VLBA Technical Report No. 15 (Rev. A)

# AN INTRODUCTION TO THE VLBA

# RECEIVING AND RECORDING SYSTEM

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March 10, 1993

## Acknowledgements

In addition to the author, L. R. D'Addario and D. S. Bagri have also served as Systems Engineer of the VLBA project, and contributed to the overall system design described in this report. A. E. E. Rogers and colleagues at Haystack Observatory have been responsible for the system design of the Data Acquisition and Recorder Racks. A large number of people have contributed to the design of individual modules and other parts of the electronics.

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# 1 Introduction

The Very Long Baseline Array (VLBA) is an array of ten antennas, at locations across the continental United States and in Hawaii and St Croix, which operates in the very long baseline interferometry (VLBI) mode. Spacings between the antennas vary up to approximately ten thousand kilometers, providing angular resolution on the sky as fine as 50 micro-arcseconds. Because the distances between the antennas are so great, the signals received are not combined in real time, but are recorded on magnetic tape. The tapes are shipped to the Array Operations Center (AOC) in Socorro, NM. Then, for each observation, the tapes from all antennas are simultaneously replayed into a correlator. The correlator combines and processes the signals into a form from which the desired data can be obtained. To preserve the coherence of the phase of the signals the times at which they are received must be accountable to an accuracy of a few nanoseconds. This accuracy is achieved by using a hydrogen maser frequency standard at each antenna to provide frequency references for the local oscillators and a time standard. Observations of this type are used to study the structure of very compact radio sources, to provide very accurate celestial positions, and to measure motions of the Earth's crust revealed by changes in the relative positions of the antennas.

This report describes the parts of the receiving system at the antennas, which includes the following sub-systems: the antenna and feeds, the low-noise front-ends, the frequency converters and IF system, the local oscillator (LO) system, the baseband converters and amplifiers, the digital samplers, the formatter, and the tape recorders. It does not include the playback system, the correlator or any of the computers for array control or data processing. The report is intended to provide a broad introductory overview. More detailed descriptions of the various components can be found in other reports in this series.

A block diagram showing the interconnections of the main subsystems of the receiving electronics is shown in Fig. 1.1. Part of the system at each site is located in the vertex room of the antenna and part in the electronics room of the station building. The two parts are connected by a series of coaxial cables that run down the antenna and through an underground duct to the building. These cables carry reference frequencies from the maser for synthesis of the local oscillator signals required to convert the received signals to IF. Other cables bring the IF signals down to the station building where they are filtered by amplifiers with baseband frequency responses, digitized, arranged into formatted data streams, and recorded on magnetic tape. A control computer connects to all subsystems of the electronics through a bus and a series of interfaces that transmit control and monitor data.

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| A | 8-14-92 | DGS | A/D CONVERTERS BLOCK WAS D/A | — |

