	2d
34	9.7.1.3.14	Nutator	2/8/2002	2/16/2002	3d
35	9.7.1.3.15	Alignment of Receiver Optical Systems	2/8/2002	2/12/2002	2d
36	9.7.1.3.16	Control Interfaces	2/20/2002	3/5/2002	14d
37	9.7.1.3.17	Optical Pointing System	3/6/2002	3/9/2002	4d
38	9.7.1.3.18	Calibration Systems	3/6/2002	3/12/2002	7d
39	9.7.1.3.19	Evaluation Receiver	3/6/2002	3/9/2002	4d
40	9.7.1.3.20	Prime Focus Holography Receiver	3/6/2002	3/7/2002	2d
41	9.7.2	System Tests	3/13/2002	11/24/2002	257d
42	9.7.2.1	General Mechanical Inspection	3/13/2002	4/16/2002	35d
43	9.7.2.1.1	Wiring, Power, and UPS	3/13/2002	3/15/2002	3d
44	9.7.2.1.2	Brakes	3/16/2002	3/18/2002	3d
45	9.7.2.1.3	Interface Integrity	3/20/2002	3/22/2002	3d



Milestones: **bold type**
Summary Tasks: **underline**

Joint Task
Summary (Joint)
Progress
Summ. Progress
Eur Task
Summary (Eur)
Milestone
Split
US Task
Summary (US)
Completed Mlstn

ALMA Task Scheduling

Antenna Testing selected

ID	WBS (f)	Task	Start	Finish	Duration
46	9.7.2.1.4	Slew Rate Check	3/26/2002	3/26/2002	1d
47	9.7.2.1.5	Tracking Check	3/16/2002	3/19/2002	4d
48	9.7.2.1.6	Weather Proofing Check	3/19/2002	3/25/2002	7d
49	9.7.2.1.7	AUI Equipment Installation and Removal Checks	3/23/2002	3/23/2002	1d
50	9.7.2.1.8	Grounding Checks	3/27/2002	3/27/2002	1d
51	9.7.2.1.9	Antenna "hard-stop" Motion Tests	3/24/2002	3/24/2002	1d
52	9.7.2.1.10	Optics Check	3/25/2002	3/31/2002	7d
53	9.7.2.1.11	Cable Wrap Tests	3/28/2002	3/29/2002	2d
54	9.7.2.1.12	Transporter Interface	3/30/2002	3/30/2002	1d
55	9.7.2.1.13	Safety Inspection	4/1/2002	4/2/2002	2d
56	9.7.2.1.14	Surface Setting	4/3/2002	4/16/2002	14d
<u>57</u>	<u>9.7.2.2</u>	<u>Dynamical/Mechanical Tests</u>	<u>4/17/2002</u>	<u>5/2/2002</u>	<u>15.5d</u>
58	9.7.2.2.1	Tiltmeter Checks of AZ	4/17/2002	4/19/2002	3d
59	9.7.2.2.2	Resonant Frequency Measurements	4/17/2002	4/17/2002	1d
60	9.7.2.2.3	Acceleration Measurements	4/20/2002	4/21/2002	1d
61	9.7.2.2.4	Movement Tests	4/21/2002	4/22/2002	1d
62	9.7.2.2.5	Apex Translations	4/22/2002	4/23/2002	1d
63	9.7.2.2.6	Optical Telescope Operation and Stability	4/20/2002	4/21/2002	1.5d
64	9.7.2.2.7	Panel Mounting Stability	4/23/2002	4/26/2002	3d
65	9.7.2.2.8	Transporter Testing of Antenna	4/21/2002	4/24/2002	3d
66	9.7.2.2.9	Nutator Testing	4/17/2002	4/19/2002	3d
67	9.7.2.2.10	Vertex Shutter	4/26/2002	4/29/2002	3d
68	9.7.2.2.11	Receiver Cabin Temperature Stability and Capac	4/17/2002	4/20/2002	1d
69	9.7.2.2.12	Calibration System Testing	4/17/2002	4/30/2002	14d
70	9.7.2.2.13	Test Antenna Transporter Survival Conditions	4/24/2002	4/25/2002	1d
71	9.7.2.2.14	Verify Code Compliance of Antenna	4/25/2002	4/26/2002	1d
72	9.7.2.2.15	Test Antenna RFI/EMI	4/17/2002	4/19/2002	3d
73	9.7.2.2.16	Verify Antenna Alignment	4/29/2002	5/2/2002	3d
74	9.7.2.2.17	Evaluate Antenna Electrical Cooling at Altitude	4/26/2002	4/27/2002	1d
75	9.7.2.2.18	Check Auto Stow, Emergency Stops, and Range	4/27/2002	4/28/2002	1d
76	9.7.2.2.19	Evaluation of Antenna Manuals	4/28/2002	4/29/2002	1d

2002: F M A M J J A S O N D | J F M

Milestones: **bold type**
Summary Tasks: <u>**underline**</u>

Joint Task | Summary (Joint) | Progress | Summ. Progress
Eur Task | Summary (Eur) | Milestone | Split
US Task | Summary (US) | Completed Mlstn

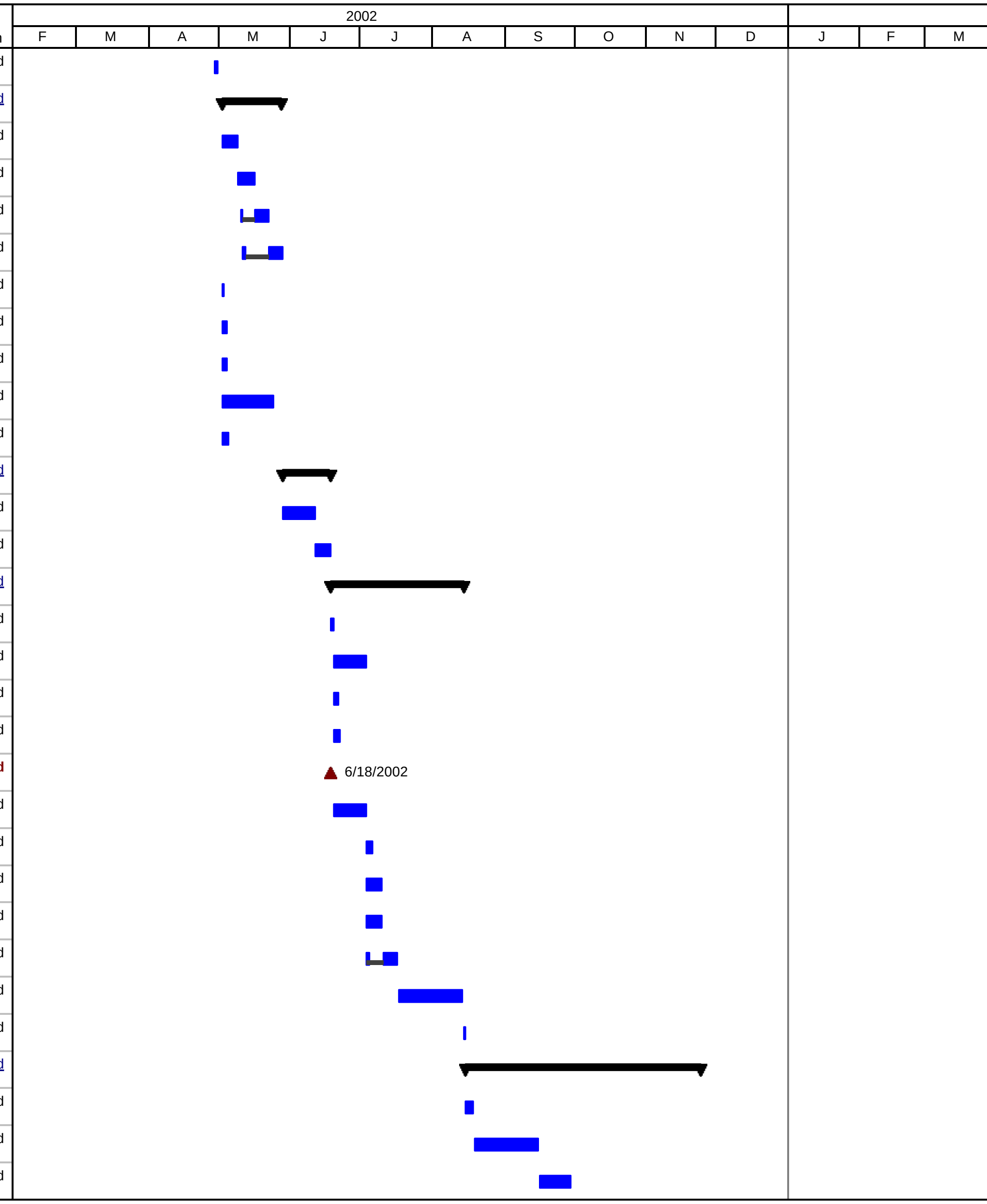
Atacama
Large
Millimeter
Array

ALMA Task Scheduling

Antenna Testing selected

File: almaantennaprototypingtestsrev01.mpp
View: Clean Gantt View
Printed: 9:28 AM Wed 2/16/00

ID	WBS (f)	Task	Start	Finish	Duration
77	9.7.2.2.20	Inspect Corrosion Resistant Compliance	4/29/2002	4/30/2002	1d
78	9.7.2.3	Monitoring	5/2/2002	5/28/2002	26d
79	9.7.2.3.1	Temperatures	5/2/2002	5/9/2002	7d
80	9.7.2.3.2	Tiltmeters	5/9/2002	5/16/2002	7d
81	9.7.2.3.3	Motor Currents and Temperatures	5/10/2002	5/22/2002	7d
82	9.7.2.3.4	Weather	5/11/2002	5/28/2002	7d
83	9.7.2.3.5	Acceleration	5/2/2002	5/3/2002	1d
84	9.7.2.3.6	Strain	5/2/2002	5/4/2002	2d
85	9.7.2.3.7	Quadrant Motion	5/2/2002	5/4/2002	2d
86	9.7.2.3.8	General Correlations	5/2/2002	5/24/2002	21d
87	9.7.2.3.9	Receiver, Rack Equipment, Cryogenics, and Sa	5/2/2002	5/5/2002	3d
88	9.7.2.4	Optical Tracking and Pointing	5/28/2002	6/18/2002	21d
89	9.7.2.4.1	Optical Pointing Model	5/28/2002	6/11/2002	14d
90	9.7.2.4.2	Optical Guide Star Tracking	6/11/2002	6/18/2002	7d
91	9.7.2.5	Holography	6/18/2002	8/14/2002	57.5d
92	9.7.2.5.1	Remove Subreflector	6/18/2002	6/19/2002	1d
93	9.7.2.5.2	Pointing and Tracking System	6/19/2002	7/3/2002	14d
94	9.7.2.5.3	Control Interface	6/19/2002	6/21/2002	2d
95	9.7.2.5.4	Holography Frontend/Backend	6/19/2002	6/22/2002	3d
96	**9.7.2.5.5**	**Reference Feed Measurement**	**6/18/2002**	**6/18/2002**	**0d**
97	9.7.2.5.6	Holographic Data Acquisition	6/19/2002	7/3/2002	14d
98	9.7.2.5.7	Raster Scanning	7/3/2002	7/6/2002	3d
99	9.7.2.5.8	Holography Data Analysis System	7/3/2002	7/10/2002	7d
100	9.7.2.5.9	Mountain-Top Beacon	7/3/2002	7/10/2002	7d
101	9.7.2.5.10	Mast-Top Near Field Measurement	7/3/2002	7/16/2002	7d
102	9.7.2.5.11	First Holographic Maps	7/17/2002	8/13/2002	28d
103	9.7.2.5.12	Re-install Subreflector	8/14/2002	8/14/2002	1d
104	9.7.2.6	Millimeter Receiver Tests	8/15/2002	11/24/2002	102d
105	9.7.2.6.1	Apex Focus, Translation, and Receiver Alignment	8/15/2002	8/18/2002	4d
106	9.7.2.6.2	Radio Pointing (90/230 GHz)	8/19/2002	9/15/2002	28d
107	9.7.2.6.3	Radio/Optical Pointing Comparison	9/16/2002	9/29/2002	14d



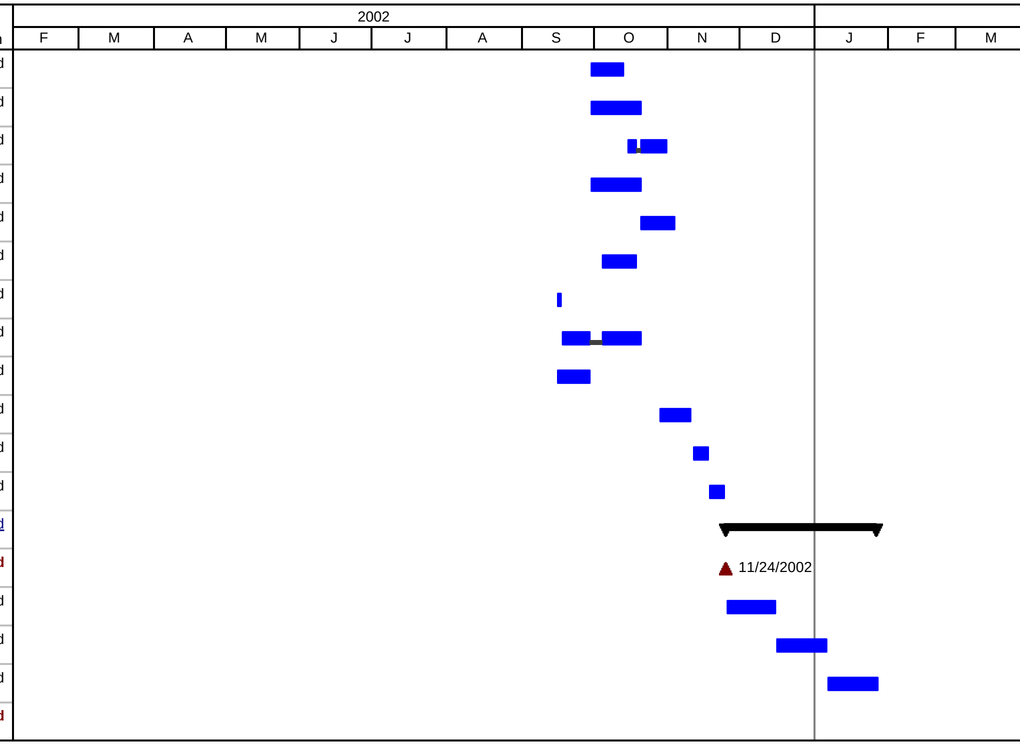
Milestones: **bold type**
Summary Tasks: **underline**

Joint Task
Summary (Joint)
Progress
Summ. Progress
Eur Task
Summary (Eur)
Milestone
Split
US Task
Summary (US)
Completed Mlstn

ALMA Task Scheduling

Antenna Testing selected

ID	WBS (f)	Task	Start	Finish	Duration
108	9.7.2.6.4	Radio Tracking Tests	9/30/2002	10/13/2002	14d
109	9.7.2.6.5	Efficiency Tests	9/30/2002	10/20/2002	21d
110	9.7.2.6.6	Beam Studies	10/15/2002	10/31/2002	14d
111	9.7.2.6.7	Forward/Rear Spillover Efficiency Studies	9/30/2002	10/20/2002	21d
112	9.7.2.6.8	Fast Switching Tests (230 GHz)	10/20/2002	11/3/2002	14d
113	9.7.2.6.9	OTF Turn-Around Performance	10/4/2002	10/18/2002	14d
114	9.7.2.6.10	Solar Observation Test	9/16/2002	9/17/2002	2d
115	9.7.2.6.11	Nutation/Total Power Tests	9/18/2002	10/20/2002	28d
116	9.7.2.6.12	Spectral Baseline Stability Tests	9/16/2002	9/29/2002	14d
117	9.7.2.6.13	Testing of Calibration Systems	10/28/2002	11/10/2002	14d
118	9.7.2.6.14	Stability with Transport	11/11/2002	11/17/2002	7d
119	9.7.2.6.15	Verify Surface Accuracy Budget	11/18/2002	11/24/2002	7d
120	9.7.3	Interferometer Tests	11/24/2002	1/26/2003	63d
121	**9.7.3.1**	**Check Close Packing Limitations**	**11/24/2002**	**11/24/2002**	**0d**
122	9.7.3.2	Phase Stability and Electronics Tests	11/25/2002	12/15/2002	21d
123	9.7.3.3	Radio Pointing Tests	12/16/2002	1/5/2003	21d
124	9.7.3.4	Interferometric Holography	1/6/2003	1/26/2003	21d
125	**9.7.4**	**Selection of production antenna design**	**4/1/2003**	**4/1/2003**	**0d**



Milestones: **bold type**
Summary Tasks: **underline**

Joint Task
Eur Task
US Task
Summary (Joint)
Summary (Eur)
Summary (US)
Progress
Milestone
Completed Mlstn
Summ. Progress
Split

Atacama
Large
Millimeter
Array

ALMA Task Scheduling

Antenna Testing selected

File: almaantennaprototypingtestsrev01.mpp
View: Clean Gantt View
Printed: 9:28 AM Wed 2/16/00

2003									2004																
A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M

Milestones: **bold type**
Summary Tasks: **underline**

Joint Task
Eur Task
US Task
Summary (Joint)
Summary (Eur)
Summary (US)
Progress
Milestone
Completed Mlstn
Summ. Progress
Split

Atacama
Large
Millimeter
Array

ALMA Task Scheduling

Antenna Testing selected

File: almaantennaprototypingtestsrev01.mpp
View: Clean Gantt View
Printed: 9:28 AM Wed 2/16/00

2003									2004																	
A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	

4/1/2003

Milestones: **bold type**
Summary Tasks: **underline**

Joint Task
Eur Task
US Task
Summary (Joint)
Summary (Eur)
Summary (US)
Progress
Milestone
Completed Mlstn
Summ. Progress
Split

ALMA Test Interferometer Project Book, Chapter 4

SYSTEM DESIGN

Larry D'Addario
Last revised 2000-Feb-23

4.1 General

A basic principle of the design is to follow closely the design of the array. Whenever possible, devices constructed for the test interferometer at the major subassembly level ("modules") should be prototypes of those that will be used in the array. There are necessarily some exceptions to this, either because the array design is not yet decided or because there is insufficient time to build the prototype before it is needed in the test interferometer. In the first case, we choose the design for the test interferometer that seems most likely to be chosen for the array; in the second case, an expedient substitute is used.

This section of the project book will describe each major subsystem of the test interferometer in turn, concentrating on the differences from the array design. Details that are identical to the present baseline design for the array will be covered by reference to the main ALMA Project Book.

Figure 1 is an overall block diagram of the test interferometer. We will refer to this often in the following discussion. Table 1 lists some major parameters.

Table 1: KEY PARAMETERS

	Test System	Array
Receiving bands		
#1	31.3-45 GHz HFET	31.3-45 GHz HFET
#3	85-110 GHz HFET	89-116 GHz TBD
	90-116 GHz SIS	
#6	211-270 GHz SIS	211-270 GHz SIS
Polarization	all: dual linear	all: dual linear
1st LO reference	laser synth, 28-110GHz	laser synth, 28-122GHz
1st LO source	YTO, GDOs	YTO, mult chain, pwr amp
IF band	#1: 4-12 GHz	all: 4-12 GHz
	#3,6: 4-6 GHz	
IF channels	2/band (pol)	4/band (pol,sideband)
Baseband channels	2	8 (4 pol pairs)
2nd LOs	4	4 (each pol pair)
Baseband channel width	800 MHz	2000 MHz
	100 MHz	
Signal transmission	1 10Gb/s opt channel	12 10Gb/s opt channels
Correlator capacity		
Cross-correlation	512 chan, all pols	512 chan/BB * 8 @2GHz
Auto correlation	512 chan, 4 inputs	512 chan/BB * 8 @2GHz

4.2 Front Ends

The package containing input optics, RF stages with conversion to IF, vacuum dewar and cryogenics, along with associated bias supplies and controls, is known as an "evaluation receiver." This is to indicate that it is substantially different from the array receivers, and was originally intended only to allow evaluation of the antennas.

A basic difference from the array receiver is that only three of the 10 ALMA bands are supported, namely bands 1, 3, and 6 (see Table 1). On the other hand, two front ends are included for Band 3, an HFET version and an SIS version. This is to allow the HFET receiver to be fully evaluated at the relatively high frequency, and also because it is can provide the full

8 GHz of instantaneous bandwidth whereas the available SIS mixers cannot. The principal devices used to implement each front end are also different from those expected to be used in the array receivers, resulting in significant performance differences. The Band 1 assembly should be a true
prototype for the array, using optics, HFET amplifiers, and other components very close to those of the array. The other assemblies will be quite different. For Band 3, the HFET amplifier will likely not cover the upper end of the ALMA band; but it will extend lower in frequency, providing coverage of the important SiO line at 86 Ghz. The Band 3 SIS mixers will be single- ended with movable backshorts, unlike the fixed-tuned, balanced, sideband-separating mixers that are planned for the array. The Band 6 SIS mixers will be fixed tuned, but also single ended. The IF range of both bands' SIS mixers will be 4-6 GHz rather than the full 4-12 GHz of ALMA.

See chapter 6 of this book for further details.

4.3 Cryogenics

The evaluation receivers will include 3-stage cryocoolers that are copies of those used at NRAO. They include a commercial 2-stage GM refrigerator (CTI model 1020) and a Joule-Thomson expansion circuit whose design was developed at JPL, NRAO, and CSIRO in the 1970s. The helium compressor is based on commercial scroll pumps (Hitachi model 500RHH) and is integrated at the NRAO with the necessary oil cooling and separation equipment as well as control and monitoring electronics.

The cryocoolers for the array receivers are expected to be very different, but details are not yet known.

See chapter 6 of this book for further details.

4.4 Local oscillators

4.4.1 Central reference generation and transmission

Nearly all time-dependent functions in the array must be coherent with a single master oscillator from which reference signals are derived and distributed. For the array, this will be a hydrogen maser; for the test interferometer, the absolute frequency and stability of the master is less critical, and another type of oscillator (TBD) may be used.

As shown in Figure 4.1, we begin by generating from the master a set of fixed-frequency signals covering the range 20 Hz through 2.0 GHz. The Central Reference Generator assembly should be a prototype for the array, except that a reference at 100.0 MHz is needed for the Test Correlator clock and this frequency is not needed in the array.

A mm-wavelength reference is then synthesized for the first LO at each antenna. This process is identical to that planned for the array. It uses a microwave synthesizer to produce 8.6-10.5 GHz in 5 MHz steps (using primarily the 2 GHz and 5 MHz references from the master), followed by synthesis of 27-122 GHz as the difference between two laser-generated optical frequencies. The lasers are designated as "master" and "slave," with one master required for the array and one slave for each subarray. For the test interferometer, there is only one "subarray," but we choose to provide two slave lasers and two independent laser synthesizers so as to be able to operate the antennas independently and on different frequencies during single- dish testing (See Fig. 4.1, sheets 1 and 2). The two-frequency optical signal is sent to each antenna on a single-mode fiber. For each antenna separately, the optical signal passes through a line-length stabilizer based on two-way optical phase measurement of the master laser signal. For details, see section 7.3.2 of this book.

For the test interferometer, the mm reference range required is 27-110 GHz, but a minimum range of 27-122 GHz will be covered as the array prototype. In support of a possible direct-photonic LO system, tests of the synthesizer at much higher frequencies will be conducted. The 8.6-10.5 GHz microwave synthesizers for the array will use a custom design with careful attention to long-term phase stability and phase noise. However, for the test interferometer, commercial synthesizers may be used temporarily, so as to allow more time for development of the custom version.

Meanwhile, the 2 GHz reference is transmitted to each antenna as intensity modulation on the master laser carrier; and the 20 Hz and 25 MHz references are multiplexed and transmitted on a dedicated optical carrier (by a modulation method TBD), probably on a separate fiber. This also is identical to the baseline design for the array, and thus serves as a prototype.

At each antenna, the Reference Receiver assembly (Fig. 4.1, sheet 2) demodulates the 20 Hz, 25 MHz, and 2 GHz signals from their carriers; frequency-shifts the master laser carrier and transmits it back on the same fiber to the center for line length stabilization; produces additional fixed references at 100 MHz and 125 MHz; and distributes all the fixed references to various devices in the receiver cabin. Except for producing the 100 MHz reference (needed by the test interferometer digitizers and not needed for the array), this module is identical to the array baseline and serves as a prototype.

4.4.2 First LOs

At the antenna, the mm reference is recovered by photomixing and used to phase lock a mm wavelength VCO. The VCO is part of a "driver" module (Fig. 4.1, sheet 6), which must provide sufficient power to generate the required LO signals. In the array, five such drivers will be required to cover the necessary frequencies up to 122 GHz. In the test interferometer, three drivers are sufficient to cover bands 1, 3, and 6. The concept is the same in both cases, but the implementations of the drivers are quite different. For the array, they will consist of YTOs followed by one or more frequency doublers and power amplifiers. This allows the necessary range to be covered with electronic tuning only. For the test interferometer, two drivers will use fundamental Gunn diode oscillators; these require mechanical adjustment to cover the necessary ranges, and automated tuning hardware will be included. One driver, for 27.3-33 GHz, will use a YTO for both the test interferometer and the array.

The PLL is offset by approximately 31 MHz from the main reference, using a direct digital synthesizer. The offset reference includes fringe rotation and phase switching.

The driver modules are supported by a First LO Controller and PLL assembly (sheet 5), which may be combined in one module.

4.4.3 2nd LOs

The second conversion (IF to baseband) requires LOs at 6-10 GHz. See the discussion in 4.5 below regarding the channelization differences between the array and the test interferometer. The array requires four second-LO synthesizers to provide full tuning flexibility, but two per antenna are sufficient for the test interferometer with the addition of a transfer switch.

Each second-LO synthesizer is a prototype for the array. The design covers the range in 62.5 MHz steps, with the possibility of finely-adjustable offsets from the nominal frequencies of several MHz. The offset includes fringe rotation, sideband suppression, and phase switching capability. (See Fig. 4.1, sheet 7 and section 7.4 of this book.)

4.5 Downconversion

Each of the two 4-12 GHz IF bands (one per polarization in the test interferometer, vs. 4 at two per polarization in the array) can be converted to baseband using one or more of the four baseband channels provided by the Downconverter module (sheet 8 and section 8.1 of this book). The Downconverter is nearly identical to the array version, and serves as a prototype. However, the array will have two such modules, one for each polarization, while the test interferometer needs only one. Although there are four baseband channels, only two can be processed by the test correlator. The second LO scheme (with two synthesizers) allowsthe two active channels to be tuned independently in any configuration. There are two baseband channels that cover the lower half of the IF band (4-8 GHz) and two that cover the upper half (8-12 GHz). Each IF input (polarization) can drive one channel in any permutation, or one IF can drive any two channels.

The only difference between the array and test interferometer downconverters is in the baseband channel frequency range. This is 2-4 GHz for the array, and either 1.6-2.4 GHz or 1.6-1.7 GHz for the test interferometer. All three ranges can be supported within a single module design by replacing the bandpass filters that determine the output frequencies. For the test interferometer, we will (funds permitting) build two modules per antenna and install the 1.6-2.4 Ghz filters in one and the 1.6-1.7 GHz filters in the other; changing bandwidth can then be accomplished by swapping the plug-in modules.

4.6 Digitization and signal transmission

A major constraint on the test interferometer design is produced by the properties of the test correlator, which is a "clone" of the GBT/12m telescope spectrometers. This correlator handles two signal channels per antenna, each of maximum bandwidth 800 MHz, and it operates at a 100 MHz clock rate (see further discussion in 4.7 below). At the 800 MHz bandwidth, sampling at 1600 Msamp/sec with three-level quantization is required. To support this, digitizer
modules that are exact copies of those constructed for the GBT and 12m telescopes will be used. Each digitizer requires a 100 MHz clock (internally multiplies to 1600 MHz) and each sample is encoded into 2b and demultiplexed by 16x to provide 32 bitstreams at 100 Mb/sec.

The GBT digitizers were designed for bandpass sampling of 800-1600 MHz signals. In our system, this would make it very difficult to obtain reasonable image rejection in the Downconverter. Therefore, we plan bandpass sampling at 1600-2400 MHz, and the digitizers have been tested over this range and found to provide satisfactory performance.

All four baseband channels will be digitized. The digitizer designs already exist and are straightforward to duplicate, and it is easier to provide the 4:2 channel selection digitally.
The two selected channels will be transmitted digitally to the center. This requires a total capacity of 6.4 Gb/sec, which fits within a single 10 Gb/sec optical channel of the type planned for the array. (The array antennas will require 8-12 of these channels.) In order to make the optical channel a prototype for the array, which uses 125 Mb/sec fully-demultiplexed bitstreams, the 100 Mb/sec streams will be converted to 125 Mb/sec by inserting a dummy bit for each 4 data bits. Every 5 of the rate-converted streams will be multiplexed by 5 to produce 16 streams of 625 Mb/sec each, and these will be further multiplexed to 10 Gb/sec for modulation onto the optical carrier. At the center, a receiving system reverses these steps to recover the original 64 bitstreams of 100 Mb/sec each.

For further details, see section 8.2 of this book.

4.7 Correlation

As mentioned above, the test correlator is a clone of the GBT/12m spectrometers. Its principal parameters are listed in Figure 1. The four input channels (2 per antenna) can be fully cross correlated (four cross-spectra, including cross-polarization products) or each can be autocorrelated (four spectra), but not both simultaneously. At 800 MHz bandwidth, 512 cross-correlation frequency channels are obtained. It also supports a 100 MHz bandwidth mode in which every 8th sample is processed and the other are ignored; this produces 8x as many channels or 1/64 the frequency resolution. Support of this mode is the reason for having a Downconverter version with 100 MHz bandwidth. For autocorrelation, the number of channels is doubled at either bandwidth.

For further details, see section 9 of this book.

4.8 Additional facilities

Although not shown in Figure 4.1, each test interferometer antenna will also be equipped with a nutating subreflector, for which the electro-mechanical drive mechanism and controls will be provided by NRAO. There will also be a holography system for operation at 94 GHz, consisting of a prime-focus front end that can be mounted in place of the subreflector; a cross- correlating back end; and a CW transmitter mounted on a tower. The holography system is further described in section 5 of this book.