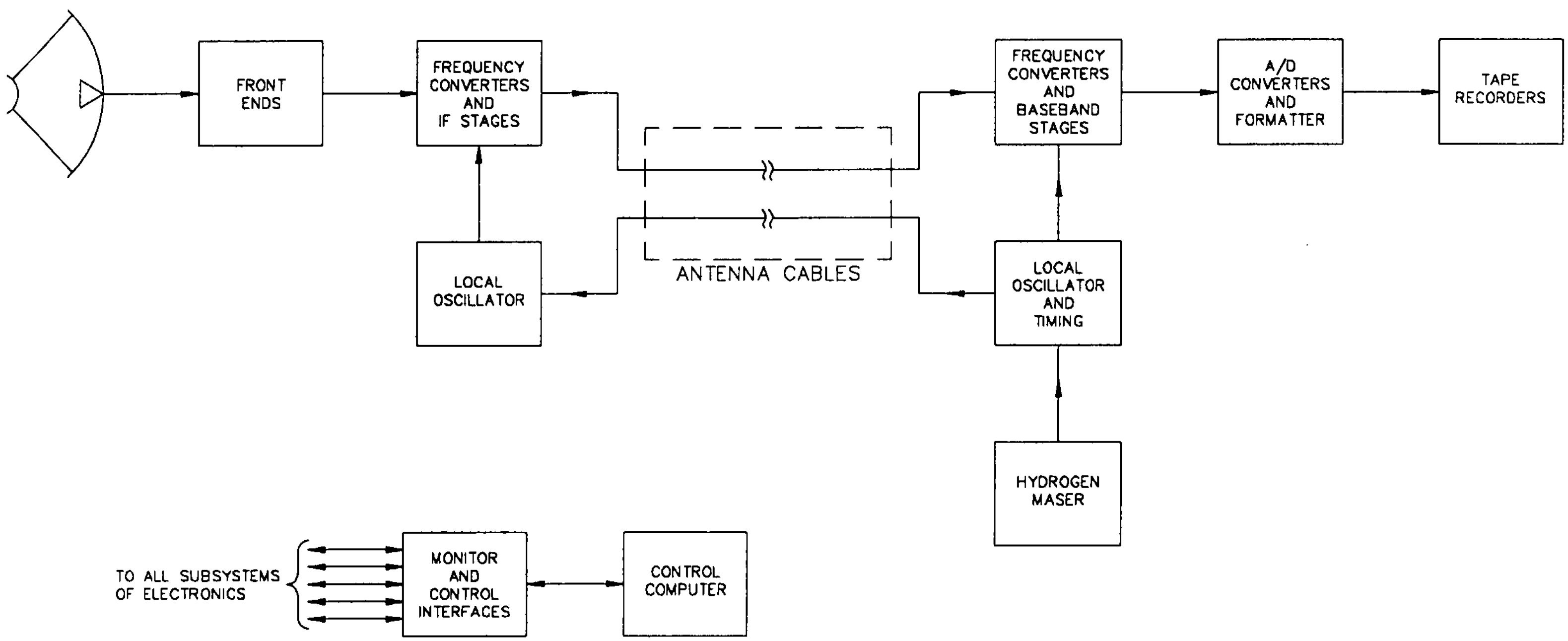


Figure 1.1 Subsystems of the VLBA Receiving System.

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CHARLOTTESVILLE, VA. 22903

| | | | | |
|---|---|---|---|---|
| TITLE | RECEIVING SYSTEM SIMPLIFIED BLOCK DIAGRAM | | | |
| PROJECT | VLBA | | | |
| DESIGN | ART | | COMPUTER DRAWING | VLBA\58001\K005 |
| DRAWN | DGS | 5-14-92 | MATERIAL | |
| SHEET | 1 OF 1 | | FINISH | |
| SCALE | — | | DWG. NO. B58001K005 | REVISION A |

The locations of the parts of the receiving system described in this report are shown in Fig. 1.2. For receiving bands at frequencies below 1 GHz, the antenna feeds are at the prime focus, and the front-end amplifiers are in a box close to the feeds. For bands above 1 GHz, the feeds are at the Cassegrain focus and are mounted in a housing in the shape of a truncated cone in the top of the antenna vertex room. The front-ends for these higher frequency bands are also located in the feed cone, mounted directly to the outputs of the feeds to avoid waveguide loss. The monitor and control interfaces between the front-ends and the station control computer, and the power supplies for all the electronics in the vertex room, are mounted in the Front-End Interface Rack (Rack A) which is in the vertex room as shown in Fig. 1.2. The signals received are transmitted by coaxial cables from the front ends to the IF/LO Rack (Rack B) which is also in the vertex room. Rack B contains frequency converters, IF stages, and the LO system. In this rack the signals are converted to an IF band that extends from 500 MHz to 1000 MHz. The amplified IF signals are transmitted by cable to the electronics room of the station building. The Master LO Rack (Rack C), and the maser frequency standard are located in the electronics room. LO reference signals that are required in the vertex room are transmitted from Rack C by coaxial cable. Rack C also contains amplifiers that boost the IF signals from the vertex room before they go to the Data Acquisition Rack (Rack D). In Rack D, selected frequency bands within the IF responses are converted to baseband frequencies, sampled and digitized. The baseband responses extend up to a maximum of 16 MHz, and up to sixteen such bands can be processed at each antenna. The sampled bits from the digitizers are passed to the formatter within Rack D, where they are arranged into 32-bit streams that go the 32 heads on the tape recorder. There are two tape recorders at each antenna station to simplify changing of tapes and to allow twice the normal recording rate when necessary. The recorded tapes are shipped by air to the AOC. The operation of the antenna and electronics at each site is under the control of the station computer which is located in the electronics building. The station computer receives observing schedules and instructions from the main operations computer at the AOC.

The ten antennas of the VLBA provide 45 combinations of antenna pairs, each of which is characterized by the baseline, *i.e.*, the distance and direction of the spacing between the antennas. This number may be compared to the number of 351 baselines of the 27 antennas of the VLA. However, the correlator in which the signals are combined has inputs for a total of 20 tapes from different antennas, so observations from other non-VLBA antennas can be included. This allows for possibilities such as a worldwide array with antennas on several continents, or space VLBI in which one or more antennas are on spacecraft and thus provide even longer baselines than are available on Earth. Some other technical points in which the VLBA differs from the VLA should be noted. In the VLBA, the compensation for the natural fringe frequency takes place in the correlator, so there is no need to offset a local oscillator as in the VLA. Also, in the VLBA there is no phase switching of the local oscillators. Compensation for the different propagation times from the radio source to the individual antennas is achieved in the VLBA largely by adjustment of the timing of the playback tape recorders, whereas in the VLA the corresponding delays have to be implemented in digital hardware. In the

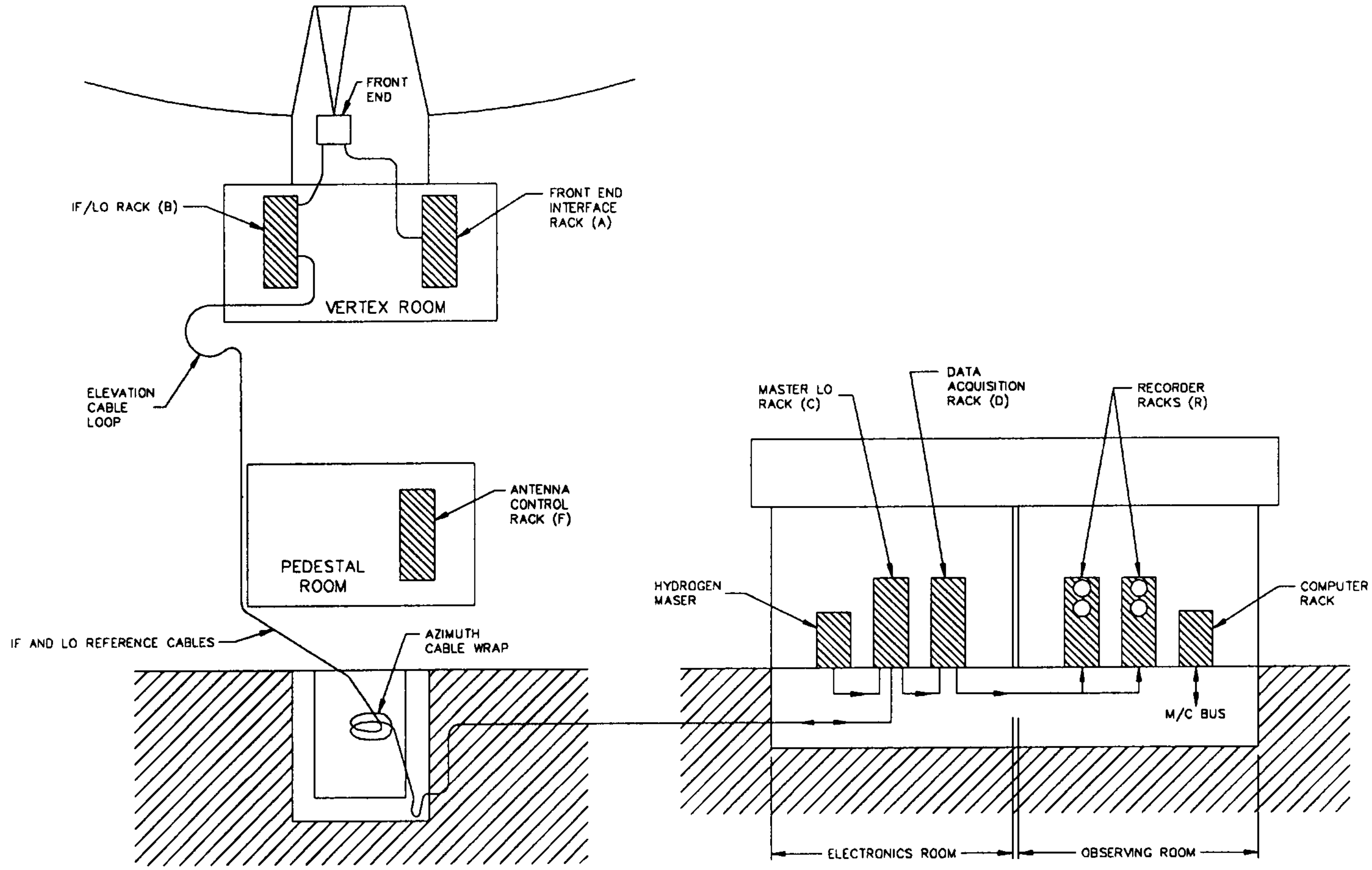



Figure 1.2 Locations of major units of the receiving system.

| NATIONAL RADIO ASTRONOMY OBSERVATORY<br>CHARLOTTESVILLE, VA. 22903 | | | | |
|---|---|---|---|---|
| TITLE: ELECTRONIC RACK LOCATIONS | | | | |
| PROJECT: VLBA SITE | | | | |
| DESIGN | ART | 10-1-86 | COMPUTER DRAWING | VLBA\58001\Y001 |
| DRAWN | DGS | 5-15-92 | MATERIAL | |
| SHEET | 1 OF 1 | | FINISH | |
| SCALE | —— | | DWG. NO. | C58001Y001 (REVISION: ) |

VLBA only a small range of delays implemented in hardware is required, to allow for fine adjustments. The VLBA incorporates a special system to calibrate changes in the time delays of the signal paths in the electronics. This is referred to as the pulse calibration system and functions by the introduction of a train of very short duration pulses (< 25 ps) into the front-ends. The frequency spectrum