4.9 **Device List**

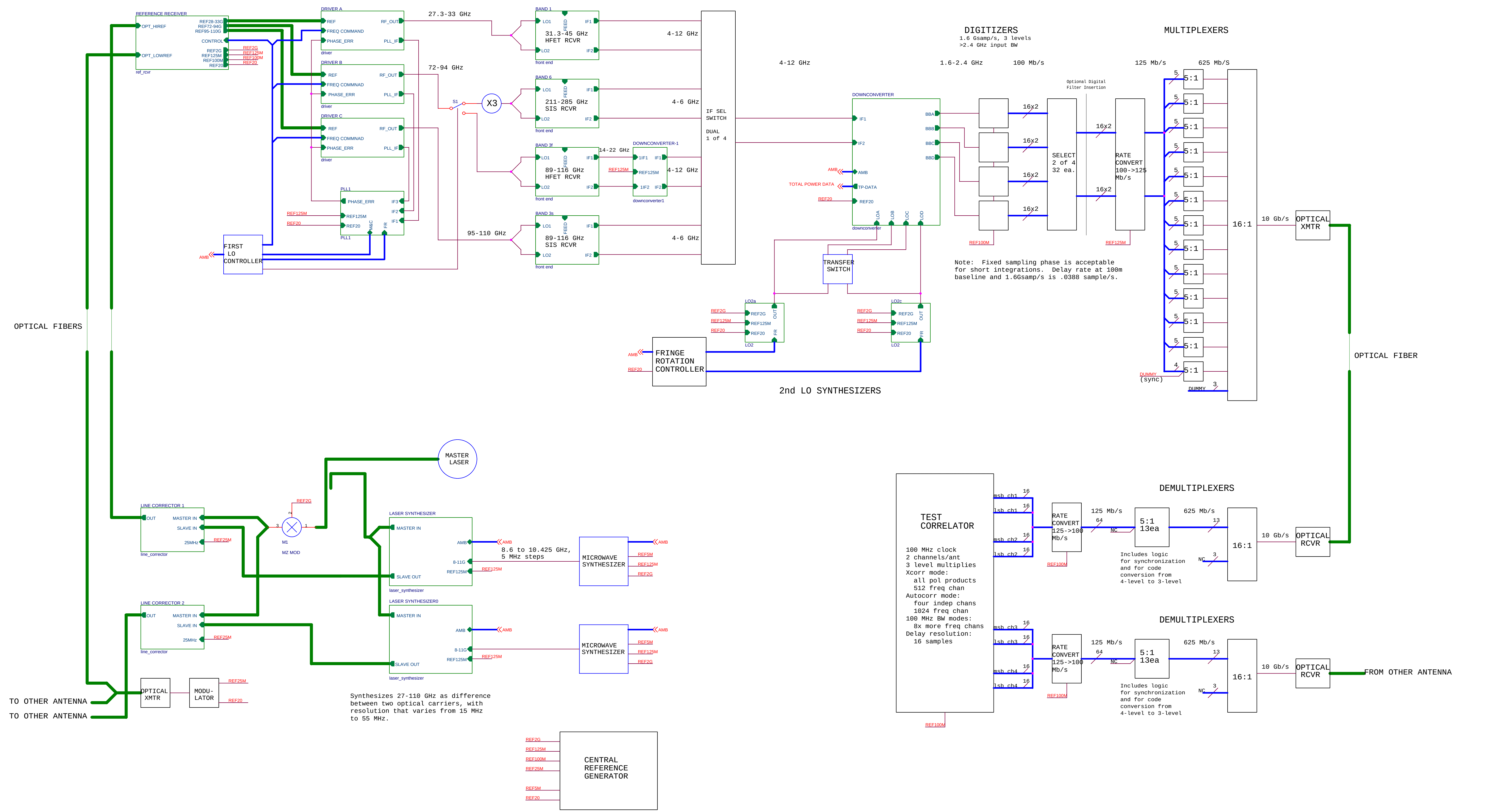
Table 2 lists the various major assemblies required to construct the test interferometer. Most of them have been mentioned above, and others are covered in the appropriate sections of this book. For each, we give the quantity needed and the status with respect to prototyping for the array.

Table 2: TEST INTERFEROMETER -- DEVICES NEEDED

	Ea.ant	Total	Status	Notes
Rcvr#1 31.7-45 GHz	1	2	P	
Rcvr#3s 90-116 GHz	1	2	x	
Rcvr#3h 85-110 GHz	1	2	P	includes downconv w/ 26 GHz PLO
Rcvr#6 211-285 Ghz	1	2	x	includes LO tripler
Rcvr M/C & bias modules	4?	8?	P	one for each receiver (?)
Receiver assembly	1	2	x	dewar and cryogenics; packaging
Driver A 27-33 GHz	1	2	s	based on YTO; includes photodet
Driver B 75-96 GHz	1	2	x	based on GDO; includes photodet
Driver C 95-110 GHz	1	2	x	based on GDO; includes photodet
1st LO controller	1	2	s	includes PLL1
Ref receiver (ant)	1	2	s	both hiref and lowref
IF select switch	1	2	s	
Downconverter	1	2	P	includes input 2x4 matrix sw
2nd LO synthesizer	4	8	P	
Fringe rot. controller	1	2	P	
Digitizers	4	8	x	2-3 GHz in, 1.6GHz sampling
Rate converter (up)	1	2	x	100 Mb/s to 125 Mb/s x 64
Formatters 10Gb/s	1	2	P	Mux and sync
Opt xmtr/rcvr pairs	1	2	P	10 Gb/s
Deformatters	1	2	P	Demux and sync
Rate converter (dn)	1	2	x	125 Mb/s to 100 Mb/s x 64
Digital filters	none			-
Test correlator	1		x	100 MHz clock
Ref generator (central)	1		s	
2-laser synthesizer	1		P	Includes 2nd ref, excludes EDFAs
8.6-10.5/.005G synth	1		P	Input to laser syn; temporary COTS
Line length corrector	1	2	P	
Low ref xmtr	1		P	
Power supplies, various	?	?	P	
Antenna bus driver	1	2	P	processor and software
Central computer	1		P	computer and software
Computer communications	1	2	P	central-to-antenna hardware
Subreflector controller	1	2	P	focus tracking; optional nutation
Holography system	1		P	FE, back end, xmtr
Antenna instrumentation	1	2	x	thermometers, tilt meters, etc.

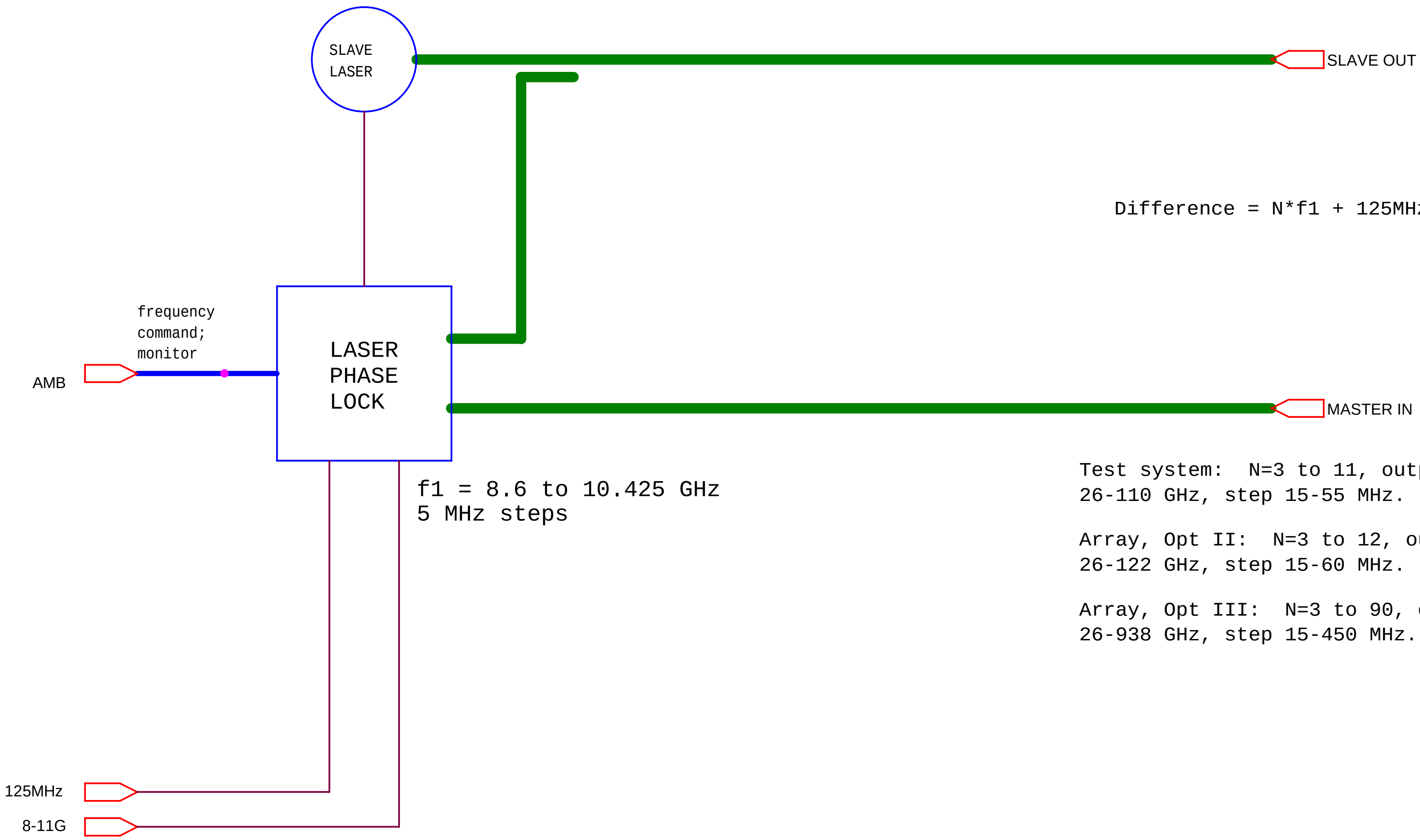
Status column legend:
P = prototype of array design
s = similar to or subset of array design, but modified
x = temporary throw-away; for test interferometer only

ALMA TEST INTERFEROMETER



NOTES:
1. Many devices require conncections to monitor and control bus. These will be shown on future versions of this schematic.
2. Arrangement of components into heirarchical blocks on this schematic does not imply anything about the physical layout or packaging.

Title	ALMA TEST INTERFEROMETER -- TOP BLOCK DIAGRAM	
Size D	Document Number	Rev
Date: Friday, February 11, 2000	Sheet 1 of 8	



Difference = N*f1 + 125MHz

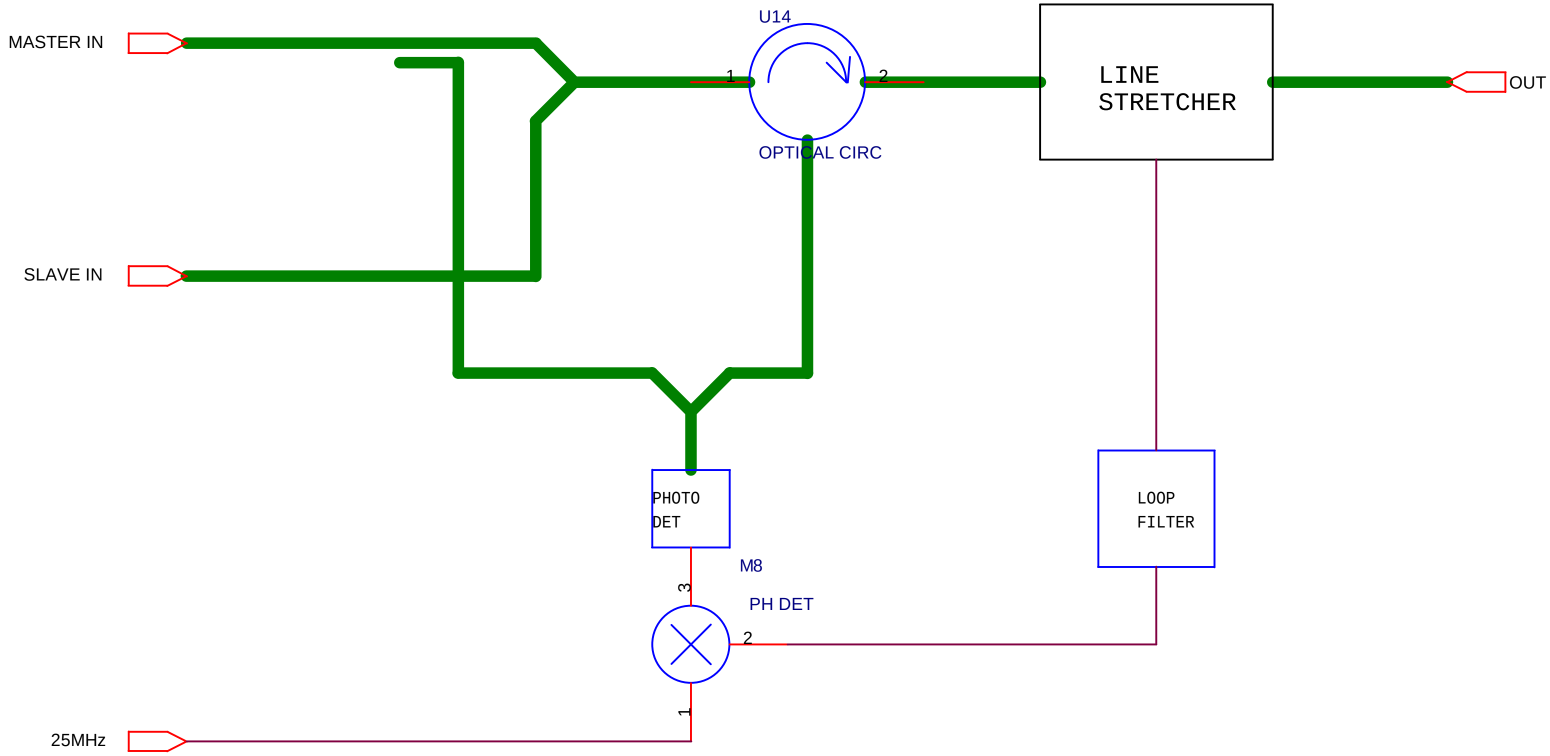
f1 = 8.6 to 10.425 GHz
5 MHz steps

Test system: N=3 to 11, output
26-110 GHz, step 15-55 MHz.

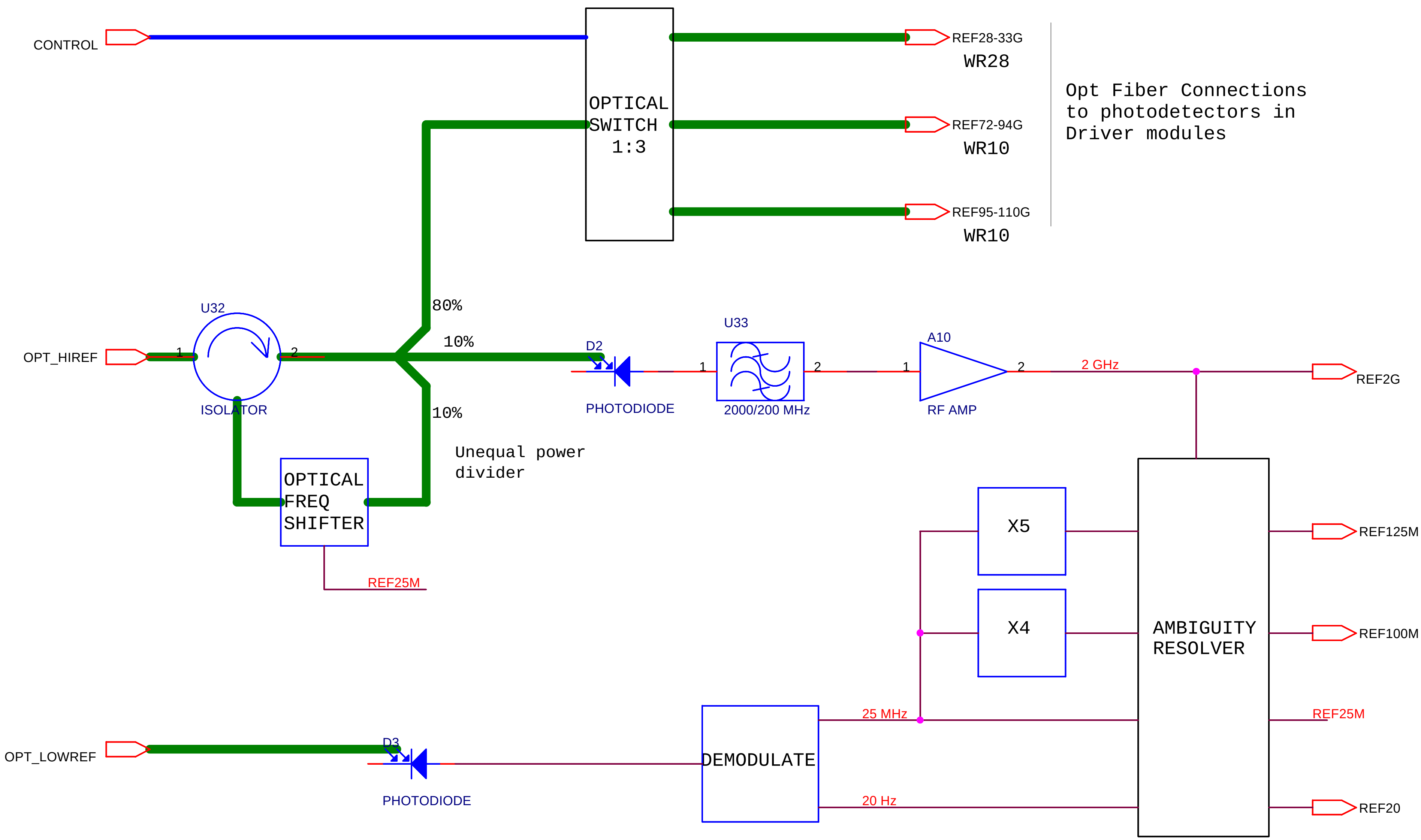
Array, Opt II: N=3 to 12, output
26-122 GHz, step 15-60 MHz.

Array, Opt III: N=3 to 90, output
26-938 GHz, step 15-450 MHz.

Title: ALMA Test System: Laser Synthesizer Block			
Size: A	Document Number		Rev
Date: Friday, February 11, 2000		Sheet 2 of 8	



Title	ALMA Test System: Line Corrector block		
Size A	Document Number {Doc}		Rev
Date: Friday, February 11, 2000	Sheet 3 of 8		

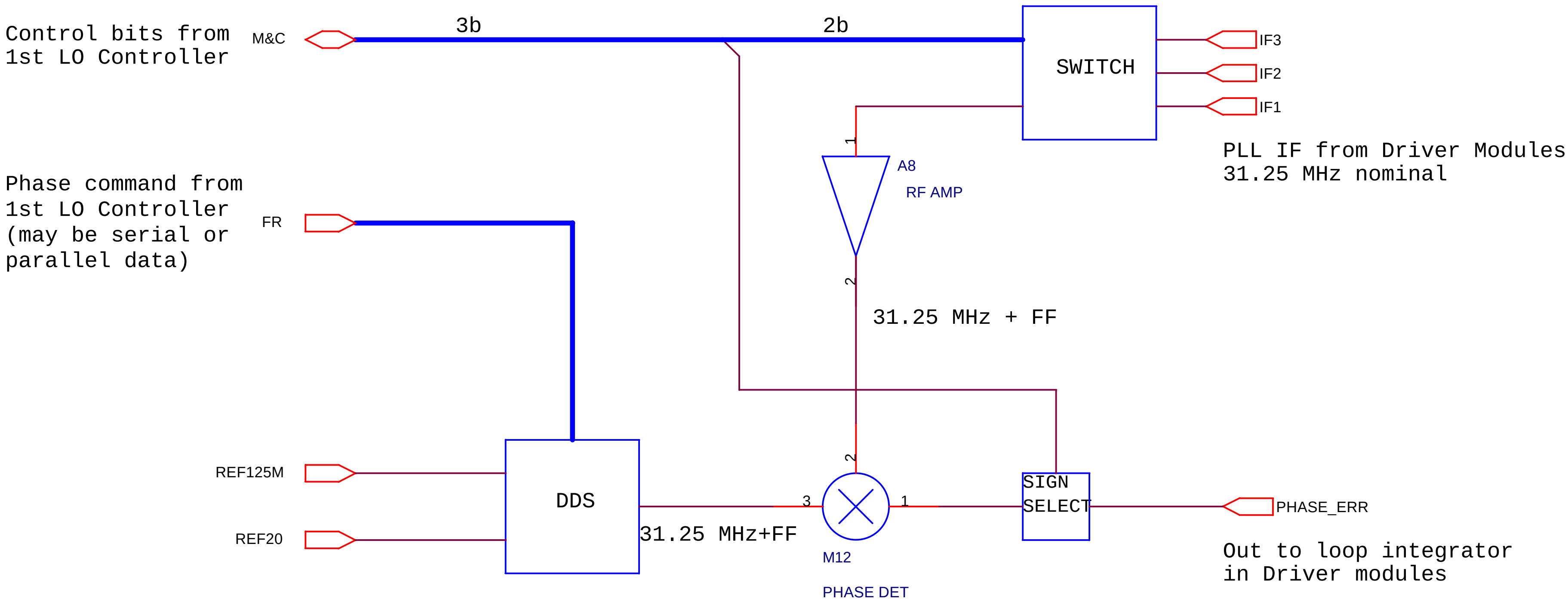


Ambiguity resolution is accomplished by capturing each signal on the next positive zero crossing of the next faster signal, using fast flip-flops. This transfers the phase stability of the fastest signal to the others. It requires an initial timing adjustment and then stability better than about 20% of the period of the next faster signal.

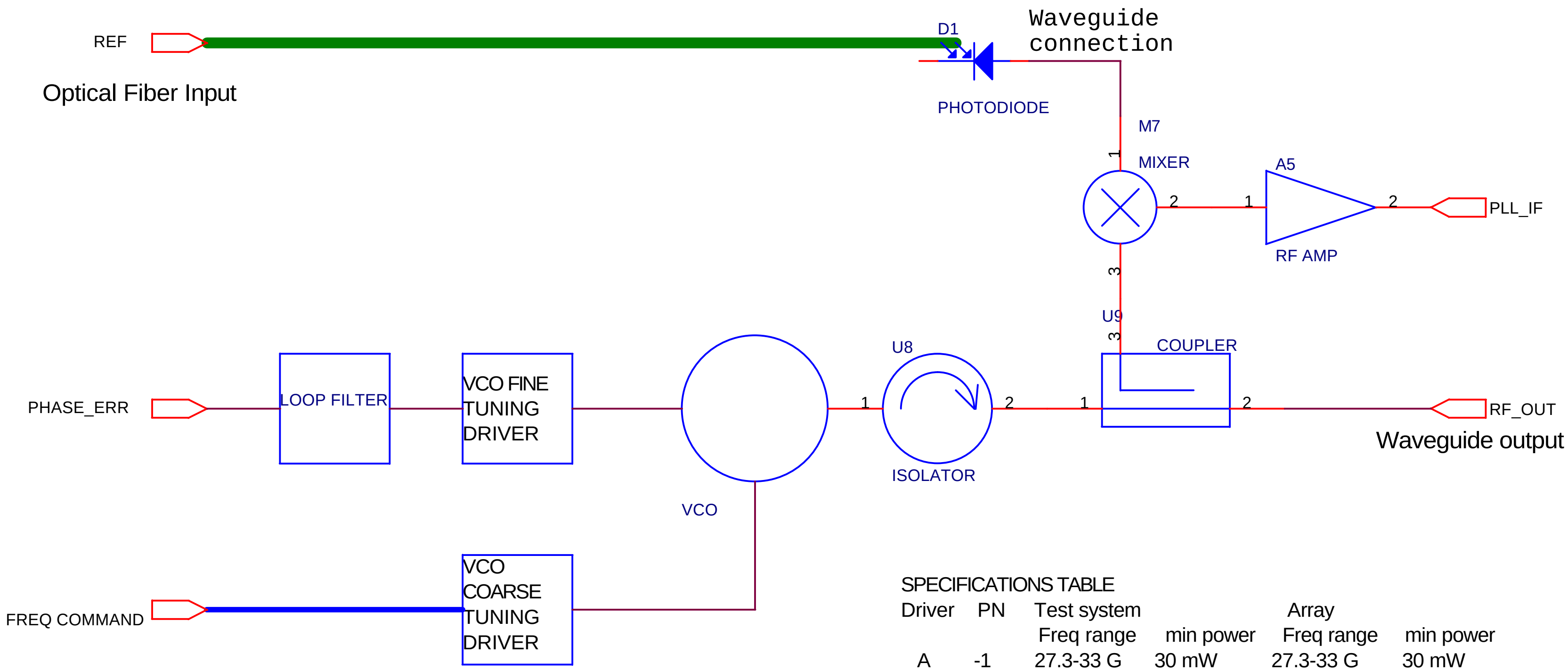
Title: ALMA Test System: Reference Receiver Block

Size: A | Document Number | Rev

Date: Friday, February 11, 2000 | Sheet 4 of 8



Title	ALMA Test System: PLL1 block		
Size A	Document Number		Rev
Date:	Friday, February 11, 2000	Sheet 5 of 8	



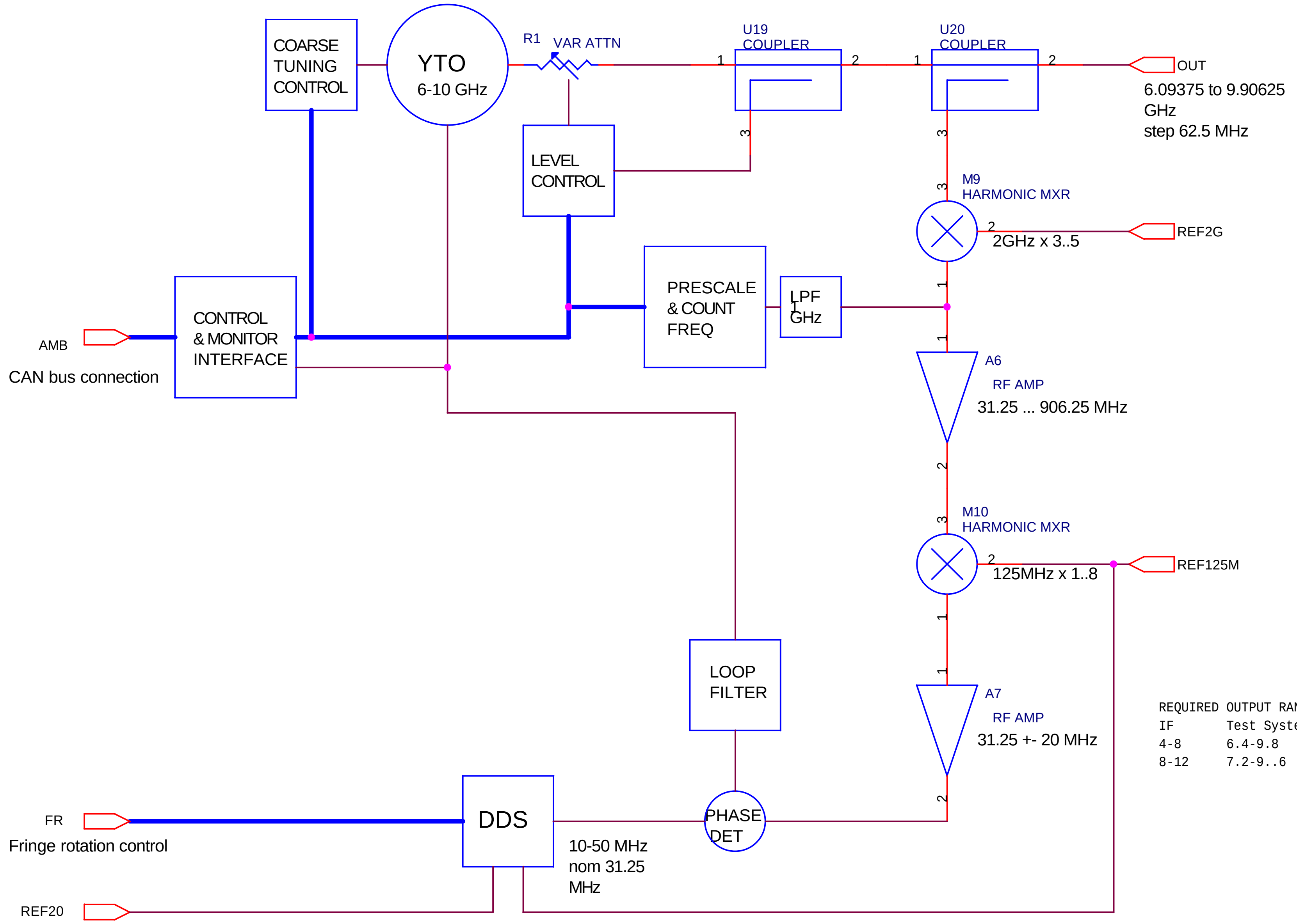
SPECIFICATIONS TABLE

Driver	PN	Test system Freq range	Test system min power	Array Freq range	Array min power
A	-1	27.3-33 G	30 mW	27.3-33 G	30 mW
B	-2	72-94 G	80 mW	75-96 G	100 mW
C	-3	95-110 G	10 mW	99-148 G	100 mW

NOTES

1. VCO may include power amplifier(s) and frequency multiplier(s) if needed to meet specifications.
2. For ALMA test interferometer, VCOs are expected to be: A:YTO, B:GDO, C:GDO.
3. Coarse tuning driver interfaces to external digital contoller, not directly to AMB.
4. Coarse tuning driver may include both mechanical and electrical controls, depending on type of VCO.

Title	ALMA Test System: LO Driver block	
Size A	Document Number {Doc}	Rev
Date: Friday, February 11, 2000	Sheet 6 of 8	



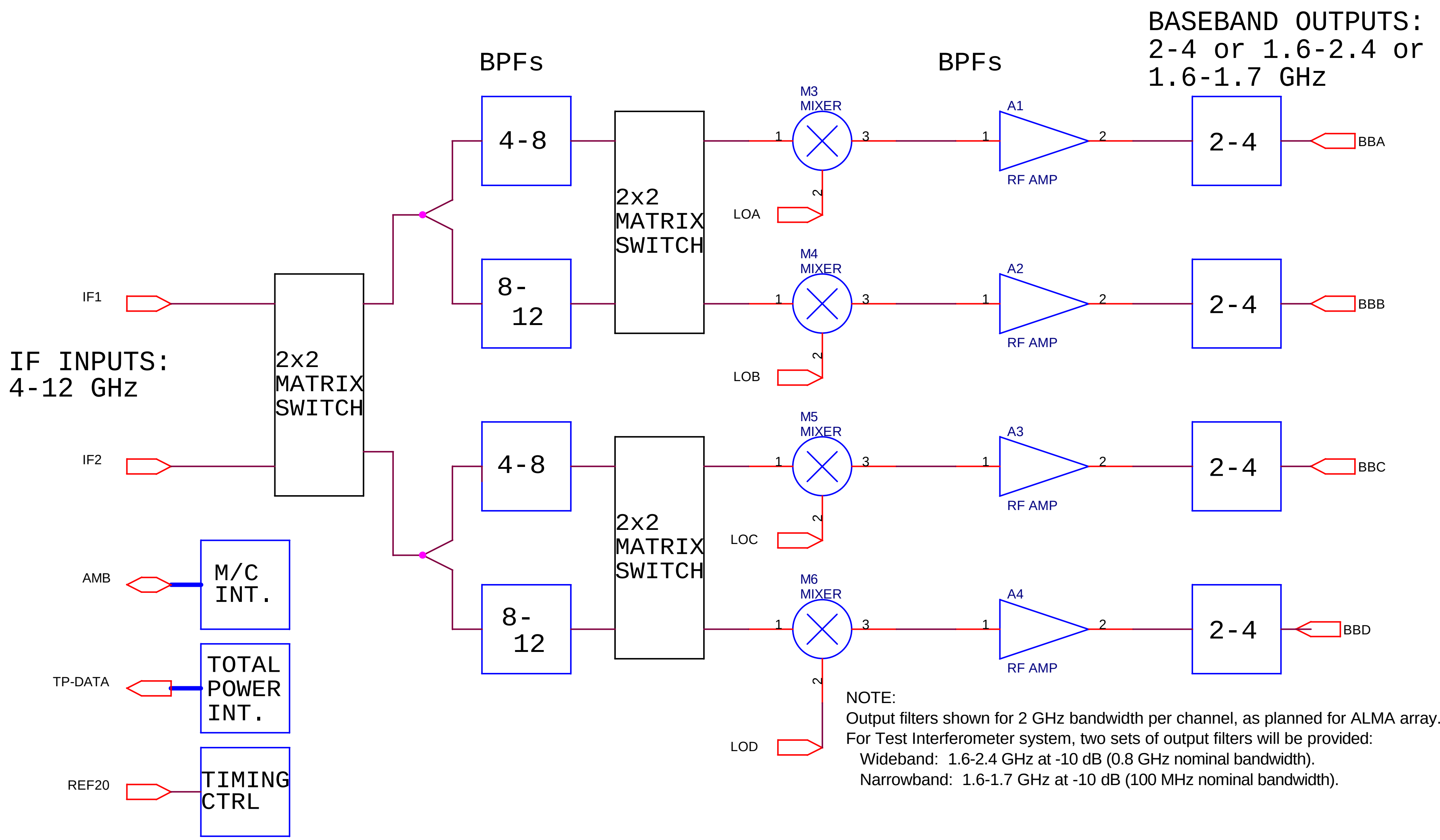
REQUIRED OUTPUT RANGE:

IF	Test System	Prototype
4-8	6.4-9.8	8.0-10.0
8-12	7.2-9..6	6.0-8.0

Title
SECOND LOCAL OSCILLATOR BLOCK

Size	Document Number	Rev
A		

Date: Friday, February 11, 2000 Sheet 7 of 8



NOTE:
Output filters shown for 2 GHz bandwidth per channel, as planned for ALMA array.
For Test Interferometer system, two sets of output filters will be provided:
Wideband: 1.6-2.4 GHz at -10 dB (0.8 GHz nominal bandwidth).
Narrowband: 1.6-1.7 GHz at -10 dB (100 MHz nominal bandwidth).

IMPORTANT DETAILS NOT YET SHOWN:
1. Square law detectors required for each IF input signal (4-12 GHz) and each BB output signal (2-4 GHz).
2. Gain must be adjustable via command from computer, resolution 1dB or less.

Title	DOWNCONVERTER BLOCK		
Size A	Document Number		Rev
Date:	Friday, February 11, 2000	Sheet 8	of 8

ALMA Test Interferometer Project Book, Chapter 5.

Holography System

Darrel Emerson
Antonio Perfetto
Last modified 2000-February-14

Revision History
1998-11-10: Added specifications summary table, project time scale table and section/sub-section numbering.
2000-02-14: Modified to reflect the recommendations of the holography system PDR and to comply with the ALMA Test Interferometer Project Book.

Summary

This chapter describes the hardware and software requirements for a holography system that will be used to measure the first ALMA dishes. The objectives of holographic measurements are (1) to determine the primary reflector rms deviation from the ideal parabolic shape and (2) to generate a list of adjustments for each point on the dish that can be calibrated mechanically in order to achieve the best surface accuracy. The holography system will be compatible with both the US and European prototype antennas. Table 5.1 summarizes the main specifications and requirements for the ALMA holography system. This system will be designed, built and tested during the ALMA D&D phase. The main milestones are shown on Table 5.2.

Table 5.1 - Holography System Specifications and Requirements.

Single Dish Holography	
Item	**Specifications**
Measurement Accuracy (rms)	10 microns
Measurement Resolution	Approx. 10 cm
Holographic Map Sizes	Grids of 257*257, 129*129 and 65*65 points
Measurement time	About 1 hour
Holography Hardware	Land Beacon Transmitter Prime Focus Dual Channel Receiver Digital Back-end (A/D, DSP and Data Storage systems) Specifications: tbd
Interferometric Holography	
Requirements: Interferometric holography requires that most of the ALMA systems be operational.	

Table 5.2 - Holography Milestones.

Holography Hardware Design Review	March 1999
Deliver Holography System Software	March 2001
Deliver Holography System to Antenna Test Site	March 2001

5.1 Introduction

Holography will be used to measure the first ALMA 12 meter dishes, soon after they are first installed at the VLA site. The requirements are a measurement accuracy (rms) of 10 microns, and a resolution on the surface such that several independent points are available for each panel. In practice, this means the dish should be sampled at about 10 cm intervals. This in turn means that a 12 meter dish will need to be measured by about a 120*120 array of points. In practice, most holographic maps will probably be made at 256*256 or 128*128 points, with occasional measurements at 64*64 points. There is no requirement for the data to be measured on a 2^{N} grid - in fact an odd number of points, giving a symmetrical grid with the center point on the bore sight, is advantageous. For example, measurements on the Kitt Peak 12 Meter Telescope used a grid 129*129 or 65*65 points.

Note that, unlike standard single dish astronomical measurements, holographic measurements record complex pairs at each sample in the sky plane, rather than just a single total power value. This implies that Nyquist sampling is defined as (lambda/D) radians, rather than (lambda/2.D). D is of course the dish diameter, and lambda the wavelength at which holographic measurements are being made. The number of complex data points (e.g. 129*129) mapped in the sky plane, giving the complex antenna beam pattern, equals the number of data points (for example 129*129) describing the complex antenna illumination pattern.
So, the total angular extent of the necessary beam map is simply calculated, once the holographic wavelength, dish diameter, and necessary sampling interval on the dish surface are determined. For example, if a wavelength of 3.33 mm (90 GHz) is chosen, lambda/D for a 12 meter dish becomes 0.000275 radians, or about 57 arc sec. If a grid 257*257 is needed, the total map extent becomes 257*57" or about 4 degrees. In practice a little oversampling is always necessary, by perhaps 20%; in this example a sampling interval (after gridding) of about 46" would be appropriate.

Holography will be carried out in 2 distinct modes. In both cases, the aim is to produce a complex beam pattern - that is to say a map of relative amplitude and phase of the antenna being measured.

a. Single dish observations: the phase reference for the measurement of complex antenna pattern will be provided by a small feed looking towards the transmitter, behind the main dish feed, at the prime focus of the antenna. The antenna will be scanned back and forth over the source, to map its detailed, complex beam pattern.
b. Interferometric observations: this will use a pair of antennas, with one antenna tracking the source and providing the phase reference for the second antenna. The second antenna will scan back and forth across the source, to produce a 2-D map of its own complex beam pattern.This will allow antenna surface measurements over a range of elevation angles, but because of more limited signal-to-noise ratio, there will be an inevitable tradeoff between precision of surface

measurement and less frequent sampling along the antenna surface. This measurement also requires two antennas to be fully operational, with correlator and phase-stable LO distribution. Frequencies of ~86 and ~240 GHz will be used.

Case (a), the single dish mode, is in general a little more complex because of the necessary calibration procedures. Case (b), the interferometric mode is closer to a normal, astronomical mode of observing. In what follows, only the single dish mode, case (a), is considered.

5.2 Holography Hardware

5.2.1 Choice of observing frequency

The precise frequency is not critical. Holography measures physical distances; the lower the frequency, the smaller the phase change corresponding to a given distance, and so the higher the signal-to-noise required. If the frequency is too low, diffraction effects (diffraction shadows around the feedlegs, and diffraction around the central antenna blockage) can become significant. The lower the frequency, the larger the area on the sky around the boresight which has to be mapped, for a given linear resolution on the dish surface; this may ultimately present difficulties to the antenna drive and control system, in order for it to be possible to make a sufficiently large map in a reasonable amount of time.

The required signal-to-noise ratio and dynamic range requirement both increase inversely with frequency. At too low a frequency, the needed dynamic range can become a serious problem, and even small cross-talk between the two receiver channels (dish feed and reference horn) can introduce serious errors.

If the frequency is too high, then ambiguities can arise in the measures of the dish surface; fundamentally, holography cannot distinguish between a patch on the dish surface lambda/4 too high, or a patch 3*lambda/4 too low. At the frequency becomes higher, several factors cause the signal-to-noise ratio to become worse - receiver noise temperatures are higher, and the available signal power may become less. Interestingly, the antenna capture area of the reference feed does not vary with frequency; the beam solid angle needed for a given resolution on the dish surface decreases with the square of frequency, exactly as the beamwidth of an antenna with constant physical size. The physical size of the reference feed approximates to the limiting physical resolution of the final holographic map of the dish surface.

The ideal frequency is probably around 90 GHz. Ideally a signal source would be in the far field, but this is not essential. Several groups have achieved excellent holographic measurements of mm-wave or submm-wave telescopes using an artificial beacon a few km or even a fraction of km distant. For the reasons mentioned above, frequencies below 30 GHz are probably not suitable. Unfortunately, no satellite beacon transmissions suitable for ALMA holography have yet been identified. Also, all suitable mountain tops near the ALMA test site (VLA) present an unacceptably small elevation angle (< 2 degrees). The next best solution is to have the land beacon mounted on a tower, a few hundred meters from the antenna being measured. The near-field correction to the measurements is an important issue, but as demonstrated by other groups, a manageable one.

5.2.2 Frontend

The single-dish holographic measurements will be made, at least initially, with a prime focus receiver. For the duration of the measurements the holography receiver box will be mounted at prime focus instead of the normal subreflector. The main advantage of prime focus holography is that potential measurement uncertainties resulting from inaccuracies of the subreflector are avoided. The holography frontend will have two feeds; the first, mounted close to the true focal point, will illuminate the dish in the normal way. (Note however that for holographic measurements it is advantageous to over-illuminate the antenna; G/T optimization is not an issue for holography.) The second feed will point away from the dish, along the boresight of the antenna; this feed serves to provide the reference signal for the holographic system. The beamwidth of this reference feed should be somewhat larger than the maximum anticipated holographic map - for example, 5 degrees. Note the comment above that, in this receiver arrangement, the ultimate physical resolution on the dish surface approximates to the physical size of the reference feed, whatever frequency is chosen for measurements.

Both feeds have independent mm-wave mixers. The independent mixers will be fed from a common local oscillator source. The two resultant i.f. signals will be fed independently to the backed processor, which will be mounted in the antenna cabin. Temperatures, and hence phase drifts, in the two mixer and i.f. chains, with their cables, should be well matched to avoid measurement errors.

5.2.3 Backend

The measurements will be made on a CW signal. To optimize signal-to-noise ratio, a receiver bandwidth of perhaps 100 Hz will be used. The two IF signals will be filtered to a few kHz of bandwidth, then digitized directly. A DSP card will perform FFTs on the data samples to produce a spectrum with perhaps a few Hz resolution. The peak signal (amplitude and phase) will be chosen and stored for later analysis. Data from the main beam (the telescope feed) need to be sampled often enough to match the holography on-the-fly mapping rate. Something like 10 ms will probably be appropriate. The reference channel, with its much larger beam, should be integrated later in the data reduction software, to improve signal-to-noise ratio; this will reduce its effective data rate by about 2 orders of magnitude. However, at the raw data stage, it will also be sampled and stored at up to the 10 ms rate

5.2.4 General Telescope System

In order for holography observations to be possible, much of the telescope system needs to be fully operational. The most critical area is the telescope pointing; this has to be well understood and reproducible before any holography observations can be attempted. Proven observing techniques sufficient to check the telescope pointing frequently during a holography map will be needed. The telescope control system must already support high speed mapping operations, especially the on-the-fly mode. The holography mapping mode will be a variation of conventional on-the-fly observing; for instance, boresight pointing, amplitude and phase calibrations will be needed throughout a holography map - every mapping row, or perhaps every few rows depending on the stability of the system. The ability to make, analyse and apply pointing measurements quickly, in the course of a holography map, is an important requirement.

5.3 Holography Data Reduction Software

The data reduction will take raw data from disk, which has been observed in the on-the-fly mode, and will ultimately produce a list of adjustments, calibrated in microns, for each adjustment point of each panel of the dish.

The raw data for one holography map will consist of from 30 to 513 map rows. Each row may have up to about 5000 data samples. Each sample may be a complex spectrum of one to a hundred points.

Each data point will have associated co-ordinate information. The sampling along each row will be up to 10 times greater than the Nyquist rate for the telescope, while the sampling interval between rows will be perhaps 20% more frequent than the corresponding Nyquist rate. At the start and end of each map row, or in general after *n* map rows, there will be a calibration measurement taken on boresight. The basic observing grid will probably be in an azimuth-elevation system, with respect to the transmitter.

5.3.1 The steps in the data analysis will be:

a. >From each point in the spectrum, the complex data will be interpolated to a regular, 2-D grid. Either before or after the interpolation, some algorithm will choose the strongest point of the spectrum, reducing the spectrum to a single complex number.
   This regular grid will be an antenna-based co-ordinate system, significantly different from the original Az-El offset co-ordinate system. Note that the FFT-pair relationship between antenna far field beam pattern and aperture illumination is a function of the sine of the angular offset from boresight, rather than simply of angle. Since the holography map may extend over as much as 5 degrees, this begins to become a significant correction.
b. The gridded data will be calibrated in amplitude and phase, based on the boresight measurement at the beginning or end of each of the *n* map rows and assuming a gradual drift in gain and instrumental phase with time.
c. Phase corrections will be applied to the gridded data, to bring the antenna reference field close to the plane of the antenna surface. This is analogous to a refocus operation.
d. Amplitude and phase corrections will be applied to the gridded data, to allow for the complex antenna response of the holography reference feed.
e. Some tapering may be applied to the gridded data, to reduce the sidelobes of the point spread function after the FFT.
f. A Fourier Transform is made of the gridded, corrected data. Note that in general the grid will not be 2^m points, and will usually be an odd number, to put the antenna boresight on a grid point at the center of the field before the FT. After the FT, the data represent the aperture illumination pattern, and the aperture phase pattern, of the dish.
g. After the FT, some correction needs to be applied to allow for diffraction fringes from the edge of the dish, from the feed-legs, and from the central blockage. The shadowed areas will also need to be masked out.
h. A feed displacement correction needs to be applied. This will be a sum of:
   1. A least squares fit to a 2-D linear gradient across the phase map. This corresponds to a systematic pointing error, if any, during the observations.
   2. A fit to an out-of-focus term. This corresponds to an axial out-of-focus term. It approximates, but is not exactly, a quadratic distribution across the antenna.
   3. Higher order aberrations, such as coma lobes causes by radial offsets in the holography feed mount.
i. The corrected phase map now corresponds to an estimate of the errors in the dish surface, normal to the wavefront. From the phase map, we need to derive the errors normal to the dish surface, at the panel mounting points. If feasible, some algorithm should take account in some way of the finite resolution of the holography map.
j. Taking account of some structural model of panel and backup structure deformations, a table of corrections needs to be calculated for use by the antenna adjuster crew.

During the holography measurement campaign, the maps will be observed at night while the temperature is stable, and differential panel adjustments will be made during the day. The overnight holography data needs to be analysed in time for the morning adjustment crew to take the panel adjustment correction tables.

It is also likely that unexpected problems will be found during the holography observations and data analysis. It is important that the software analysis system be sufficiently versatile that any of the above steps can be modified, or additional analysis algorithms can be applied, in a timely fashion. It should be possible to introduce some new step into the analysis with not more than about one hour of programming effort.

5.4 Work Plan

In order to accomplish the above plan, the basic steps are:

a. Define in detail the holography system specifications, including transmitter frequency, needed power and signal to noise ratios, front-end and backed requirements.
b. Continue the search for a suitable satellite beacon, which would complement measurements with a terrestrial transmitter.
c. Study the possibilities for single dish holography with astronomical sources (e.g. SiO masers). Coarse resolution holography may be possible on these sources, enabling large scale dish deformations as function of elevation to be studied.
d. Define in detail the design for the holography hardware, including transmitter, receiver front-end, correlator, DSP etc.
e. Define in more detail, in collaboration with the AIPS++ group, the specifications for data analysis software.
f. Define in detail the interferometric holography requirements. Interferometric holography will offer much higher signal-to-noise ratio on a given signal source, simply because the full 12 m aperture, rather than a broad beam reference horn, can be used to retrieve the phase reference signal. This will permit measurements using astronomical sources. However, more of the complete electronics system has to be operational reliably for interferometric holographic measurements to be useful - fringes have to tracked with high phase stability. In the much longer term, holographic measurements with the ALMA will probably become exclusively interferometric.
g. Define the timescales for all the above, taking into account antenna delivery schedules etc..

MMA Holography Design Review

1999-April-19

Summary and Recommendations.

Last revised 1999-May-28

Participation:

The review panel consisted of:

- Darrel Emerson (MMA, NRAO Tuc), chair
- Ron Maddalena (NRAO GB)
- Bob Martin (ASIAA)
- Peter Napier (MMA, NRAO Soc)
- Rick Perley (NRAO Soc)
- Bill Peters (Steward Observatory, SMT/HHT)
- John Webber (MMA, NRAO CV)

In addition, as invited experts:

- Richards Hills (MRAO Cambridge, UK)
- Jaap Baars (LMT)

The meeting was a teleconference, with participation from all NRAO sites. Several other NRAO staff participated as observers.

NB: The millimeter-wave array project is now a joint venture between the US and Europe, recently named *"ALMA."* However, the plans discussed at this meeting predate ALMA, and formal arrangements for European participation in such reviews have not yet been agreed. Accordingly, throughout this document reference is to *MMA* development rather than to *ALMA*. No major changes in holography planning are anticipated resulting from the increased scope of the ALMA project.

Agenda

1. The Requirements of MMA Holography: possible alternatives
2. Overall plans and implementation
3. Specific hardware implementation
4. Realtime software needed for telescope and receiver control
5. Analysis software, requirements and implementation

   Supporting material

In advance of the meeting, written material had been prepared on all agenda items and made available on the WWW: a brief summary with links to other material was made available at: http://www.tuc.nrao.edu/~demerson/holopdr/ . The plans are as already outlined in Chapter 11 of the MMA Project Book.

---

1. Requirements of MMA Holography

Darrel Emerson summarized the basic requirements:

The goals of measurements made on the prototype antennas:

- Is it possible to set the surface to sufficient precision?
- Does the surface retain its precise shape:
  1. With time?
  2. When subjected to thermal (both absolute and differential) changes?
  3. After being transported?
  4. In a strong wind?
  5. As a function of elevation?

Holography should be a good tool for answering the first 3 points. The terrestrial transmitter can be used as a beacon to help set limits on pointing changes caused by wind. Deformation as a function of elevation cannot be measured easily with a terrestrial transmitter, although interferometric measurements, when 2 antennas and a complete system are available, can do so.

The specific measurement requirements become:

- a surface measurement precision of 10 microns,
- a sampling interval along the surface such that several samples per panel are obtained. In practice this corresponds to about 10 cm sampling.
- a measurement set to be completed within about one hour, so that ambient conditions - particularly temperature - will be reasonably constant during the measurements.

Discussion:
It was questioned whether 10 microns rms was sufficient - would 5 microns be more appropriate? The antenna specification is for an overall precision of 25 microns, which would for example be reached if there were as many as six such 10-micron RSS contributions.

Recommendation:
The specification should be kept at 10 microns, but with a **goal** of reaching a precision of 5 microns.
To the requirement for a measurement set to be completed within one hour should be added the goal of completing a measurement within 30 minutes.

Alternative measurement techniques:

i. Bryan Butler presented the option of **photogrammetry.** For details, see Bryan's document: Notes on Photogrammetry for measurement of antennas. At present, it seems that a precision somewhat better than 1 in 10^5 can be achieved, but not yet the 1 in 10^6 needed for the final setting of MMA 12-meter antennas.

   Recommendation:
   This technique may be convenient for the initial antenna setting, where only 100 microns precision is needed. For the prototype antennas, this is however defined to be the responsibility of the antenna manufacturer. We should not rely on photogrammetry for the

final setting of the surface, although we do need to keep up to date with developments in this field.

ii. John Lugten outlined a commercially available laser metrology system using a movable retroreflector, which would be dragged over the antenna surface; see Laser CMM for Measuring the Primary Mirror Surface. Potentially this technique would be able to reach the required precision, but reservations expressed during the meeting included uncertainty in the magnitude of residual systematic effects, difficulties of maintaining continuity as the laser beams crossed obstacles such as the feed legs, and some degree of uncertainty as to how well the technique might perform in a relatively harsh exterior environment.

Recommendation:
We should watch developments in the area of laser metrology. This may be a viable alternative to holography. However, at the moment the panel does not recommend abandoning the existing holographic measurement plans in favor of such a scheme.

iii. Other options: the possibility of using **phase retrieval holography** was discussed. This has the advantage of simplicity of hardware implementation; no special, dedicated holographic receiver would have to be constructed. However, experience at other telescopes indicates that, although phase retrievable holography is workable, the coherent holographic technique has significant advantages; it works well with much lower signal-to-noise ratios, and there is little room for ambiguity in interpretation of the results. It is perhaps significant that at least 2 major millimeter-wave observatories (the IRAM 30-meter, and the JCMT) had originally used phase retrieval holography, but have since opted to build and use coherent holographic systems.

Recommendation:
Stay with coherent holography as planned.

iv. Richard Hills raised the question of whether we should be considering single-dish holography at all (see notes below on the different phases - single dish and interferometric - of holography implementation). The alternative is to wait until a complete, phase-stable interferometer system is available and to rely only on that. The biggest disadvantage is that the holographic measurements can then only be carried out after the full 2-element interferometric system has been sufficiently debugged and proven to be sufficiently phase stable.

Recommendation:
The advantages of having a single dish holographic measurement system available before, and decoupled from, the full interferometric system justify the construction of the single-dish system as planned.

2. Overall plans for implementation of the MMA radio holography measurement scheme

Darrel Emerson outlined the plans. There are two distinct phases of holography:

a. **Single dish mode,** to be used in the initial antenna testing and precision panel setting. A frequency of 92.4 GHz will be used. A terrestrial transmitter will be mounted on a tower, about 300 m from the antenna being measured. The near-field correction to the measurements is an important issue, but a manageable one - as has been demonstrated with the holography on CfA sub-mm antennas. The receivers, including the reference signal system, will be built specially for the holography. The receiver would be mounted at prime focus, with the reference antenna part of the main receiver package, looking away from the dish.

b. Interferometric mode, using astronomical sources. This will allow antenna surface measurements over a range of elevation angles, but because of more limited signal-to-noise ratio, there will be an inevitable tradeoff between precision of surface measurement and less frequent sampling along the antenna surface. This measurement also requires 2 antennas to be fully operational, with correlator and phase- stable LO distribution. Frequencies of ~86 and ~240 GHz will be used.

Discussion:

It was agreed that ~90 GHz is a reasonable choice of frequency; at lower frequencies diffraction effects would become inconveniently large. Richard Hills pointed out the advantages of making measurements at 2 widely spaced frequencies - the system currently being built for the JCMT will use 80 and 160 GHz. Independent measurements at different frequencies may help draw attention to spurious measurement errors, such as unexpected diffraction features. This has also been the experience at the VLA. There is some advantage in sweeping the frequency over perhaps ~100 MHz, to overcome potential multi-path effects.

The stability of the tower was of some concern. With a transmitter on a tower 300 m from the antenna, lateral movements of the tower should be kept to less than 1 mm. Although this stability may be achieved in calm conditions, some tower metrology system may be needed - for example laser measurements as demonstrated in GB for the GBT, or even a separate microwave interferometer using 2 horns mounted on the ground either side of the antenna being measured.

The choice of prime focus mounting of the holography receiver was questioned. There are pros and cons of both prime and secondary focus.

Reflections from the transmitter, its feed and enclosure may be a problem.

The near-field correction is not to be taken lightly, although there seems to be little alternative; if the tower is further from the transmitter, the maximum elevation angle becomes unacceptably small. The approximations involved in the correction become less if the antenna can be refocused on the tower; this requires a movement of at least 10 cm away from the far-field focus position of a prime-focus receiver.

The holography transmitter could also serve as an eventual test beacon for the full interferometric system, both on the US test site and at the final array location. For this purpose, it would be convenient later on to be able to incorporate a harmonic generator to give much greater wavelength coverage.

Recommendations:

The prime focus holography receiver and near-field measurement using the tower-mounted transmitter is an acceptable plan. Serious consideration should be given to arranging for the holography system to have some tunability, such as in 5 GHz steps over a 30% total bandwidth range. Instabilities of the tower should be examined further, and if necessary some form of metrology system to monitor motions of the transmitter should be implemented. The holography receiver mount must allow the receiver to be moved into focus when observing the terrestrial transmitter. The effort involved in installing and removing the prime focus holography receiver should be minimized. The transmitter design should take account of the need to minimize spurious reflections. The importance of accurate characterisation of the phase pattern of the prime focus holography feed needs some emphasis.

3. Hardware implementation.

Antonio Perfetto presented detailed plans; see the material referenced at the top of this document, in particular Description of Hardware for Phase-Coherent Holography.

Discussion:
Some of the design specs appear to be overly stringent. 120 dB for cross-talk is probably not necessary, and there is no requirement for the high frequency stability. The options of using a commercial vector voltmeter, vs. a simple home-made correlator, were discussed. It was noted that in oder to achieve an amplitude accuracy better than 1%, careful attention must be paid to detector calibration. Care must be taken that the transmitter does not interfere with the VLBA antenna at Pie Town, and that it conforms strictly to all FCC regulations.

Recommendations:
The plans as presented are reasonable. For the backend, the possibility of using an existing system should be investigated - for example, that used for the SMT, or for the GBT. Failing that, it may still be better to build a special correlator (which might be as simple as an A/D and software) rather than rely on the commercial vector voltmeter; this issue should be studied further. More careful costing, both of hardware and manpower, should be made; there was a feeling that the estimated total cost ($160k) is probably somewhat too high, while the included manpower estimates (3 man-months for each of one engineer and one technician) may be too low. *[**Correction:** At the meeting, $160k was presented as being the materials-only cost. This was incorrect; 160k$ includes both manpower and materials.]* All in all the hardware implementation plans are basically sound, although a little more investigation of alternatives is required before committing to the final design.

4. Real time and control software. Brian Glendenning presented the plans; a document Holography Software Development for the MMA had been made available in advance. The telescope control and data acquisition from the holography backend would be well integrated into the normal telescope control system.

Recommendations:

There was no disagreement on the plans as presented. Some suggestions included:

- Consider providing the option of arbitrary patterns, not just rectangular rasters. Spiral pattenrs and a rotating cloverleaf were mentioned.
- An algorithm to fit the raw measurements (amplitude or phase, or complex correlation amplitude) may be more effective than fitting the gridded aperture-plane image.

5. Data analysis software.

Brian Glendenning outlined the plans, which had been summarized in a document Holography support in AIPS++ distributed in advance. The data analysis, from gridding time-tagged holography data through to production of a telescope aperture error map, corrected for near-focus and other phase errors, and then to a detailed table of panel adjustments, would all be carried out within AIPS++.

Discussion:
It was suggested that the algorithm for deriving the table of required panel adjustments might best be implemented as an iterative calculation starting from assumed surface errors, and comparing

the raw measurements with predictions from that surface model. The model would then be adjusted for best fit to the raw data.

Recommendations:

- Before developing a complete holography analysis package, a study of existing analysis systems should be made. If possible, one of the existing packages should be used, and perhaps incorporated into the standard MMA analysis framework.

Other specific points:

- Panel adjustment: look into details of how the panels are adjusted, including e.g. bar-codes and a smart wrench.
- Software should have limits so that panels cannot be distorted so much that they are damaged.

Summary of recommendations:

The plans as presented are basically sound, although before committing to the final hardware design a little more study effort is required to consider some of the detailed design options. Specific points are covered in the individual recommendation sections.

→

ALMA Test Interferometer Project Book, Chapter 6.

Evaluation Frontends

Graham Moorey
John Payne
Last changed 2000-January-30

Revision History:
1998-11-18: Major revision
1999-05-02: Minor specification changes in Table 5.1, revised deadlines in Table 5.2.
Section 5.1.7 on Cryogenics added, and Evaluation Receiver General section 5.1.8 added.

2000-01-30: Major revision to comply with the ALMA Test Interferometer and now chapter 6.0

Definitions : A "Frontend" is the overall mechanical (frame) package containing various millimeter wave receivers together with their associated dewar, cryogenics and electronics. The frontend is mounted in the antenna electronics cabin on the axis of the cassegrain focus.