of the pulse train is a series of lines spaced by 1 MHz or 5 MHz. These components are recovered after the signals have been sampled and digitized, and a measure of the propagation time of signals through the receiving system can be obtained from the relative phases of the recovered calibration lines. As in the VLA, the stability of the phase and amplitude responses of the system and the matching of the frequency responses of the signal channels are of prime importance in the electronic design.

## 2 Description of the Electronic Receiving System

Diagrams on two D-size sheets should be found in the pocket at the end of this report. These show the System Block Diagrams for the electronics on the Antenna (drawing no. D58001K001) and in the Station Building (drawing no. D58001K002). These show the signal paths from the antenna to the tape recorders in some detail.

### 2.1 Antenna and Feeds

The VLBA antennas are reflectors of diameter 25 meters on altazimuth mounts. The azimuth motion is provided by a wheel-and-track design. A diagram of the antenna is shown in Fig. 2.1, and a mechanical parameters are given in Table 2.1. The main reflector of each antenna is shaped to deviate slightly from a parabolic profile to give improved aperture efficiency when used with a correspondingly shaped Cassegrain subreflector.

A list of the VLBA frequency bands and the types of feeds used with them is given in Table 2.2. At the two lower frequencies, 330 and 610 MHz, a Cassegrain feed would be impracticably large, so prime focus feeds are used. Since the maximum deviation of the main reflector from a paraboloid is only a few centimeters, it can be ignored at these long wavelengths. Thus, for the 330 and 610 MHz bands, the feeds are crossed dipoles mounted in front of the subreflector which acts as a ground plane. The dipoles are physically half a wavelength long at 330 MHz and are designed to resonate also at 610 MHz by the use of elements that effectively short the outer halves of the dipoles at the higher frequency. The use of crossed dipoles allows any form of polarization to be received by appropriately combining the two outputs.