A "Receiver Insert" is the removable mechanical package holding the receiver components that bolts into the dewar. The receiver insert is divided into two main sections, one inside the dewar carrying the cooled receiver components and the other outside the dewar where the room temperature IF and LO components mount.

6.1 Evaluation Receivers

Summary

The receiver development plan consists of two distinct efforts. One will result in receivers suitable for the evaluation of the first antenna. A copy of these receivers will be constructed at the end of the D&D phase permitting the first interferometry tests to proceed on delivery of the second antenna. These receivers are designed to be "throw-away" items, although many of the components and techniques developed will be used in the final receivers for the ALMA project. These initial receivers are referred to in this Chapter as "Evaluation Receivers" and are mounted in the "Evaluation Frontend". The specifications for these receivers are given in Table 6.1 and the principal milestones in Table 6.2.

The second effort will be to develop plans and some prototype components for the final receivers that will enable the construction of the receivers to proceed in a timely manner at the end of the D&D phase. Here these receivers are referred to as the "Production Receivers."

6.2 Introduction

The receivers designed for the evaluation of the first antenna and the initial interferometer tests will be independent of the receivers that will finally be mass-produced for the ALMA. Some components will be similar or identical and efforts will be made to design the receivers in such a way that some parts of the design will be transferable to the production receivers. However the focus of the effort will be to produce in over a given time a receiver Frontend that is suitable for the initial tests. This will involve the use of many components identical to those used in the present NRAO Tucson receivers.

RF Frequency Band	**Receiver Element**
31.3-45 GHz	HFET amplifier
83-95 GHz	HFET amplifier
89-116 GHz	SIS mixer
210-270 GHz	SIS mixer
All bands are dual linear polarization.	

Table 6.1 Specifications for The Evaluation Receivers.

Task	Date
Optics decision	February 2000
4k refrigerator selection	November 1999
Dewar design	March 2000
All components delivered	July 2000
Receiver assembly complete	December 2000
Receiver tests complete	March 2001
Deliver receiver to VLA site	June 2001

Table 6.2 Principal Milestones for Evaluation Receivers during D&D Phase.

6.3 Specifications

The Evaluation Frontend will be an autonomous unit equipped with four independent frequency bands of :-

31.3-45 GHz (HFET), 83-95 GHz (HFET), 89-116 GHz (SIS) and 211-270 GHz (SIS).

The cryogenics will comprise a two stage GM refrigerator (70K and 20K) coupled to a 4K Joule Thomson expansion system as developed by NRAO, JPL and CSIRO. HFET receiver inserts will be attached to the 20K stage and SIS mixers inserts to the 4K system.

All receivers will be dual channel receiving orthogonal linear polarizations.

Because existing SIS mixers design are employed the I.F. will be 4-6 GHz for the 3 mm and 1 mm SIS receivers, and 4-12 GHz for the HFET systems. An IF switch will select the required pair of orthogonal channels to be sent to the IF-LO equipment rack.

The noise performance of the receivers will be the best that can be obtained with today's components and will be more than adequate for the initial measurements. An important point is that continuum measurements will be needed to measure aperture efficiency at the various frequencies. Beam switching with the nutating sub-reflector will be used and, due to the mechanical nature of the switching mechanism, it is necessary for the detected output of the receivers to have a power spectrum that is flat down to a few Hz. There seems to be some doubt that the high frequency HFET amplifiers will satisfy this requirement and this is discussed in more detail below.

The AC supply for the helium compressor and the frontend will be 400 volts 50 Hz 3 phase and 230 volts 50Hz single phase respectively to comply with the Chilean/European power standards.

6.4 Frontend Mechanical Package.

The frontend is contained in a welded extruded aluminium frame no bigger than 900mm wide by 900mm deep by 1500mm high. This frame is divided into several compartments to facilitate the mounting of the following equipment. The frame will be enclosed with removable side panels and provision for air ducting if required.

A large dewar containing the four receiver inserts and helium refrigeration system.
A turbo molecular vacuum pump and associated valving.
A helium line interface with JT supply pressure regulator and flow gauge
The phase locked LO system. (which has to be in close proximity to the receiver inserts)
An IF selection switch module
Appropriate power supplies
Electronic modules for SIS and LNA bias
Electronic modules for the extensive remote monitor and control of the frontend.
A local monitor and control front panel
Bulkheads for terminating cables
And if space permits a roughing vacuum pump.

All calibration loads and rotating mirrors or choppers will be mounted above the frontend package and be independent of that package.

A system for transporting and installing the frontend package in the antenna receiver cabin is being investigated.

The frame bolts to an indexed 'frontend interface plate' mounted in the ceiling of the receiver cabin. It is also envisaged that the bottom of the frame will be mounted to a plinth which in turn is bolted to the floor.

Refer to document ALMA-US ICD No.1 "Antenna / Receiver Interface".

The unit containing the helium compressor and crosshead power supply is mounted outside the receiver cabin.

6.5 The Receivers' Optics.

For the Evaluation Frontend, we plan a simple optical arrangement with "clean" optics that follow the suggestions in MMA Memo #215 .

The feed horns of the receiver inserts will be located in a circular pattern around the vertical axis of the dewar as close to the axis as is mechanically and thermally possible. The required receiver will become operational, simply by offsetting the antenna pointing.

It is envisaged that the 31.3 to 45GHz band feed horn will be at room temperature and thus mounted on top of the dewar with a wave guide connection to the OMT and LNAs mounted to the 20K stage.

The 83 to 95GHz HFET receiver will employ an existing design for the feed horn mounted in the dewar and attached to the 20K stage together with the waveguide OMT and LNAs. The correcting lens however may be outside the dewar.

The 89 to 116GHz SIS receiver will use an existing design for the feed horn mounted to the 4K stage with the waveguide OMT. The correcting lens may be outside the dewar.

The 210 to 270GHz SIS receiver will use an existing lens corrected feed horn with the lens and horn mounted to the 4K stage together with a waveguide OMT now under development.

Calibration widgets such as hot loads and choppers will be mounted above and independent of the frontend then switched into the antenna beam on demand.

6.6 Polarization Diplexing

In the past, the NRAO receivers have used room temperature wire grid polarization diplexers. Recently, a full waveguide band diplexer (ortho mode transducer, OMT) has been developed for the 31.3 – 45GHz, is under development for the 83 – 95GHz and 89 – 116GHz bands and it is hoped to extend this technique to the 211 – 275GHz band.

Reference to E. Wollach et al.

This will result in lower receiver noise as the OMT will operate at cryogenic temperatures. As mentioned above the 31.3 - 45GHz and the 83 - 95GHz HFET receiver OMTs will be attached to the 20 K stage of the refrigerator and the 89 – 116GHz and 210 – 270GHz SIS receiver OMTs attached to the 4K stage.

If there are insurmountable problems with the 210 – 275GHz band OMT then a wire grid type polarization diplexer with associated mirrors could be substituted and mounted on top of the receiver insert within the dewar. This demonstrates the beauty of a receiver insert.

6.7 Evaluation Frontend Block Diagram

The aim is to make the evaluation frontend as self contained as possible with DC supplies, LO systems, vacuum pumps and Local/remote control and monitoring all built in.

This reduces the external interfaces to the frontend to AC power, helium line connections, refrigerator drive power, LO reference signals, IF outputs and CAN bus connections.

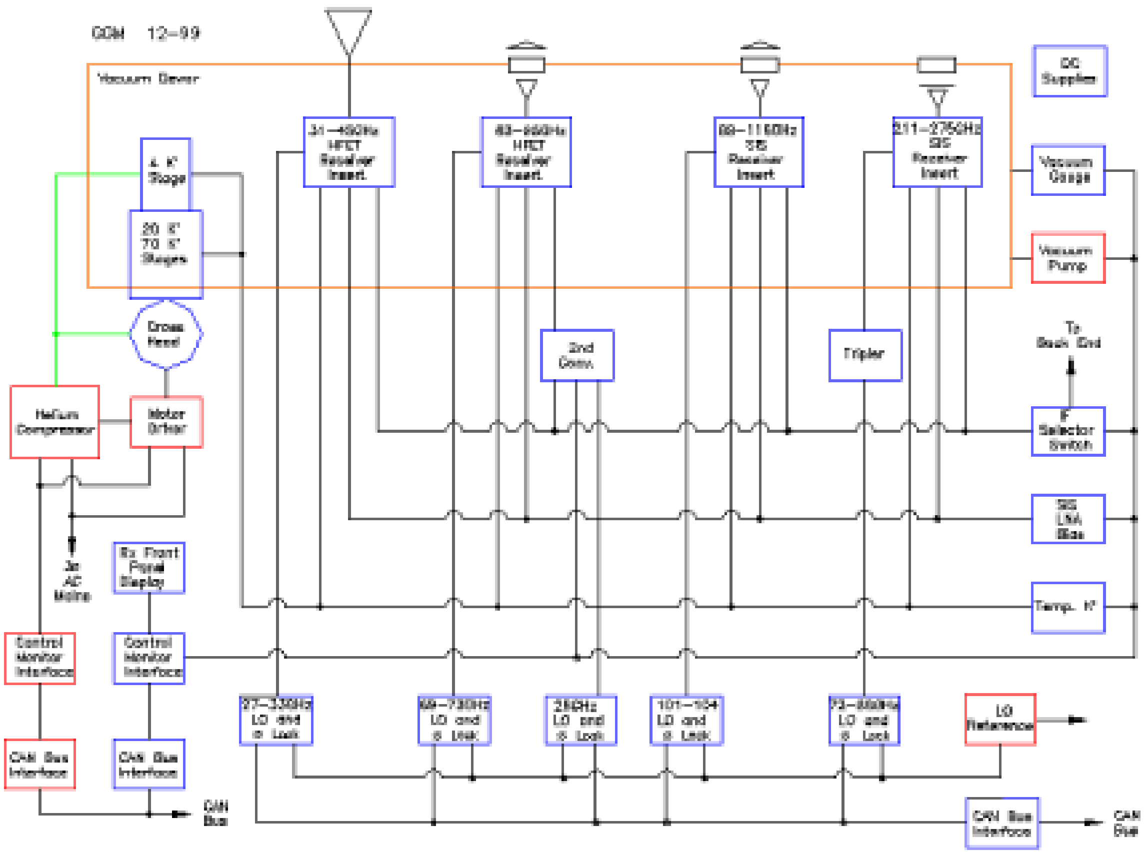


Figure 6.2 shows the major components in the Frontend package.

6.8 The Receiver Dewar

The layout of the dewar will be similar to that shown in Figure 1, which may be regarded as a baseline design. This layout follows the ideas that are used in the present Tucson Frontends with the exception that the change in frequency bands is achieved by simply changing the pointing of the antenna rather than rotating external optics. This system results in errors due to off-axis operation (see MMA Memo 175_), but these errors, coma, etc., are shown to be negligible.

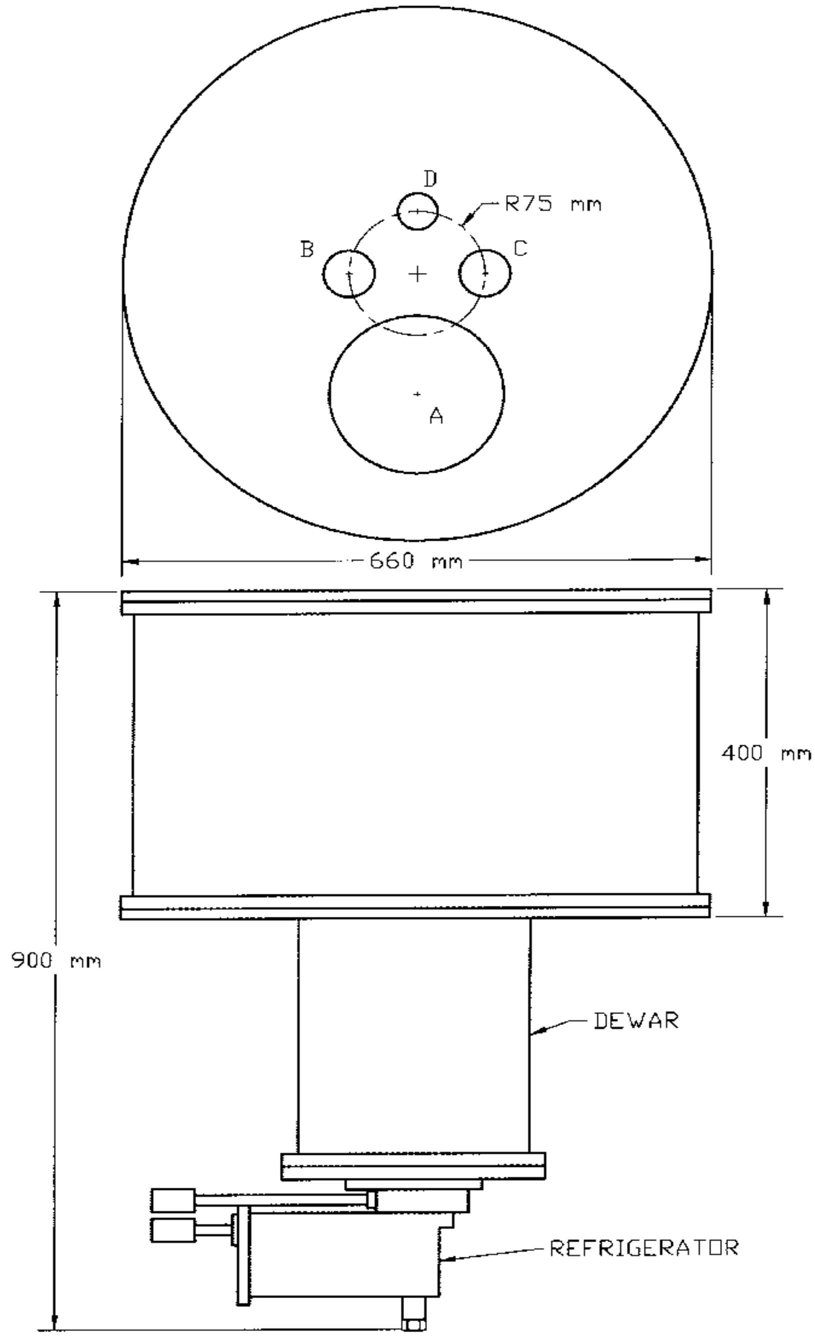


Figure 6.3 The Evaluation Frontend Dewar

6.9 Receiver Insert Block Diagrams

Each Receiver Insert covers an RF band as specified earlier. It is planed that the mechanical structure of the receiver insert within the dewar carry the cooled RF components and the structure outside the dewar be used to mount the room temperature IF and some of the LO components. This will enable a complete receiver (insert) to be tested as an entity independent of other inserts and the main dewar.

There is uncertainty at present about the performance of the HFET amplifiers for use at W-band frequencies. What is proposed here is that the evaluation receivers contain two receivers inserts in this band : one, a dual polarization receiver using HFET amplifiers, the other a receiver using SIS mixers. In this way we hope to make an evaluation of the low frequency post detection noise that will be critical for continuum observations using the nutating sub-reflector.

Although it should be possible to evaluate the receiver performance in the laboratory prior to telescope observations it is felt that telescope observations will give the most unambiguous results. Block diagrams of both these receivers are shown in Figures 6.4 and 6.5. The 89 to 116GHz SIS receiver will use the tuneable mixers that are in use on the Tucson 12m antenna today.

6.9.1 The 31-45 GHz HFET Receiver

The simplified block diagram for the 31.3 to 45 Ghz receiver insert is shown in Figure 6.4. This illustrates a single upper sideband conversion from the RF input band to an IF of 4 to 12 GHz. The waveguide OMT and the LNAs will be mounted on the 20K stage of the refrigerator. It is TBD if the mixer is cooled or mounted external to the dewar.

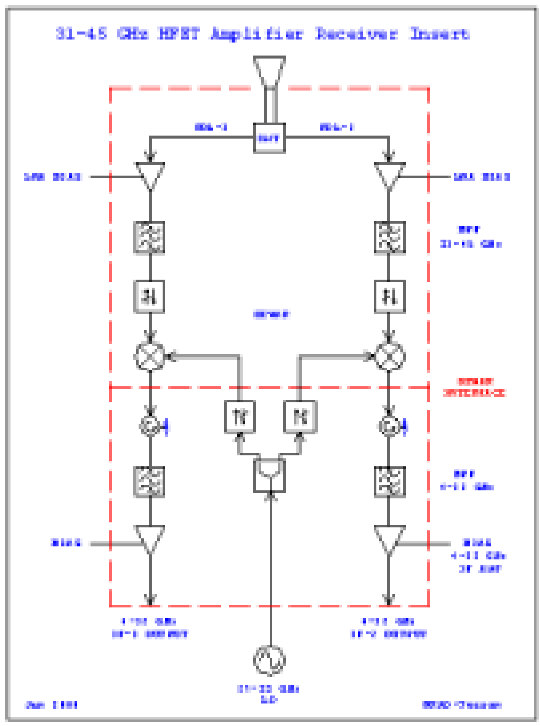


Figure 6.4 The 31-45 GHz HFET Receiver.

6.9.2 The 83-95 GHz HFET Receiver

The simplified block diagram of the 83 to 95 GHz HFET receiver insert is show in figure 6.5 and depicts a double conversion system with a tunable 1st LO and a fixed 2nd LO.

The RF frequency band was chosen to cover both the SiO maser at 86.2 GHz and the Holography beacon at 92.4 GHz. Another band setting factor is the RF, LO and IF bandwith of commercially available mixers. Under an NRAO VLBA project a coolable mixer covering approximately 80 to 96 GHz is being developed and should be suitable for this evaluation frontend insert.

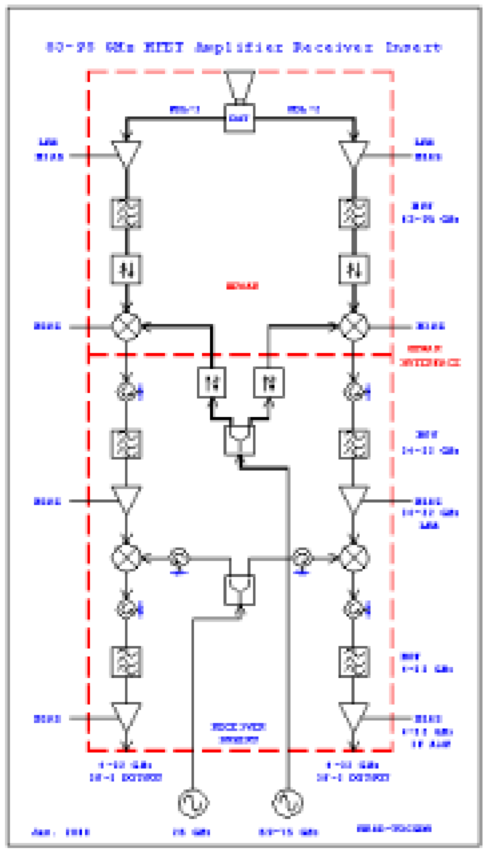


Figure 6.5 The 83-95 GHz HFET Receiver.

6.9.3 The 89-116GHz SIS Receiver

A block diagram of the single conversion 89 to 116 GHz SIS receiver insert is shown in figure 6.6 . This receiver insert will utilize an existing NRAO design for a tunable SIS mixer to save development time and money. Other components found in the 3mm receivers on the 12M antenna in Tucson will also be used.

The major development is in the waveguide OMT as described by E.Wollack add ref.

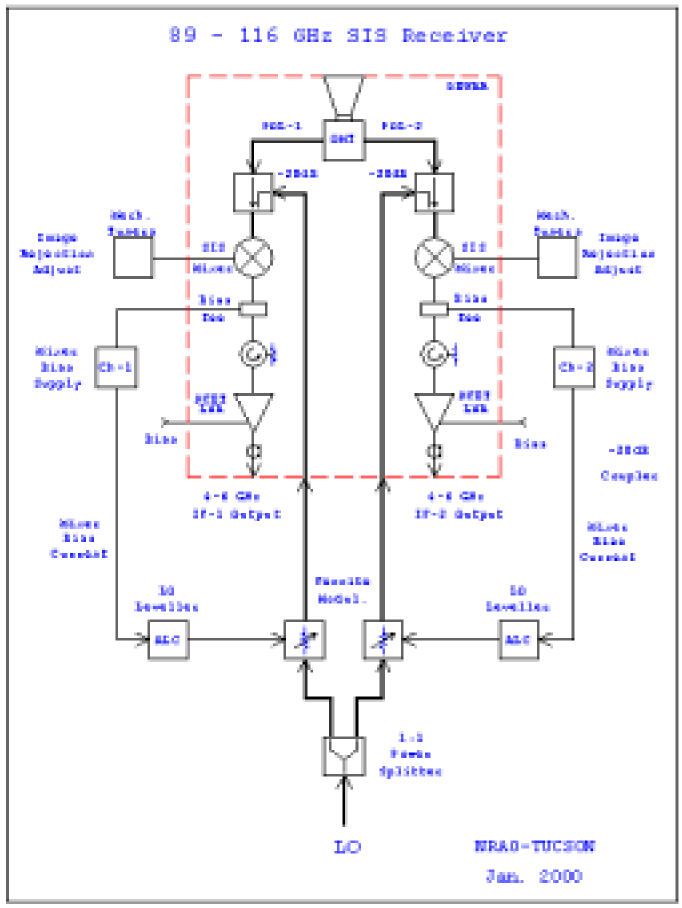


Figure 6.6 The 89-116 GHz SIS Receiver.

5.9.4 The 210-270 GHz SIS Receiver

A simplified block diagram of this single conversion SIS receiver is shown in Figure 5.7 The components are all today's technology, although it is anticipated that a major effort will go into achieving phase stability.

The fixed tuned mixers used have been manufactured by the National Research Council of Canada using NRAO designed mixer chips.

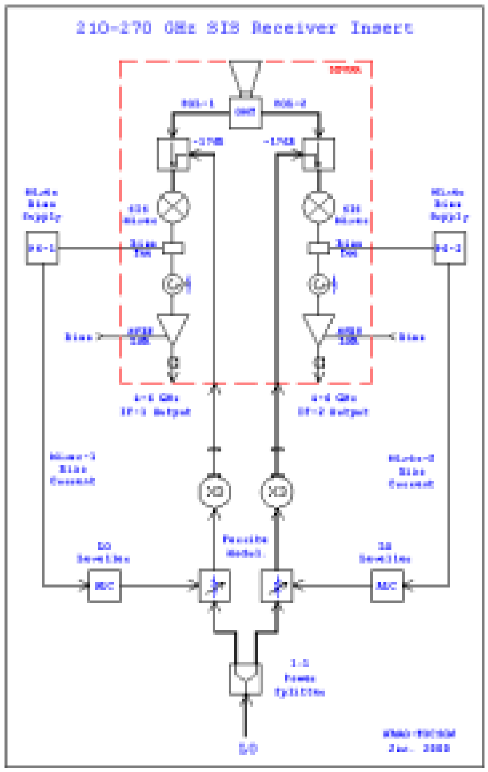


Figure 6.7 The 210-270 GHz SIS Receiver.

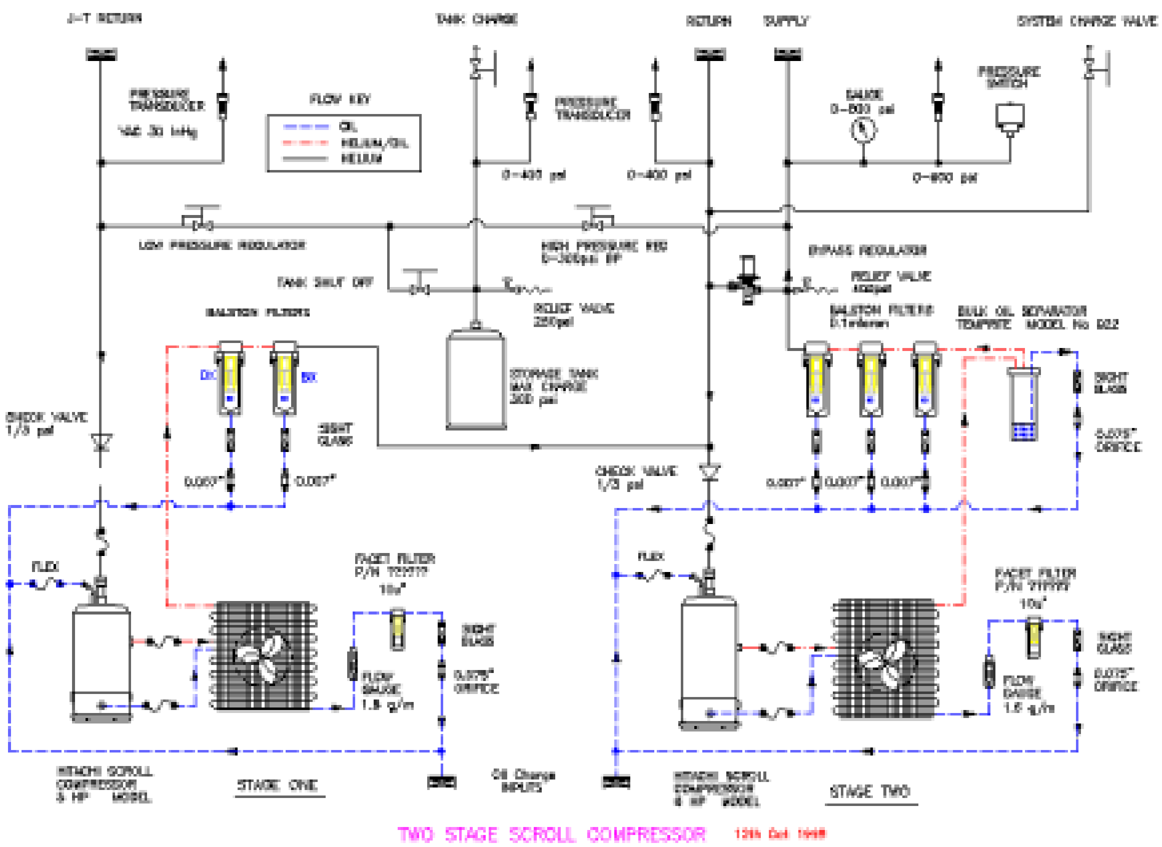
6.10 Evaluation Frontend Cryogenics

6.10.1 Helium Compressors

A decision has been made to power all electronics and helium compressors from 400 Volt, 3 phase 50 Hz, or 230 Volt single-phase 50 Hz ; this corresponds to the standard Chilean power grid. As a result of the 50 Hz mains frequency the rotational speed of the compressor motors will drop by ~17%, lowering the helium flow rate proportionally. To provide sufficient helium flow to the GM refrigerator a new prototype compressor system will be developed using a 5HP Scroll compressors for the GM section, and a 5HP scroll for the JT circuit. The altitude, ambient temperature and air density at the Chilean site where these compressors could operate will be considered when designing the heat exchangers and specifying components.

Comprehensive local and remote monitoring of all critical pressures, temperatures and electrical systems will be installed together with a local/remote power on/off. The remote monitor /control will be via a CAN bus interface.

See figure 6.8 for a schematic diagram of the helium compressors.



6.10.2 Cryogenic Refrigerator System.

The Evaluation Frontend will employ a two stage CTI 1020 GM helium refrigerator to provide the 70K and 20K cold stations. Coupled to this refrigerator will be a standard NRAO 4K JT system. The refrigerator motor drive power supply (Scott Tee transformers) will be located in the helium compressor chassis. This supply has sufficient capacity and voltage taps to simultaneously drive up to four CTI refrigerator motors in combinations of models 1020, 350 and system 22.

The JT helium supply regulator and a flow meter will be mounted in the frontend with suitable monitoring via the CAN bus.

6.10.3 Dewar Vacuum System.

It is planned to incorporate an automated evacuation system utilizing a turbo molecular pump and a scroll roughing pump for the first stage. The turbo pump will be attached as close to the dewar as practical with the associated, manual valve for maintenance, and electromechanical valving for automatic pump down. It is hoped that the roughing pump can be continually connected and mounted in the bottom of the frontend frame.

6.11 IF Switching Module

The dual polarisation IF outputs from the four receiver inserts are sent to a double pole multy way microwave switch which by way of a control command selects the required pair of signals to be sent to the backend equipment. The IF switch module may contain band pass filters, amplifiers, line equalisation and the necessary control and monitoring circuitry with a local display interface. The module will be designed to cover the full ALMA IF band of 4 to 12 GHz.

The output power available at the connector bulkhead will be –30dBm / Ghz.

6.12 Local Oscillator system

The initial LO sources will be tunable phase-locked Gunn oscillators with a tripler for the 210 to 270GHz band. (To be completed)

6.13 Power Supplies

The evaluation receivers will be equipped with an integral power supply system. (To be completed.)

6.14 Control and Monitoring

Local control and monitoring will be provided through a Receiver front panel and remote control and monitoring via a simple I/O interface bus. (To be Completed.)

Local Oscillators

7.1 Overview

For a description of the overall plan for the local oscillator subsystem, please see section 4.4 and Figure 4.1 of this book. This chapter gives additional details, some of which apply to the ALMA array as well as to the test interferometer.

7.2 Reference Distribution

John Battle, 2000-02-15

7.2.1 Low frequency reference generator

The Low Frequency Reference Transmitter in the central electronics building will combine the 20 Hz and 25 MHz reference signals and intensity modulate a laser signal which is then transmitted over an uncompensated fiber link to the two antennas of the test interferometer antennas. The unit will consist of a laser diode and an MZ modulator and appropriate temperature control and modulation control circuitry. There will be a microprocessor which will perform control tasks as well as communicating status over the Monitor/Control CAN network.

Specifications - Low Frequency Reference Transmitter

Input Signals:

Reference freq	25.0 MHz @ +10 dBm, 50 ohms
Reference freq	20.0 Hz @ 1 volt, high impedance

Output Signals:

Laser   two way split

7.2.2 Reference receiver

The purpose of the Reference Receiver is to receive both the low-frequency laser reference and the dual laser reference signals and process them in order to produce the fundamental LO reference signals at the antenna. The dual laser signal is then passed on to the LO drivers where the photonic reference first LO signal is generated. The dual laser signal is also frequency shifted by 25 MHz in an acousto-optic modulator and returned to the central electronics building LO for use in the path length correction system. The acousto-optic modulator is a true single sideband modulator and its output consists of only the shifted frequency.

The Reference Receiver unit will include a monitor and control interface which will provide self test and status information to the central control computer.

In order to establish the correct relative phase of the various reference signals generated in this module, a circuit called an "Ambiguity Resolver" is used to synchronize the zero crossings of each signal with the next higher frequency's zero crossings. Detail design and specifications for this device have yet to be worked out.

Specifications - Reference Receiver

Inputs:

High reference, optical wavelength	1550 nm (intensity TBD)
Low Reference, optical wavelength	1550 nm (intensity TBD)

Outputs:

Reference frequencies	2.0 GHz @ +20 dBm, 50 Ohms
	125.0MHz @ +20 dBm, 50 Ohms
	100.0 MHz @ +20 dBm, 50 Ohms
	25.0 MHz @ +20 dBm, 50 Ohms
	20 Hz @ 1 volt RMS, High Z

7.3 First Local Oscillator

A simplified schematic of the first local oscillator consisting of synthesizer, distribution system, a high-frequency photomixer, and phase-locked oscillator is shown in Fig. 7.1. The reference is generated photonically at the central building and distributed to each antenna by optical fiber. Three LO drivers are needed to cover the receiving bands of the evaluation receivers (see Chapter 6 of this book). An LO driver includes a Gunn oscillator or a YIG-tuned oscillator. The 211-275 GHz receiver will incorporate a tripler. The oscillators in these LO drivers will be phase locked to the photonic reference at the receiver. Coherence between the receivers at each antenna is maintained by a continuous round trip correction of the fiber optic distribution to the antennas. The round trip correction is achieved by means of an optical interferometer that keeps the number of optical wavelengths of a master laser constant to within an optical fringe.

7.3.1 Laser Synthesizer

Bill Shillue, 2000-02-15

Fig. 4-1 sheet 2 is a schematic of the laser synthesizer. The master laser is split and a pair of slave lasers are in turn phase locked to the master laser in two laser synthesizer modules, one for each antenna. These are inside the central station, and the laser synthesizer includes frequency references from the central reference generator module and an X-band microwave synthesizer. The laser synthesizer employs light from two lasers, tuning the second laser to a fixed offset from the first laser. The two wavelengths of light are then sent along the fiber where they are converted to the appropriate millimeter-wave reference by a photomixer.

A master laser and a slave laser are phase locked to each other at a difference frequency of from 27-122 GHz by use of two microwave references. The master laser is input to a device called an optical comb generator. The optical comb generator uses a resonant modulation technique to phase modulate the laser at extremely high modulation index. This creates a spectrum of "comb-lines" equally spaced from the carrier by the modulation frequency. A high-Q optical filter then selects the desired comb-line. The end result is that the master laser frequency has

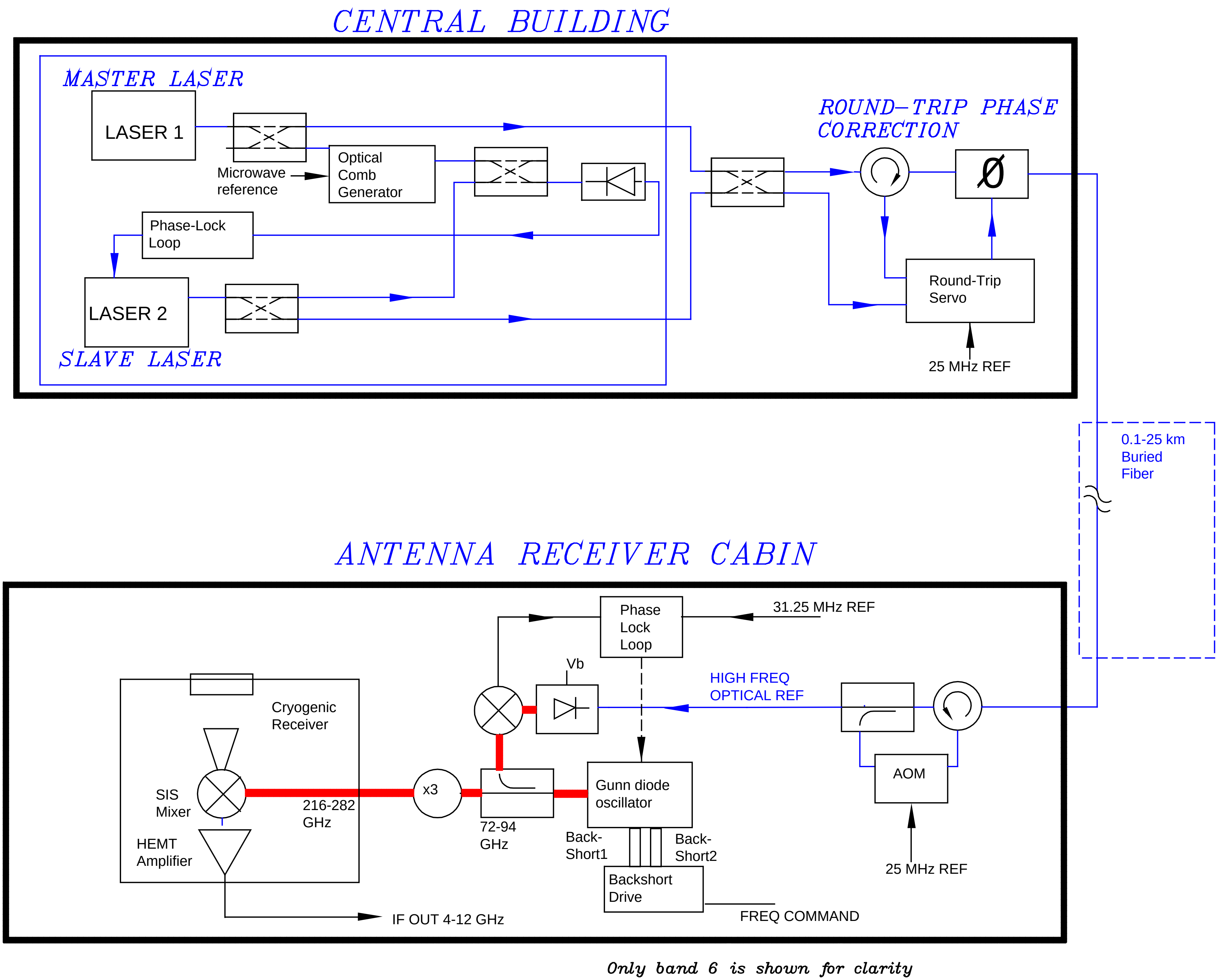


Figure 7.1: Simplified block diagram of first LO chain.

been shifted by the modulation frequency times a fixed integer value. The slave laser is then offset-locked to this shifted frequency.

For a more complete description of the technique for phase locking two lasers and some typical phase noise results, see
http://www.tuc.nrao.edu/~demerson/project_book/chap7/chap7.1/chap7.1.html.

For a more complete description of the details of the optical comb generator, see
http://www.mma.nrao.edu/memos/html-memos/mma200/memo200.html.

7.3.2 Round Trip Correction

Bill Shillue, 2000-02-15

The first local oscillator must be coherent between both of the antennas in the test interferometer. Ideally, the phase error associated with the distribution of the first LO reference should be a negligible contributor to the overall phase noise. The idea of stabilizing the fiber distribution to an optical fringe came about because it was realized that for the ALMA array, the coherent distribution must be stable to within a small fraction of the shortest observing wavelength, which is 350 microns. By tracking with an optical interferometer, the overall path length error must be smaller than half of the optical wavelength, or 0.78 microns.

The technique of round trip correction by optical interferometer is described in some detail in http://www.tuc.nrao.edu/~demerson/project_book/chap8/chap8.3/chap8.3.html and in http://www.mma.nrao.edu/memos/html-memos/alma267/memo267.pdf.

The difference frequency is transmitted to each antenna by optical fiber. The fiber first goes to a module called the reference receiver. At the reference receiver a small portion of the light is tapped off and frequency shifted, then sent back to the central building thus completing the round-trip

The technique of round trip correction relies upon the exceptional linewidth of the best commercially available 1.55 micron band lasers, which are less than 5 kHz. This gives a coherence length of greater than 50 km, allowing the optical interferometer to operate at the longest baselines being considered for ALMA. Also, the phase correction requires a high degree of absolute stability of the master laser. The absolute stability required is proportional to the (distance * frequency difference), and for the most difficult case of 950 GHz over 25 km, a stability of better than 100kHz will be required. Stability better than this can be obtained from commercially available lasers. For the ALMA array a master laser combining exceptional linewidth with this frequency stability will be required. However, for the test interferometer the distance is quite small, less than 1 km, and the maximum frequency difference after multiplication is 279 GHz. The construction of the fiber line corrector for the test interferometer will be combined with developing a technique to stabilize the absolute frequency of the master laser to the degree required for the ALMA array.

The most recent test result of a lab-based round trip system uses a 25 GHz beatnote (frequency difference and a 25 km spool of fiber, for a 50 km round-trip. Fig. 7.2 shows the result for a two-minute tracking cycle. The top trace shows the phase drift. The corrector tracks for the first minute, and the phase drift is less than ten degrees. With the corrector off, the phase drifts greater than 50 degrees in the next minute. The bottom plot shows the amount of fiber stretch that is used to compensate for the phase drift. The small drift in the tracking state is due to frequency drift of the master laser. As mentioned, stabilization of the laser to the degree that will be required is quite common.

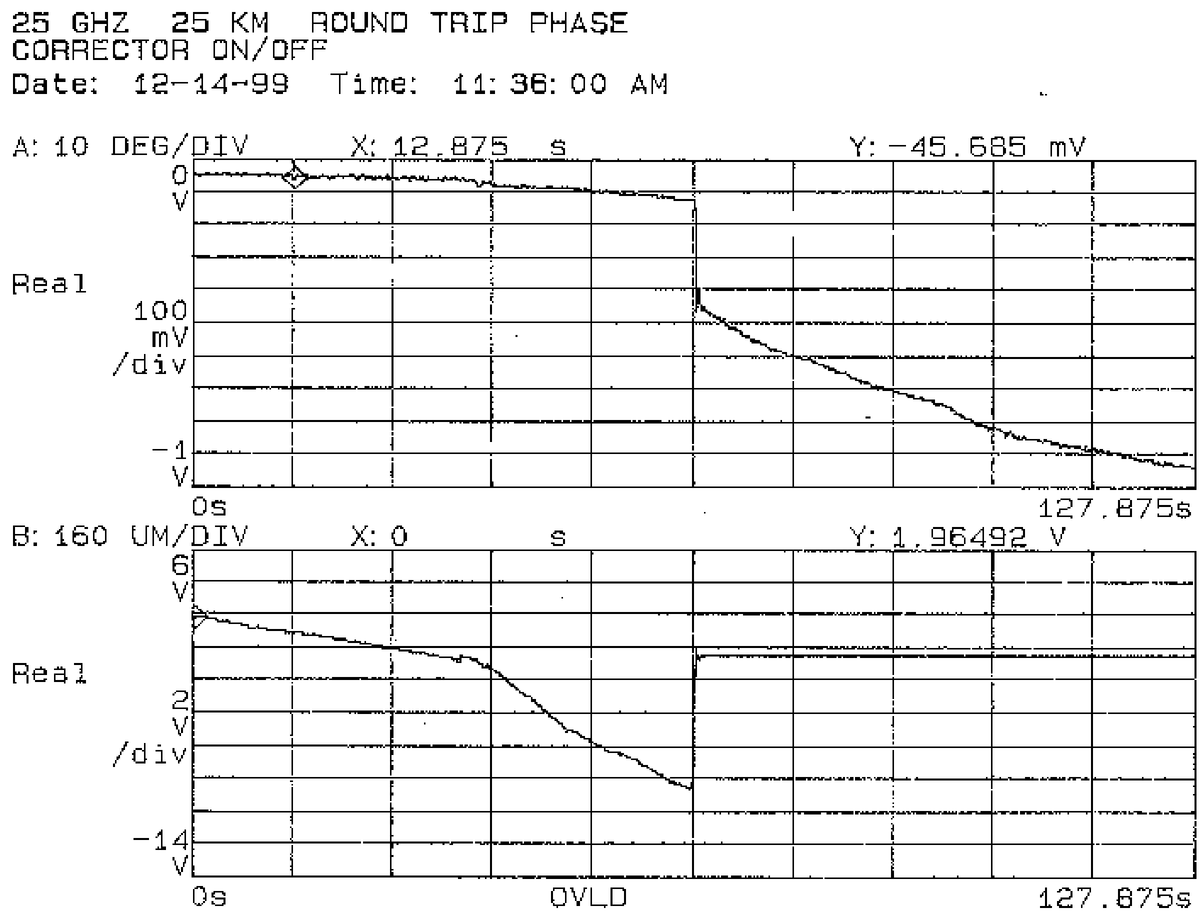


Figure 7.2: Round Trip Phase Correction with 25 GHz Beatnote and 25 km fiber. Top trace is the phase difference between the beatnotes at opposite ends of fiber. The bottom trace is the position of the fiber line stretcher with the scale given in microns. The line corrector was turned off halfway through the test.

7.3.3 Drivers and Multiplier

7.3.3.1 Photomixers

For the test interferometer, photomixer devices spanning 27-122 GHz in discrete bands will be required. A minimum output power of one microwatt is required, although ten microwatts is expected. Many details of the design and state-of-the-art of both commercial and research-grade high frequency photomixers is given in http://www.tuc.nrao.edu/~demerson/project_book/chap7/chap7.1/chap7.1.html. That discussion assumes that a direct photonic approach is being used, but for the photonic reference, all of the same considerations apply, but the output power specification is relaxed.

An NRAO test of a commercial photodetector (NTT KEPD2525VPG) resulted in measured output powers of 9 microwatts at 78 GHz and 0.2 microwatts at 110 GHz. However, that particular detector had a coaxial output connector that was overmoded above 60 GHz and also required a bias tee on its output. The only available bias tee also had coaxial connectors, so it was estimated that at least 10 dB more and perhaps higher output power would be available from such a device if the bias and output circuit were properly configured. This type of device can be used for the 31-45 GHz HFET receiver frequency reference, locking a 27-33 GHz YIG tuned oscillator. For the higher frequency bands, a photomixer with a waveguide output and integrated bias tee would be more practical.

A photomixer manufacturer has been found that sells a suitable device in chip form (http://www.u2t.de). These chips are inexpensive, high current (6 mA), have an integrated bias tee, and have been used above 100 GHz. It is our intention to characterize the device in chip form, and then integrate the device with a transition to fundamental mode waveguide.

7.3.3.2 Oscillators — Graham Moorey

<to be written>

7.3.3.3 Tripler (72-90 to 217-269 Ghz) — Graham Moorey

<to be written>

7.3.4 Controller and PLL — Graham Moorey

<to be written>

7.4 Second LO Synthesizers — John Battle, 2000-02-15

The second LO synthesizers provide the local oscillator source for the second mixers used to demultiplex the sideband IF into four 2 GHz channels which are arbitrarily located relative to the input band. Four of these synthesizers are required for each antenna and each must be independently tunable in 62.5 GHz steps. Each will include an independently tunable Fringe Rate Generator which provides a frequency offset tunable in one milli-Hertz steps over a tuning range of approximately 1 MHz. The second synthesizer must return to the same absolute phase when tuned away from a frequency and then returned to the same frequency at a later time. The output power required must be at least +10 dBm over the entire frequency tuning range of 6.000 GHz to 10.000 GHz.

Figure 7.3 is a preliminary block diagram of the 2nd Synthesizer. The output is derived from a 125 MHz reference signal which is transmitted over the fiber. The output of a 125 MHz harmonic generator is mixed with the output of the YIG to produce a 31.25 MHz IF signal whenever the YIG is tuned to 31.25 x (2n+1) MHz. The output of the 31.25 MHz IF is phase detected with the 31.25 MHz output from the fringe generator and the output of this phase detector is used to close the loop around the YIG oscillator. The output of the YIG is pre-scaled so that the microprocessor can be used to measure the approximate frequency of the YIG, allowing the microprocessor to "coarse tune" to the desired frequency. The phase-lock-loop is then closed and allowed to lock. Since the counters are not actually part of the loop, none of their phase noise contributes to the final signal.

Specifications - Second LO Synthesizer

Input Signals

Reference freq, high	125.0 MHz @ 0 dBm, 50 ohms
Reference freq, low	20 Hz @ 1.0 volts RMS, high z

Output Signals

Tuning Range	6.0 - 10.0 GHz
Tuning Step Size	62.5 MHz
Power Output:	+8 dBm to +12 dBm adjustable
Fine Tuning Range	+/- 1.0 MHz Min
Fine Tuning Steps	0.001 Hz Max
Phase Steps	0.1 Degree Max

M/C Bus: High Speed Controller Area Network (CAN)

Control Functions:

- Set Main Tuning Frequency
- Set Fine Tuning Frequency
- Set Phase
- Set Power Output
- Upload Frequency Parameters
- Upload Phase Parameters
- Output On/Off
- Self Test

Monitor Functions:

- Power Supplies Ready
- Output Present
- Output Power Level
- Coarse Tuning Frequency
- PLL Locked
- Module Temperature
- Start Programs

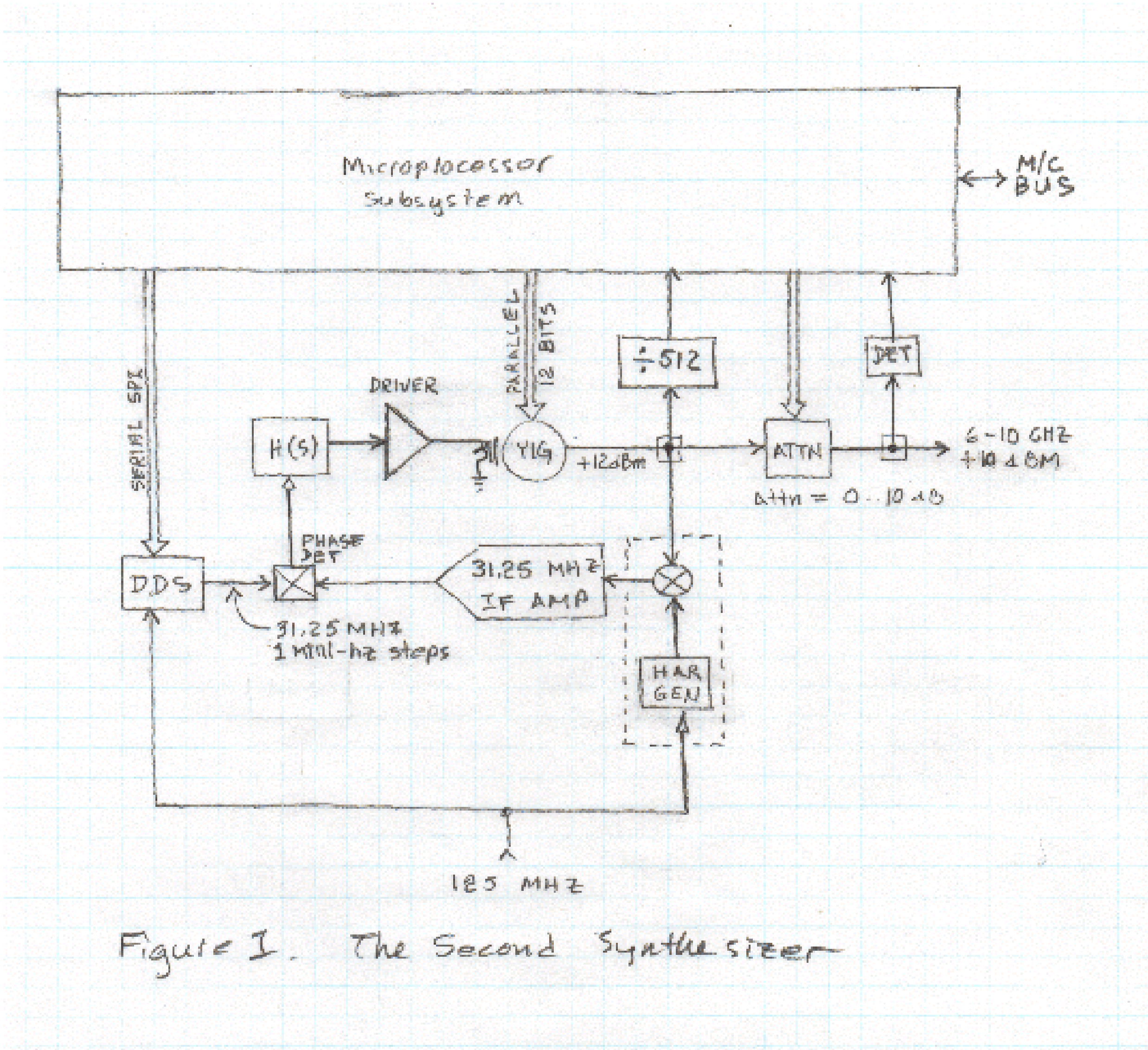


Figure 7.3: Second LO synthesizer block diagram.

Report on the ALMA Photonic Systems PDR

J. M. Payne & D.T. Emerson
Last Revised 1999-November-19

This is a report on the ALMA Photonic Local Oscillator and Phase Calibration PDR. It is especially significant in that it is the first to involve complete European participation in the new joint project. The PDR followed the guidelines established in the earlier MMA project and took place in Tucson on the 28th and 29th of September 1999.

The Review Panel

The Review Panel consisted of the following:

Darrel Emerson (NRAO, Chair)
Brian Ellison (RAL)
Harold Fetterman (UCLA)
John Payne (NRAO)
John Pearson (JPL)
Richard Sramek (NRAO)
John Webber (NRAO)
Sander Weinreb (JPL)
Wolfgang Wild (SRON)

Introduction

The list of presentations given at the meeting is below. This report will not attempt to summarize these various presentations but will focus on the recommendations of the Review Panel. Prior to this meeting, NRAO had been considering three separate photonic options for the ALMA receiver systems. "*Option I*" is purely conventional, with the transmission of a relatively low frequency reference (e.g. 13 GHz) signal over optical fiber, using off-the-shelf fiber optics modulators and demodulators. In "*Option II*" a LO reference signal up to about 120 GHz is generated at a central site, as a difference frequency between two lasers. The 2 lasers signals are then sent out along a single fiber to each antenna, where a photodetector generates the ~120 GHz microwave signal. This is then used to phase lock a local YIG or Gunn oscillator; higher frequencies, into the sub-mm region, are generated by a succession of multipliers from this signal. "*Option III*" is a further development, where the LO signal is generated at the central site as a difference frequency between 2 lasers, over the entire frequency of operation of ALMA. This signal is sent to each antenna, where a photodetector produces the needed LO frequency at the receiver directly, without further phase locking or multiplication.

Option II had been chosen by NRAO as its favored basline plan, although it is hoped that Option III may eventually be developed to a sufficient degree that it becomes a viable alternative - leading to considerable simplification of the receiver systems.

SUMMARY OF THE AGENDA:

Introduction - Scope and goal of this meeting — Darrel Emerson

Specifications - Summary of scientific requirements and how they translate into engineering specifications — Darrel Emerson & Simon Radford

US Baseline Design:

1. LO Baseline Plan - Description and rationale — Larry D'Addario
2. Test Interferometer LO Plan — Larry D'Addario

Photonic Systems:

1. General introduction to photonic LO issues — John Payne
2. Phase locking, round trip correction, photomixer development — Bill Shillue
3. Photonic phase calibration - Systems aspects and implementation — Darrel Emerson & Andrea Vaccari

Multipliers and LO source generation

(This section is strictly not part of this design review, having been presented at an independent PDR. However, presentations were included in order to put the photonic development in context within the overall system.)

1. LO sources (locked to reference) — Skip Thacker/Eric Bryerton
   a. Details of LO generation and meeting the phase specs
   b. Current status and results.

2. Mmwave Multipliers — John Webber
   a. Current status
   b. Research areas - Frequency plan; amplitude noise

European Activities

(This meeting is the first joint PDR with the Europeans. Although plans within Europe are inevitably not yet so advanced as those from the US, a summary of European capabilities was presented.)

1. European photonics plans and activities — Rolf Guesten
   (presented in Guesten's absence by John Payne)

2. UK activities — Brian Ellison

Schedule and timeline

The schedule and timeline — Larry D'Addario

Discussion on US/European collaboration — All

The Panel's Comments

1– The approach taken for the baseline plan, in the photonic distribution of the reference to each antenna ("Option II") is good and the correct choice. "Option III" is still attractive, provided that it can be shown to be viable in an appropriate timescale. Thought should be given to a possible upgrade path from Option II to Option III.

2– Specifications: Some areas require further work. The tuning granularity of the first local oscillator was a subject of some discussion. The noise floor of the first local oscillator as it affects the dynamic range of single dish observations needs to be added to the list of LO specifications. The oscillator switching times, both for single dish frequency-switched observations with a limited range of frequency switching, and for general tuning within a single receiver band, may need respecifying; the former may need a faster response (1 ms?), while the latter requirement may be relaxed (1 second?) The LO power requirements were not well defined, and have perhaps been unnecessarily overestimated by the mixer designers in order to ensure an adequate margin. Since power is expensive at sub-mm frequencies, this area deserves more careful study.

3– A more detailed analysis of phase noise in all parts of the LO chain should be made, including the performance of the various phase lock loops. There are many sources of noise in solid state lasers, and further investigation is needed. Conclusions should be written up in a readily available form, probably part of the ALMA memo series.

4– Some members of the panel felt that the physical properties of optical fiber, for example dispersion and standing waves, had not been adequately studied. Again, studies should be written up in a readily available form.

5– Increased effort on the photonic calibration system was encouraged; this should be given at least as much attention as the round trip correction schemes (which themselves become part of the calibration system).

6– The panel felt that a major effort should be mounted for the ALMA personnel to fully acquaint themselves with the work being undertaken by various groups in high frequency photonics in the U.S., and in Europe. More manpower may be needed in the photonics group in Tucson; a detailed study of the list of tasks and labor estimates would show precisely how much extra manpower might be required to meet the schedule, but there seems to be an immediate need for at least one extra engineer and one technician.

7– Collaboration with the Japanese was strongly encouraged. An effort should be made to acquire an NTT diode, even if purchasing a new mount and cutting the diode out of it is required.

8– It was felt that although the approach is basically sound, the schedule is ambitious and aggressive and more detailed and careful planning is required.

Conclusions

The panel was supportive of the decision to adopt Option II as the baseline design for the array. There should be a clear path towards the realization of Option III. There should be an increased effort in both the high frequency photo detector work and the photonic calibration system. More manpower in the Tucson photonics group may be required in order to have a working system by the time the antennas are delivered.

The panel agreed that a top priority should be for ALMA staff to visit other groups in the U.S. and Europe to learn of efforts in the development of high frequency photodetectors.

The path adopted is fundamentally sound, but some more careful definition of specifications, and some further detailed studies in a variety of areas as outlined above, were recommended.

IF Processing and Data Transmission

Dick Sramek
Bill Brundage
Dan Edmans
Last revised 2000 Feb 15

Summary

This Chapter describes the signal processing from the IF outputs of the front end through the baseband digital inputs of the correlator. Accordingly, it includes

1) the intermediate frequency (IF) down-converter
2) the digitizers
2) the fiber optic digital link

The signals from the active receiver at each antenna will pass through an IF selector switch and into an IF down-converter. The down-converter analog output signals will then go to digitizers, then to the fiber optic link which will carry the signals to the central electronics building, then into the correlator.

8.1 IF Down-Converter

The IF down-converter for the Test Interferometer uses the same design, with a few minor variations, as that proposed for the ALMA telescope. In this way the design can be developed and thoroughly tested before going into quantity production for ALMA.

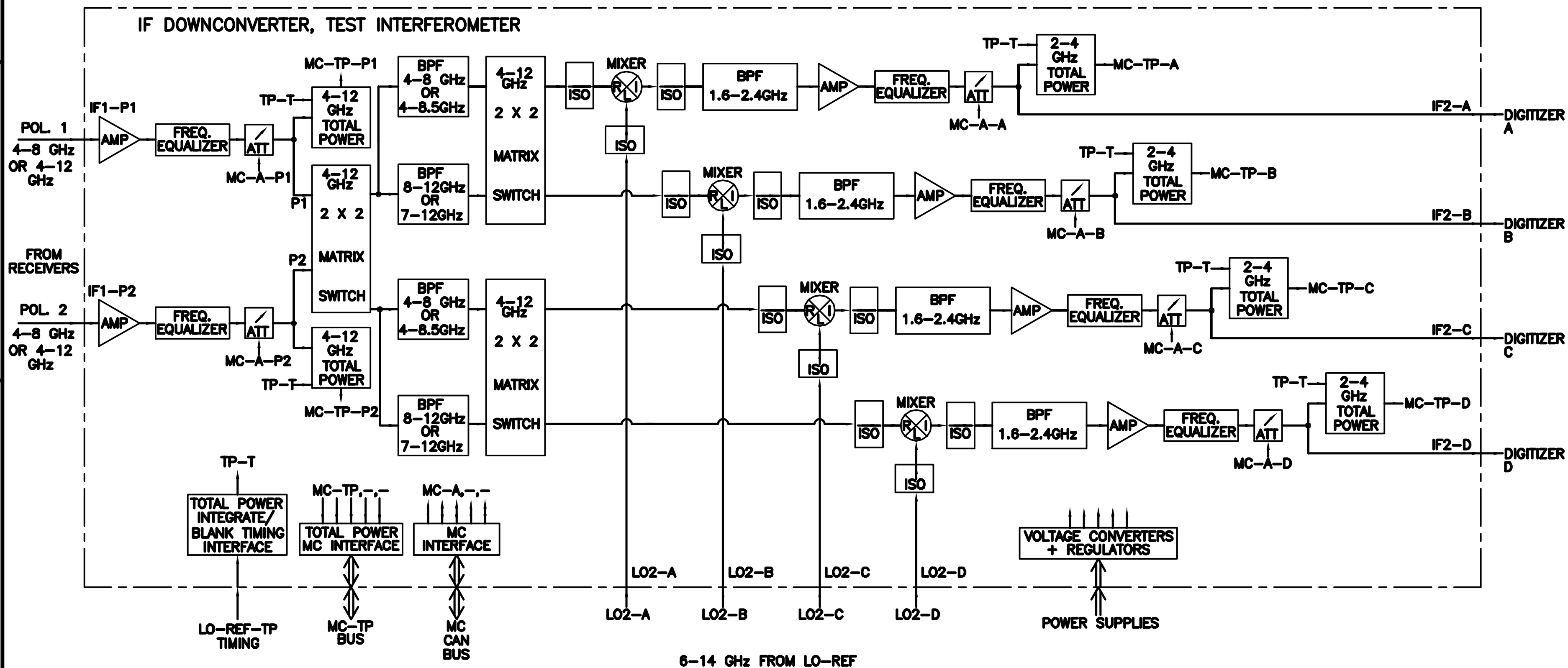
In the Test Interferometer, the two inputs to the single down-converter module will be the two polarization signals from the front-end. In the ALMA telescope, there will be two down-converter modules at each antenna, one for each polarization, and the two inputs to each module will carry upper and lower side-band signals.