For the frequency bands above 1 GHz, the feeds are horns located to receive signals from the Cassegrain subreflector. The subreflector has a non-symmetrical, tilted shape which brings the received radiation to a focus at a point 85 cm from the axis of symmetry of the main reflector. The subreflector is mounted so that it can be rotated about an axis that is coincident with the axis of the main reflector, and when it is so rotated the focal point moves in a circle of radius 85 cm. The feed horns are mounted on this circle at the top of the feed cone, and the radiation can be directed into any feed desired by rotating the subreflector to the correct angle. The rotation of the subreflector, as well as adjustment of its position along the antenna axis for focusing, are performed under computer control. The positioning mechanism for the subreflector is referred to as the focus/rotation mount. The positions of the feeds on the focus circle are shown in Fig. 2.2.

The feed horn for 1.5 GHz is a lightweight structure made up of aluminum plates and rings held together by a fiberglass envelope. It is bell-shaped in profile which results in a more compact design than a linear taper.

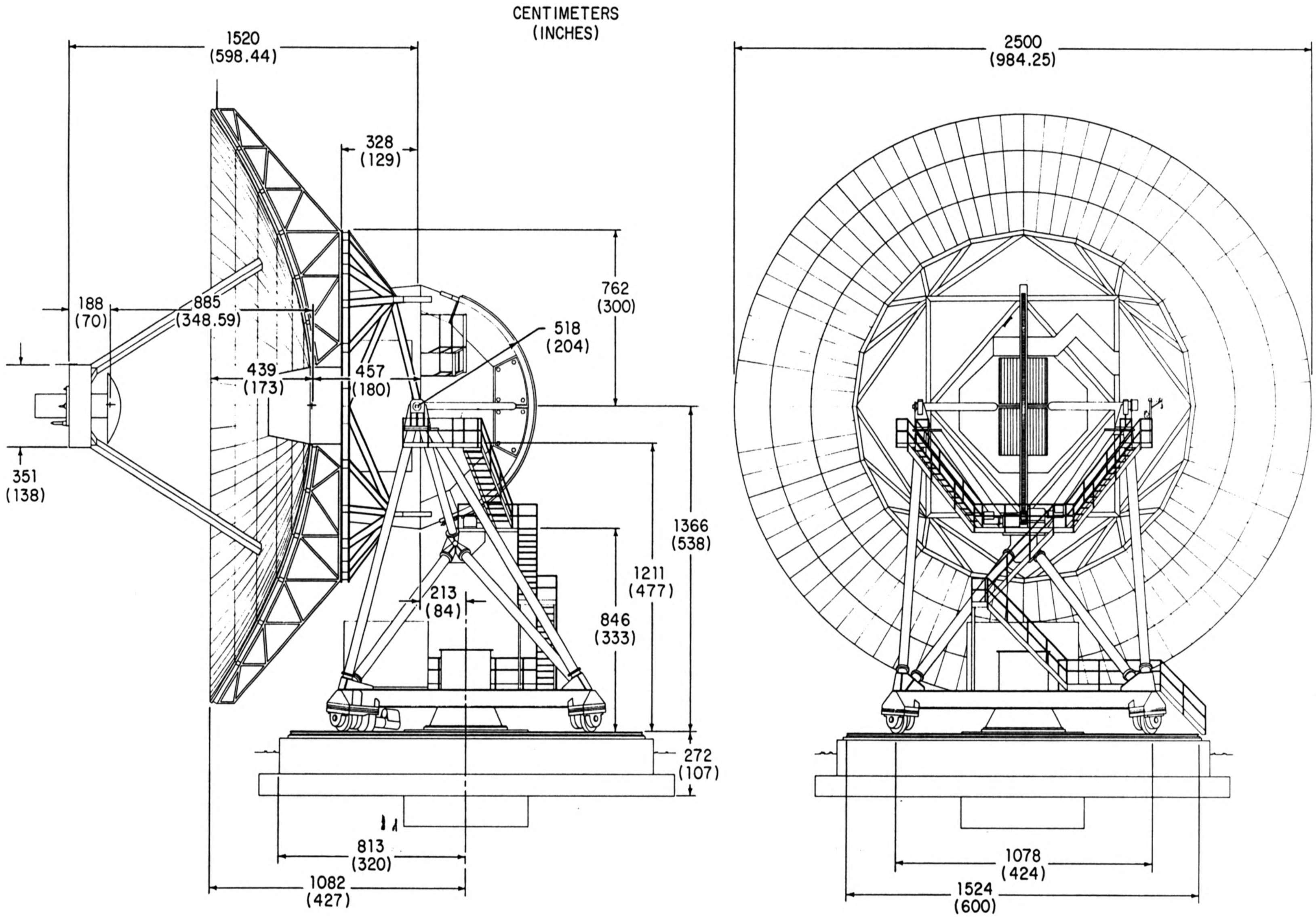



Figure 2.1 The VLBA antenna.

TABLE 2.1. Mechanical Parameters of VLBA Antennas

| MAIN REFLECTOR | | | |
|---|---|---|---|
| Diameter | 25 m | | |
| f/D | 0.354 | | |
| Surface | Shaped figure of revolution | | |
| Accuracy | (see below) | | |
| **CASSEGRAIN REFLECTOR**[1] | | | |
| Diameter | 3.5 m | | |
| Surface | Shaped asymmetric figure | | |
| Accuracy | 0.150 mm | | |
| **STRUCTURE** | | | |
| Type | Wheel-and-track, with advanced design reflector support structure | | |