A block diagram of the down-converter in its Test Interferometer variation is shown in Figure 8.1 and the specifications are in Table 8.1. The input and output nosie spectral power distribution will be nominally flat over the band-pass as given in the specifications.

The down-converter will take the wideband 4 - 12 GHz input signals received from the front-end system and produce four output signals each with a band-pass of 1.6 to 2.4 GHz suitable for band-pass sampling at the digitizers, which in the Test Interferometer are clocked at 1.6 GS/sec.

In addition to gain, frequency conversion and band-pass definition, the down-converter module provides total power measurement of both the two wideband input signals and the four narrowband output signals, plus a switching capability which allows any output channel to tune either the upper or lower frequency portion of either input channel (4-8 GHz or 8-12 GHz).

In discussing the specifications for the down-converter, the following definitions are used; values within square brackets [ ] are tentative. Values To-Be-Determined are marked TBD.



REV	DATE	DRAWN BY	APPRV'D BY	DESCRIPTION

ACAD : TI–IFDC–CBD

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCES : ANGLES ±	1°
3 PLACE DECIMALS (.XXX) ±	.0005 .005
2 PLACE DECIMALS (.XX) ±	.01
1 PLACE DECIMALS (.X) ±	.1

MATERIAL :

FINISH :

NEXT ASSEMBLY | DWG. TYPE

ALMA PROJECT: ALMA–US–D&D TEST–INTERFEROMETER IF DOWNCONVERTER

TITLE: CONCEPTUAL BLOCK DIAGRAM

NATIONAL RADIO ASTRONOMY OBSERVATORY
SOCORRO, NEW MEXICO 87801

DRAWN BY M. SULLIVAN	DATE 2/9/00
DESIGNED BY B.BRUNDAGE	DATE 2/8/00
APPROVED BY	DATE

SHEET NUMBER 1 OF 1 | DRAWING NUMBER TI–IFDC–CBD | REV. – | SCALE NONE

Define *signal-to-noise-ratio (SNRx)* at IF system location x as the ratio of total system noise spectral power to the equivalent internal noise spectral power looking downstream. SNRx will be > [30] dB at all IF locations.

All frequency conversions will have *image suppression (I) > [30] dB* throughout the passband. Mixer image noise will be included in all designs.

Define IF *headroom (Hx)* at IF system location x as the ratio of available *third order-intercept power (IP3)* to the *normal total system noise power (Pn) - 20 dB* at location x. Typically, detrimental non-linear effects of gain compression and inter-modulation occur when the IF total power exceeds IP3 - [20] dB. For example, if H = 0 dB, then the power of the 3rd order intermodulation frequency will be 2x20dB = 40 dB below the lower powered of the two intermodulating frequencies. Hx will be > [10] dB at all IF locations.

Define IF *Group Delay Variation (Δ GD/Δ t)* as a time delay per unit frequency interval per unit of time in units of nanosec/GHz/60minutes from system input to system output. Table 9.2 specifies Δ *GD/Δ t from IF inputs to outputs* as < [TBD] nanosec/GHz/[60] minutes. If D&D implements analog IF transmission over fiber, then the FO transmission is embedded in this specification. Note GD in terms of a measurement of phase vs frequency (via a vector network analyzer) is $GD = \Delta \Phi / (\Delta f * 360^\circ)$.

Table 8.1 IF Down-Converter Module Specifications, Test Interferometer

Number of modules	
Test Interferometer	one per antenna
ALMA	two per antenna
IF Input	
Number of IF inputs per module	two
Frequency	4 -12 GHz
Power level	[-30 dBm]
Headroom	>20 dB
LO Input	
LO inputs per module	four, independently tunable
Frequency	6 - 14 GHz
Power level	[+10 dBm]
IF Output	
Number of IF inputs per module	four
Frequency	1.6 - 2.4 GHz
Power level	TBD
Headroom	TBD
Conversion stability, input to output	
Gain stability in time	<2 dB p-p, 2 GHz bandwidth over 60 minutes
Band-pass ripple	TBD dB p-p, over 2 GHz, in [2 MHz] segments
Band-pass stability	TBD dB p-p, over 2 GHz in, [2 MHz segments], 60 min
Total Power Detectors	
Number on input	two, one for each input channel
Number on output	four, one for each output channel
Linearity	< 1% deviation, -3dB to +7 dB relative to nominal
Resolution	TBD
Stability	TBD in TBD seconds
Interface	Special total ower bus to antenna M/C system
Readout	Sigma/Delta A/D converter to M/C interface
Attenuators	
Input	[0.5] dB steps, range TBD
Output	[0.5] dB steps, range TBD

8.2 Digitizers

<to be written>

8.3 Fiber Optic Digital Link, Test Interferometer

The current plan for the serialization, synchronization and transmission of the digital data from the ALMA test interferometer antennas to the correlator is presented here. The fiber optic link for the test interferometer uses the same design as that intended for ALMA, with the addition of rate converter modules at the input and output which interface the 125 MHz fundamental clock rate of the link to the 100 MHz clock rate of the test interferometer digitizers and correlator.

A complete description of the link will be given in an ALMA memo "Digital Transmission of the IF Data for the Atacama Large Millimeter Array", by Edmans and Jackson to be released in the second quarter of 2000.

The link, starting from the antenna, consists of a rate converter, a digital multiplexer, an optical modulator and transmitter, a wavelength division multiplexer/ de-multiplexer, an optical receiver, and finally a digital de-multiplexer.

The basic link takes as input 32 2-bit signals from the two samplers of the test interferometer at a 100 MHz clock rate. These are re-clocked to 32 2-bit signals at 125 Mb/s and multiplexed x5 up to 625 Mb/s in a Xilinx FPGA and multiplexed again to 10 Gb/s. This output channel has 2 Gb/s spare capacity to allow for synchronization signals and 8b/10b coding. The reverse process occurs at the receiving end, outputting 32 2-bit signals at 100 MHz to the correlator.

One such link will be sufficient for the test interferometer. Eight or twelve links will be needed for ALMA depending on whether 2 or 3-bit signals are transmitted from the antenna. This full system will be largely a matter of replicating the prototype system. A full twelve link system is shown in Figure 8.2.

8.3.1 Transmitter

A block diagram of the Digital Fiber Optic Transmitter is shown in Figure 8.3. This diagram shows the data transmission system for a single channel for simplicity.

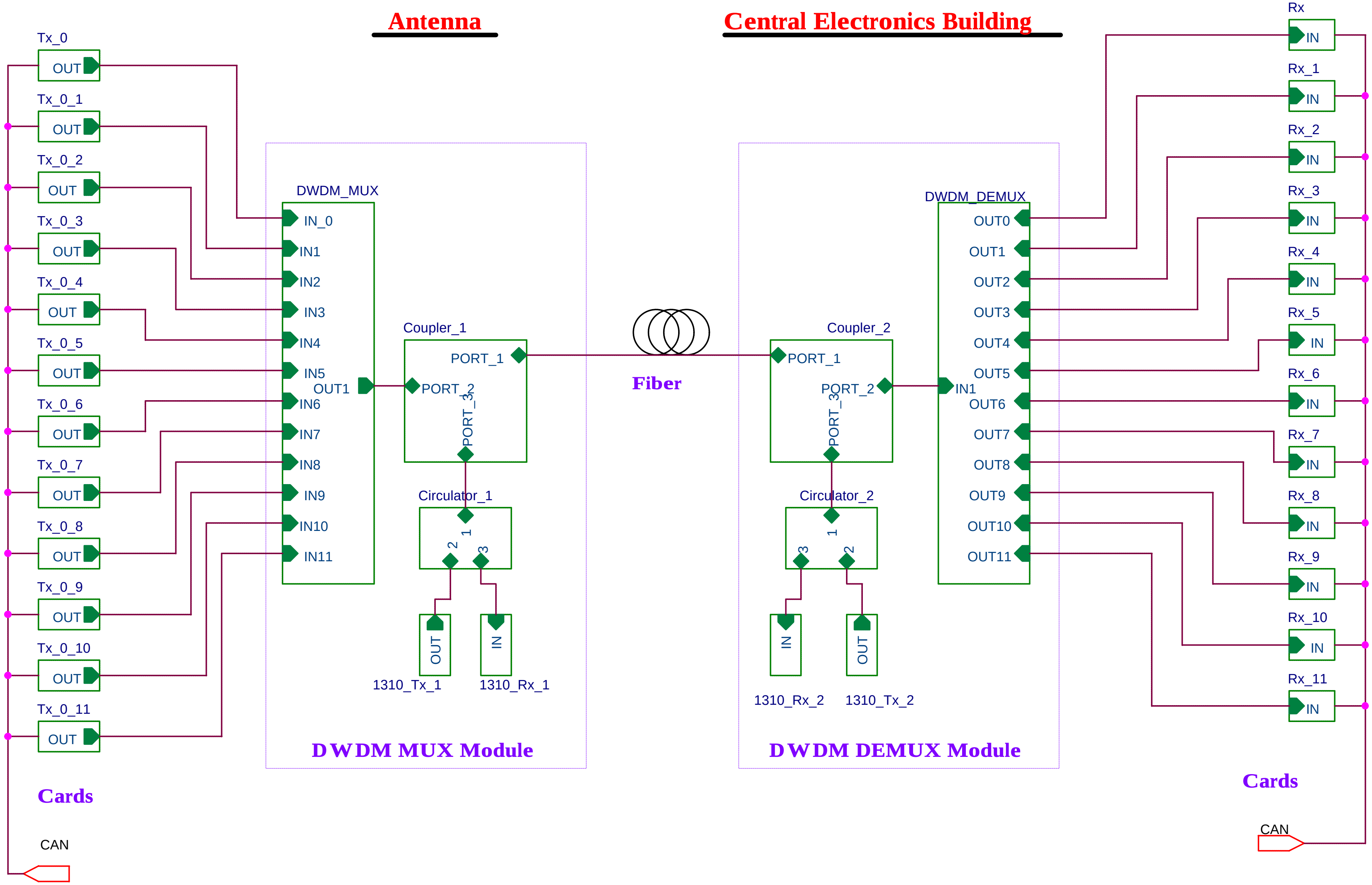
The current design contains all of the multiplexing and electrical to optical conversion on a single Euro-card style board with connections to the digitizers on the backplane. The optical to electrical conversion hardware includes the laser, laser temperature and bias current control hardware, optical modulator. In addition, there is a provision for an optical wavelength locker and the required feedback control circuit. Optical power monitoring is handled through the interface to the Laser Driver module. The card is controlled by a Monitor and Control (M&C) interface. The following list specifies the components in each element of the digital block.

<u>M&C interface:</u> This includes an Intel 82527 CAN controller and PIC 16C74 microcontroller. A relatively straightforward micro-controller design provides all necessary control signals and an interface to the rest of the system. The microprocessor controls the laser power and laser temperature control modules.

<u>Clock distribution:</u> This block includes the generation of a 625 MHz clock from the 125MHz system clock, and a 312.5 MHz clock for the FPGA. The 625 MHz clock is used for the Multiplexer.

<u>Sync Controller and Data Routing:</u> A Xilinx Virtex-E FPGA is included in the design. This device will contain all of the logic for routing the 125 MHz input data to the appropriate shift registers. Any 8B/10B coding or PRBS generators and/or sync pattern generators required in the design can be implemented in the FPGA.

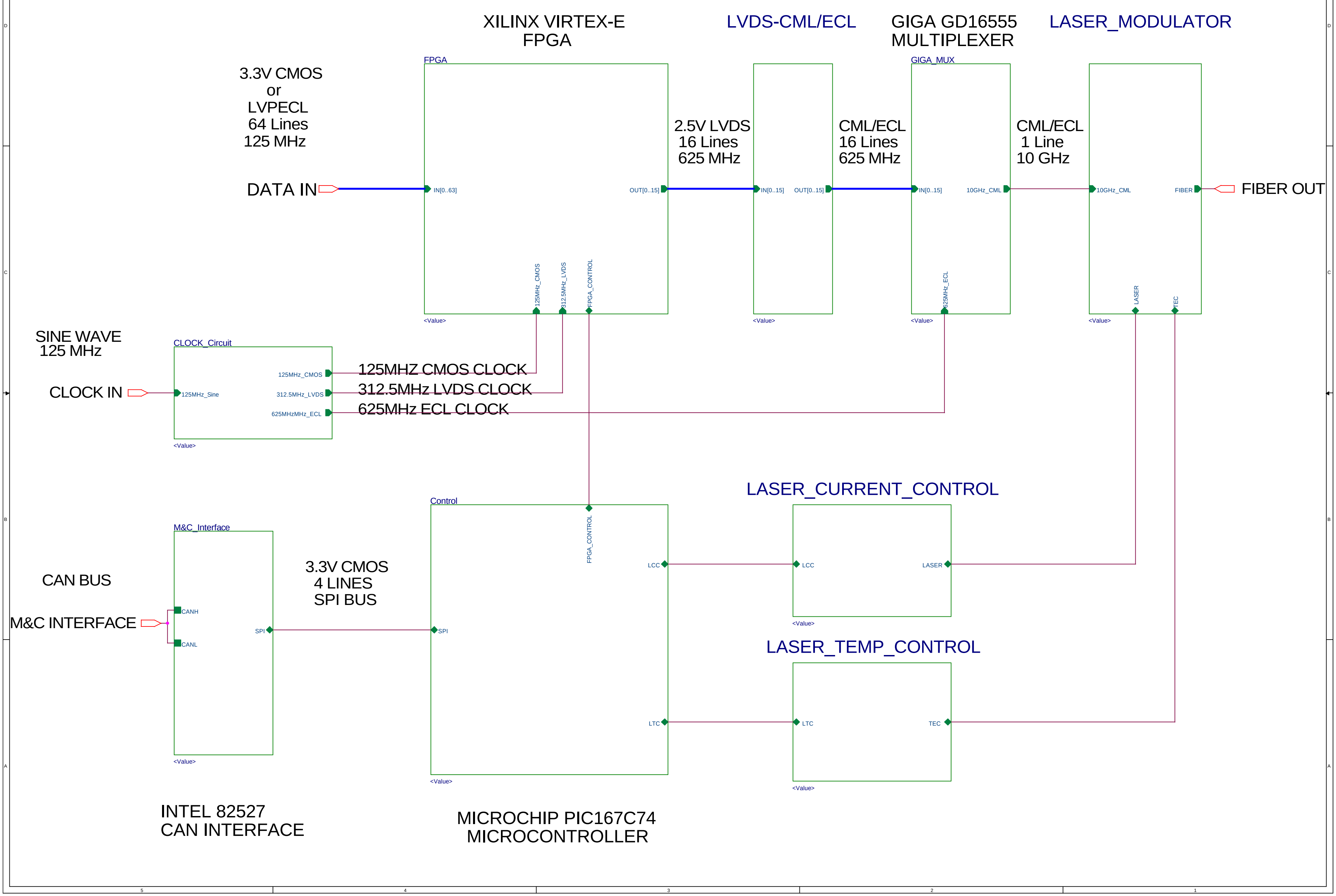
<u>LVDS to CML/ECL conversion</u>: This block contains the LVDS to CML/ECL conversion necessary



National Radio Astronomy Observatory

Title	ALMA IF Digital Fiber Optic Link 2000	
Size: A	Document Number: 2k0211:1800	Rev: 0
Date: Friday, February 11, 2000	Sheet 1 of 1	

FIBER OPTIC TRANSMITTER



between the Xilinx gate array and the Giga Multiplexer.

10 Gbps Serializer: This block consists of a Giga GD16555 10Gbps multiplexer IC and associated electronics. The multiplexer converts the 625MHz 16-bit parallel data into a 10 Gbps serial data stream for transmission over the fiber optic link. This circuit is essentially as shown in the data sheets, application notes and evaluation board design from Giga.

Laser & Modulator: This block includes the amplifier that is the driver for the Electro-Absorption modulator (EAM) plus the integrated laser/EAM package.

For ALMA, the output of this block is one of the 8 (or 12) WDM channels that are multiplexed together onto a single fiber in a separate optical module.

8.3.2 Receiver:

Figure 8.4 shows the block diagram of a receiver. The receiver consists of several major elements that are described here.

PD & Amps: This block contains a *p-i-n* photodiode, amplification, and an electrical filter. The output is a 10 Gbps data stream that is fed to the Giga Demultiplexer.

10 Gbps demultiplexer : The first demultiplexer stage is a Giga GD16544 10Gbps demultiplexer IC and the associated electronics. It converts the 10 Gbps serial data stream from the fiber optic link to 625 MHz 16-bit parallel data. This circuit is essentially the same as is shown in the data sheets, application notes and evaluation board design provided by Giga.

CML to LVDS Conversion: This block contains the CML/ECL to LVDS conversion necessary between the Giga Demultiplexer and the Xilinx gate array.

625MHz De-serializer: The Xilinx FPGA converts the 16 bit 625 MHz data from the Giga demultiplexer into 80 bit 125 MHz data for presentation to the Correlator. The FPGA also contains the synchronization recognition function and any decoding functions.

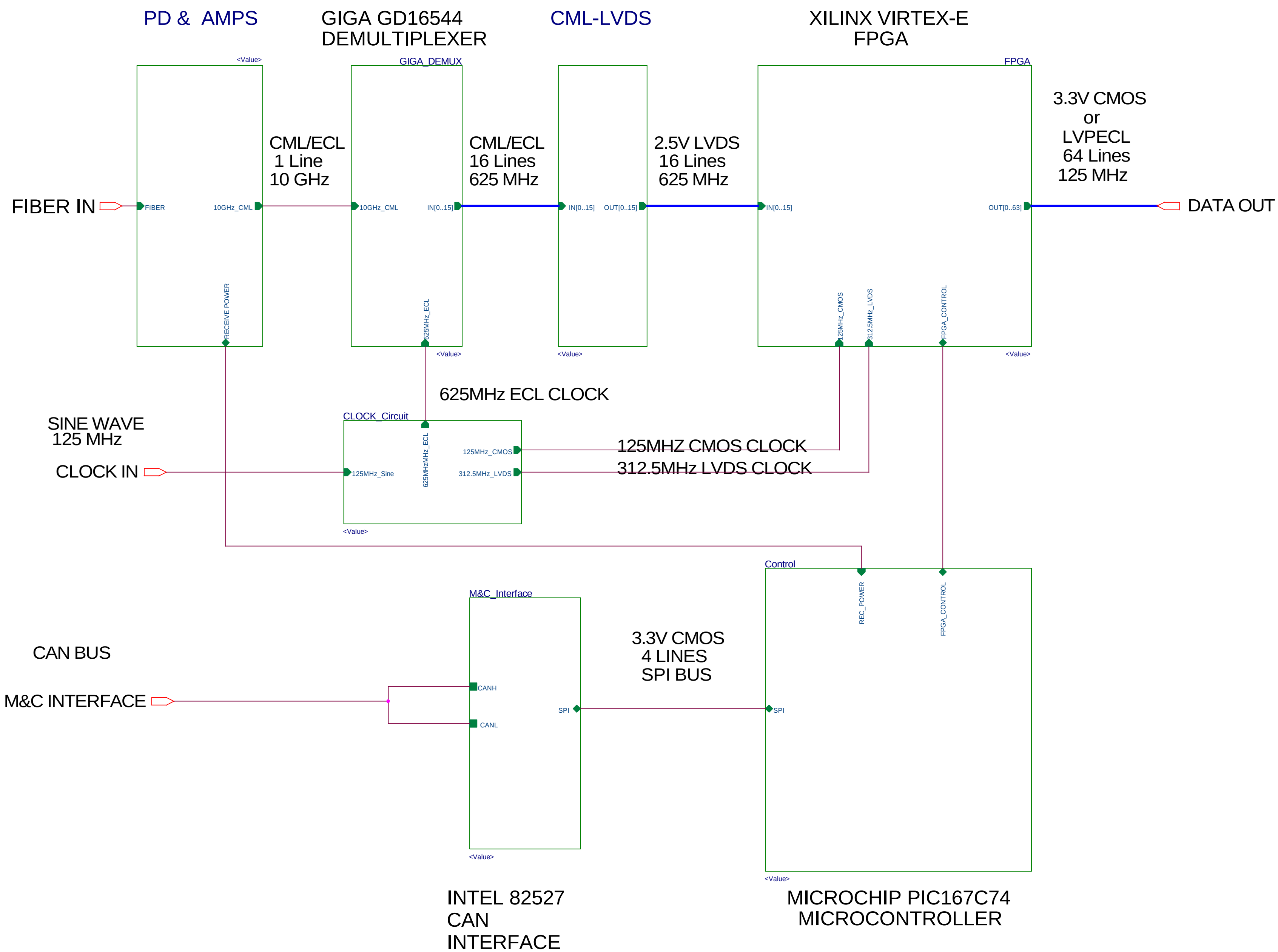
Sync Controlling and Data Routing: A Xilinx Virtex-E FPGA contains all of the 125MHz logic for routing the 125MHz input data from the appropriate shift registers to the output of the board, and any PRBS generators and sync pattern comparators required in the design. A synchronization clock control is also be implemented in the FPGA.

M&C Interface: This block contains the Intel 82527 CAN controller and a PIC 16C74 microcontroller. It is a straightforward microcontroller design providing all necessary control signals and an interface to the rest of the system.

8.2.3 Data Encoding:

In the absence of any interface specification documentation regarding the output of the ALMA digitizer or FIR filter, an optional system has been envisioned to take the place of a previously proposed 8B/10B encoding scheme. The intention is to minimize the effect of any DC offsets in the data over long run times. Dramatic DC offsets may occur, in the worst case for instance, due to hardware failures. We are using a Non-Return-to-Zero (NRZ) data format, and AC coupled amplifier stages, therefore it is possible that the data from the digitizer and FIR filter may charge the coupling capacitors between amplifier stages in the receiver. Such a situation can occur when long runs of optical logic 1's are transmitted. To ensure that the data or hardware failures do not have a detrimental effect on the performance of the fiber-optic link, two fallback schemes have been devised for implementation if necessary. Both are easily implemented in the FPGA. One scheme uses a Psuedo-Random Binary Sequence (PRBS) stream with an XOR function operating on the data so that any long runs of 1’s can be mitigated. This method can be implemented in the existing FPGA targeted for the prototype. The other alternative under consideration is simply to invert alternating words, a process that can also easily be

FIBER OPTIC RECEIVER



implemented in the FPGA. Other options exist and can also be explored.

8.3.4 Synchronization Sequence:

To synchronize the system, a predetermined bit pattern will be generated by the FPGA in the Transmitter and sent over fiber to the receiver which will search for the pattern on start-up or on demand as initiated over the M&C system. This has to be done in two stages, once to account for the synchronization of the multiplexer and a second to account for the synchronization of the serializer. The transmitter can repeatedly switch between the two patterns at some predetermined time interval. Once the receiver recognizes and syncs on the two synchronization patterns, it will signal the transmitter, via the M&C system or a dedicated low speed fiber-optic link, to send data. One variable that is as yet undetermined and which will effect the implementation is the latency in the M&C system. The total latency is the sum of the latency in the Tx and Rx cards, transmission in the optical fibers, the two CAN-bus links, the central computer, and the ATM system used to send data to the antennas. It is anticipated that this latency will be no more than one second. The following steps are required for synchronizing the system.

Synchronize the GD16555 multiplexer and GD16544 demultiplexer: - Inject a known test pattern into D0-D15 of the GD16555 multiplexer IC. In the receiver, test outputs D01-D15 of the GD16544 demultiplexer IC and determine data offset between the multiplexer and demultiplexer. This offset is stored and used to determine data routing in the 125 MHz FPGA.

Synchronize 625MHz shift registers: - Inject a known test pattern into sixteen 5-bit shift registers implemented in the transmitter FPGA. The receiver monitors the outputs of 625 MHz shift registers and switches the 125 MHz output clock through the five possible phases to determine the correct alignment. The output clock is then set to the correct phase. The receiver signals the System computer and the transmitter that it is in sync.

Once sync is recognized at both levels, the receiver signals the computer control system and the transmitter that it is in sync, and that scientific data can be transmitted.

Sync monitoring and resynchronization: – The current design has 16 unused bits in the 80 bit 125 MHz inputs. One method for monitoring synchronization is to have the transmitter continuously place a prescribed sequence such as PRBS (psuedo-random binary sequence) on one of the unused bits. The receiver would generate the same PRBS and compare the results to determine if the system is in sync. It should be possible to use this sequence to quickly resynchronize the system on the fly if synchronization is lost by only +/- a few clocks. Gross synchronization loss would require repetition of the main synchronization (steps 1 & 2). If this situation occurs, the receiver signals the transmitter to begin synchronization via the M&C system, which also flags the system.

Synchronization handshaking:
The microprocessors in each receiver-transmitter pair handshake via the dedicated link.. It has the advantage that resynchronization will take place almost instantly. This is a better alternative then handshaking through the M&C link because of the latency of communication through the M&C link which would result in a significantly larger amount of data loss should resynchronization be required.

ALMA Test Interferometer Project Book, Chapter 9

ALMA TEST CORRELATOR

John Webber
Ray Escoffier
Last revised 2000-Feb-15

Revision History:

Summary

This section describes the ALMA test correlator. The design described here is for a lag correlator with a system clock rate of 100 MHz. This correlator is based on the design of the GBT and Tucson autocorrelator spectrometers, with provision for cross-correlation operation so that both single antenna spectra and two-antenna cross-spectra can be measured.

Table 9.1 Correlator Specifications

Item	Specification
Number of antennas	2
Number of baseband inputs per antenna	2
Maximum sampling rate per baseband input	1.6 GHz
Sampling and correlation format	2 bit, 3 level
Maximum baseline delay range	10 microsec @ 800 MHz BW
Hardware cross-correlators per baseline	65536
Product pairs possible for polarization	RR, RL, LR, LL (for circular, *e.g.*)

This correlator is intended entirely for testing the performance of the two prototype antennas, using a short baseline. The maximum delay range accommodated is 10 microsec with 800 MHz bandwidth and 80 microsec with 100 MHz bandwidth. The delay resolution is 8 samples at 800 MHz bandwidth and 4 samples at 100 MHz bandwidth. This is adequate resolution if the correlator is dumped sufficiently rapidly.
Table 9.2 below shows the principal milestones for the test correlator.

Table 9.2 Principal milestones for ALMA test correlator work

Complete hardware and internal software testing	2000-03-31
Deliver to VLA site	2000-07-01

9.1 System Block Diagram

A simplified block diagram for the ALMA test correlator is given in Figure 9.1. This diagram presents a fairly conventional lag correlator except for the presence of the data format conversion stage.

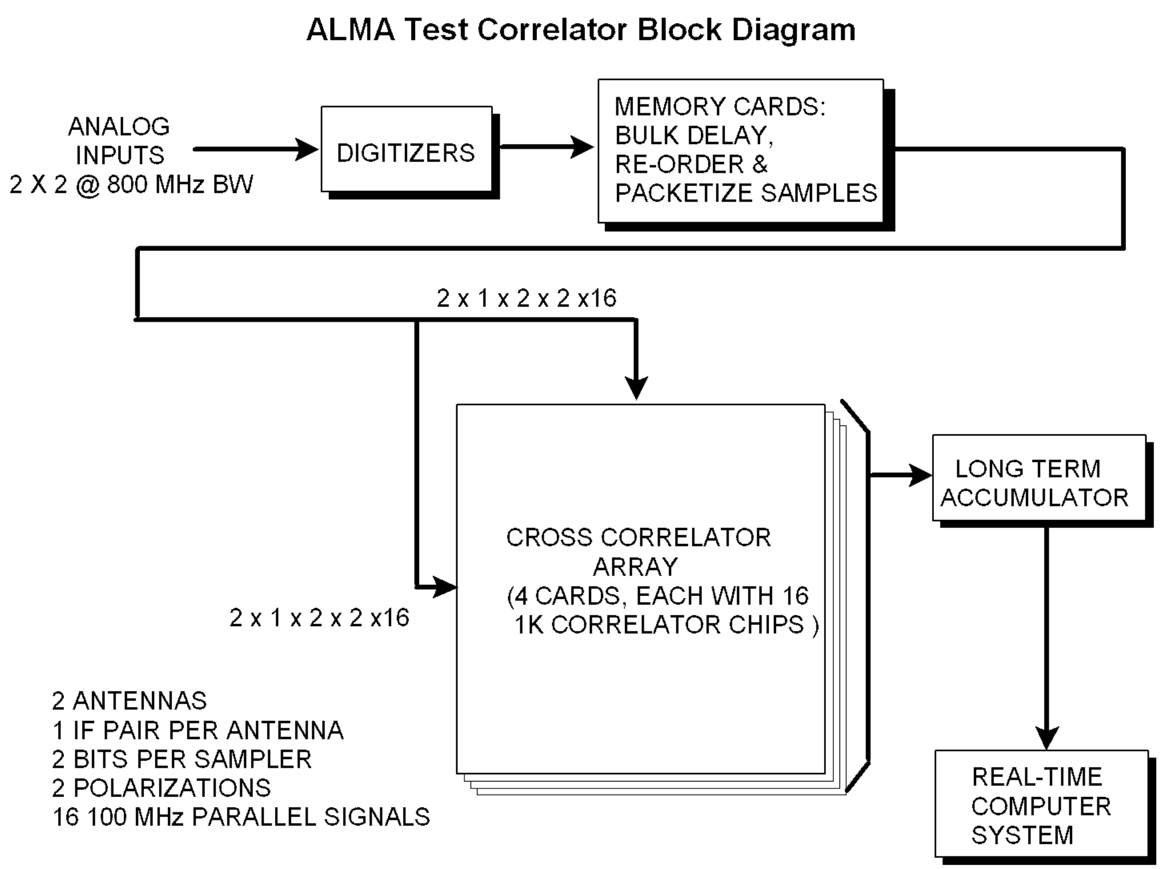


Figure 9.1: simplified correlator block diagram

The analog outputs of the baseband system, 1 polarization pair per antenna, drive four sampler inputs where 2-bit, 3-level sampling is performed at 1.6 GS/second. The analog bandwidths supported are 800 MHz and 100 MHz; bandwidths of 400, 200, and 50 MHz could be supported if a need arises.