| Elevation Motion | 0 → 125°; 30°/min. | | |
| Azimuth Motion | -90 → +450°; 90°/min. | | |
| **OPERATING CONDITIONS** | **PRECISION** | **"NORMAL"** | **SURVIVAL** |
| Temperature [C] | -18 → +32 | -30 → +40 | |
| Temp. Change [C/hr] | 2 | | |
| Temp. Diff'l. [C] | 3.5[2] | | |
| Wind [m/s] | 6 | 18 | 50 |
| Gusts [m/s] | 1 | 2.5 | |
| Rain [cm/hr] | None | 5 | |
| Snow or Ice | None | None | 20 psf OR 1 cm of ice |
| **ACCURACY** | | | |
| Main Surface (panel manufacturing RSS) | 0.125 mm | | |
| Main Surface (total RSS)[3] | 0.282 mm | | |
| Pointing (repeatable)[3] | 3′ | | |
| Pointing (non-rep., short term)[3] | 8" | | |
| Pointing (non-rep., long term)[3] | 14" | | |

[1]Not used for frequencies below 1 GHz.
[2]This condition to be met for 95% of observations.
[3]Under precision operating conditions.

TABLE 2.2. VLBA Feeds and Antenna Characteristics

| FREQUENCY BAND | TYPE OF FEED | ANTENNA TEMPERATURE[1] | APERTURE EFFICIENCY[2] |
|---|---|---|---|
| 312-342 MHz | Crossed dipoles (prime focus) | 74 K | 40% |
| 580-640 MHz | Crossed dipoles (prime focus) | 34 K | 40% |
| 1.35-1.75 GHz | Compact corrugated horn | 18 K | 57% |
| 2.15-2.35 GHz | Conical corrugated horn | 20 K | 58% |
| 4.6-5.1 GHz | Conical corrugated horn | 15 K | 72% |
| 8.0-8.8 GHz | Conical corrugated horn | 21 K | 70% |
| 10.2-11.2 GHz | Conical corrugated horn | 16 K | 70% |
| 12.0-15.4 GHz | Conical corrugated horn | 18 K | 69% |
| 21.7-24.1 GHz | Conical corrugated horn | 27 K | 62% |
| 41.0-45.0 GHz | Conical corrugated horn | 35 K | 51% |

[1]Antenna temperatures are from calculations by P. J. Napier (VLBA Project Book, Section 5).

[2]Aperture efficiencies are measured values.