The data format conversion block takes the 16 parallel outputs of each sampler and, using RAMs, both adjusts delays and re-sorts the samples. In this block, the 16 parallel outputs of a high speed sampler are converted from each carrying every 16th sample to each carrying short (1.3 msec) bursts of contiguous samples.

By using the format conversion scheme, the 16-wide parallel output from a sampler are transformed into 16 parallel signals, each carrying 1.3 millisecond packets of contiguous samples. This simplification in the correlator circuit requirements is obtained at the cost of an inefficiency of about 0.8% which results because the end bits in adjacent 1.3 msec time segments of samples will not get correlated.

An additional benefit of the format conversion strategy is that it allows the system the same advantage as a recirculating correlator: when the bandwidth being processed is reduced by a factor of 2, the number of lags the system is capable of generating goes up by a factor of 2. This results in a factor of 4 increase in frequency resolution for a factor of 2 decrease in bandwidth.

The custom lag correlator chip provides 1K lags and is the "Quaint" chip designed by John Canaris. The chip can be programmed via a microprocessor supplied program word.

The long term accumulation block seen in figure 9.1 integrates the correlator outputs for the desired duration.

9.2 Performance

This section gives performance parameters for the operating modes of the ALMA test correlator.

Table 10.3 below gives the supported autocorrelation modes.

Table 9.3 Autocorrelator modes

Bandwidth (MHz)	Number of antennas	Number of IFs per antenna	Number of spectral channels	Frequency resolution (kHz)
800	2	2	1024	781
100	1	2	8192	12

Other modes could in principle be supported, such as 2 antennas, one polarization each, with 100 MHz bandwidth; however, these would require some hardware work and expense, and will be omitted unless there is a proven need for them.

Table 9.4 below gives the supported cross-correlation modes.

Table 9.4 Cross-correlator modes

Bandwidth (MHz)	Two polarizations, no cross-products		Two polarizations, all cross-products	
	Spectral channels	Resolution (kHz)	Spectral channels	Resolution (kHz)
800	1024	781	512	1563
100	8192	12	4096	24

Note that if 400 MHz and 50 MHz analog filters were provided, it would be possible to achieve a factor of two higher spectral resolution in any mode by operating the correlator in oversampled mode, which involves only throwing a hardware switch.

The minimum dump time supported by the correlator is 1.3 msec. However, the VME computer which receives the data from the LTA is thought to be capable of accepting the data at a rate which will give a minimum dump time of ~100 msec. The maximum integration time in the LTA before overflow is 85 seconds.

9.3 Interface Requirements

The correlator occupies one 24-inch EMI shielded rack. The four samplers are housed in a VLBA bin within the correlator rack, allowing stand-alone operation. Two extra VLBA bins, at present unwired, will be used to house the samplers at the antennas. Interfacing them to the correlator after the fiber optic link will be by means of special multi-signal cables.

The stand-alone correlator dissipates 1 kW and requires refrigerated air from the floor.

The correlator without samplers requires the following:

Clock input: 100 MHz sinewave, 50 ohms, 0 dBm (SMA connector)

Sync input: typically 1 PPS, TTL logic levels, into 50 ohms

Data input:

16 single-ended 2-bit 3-level ECL signals from each of 4 samplers (terminated with 50 ohms into -2V)

Communications: Ethernet interface

AC power: 30 amp 3-phase circuit for digital logic, 117 VAC for VME crate

The 4 samplers each require:

Clock input: 100 MHz sinewave, 2 V peak-to-peak, terminated in 50 ohms

RF input to samplers: 1.6 to 2.4 GHz, 50 ohms, -14 dBm

DC power:

0.03 A @ +5V
1.9 A @ -5.2 V
0.06 A @ +12 V
0.01 A @ -12 V
0.1 A @ +15V

Each sampler dissipates about 15W and requires modest forced-air cooling.

Monitor and Control

Mick Brooks
Brian Glendenning
Larry D'Addario

Last revised 2000-February-15

Revision History:
2000-2-15: Fixed some typos and removed task diagram from Section 10.4
2000-2-14: Altered heading numbers for new project book
2000-2-4: Revised to include design decisions and implementation information for test interferometer
1999-4-8: Add in new detail on M&C data sizes and rates; minor changes to discussion points
1998-11-16: Combine previous contributions – favor distributed computing model

10.1 Summary

This section describes hardware and communications considerations and design decisions for the Monitor and Control (M&C) system, and some consideration of task structure. Other software considerations are described in Chapter 11.

Data rates for the M&C system are modest in most situations, ~4000 Bytes/second/antenna. Sampling of total power data, video data from an optical telescope, and FPGA downloads are some of the possible situations where the data load is significantly larger. An architecture in which as-dumb-as-possible devices communicate via a field bus, mastered by M&C computers at each antenna, is described. Separate, dedicated communications media will be required for the higher throughput subsystems.

Table 10.1.1 Principal M&C milestones, D&D phase

Standard bus interface circuit prototype	2000/02/25
M&C draft interface specifications	2000/03/25
Critical design review (M&C)	2000/06/31
Deliver single dish antenna test system	2001/09/01

10.2 Design Considerations

This is a list of high-level issues that have affected the choice of communication hardware and protocols; the type and distribution of computers; and the design of real-time control software.

1. The principle guiding the design of individual devices is to limit their intelligence. It is proposed that individual subsystems contain micro-controllers at least for maintaining communications with the computing system. These local processors may be required to perform some local hardware control, but in general will be mere input/output processors. Accordingly they should not be required to run an operating system or require large amounts of memory or rotating disk media.
2. Data rates at each device should be modest, and large amounts of data should not require tight timing constraints. The worst case latency for any M&C message should be no

greater than 1 ms. This requirement is intended to give sufficient scan time to sample several M&C points on the bus for presentation in a “virtual oscilloscope” fashion. The M&C medium should be deterministic such that priorities may be assigned to ensure that certain M&C values reach their destination within a timing tolerance of 1 ms.

3. The proposed allocation of “intelligence” is that each device at an antenna subsystem be considered as quite dumb. Control tasks requiring sub-millisecond timing should be handled within the subsystem. A field bus linking these subsystems and mastered by a real-time computer at each antenna will attend to control tasks above the sub-millisecond level.
4. The M&C communication system should support development and maintenance in the absence of the complete monitor and control system. Control signals must be provided and monitor signals recorded and displayed not only during normal operation of the array but also during development and testing. An individual device must be testable in the laboratory without the master computer or any subordinate computer of the M&C system. A collection of devices forming a subsystem, or a complete antenna's hardware, should be separately testable without support from the master computer (which might be busy with software tests or otherwise unavailable). It is intended to use LabView to support laboratory access to the M&C communication medium.
5. The current proposal is for a master computer housed in a control building of some sort. There will be a separate communications path from there to each antenna (a star configuration) run via optical fiber. A possible protocol for use here is ATM, providing a mix of dedicated real-time bandwidth and general purpose TCP/IP connections. A bus master, comprising a real-time computer, will be situated at each antenna and provides access to individual devices via a field bus. This topology assumes that devices on one antenna do not need to communicate with devices at another antenna.
6. The M&C system should make use of commercially available solutions wherever possible. Distributed control systems are common in the industrial process control and factory automation industries. In the past, NRAO has developed communications protocols and interfaces itself. Commercial products offer advantages in terms of cost, development time and fault tolerance.

10.3 Data Rates

The rate at which devices will have to be monitored or controlled is known to first order at this time. Current estimates follow. The first table, Table 10.3.1, summarizes the average and peak data rates at each antenna, according to information at the time of writing.

Table 10.3.1 Average and Peak Data Rates at Each Antenna

Mode	Average Data Rate (kB/s)	Peak Data Rate (kB/s)
Normal Observing	4.1	8.3
Total Power OTF	16.0	32.0
Video Data	4 200	4 200
Holography	4.3	8.3

Note that the net data rates are low (excluding science data of course) if we exclude the possibility of video data and total power, both of which should not be considered as monitor data. Sporadic data such as FPGA downloads may be quite large (20 Mbytes) but require only soft delivery deadlines; these account for the peak rates.

In Table 10.3.2, each subsystem at an antenna is listed with the numbers of M&C points allocated to each. The total shows that 75% of M&C traffic will be monitor data.

Table 10.3.2 Total Monitor and Control Points for devices at each antenna

Item	Control Points	Monitor Points
ACU	45	60
Metrology	4	10
Subreflector	4	4
Cryogenics	4	19
Dewar	1	8
HFET Receivers (3)	14	52
SIS Receivers (7)	14	52
Optical Telescope	8	8
Local Oscillator	4	18
IF System	14	8
Fiber Optics	8	12
Samplers and Filters	10	20
Other (environmental, safety, etc).		32
Totals	242	719

In Table 10.3.3, the most time critical M&C points for each subsystem are listed with their typical access intervals. The shortest interval is that of the Antenna Control Unit, requiring trajectory commands and position data to be transferred once every 50 ms.

Table 10.3.3 Time critical monitor and control points for devices at each antenna

Item	Control		Monitor	
	Size (B)	Time (s)	Size (B)	Time (s)
ACU mount positions	16	0.05[1]	20	0.05
Metrology	2	Rare	10	0.5
Subreflector nutation control	6	0.1	6	0.1
Cryogenics	10	Rare	100	600
Dewar	2	Rare	30	600
HFET Receivers (3)	10	Rare	180	60
SIS Receivers (7)	10	Rare	180	60
Optical Telescope	8	Rare	8	Rare
Local Oscillator	2	0.1	10	1
IF System	10	10		
Fiber Optics			12	10
Samplers and Filters	10	1	10	10
Other (environmental, safety, etc).			32	600

In Tables 10.3.4 and 10.3.5, the numbers of M&C points located in the central control building are broken down by subsystem. Note that in the case of the correlator, many of the M&C points may be broadcast

[1] This rate is an update for position and velocity commands. The actual servo period will be much shorter.

Table 10.3.4 Total monitor and control points for common devices, at central building

Item	Control Points	Monitor Points
Timing standard	10	60
LO System	10	10
Optical Transmitters	10	10
Reference signal generation	10	20
Weather instruments	1	8
Totals	41	108

Table 10.3.5 Total monitor and control points for correlator related subsystems

Item	Control Points	Monitor Points
Input configuration	200	20
Delay tracking	200	20
Output configuration	200	20
Totals	600	60

10.4 Conceptual Design

The design presented here is currently under review.

- **Device Complexity.** Devices are allowed to have a wide range of complexity and built-in “intelligence”. There is no requirement for some minimum processing capability, and most devices may be completely “dumb”. A dumb device is one that sets its state to that given in a coded instruction immediately upon receipt of the instruction, without further processing. A somewhat intelligent device might execute instructions at specified future times, or interpolate between instructions, or derive its new internal state from a combination of the present instruction and its current state. In all cases, device intelligence is considered "embedded" - part of the hardware - and therefore not part of the monitor/control system.
- **Overall Communication**. The correlator and all antennas are joined at the master computer by a fiber network, arranged in a star topology. A standard networking protocol, most probably ATM, will be used to implement this communication. Many recent telescope control systems have used commodity networking to good effect.
- **Distribution of Intelligence.** Besides the master computer and embedded processors, there will be a separate computer for the control of the correlator, and a computer at each antenna. The role of this antenna computer is twofold: to organize communications between devices at the antenna and the central computer, and to implement tasks that can most profitably be executed locally.
- **Intra-antenna Communication.** At each antenna there shall be one or more local buses which interface the devices situated at the antenna to the antenna computer, which in turn organizes communication with the master computer over the fiber network. These buses will be commercial systems based on the CAN network, ISO 11898. In addition, a non-standard higher layer protocol will be developed to provide application level services. A separate communications path would be provided to carry the video signal from the optical telescope to a computer with a frame grabber and to collect total power samples.

- **Real Time Boundary.** Any loop requiring a response to an event with a hard deadline of less than 1 millisecond should close the control loop within the local device. Closed loop systems with looser deadlines may be closed by the "bus master".
- **Time.** All M&C computers shall know the time to an accuracy of least 0.1ms, and shall be capable of delivering a periodic signal with a jitter of less than 0.05ms (these values are subject to revision during detailed design). Low-speed devices thus do not need any knowledge of time; the M&C computer can time them appropriately. A 50 Hz period, sub-microsecond jitter distributed time signal will be required for other purposes in ALMA. It is anticipated that the M&C system will tap into this system for time synchronization.

This design essentially uses a computer to couple a local intra-antenna bus to a wider ALMA network. The aggregate computing power at each antenna exceeds that which is required for its coordination role. On the other hand this design allows for much flexibility in handling antennas with special instrumentation, implementing high-speed sampling for debugging devices at the antenna remotely ("virtual oscilloscope"), and other requirements which are unknown now but will inevitably become important later.

Testing outside of the M&C system can be accomplished in two ways. First, the entire antenna may be unplugged from the M&C system and into another computer (*e.g.*, a technician's laptop or a computer on the antenna transporter). Similarly, a particular device may be plugged into a local bus that is attached to some other computer. This allows for testing during development when a full M&C software system is not available. For example, a PC with a commercial CAN bus interface card will be used to act as a bus master in the lab. National Instruments LabView is the defacto standard for test software in this phase.

10.5 Implementation Details

The current state of M&C implementation is summarized as follows:

- Slave node software has been developed supporting the CAN bus and the non-standard higher layer protocol. This software is written in C and is available for Siemens C167 and Microchip PIC16C74 micro-controllers.
- A prototype standard M&C interface circuit is currently being fabricated and will be tested shortly. This standard circuit is based on the Siemens C167 micro-controller and includes flexible digital and analog I/O options.
- A prototype M&C interface has been tested for the Fiber Optic laser temperature/current controller making use of the PIC16C74 micro-controller.
- Bus master Virtual Instruments have been developed for use in LabView and have been tested with the prototype slave nodes available. This software has been tested on a standard PC running Windows NT and using the National Instruments PCI CAN board.
- Bus master software has been written for use in VxWorks PowerPC systems. A test system using an MVME1603 motherboard and an SBS Greenspring PMC-ECAN-1 CAN interface board has been tested with the prototype slave nodes available. This software was written in C and makes use of a VxWorks device driver supplied by SBS Greenspring.

10.6 Reference Documents

[1] ALMA-US Computing Memo #1 Monitor and Control Points for the MMA, F. Stauffer, 1999-May-11

[2] ALMA-US Computing Memo #5 ALMA Monitor and Control Bus Requirements, M. Brooks, 1999-Jun-02

[3] ALMA-US Computing Memo #6 ALMA Monitor and Control System, M. Brooks, 1999-Jun-07

[4] ALMA-US Computing Memo #7 ALMA Monitor and Control Bus Draft Specifications, M. Brooks, 1999-December-09

[5] "CAN System Engineering", Wolfhard Lawrenz, Springer-Verlag, 1997

[6] ISO 11898:1993 Road vehicles - Interchange of digital information - Controller area network (CAN) for high-speed communication

11 Computing

B.E. Glendenning, G. Raffi

2000-Feb-15

11.1 Introduction

The role of software for the test interferometer is two-fold. First, it is required for testing the prototype antennas. Second, it is a prototype of some aspects of the final array software and use on the test interferometer can be used to prove some aspects of its design. This second use must not jeopardize the primary objective: testing the antennas.

The software group leaders have decided that prudence dictates that there should be a backup strategy to be employed if it appears that the new joint developments will not be ready in time to test the antennas. In this eventuality ESO/VLT common and control software will be modified to handle these tests. This backup approach was successfully tested in November 1999 by modifying ESO/VLT software to perform optical pointing measurements on the NRAO 12m telescope on Kitt Peak. As this plan would entail considerable original work to integrate radio-astronomy specific devices, it will be employed only if the new software development becomes delayed.

There is no intention to test advanced observing systems for the test interferometer. That is, sophisticated archiving, dynamic scheduling, image pipelines, and advanced observer preparation tools are not considered to be necessary for the antenna tests. The elements of the final software that will be prototyped on the test interferometer are those that are related to common and control software.

11.2 Software Engineering Practices

It is important that a distributed software development effort that will last for a decade agree upon software engineering practices. An important product of Phase 1 is a list of agreed upon software engineering practices in the areas of:

- Design Process (almost certain to follow the Rational Unified Process, using UML as a design language).
- Release Strategy (fixed date *vs*. fixed content).
- Documentation standards and formats (likely MS Word).
- Review procedures (based on ESO practice, emphasizing written comments in advance of review meeting).
- Code acceptance and documentation standards.
- Testing (unit and integration).
- Maintain a list of supported platforms.
  - Language: C/C++, Java, and TBD scripting.
  - OS (likely a mixture of VxWorks, Linux, and Windows).
- Configuration management.

While there are no jointly agreed upon standards yet, there are some proposals outlined by Harris *et. al.* (1999).

11.3 Common Software

ALMA will require a considerable software effort of many different types. However, a large part of the software can be shared, with the same API used by many software systems both real-time and non-real-time.

This common software is useful for several reasons:

- It provides common services required by more than one software subsystem. This avoids duplication of effort, and ensures that those common services behave the same in different software subsystems.
- It provides communication and interaction mechanisms between software systems, and provides for a common style of programming (*e.g.,* event driven).

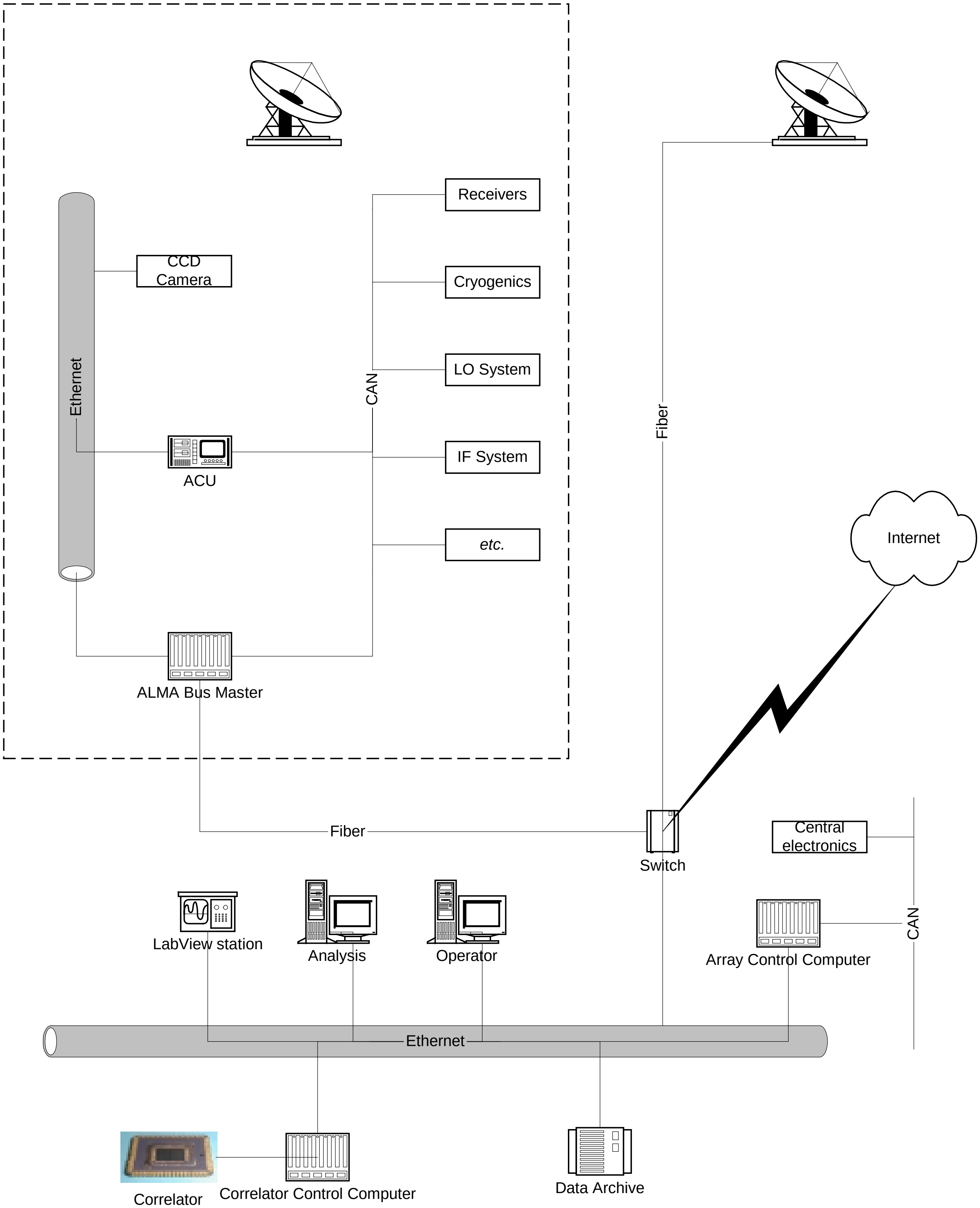
That is, the role of the common software group is to provide tools and libraries that implement common solutions. This enforces standards and similarities in applications, which then become really maintainable by integration and support team.

Where possible, we expect the common software will wrap existing functionality into a consistent interface. For example, rather than writing FITS code from scratch we will almost certainly reuse existing FITS code (for example, the well-known FITSIO library).

Capabilities anticipated for the common software include:

- Communications and remote execution (provided by CORBA).
- Alarms and logging.
- Event handling.
- Scripting support.
- Various utilities (astronomical calculations, FITS, mathematics, *etc*.)

A discussion document describing some desired capabilities and implementation considerations is described by Chiozzi (1999).


Receivers
CCD Camera
Cryogenics
LO System
Ethernet
CAN
Fiber
ACU
IF System
Internet
etc.
ALMA Bus Master
Fiber
Switch
Central electronics
LabView station
Analysis
Operator
Array Control Computer
CAN
Ethernet
Correlator
Correlator Control Computer
Data Archive

11.4 Control Software

For more details on considerations related to Control Software, please see the “Monitor and Control” chapter of this project book.

11.4.1 Device interface

Most devices will be monitored and controlled through a CAN bus connection. CAN is a message-based deterministic fieldbus first used in automotive applications. CAN is inherently a peer-to-peer network; however, we are using it in a master slave fashion using a non-standard protocol to guarantee message delivery time for all message priorities. We have added a non-standard reset line to the connector and cabling to allow hung devices to be reset remotely. Running at 1Mbps we can achieve a throughput of more than 2000 messages per second and more than 600 kbps data transfer after subtracting framing and other overheads. Each CAN bus may contain 64 nodes, and each node is assigned 2^{18} messages. Stauffer (1999) has enumerated the M&C points, with their associated rates, anticipated for ALMA, and Brooks (1999a) describes some further requirements.

Device designers may choose to use either a standard circuit, which provides some A/D, D/A, digital, serial, and I2C I/O, implemented with a Siemens C167CR microcontroller. Device designers may choose to lay the circuit out directly on their own boards, or they can use it via a standard daughtercard. If they do not want to use the standard circuit, they must only conform to the protocol, which is available from the ALMA software group as (relatively) portable “C” source code.

The M&C connector, protocol, and standard circuit are defined by Brooks (1999c). Brooks and Glendenning (2000) provide the reasoning for some of the design choices, which is described in more detail in a memo by Brooks (1999b).

The CAN bus is mastered by a general-purpose computer. For lab testing this mastering can be done with a Windows PC running LabView; in the field we will use a VME PowerPC based system running VxWorks.

At the antenna the CCD camera will not be on the CAN bus. It will be controlled, and data will be transferred, via Ethernet. The ACU supplied by the vendor will be on both CAN and Ethernet, the latter to provide for a path for software upgrades and debugging, and to allow access to “static” parameters (for example, servo loop parameters). The total power detectors might or might not be on CAN as they could take up approximately 50% of its bandwidth (however it is possible to have multiple CAN buses at the antenna).

11.4.2 Network Distribution

All devices requiring monitor and control at an antenna are connected to a bus master, which is a general-purpose computer. Most devices are connected to the master via the CAN bus; however some may be connected via Ethernet or possibly a special-purpose connection in rare instances. The bus masters in turn are connected to a central master computer (ACC – array control computer), probably through a switch, via general-purpose networking. If quality-of-service guarantees are considered to be important this protocol will be based on ATM.

At the center, there will be some electronics on the CAN bus, and there will also be general-purpose computers for operations, telescope calibration, data archiving, and engineering data analysis using LabView. There will also be a general-purpose (but real-time) computer to control the correlator. Additional computers may be used, depending on the details of where computations take place, for example delay calculations. These computers will all be on a general-purpose (possibly switched) network.

11.4.3 Synchronization

The system will provide a prevalent 20Hz pulse. This pulse will be distributed to all devices (possibly via an unused pin in the M&C connector) that require precise timing. Commands will be delivered to those devices in advance of the next pulse, and will be "strobed" into effect on the next pulse. These commands might take the form of polynomials or table lookups for commands that need an effective rate greater than 20Hz.

Whether the commands from the center to the bus-masters at the antenna consist of real-time commands or time-tagged commands sent in advance of when the commands are required is still TBD. Similarly, whether array time is required to be known by any computer other than the ACC is still being debated.

11.4.4 Correlator

The Test correlator that will be used on the test interferometer is closely based on the design of the GBT spectrometer (hence it is often referred to as "GBT clone correlator") and the MAC spectrometer of the NRAO 12m telescope, modified to provide delays and cross-correlation capabilities. The software that will be used is thus largely based on the existing software developed by J. Hagen of NRAO 12m operations, with modifications made as necessary to allow the correlator to be used in an interferometer, and in a new control system.

Pisano (2000) describes the design of the test correlator software. It is hoped that this design can carry forward to the Prototype and Baseline correlators.

The data rates of the Prototype and Baseline correlators will be very large (Pisano, 1999). Parallel DSP processing system and Beowulf cluster solutions have been proposed as solutions for carrying out the required processing. While not necessary for the Test correlator, we might want to prototype such a solution with it.

11.5 Telescope Calibration

Numerous telescope calibrations will be required for the test interferometer. The approach adopted is to reuse existing software for this purpose whenever possible. This will require that the control system be capable of producing data in the appropriate formats.

We expect the bulk of the telescope calibration (*e.g.*, baseline determination, radio pointing) to come from the existing IRAM software suite. Optical pointing determination software will be based upon existing NRAO 12m software, and the pointing analysis will be done using the TPOINT software of P. Wallace. Single-dish holography might require new development. Holography requirements are outlined in a memo by Glendenning (1999).

11.6 Post-Processing

No post-processing development is anticipated for the test interferometer. Post-processing will take place in existing systems. Data will have to be written in appropriate formats, UVFITS for interferometric data, and possibly SDFITS for single dish data.

While some algorithm development may be occurring during the single dish tests, that development will not be the responsibility of the computing group. Instead it will be undertaken by the science/imaging and calibration groups, or outside of the ALMA project altogether.

11.7 References

The precise URL's for the following documents are subject to change as they become reviewed by the joint project, however they may all be found under the software development pages of the ALMA web site: http://www.alma.nrao.edu/development/computing/index.html.

Mick Brooks, *ALMA Monitor and Control Bus Requirements*, 1999-06-02.

Mick Brooks, *ALMA Monitor and Control System*, 1999-06-07.

Mick Brooks, *ALMA Monitor and Control Bus Draft Interface Specification*, 1999-12-09.

M. Brooks, B.E. Glendenning, *M&C Frequently Asked Questions*, 2000-01-11.

G. Chiozzi, *ALMA Common Software Feature List (prep. 2)*, 2000-01-15.

B.E. Glendenning, *Holography Software Development for the MMA*, 1999-04-15.

G.S. Harris, F. Stauffer, B.E. Glendenning, *Suggested Software Engineering Practices, ALMA Phase 1*, 1999-11-18.

J. Pisano, *ALMA Correlator Output Data and Computer Processing Rates*, 1999-11-12.

J. Pisano, *ALMA GBT Clone Correlator Control Computer Software Design*, 2000-01-04.

F. Stauffer, *Monitor and Control Points for the MMA*, 1999-05-11.

DRAFT P. Napier, 2000-Feb-09.

12 Site development

The general location of the ALMA test site at the VLA is shown in Figure 12.1 and a more detailed layout of the antenna foundations and control room is shown in Figure 12.2.

Antenna Foundations: The baseline plan for antenna foundations is, at least initially, to provide only 3 foundations giving a long interferometer baseline of 100 m and a short baseline of 25 m. The two foundations on the 100 m baseline will be used for initial assembly and acceptance testing of the antennas by the two contractors, for initial single-dish testing of the antennas by the ALMA project and for interferometric tests that require the 100 m baseline. The 25 m baseline will be used for early interferometer tests and for tests that require the best possible phase stability, such as antenna holography using astronomical sources. The antenna foundations will be designed by the antenna contractors and installed under the responsibility of the ALMA Project. It appears likely that the two antennas will require significantly different foundation designs and so the two antennas will not be able to sit on each others foundations. This raises the issue of which of the two antennas should be moved from its initial assembly foundation to the 25 m baseline foundation. It currently appears that budget constraints will not allow procurement of an ALMA antenna transporter until after the time when an antenna must be moved to the 25 m baseline foundation. This means that the antenna will have to be moved by picking it up with a mobile crane and placing it on a low-boy trailer, pulling the trailer to the 25 m foundation and then placing the antenna on the foundation using the crane. Since current design concepts show the European antenna being significantly lighter than the US antenna, it will be easier to move it. Accordingly, the plan is to make the western antenna foundation a US foundation and the other two foundations will be suitable for the European antenna.

Baselines longer than 100 m can be provided if the project wishes to pay the cost of additional foundations and their fiber optic links. By placing a foundation out on an arm of the VLA baselines as long as the longest ALMA baseline, 10 km, could be obtained if necessary provided that locations are chosen where road access for the antenna transporter exists.

Holography Tower: Single-dish holography will be performed using a near-field beacon mounted on top of a tower. The tower will subtend an elevation angle of about 8 degrees which could be provided, for example, by a 50 m high tower at a range of 300 m or a 100 m tower at a range of 600 m. Figure 12.1 shows a location for the tower for a 300 m range and locations for ranges longer than this are available to the SE of this location. The final choice of the tower location is a tradeoff between the difficulty of the near-field correction and the height of the tower. The 300 m range is 0.004 of the far-field distance ($2D^2/ \lambda$) at 86 GHz. Since the JCMT has demonstrated near-field holography to the required accuracy at a distance of 0.005 of the far-field distance, the 300 m range is probably adequate.

Electrical Supply: The antennas are specified to operate correctly on both 50 Hz and 60 Hz electrical supply frequency, on the European standard voltage of 400 volts 3 phase, 230 volts single phase. The baseline plan is to provide these voltages to the test interferometer at 60 Hz from a transformer connected to the VLA site electrical supply. If a test at 50 Hz supply frequency is considered essential before sending equipment to Chile a motor/generator will be rented for a few months (cost approx $2300/month). If it is considered essential to operate on a 50 Hz supply for the full duration of testing at the VLA this baseline plan will have to be changed to one in which the project purchases a motor/generator prior to antenna acceptance. As well as the 400/230 volt supply a supply at the US standard voltages (208 volts 3 phase, 110 volts single phase, 60 Hz) will be made available to the antenna contractors for their assembly equipment if they require it.

Control Room: Space for an ALMA Control Room will be made available in the VLA Control Building at the location shown in Figure 12.2 which has line-of-site to the ALMA antenna locations. Electrical wall outlets in this room will provide only 110 v, 60 Hz. Equipment requiring 230 v, 60 Hz will use portable transformers. If a 50 Hz source is available at the site and is required it can be brought to the room using temporary cabling.

Space for equipment which needs to be in a screened room because of RFI generation is available in the VLA Correlator screened room approximately 35 m from the ALMA Control Room.

Other Infrastructure: Office space, lab space and sleeping accommodations are available at the VLA site.

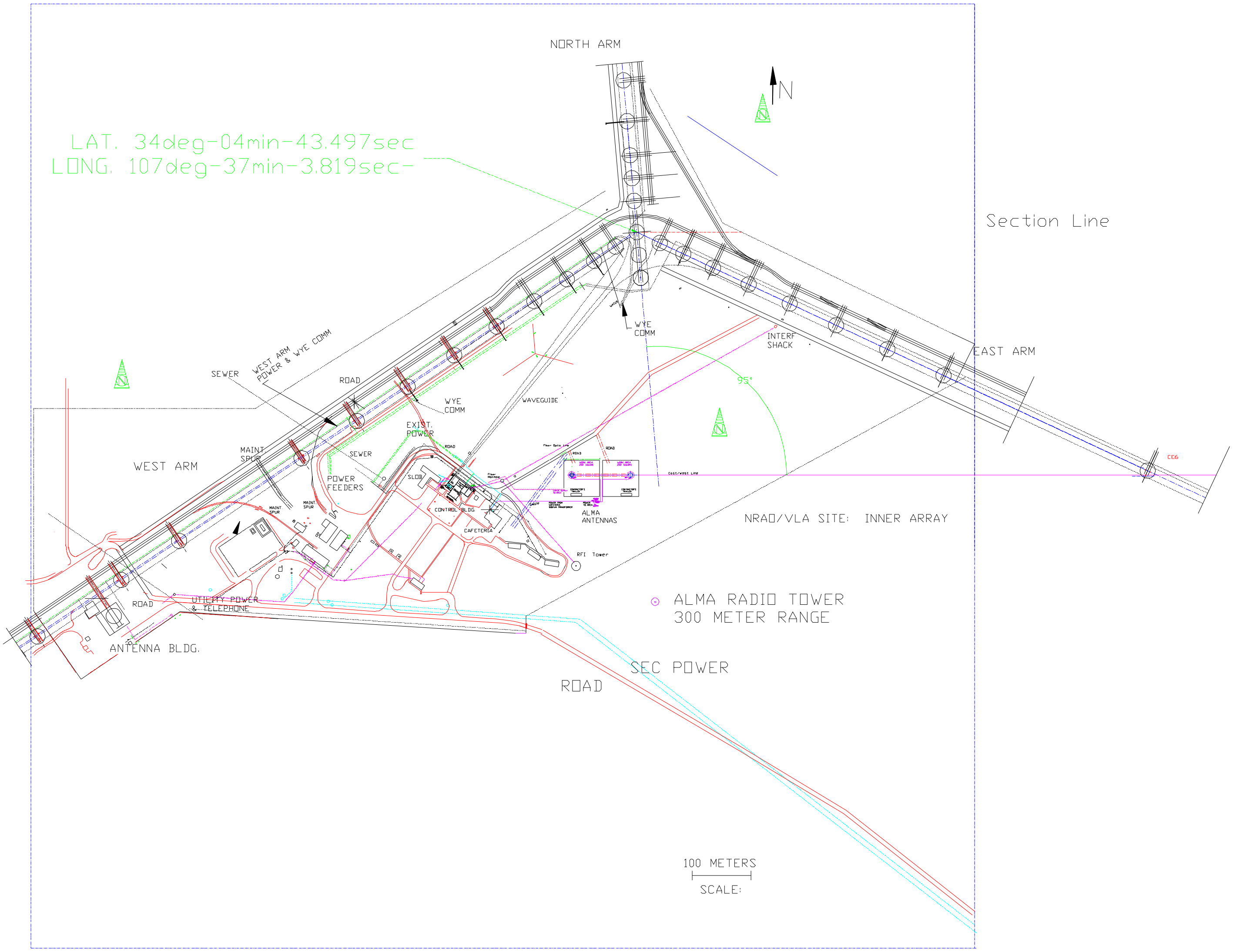


Figure 12.1 Location of the ALMA Test Site at the VLA.

The two antenna foundations for the 100 m Test Interferometer baseline are shown in the two square boxes approximately 600 m south of the center of the Y. The location of the tower for the holography beacon for a 300 m range is SSE of the Test Interferometer and tower locations for ranges longer than 300 m would be SE from there. The 1.6 km square box labeled “Section Line” marks the boundary of the property owned by NRAO. NRAO also has access to 200 m wide strips of land centered on the lines of VLA antennas. The VLA Antenna Assembly Building and Transporter Building are located in the Antenna Bldg. Complex on the left edge of the figure.

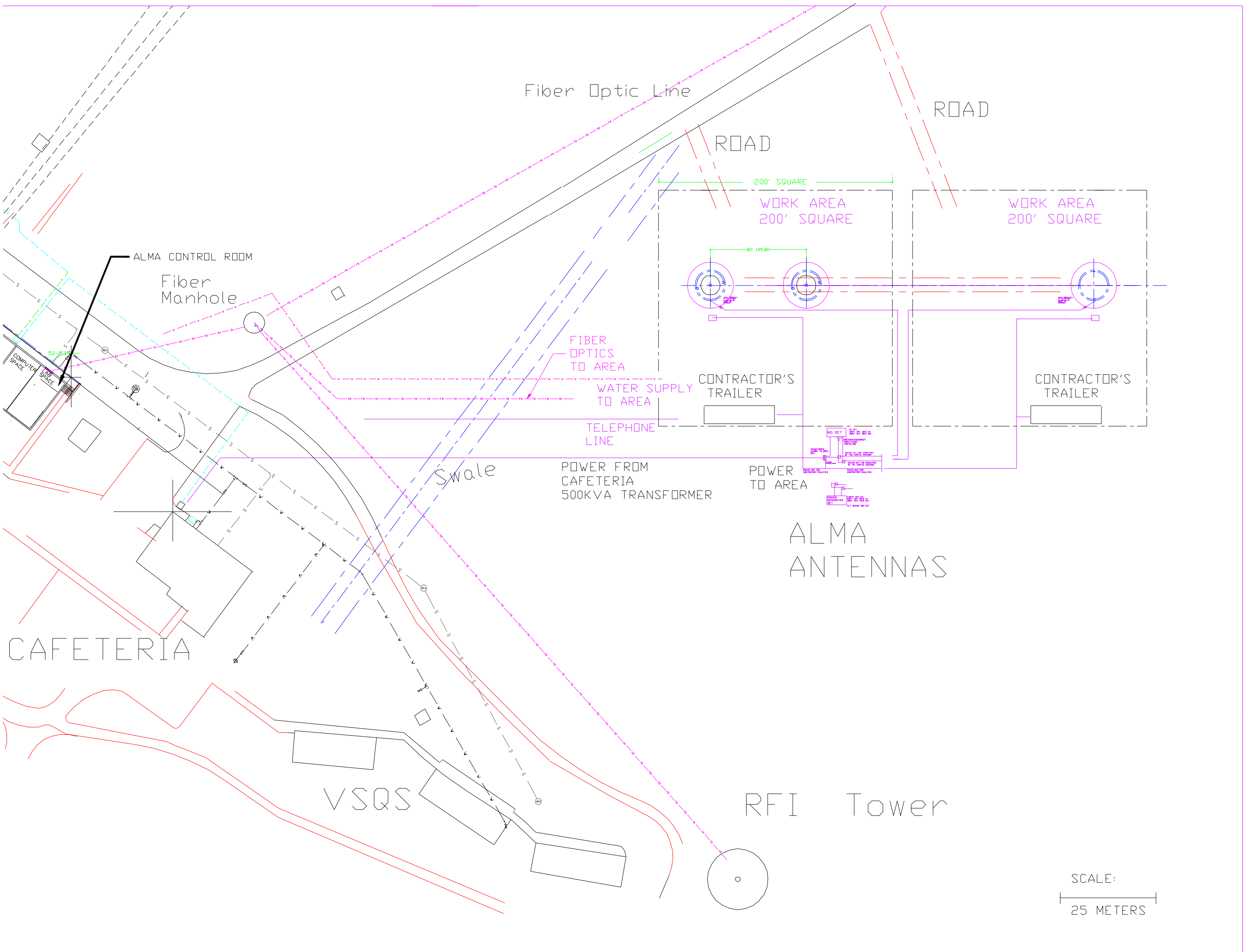


Figure 12.2 The 3 antenna pads of the ALMA Test Interferometer

The Control Room for the ALMA test interferometer is located in the VLA Control Building on the left hand side of the figure.

13 Antenna Installation

The antennas will be installed and tested for acceptance by the contractor on the two antenna foundations comprising the 100 m baseline shown in Figure 12.2. The west foundation will be for the US contractor and the east foundation will be used by the European contractor. It currently appears likely that the two contractors will be on site at the same time but the 100 m separation should prevent them interfering with each other. Each contractor will be given an access road to a work area approximately 60 m square which will be under his control.

The US contractor currently plans to assemble the antenna directly on the foundation. The European contractor has indicated that he may wish to assemble major components of the antenna inside the VLA Antenna Assembly Building or Transporter Building, shown in Figure 12.1. It will be the contractor's responsibility to move these components to the assembly foundation. Use of these buildings must be coordinated with the VLA operations staff well ahead of time.

A number of pieces of NRAO equipment will be made available to the contractors for antenna assembly. These include 30 ton and 5 ton mobile cranes, 60 ton drop-deck trailer, man lifts and fork lifts. Access to a fully equipped machine shop will be available for making field modifications. All NRAO equipment must be operated by NRAO personnel.

ALMA Test Interferometer Project Book, Chapter 14

SCHEDULE AND TIMELINE

Richard Simon
Last Changed 2000-Feb-22

Revision History:
2000-Feb-22: Initial version created (R. Simon)

Introduction

This chapter outlines the schedule and project planning for the Atacama Large Millimeter Array Project. There are two key aspects of planning for the ALMA:

- Tasks and milestones which must be accomplished
- Associated target dates.

The logical structure for the project is built around the concept of a "Work Breakdown Structure", or WBS. The WBS is simply an outline plan of all the work to be accomplished, and provides a framework for scheduling, costing, and tracking progress. Once a baseline WBS has been created, the inevitable changes and unexpected developments any real world project experiences may be incorporated into the WBS, and the impact of problems or unexpected difficulties can be allowed for.

The basic outline of the Joint WBS for the ALMA project has been drafted, but some details remain uncertain at this writing. This chapter presents the following:

- The Project WBS, expanded to level 2, presented in the form of a Gantt chart

After agreement has been reached on specific milestones in the project, they will be summarized in a separate table.

Note: For practical reasons, the HTML version of this chapter does not include detailed table listed below, other than as a link to the relevant PDF file. Readers are *strongly* encouraged to access the **PDF version** of this chapter**.**

Table 1: ALMA Task Scheduling

This Table presents a timeline for the project in the form of a Gantt chart, listing all tasks from level 1 or level 2 in the WBS.

Substantially more detailed views of the WBS are maintained at the following locations in PDF format:

The ALMA WBS *(last updated 2000-Feb-11)*

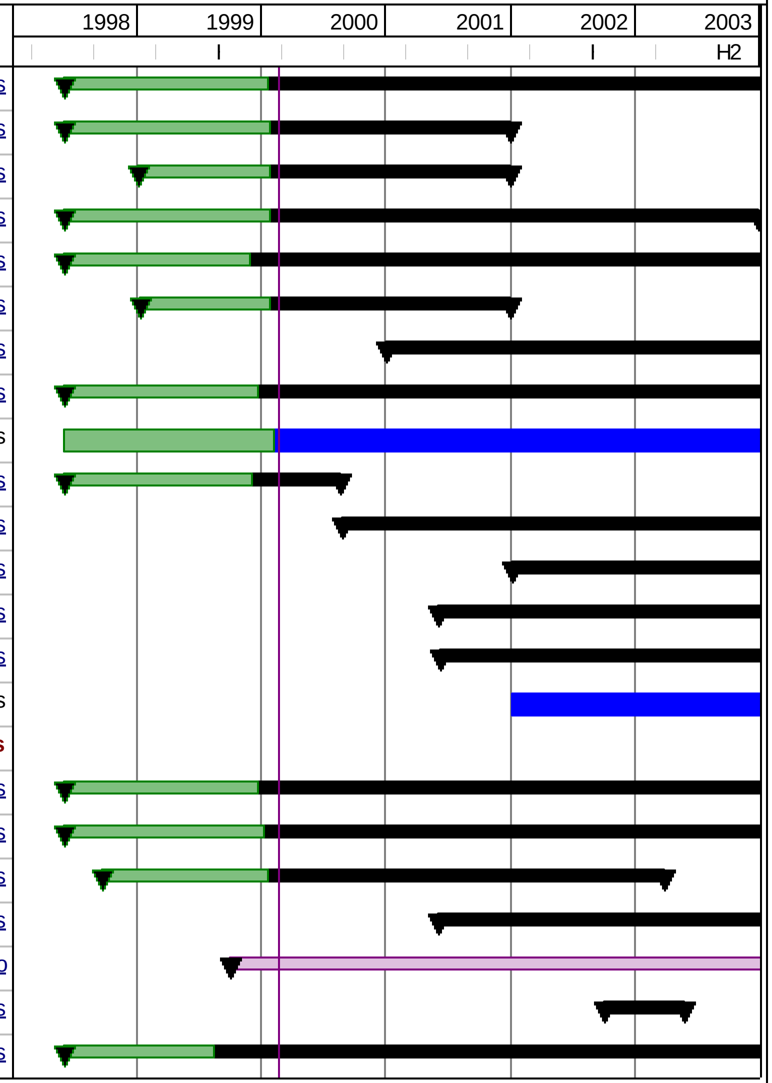
- Summary to Level 3 (http://www.cv.nrao.edu/almaplan/costing/almaplan2000feb11level3.pdf) (All tasks, Phase 1 and Phase 2, level 3 and higher, 17 pages)
- Complete ALMA WBS (http://www.cv.nrao.edu/almaplan/costing/almaplan2000feb11full.pdf) (All ~1,900 tasks; 76 pages)

Large
Millimeter
Array

All Tasks selected

File: almaplan2000feb22.mpp
View: Clean Gantt View
Printed: 15:47 Tue 00-02-22

WBS (f)	Task	Start	Finish	Duration	%Done	Eur	US
1	**Management/Administration**	1998-06-01	2009-12-31	605w	13%	Yes	Yes
1.05	Phase 1 Management	1998-06-01	2002-01-01	187.4w	33%	Yes	Yes
1.10	Phase 2 Planning	1999-01-01	2002-01-01	156.6w	17%	Yes	Yes
1.15	Facilities	1998-06-01	2003-12-31	291.6w	21%	Yes	Yes
1.20	Agreements in Chile	1998-06-01	2009-12-31	605w	20%	Yes	Yes
1.25	Partnerships and Agreements	1999-01-11	2002-01-01	155.4w	27%	Yes	Yes
1.30	Phase 2 Management	2001-01-01	2009-12-30	469.8w	0%	Yes	Yes
2	**Site Development**	1998-06-01	2009-12-31	605w	1%	Yes	Yes
2.05	Site Development Management	1998-06-01	2006-01-20	399.2w	19%	Yes	Yes
2.10	Development Plans	1998-06-01	2000-08-21	116.1w	91%	Yes	Yes
2.15	Site Legal Issues	2000-08-21	2009-12-31	488.9w	0%	Yes	Yes
2.20	Array Site	2002-01-01	2006-01-20	212w	0%	Yes	Yes
2.25	Operations Support Facility (OSF)	2001-06-01	2005-03-24	199w	0%	Yes	Yes
2.30	Array/OSF/World Links	2001-06-04	2005-06-20	211.2w	0%	Yes	Yes
2.35	Chilean Phase 2 Facilities	2002-01-01	2004-12-31	156.8w	0%	Yes	Yes
2.40	**Dedicate ALMA Site Facilities in Chile**	**2006-01-20**	**2006-01-20**	**0w**	**0%**	**Yes**	**Yes**
3	**Antenna Subsystem**	1998-06-01	2009-12-31	605w	6%	Yes	Yes
3.05	Antenna Management/Subsystem Engineering	1998-06-01	2009-12-31	605w	14%	Yes	Yes
3.10	Prototype Antennas	1998-09-22	2003-04-01	236.2w	1%	Yes	Yes
3.15	Production Antennas	2001-06-01	2009-06-30	421.8w	0%	Yes	Yes
3.20	Antenna Transporters	1999-10-01	2006-08-14	358.6w	0%	Yes	No
3.25	Antenna Foundations	2002-10-02	2003-05-28	34.2w	0%	Yes	Yes
4	**Receiver Subsystem**	1998-06-01	2009-12-31	605w	5%	Yes	Yes



Milestones: **bold type**
Summary Tasks: **underline**

Joint Task
Eur Task
US Task
Summary (Joint)
Summary (Eur)
Summary (US)
Progress
Milestone
Completed Mlstn
Summ. Progress
Split

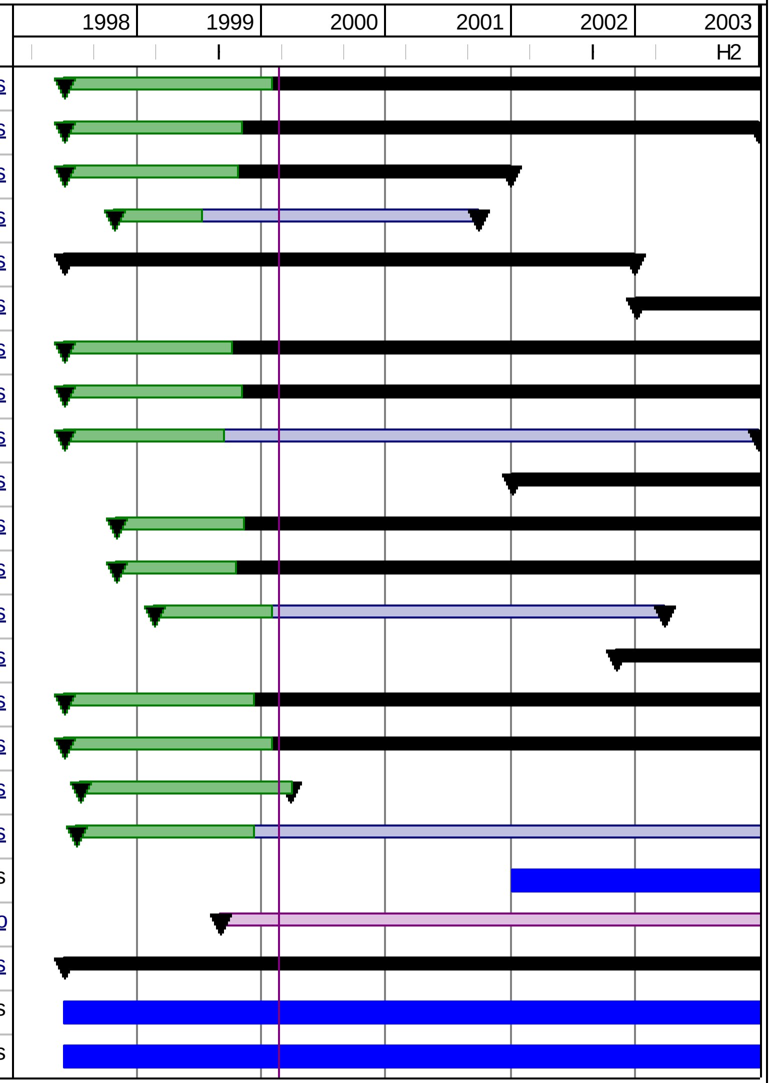
Atacama
Large
Millimeter
Array

ALMA Task Scheduling

All Tasks selected

File: almaplan2000feb22.mpp
View: Clean Gantt View
Printed: 15:47 Tue 00-02-22

WBS (f)	Task	Start	Finish	Duration	%Done	Eur	US
4.05	Receiver Management/Subsystem Engineering	1998-06-01	2009-12-31	605w	8%	Yes	Yes
4.10	SIS Mixer Development	1998-06-01	2004-01-02	292w	1%	Yes	Yes
4.15	HFET/MMIC Amplifier Development	1998-06-01	2002-01-01	187.4w	0%	Yes	Yes
4.20	Antenna Evaluation Receivers	1998-10-27	2001-10-01	153w	32%	No	Yes
4.25	Prototype Receivers	1998-06-01	2002-12-30	239.2w	0%	Yes	Yes
4.30	Production Receivers	2002-12-31	2009-12-30	365.6w	0%	Yes	Yes
5	**Local Oscillator Subsystem**	1998-06-01	2011-06-09	680w	5%	Yes	Yes
5.05	LO Management/Subsystem Engineering	1998-06-01	2011-06-09	680w	7%	Yes	Yes
5.10	Prototype LO	1998-06-01	2003-12-30	291.4w	0%	No	Yes
5.15	Production LO	2002-01-01	2009-07-28	395.4w	0%	Yes	Yes
6	**Backend Subsystem**	1998-11-02	2009-12-31	583w	11%	Yes	Yes
6.05	Backend Management/Subsystem Engineering	1998-11-02	2009-12-31	583w	8%	Yes	Yes
6.10	Prototype Backend Subsystem	1999-02-22	2003-04-01	214.4w	39%	No	Yes
6.15	Production Backend	2002-11-04	2005-09-30	152w	0%	Yes	Yes
7	**Correlator**	1998-06-01	2009-12-31	605w	1%	Yes	Yes
7.05	Correlator Management/Subsystem Engineering	1998-06-01	2009-12-31	605w	11%	Yes	Yes
7.10	Test Correlator	1998-07-20	2000-03-31	89w	99%	No	Yes
7.15	Baseline Correlator	1998-07-03	2006-06-02	413.4w	23%	No	Yes
7.20	Correlator Test Equipment/Facilities	2002-01-01	2007-12-31	313.2w	0%	Yes	Yes
7.25	Future Correlator	1999-09-01	2009-12-31	539.6w	0%	Yes	No
8	**Computing Subsystem**	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.05	Management	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.10	Science Software Requirements	1998-06-01	2009-12-31	605w	0%	Yes	Yes



Milestones: **bold type**
Summary Tasks: **underline**

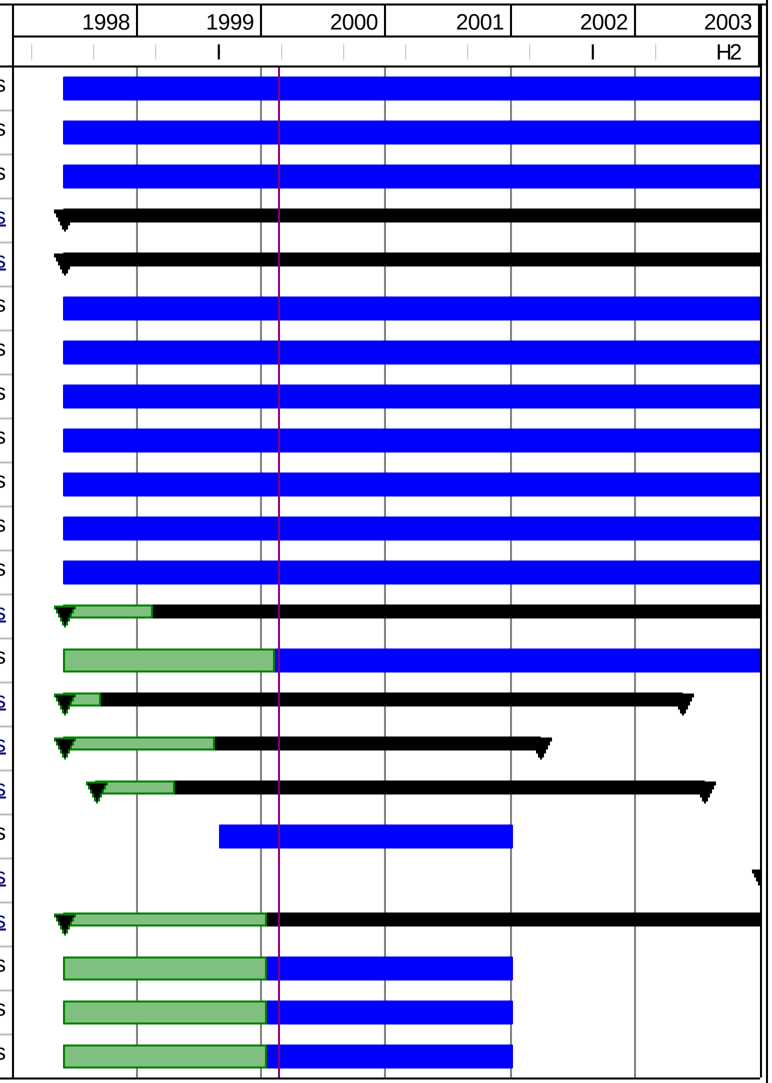
Joint Task
Eur Task
US Task
Summary (Joint)
Summary (Eur)
Summary (US)
Progress
Milestone
Completed Mlstn
Summ. Progress
Split

Atacama
Large
Millimeter
Array

ALMA Task Scheduling

All Tasks selected

WBS (f)	Task	Start	Finish	Duration	%Done	Eur	US
8.15	High Level Analysis & Design	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.20	Software Engineering	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.25	Common Software	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.30	Control Software	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.35	Correlator Software	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.40	Pipeline Software	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.45	Archiving	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.50	Scheduling	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.55	Observing Preparation & Support	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.60	Off-line Data Processing/Analysis	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.65	Telescope Calibration	1998-06-01	2009-12-31	605w	0%	Yes	Yes
8.70	Integration and Support	1998-06-01	2009-12-31	605w	0%	Yes	Yes
9	**System Engineering and Integration**	1998-06-01	2009-12-31	605w	7%	Yes	Yes
9.05	SE&I Management	1998-06-01	2009-12-31	605w	15%	Yes	Yes
9.10	System Engineering	1998-06-01	2003-05-20	259.4w	6%	Yes	Yes
9.15	Prototype Antenna Integration and Testing	1998-06-01	2002-04-01	200w	50%	Yes	Yes
9.20	Test Interferometer	1998-09-01	2003-07-25	255.8w	6%	Yes	Yes
9.25	Phase Monitoring Device	1999-09-01	2001-12-31	609d	0%	Yes	Yes
9.30	Array	2004-01-05	2009-12-31	313w	0%	Yes	Yes
10	**Science**	1998-06-01	2009-12-31	605w	32%	Yes	Yes
10.05	Scientific Requirements	1998-06-01	2001-12-31	187.2w	45%	Yes	Yes
10.10	Site Monitoring and Characterization	1998-06-01	2001-12-31	187.2w	45%	Yes	Yes
10.15	Array Design and Operation	1998-06-01	2001-12-31	187.2w	45%	Yes	Yes



Milestones: **bold type**
Summary Tasks: underline

Joint Task
Eur Task
US Task
Summary (Joint)
Summary (Eur)
Summary (US)
Progress
Milestone
Completed Mlstn
Summ. Progress
Split

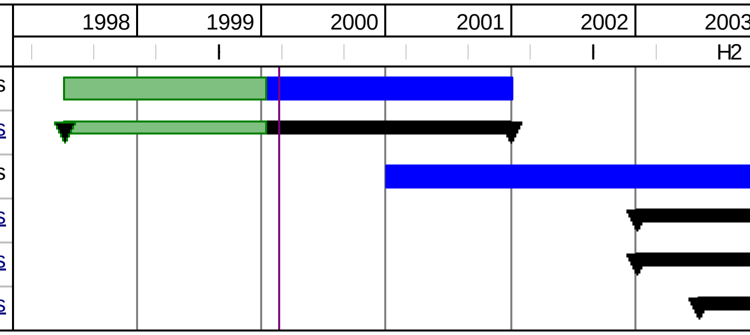
Atacama
Large
Millimeter
Array

ALMA Task Scheduling

All Tasks selected

File: almaplan2000feb22.mpp
View: Clean Gantt View
Printed: 15:47 Tue 00-02-22

WBS (f)	Task	Start	Finish	Duration	%Done	Eur	US
10.20	Calibration	1998-06-01	2001-12-31	187.2w	45%	Yes	Yes
10.25	Imaging	1998-06-01	2001-12-31	187.2w	45%	Yes	Yes
10.30	Phase 2 Science Support	2001-01-01	2009-12-31	470w	0%	Yes	Yes
11	**Operations and Maintenance**	2003-01-01	2009-12-31	365.6w	0%	Yes	Yes
11.05	Administration of Chilean Operations	2003-01-01	2009-12-31	365.6w	0%	Yes	Yes
11.10	Site Operations	2003-07-01	2009-12-31	339.8w	0%	Yes	Yes



Milestones: **bold type**
Summary Tasks: **underline**

Joint Task
Eur Task
US Task
Summary (Joint)
Summary (Eur)
Summary (US)
Progress
Milestone
Completed Mlstn
Summ. Progress
Split