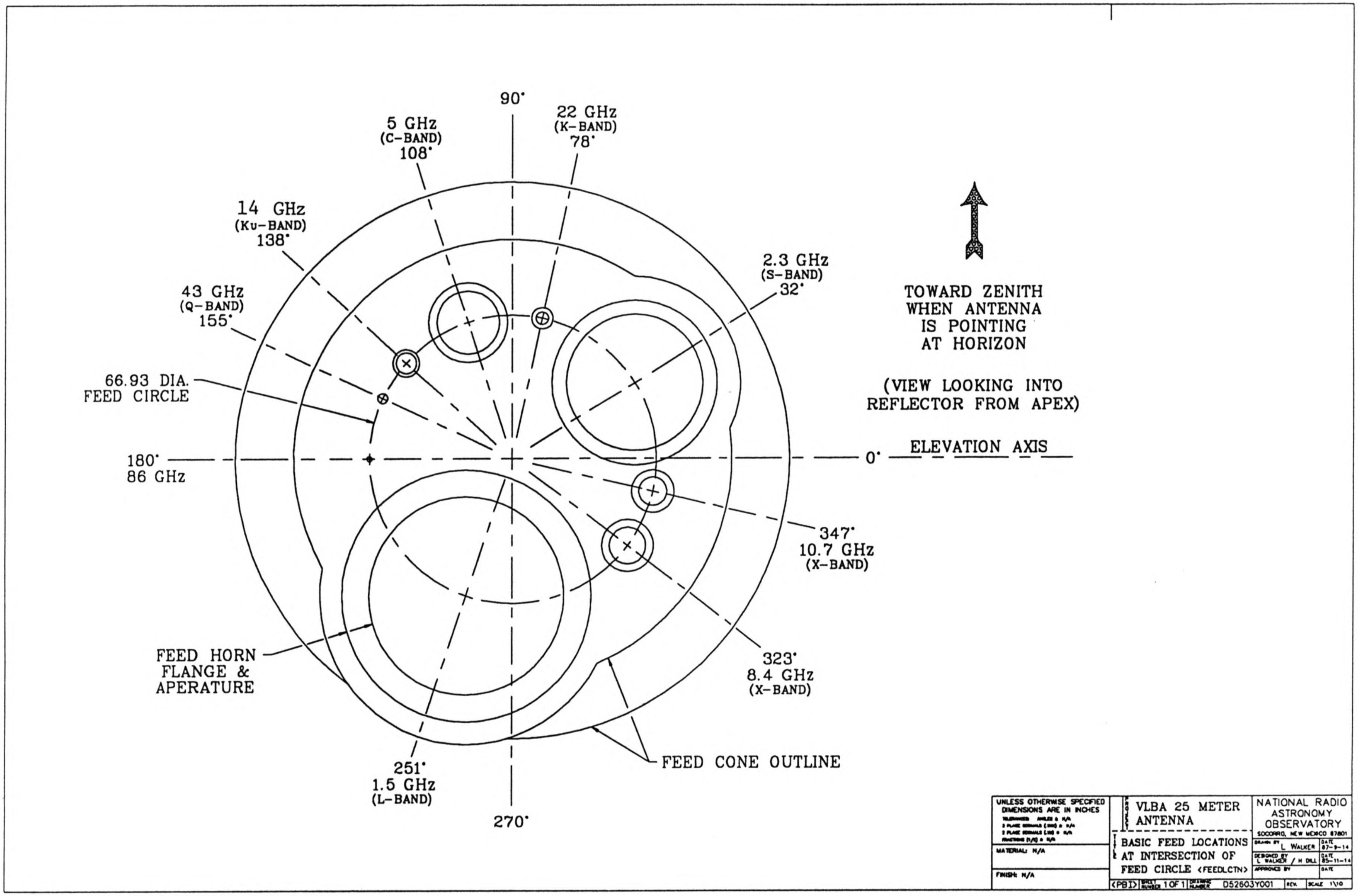


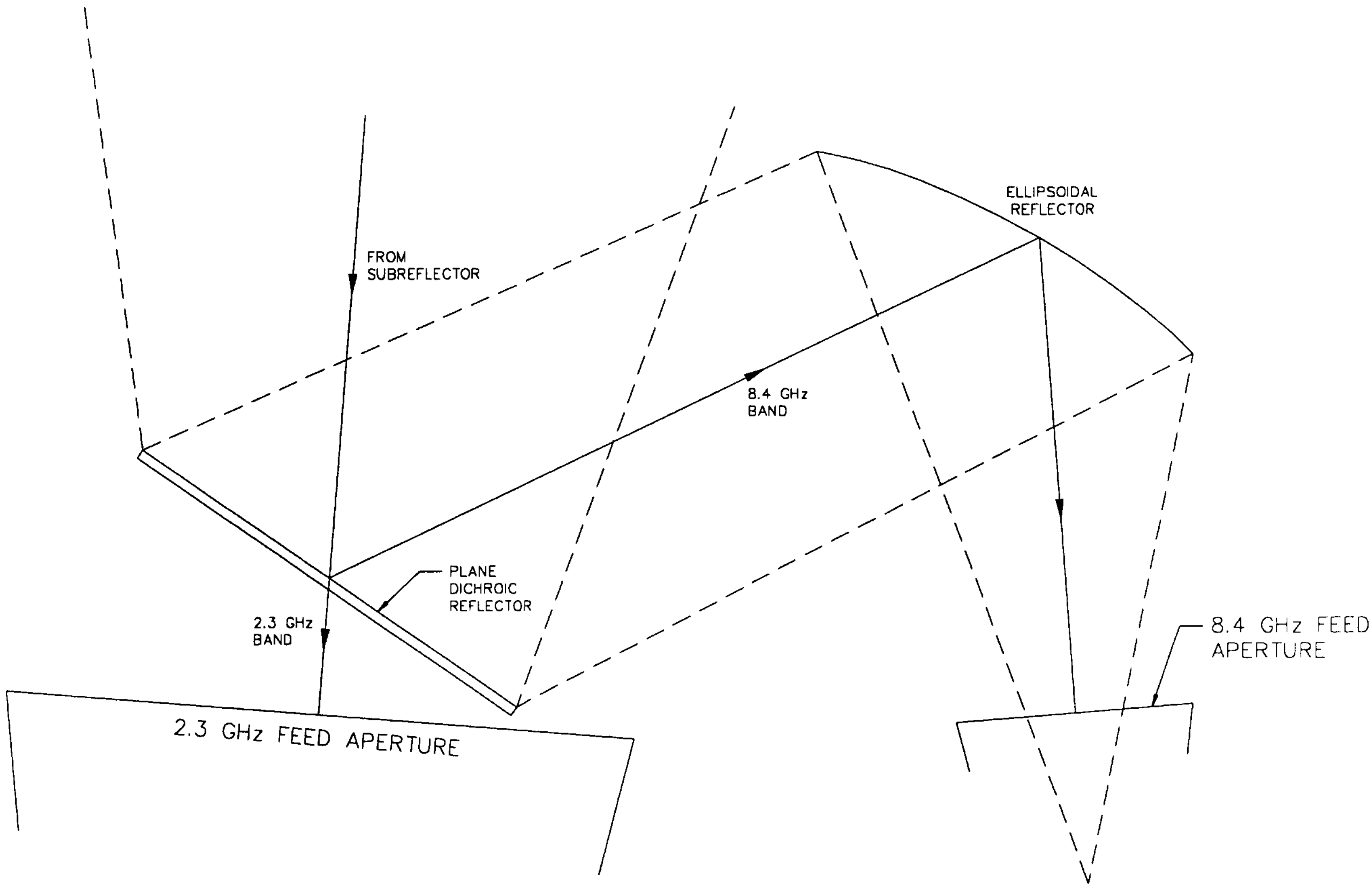

Figure 2.2 Location of the feed apertures as viewed looking at the top of the feed cone from the direction of the prime focus.

The feeds for the higher frequencies are conical horns with corrugated inner surfaces, and are machined from aluminum. The apertures of the horns at both the large and small ends are circular. The large-end apertures are covered by dielectric windows.

The preferred polarization for most radio astronomy observations is circular, both right-handed and left-handed components being received simultaneously. For the 330/610 MHz dipole feeds, the outputs are brought to the front-end box by matched coaxial cables where they are applied to two diplexers that separate the two frequency bands. For each band, the two dipole outputs are applied to a quadrature hybrid network that forms the two opposite handed circular components. For the 1.5 GHz horn, a circular waveguide orthomode junction with coaxial outputs is used at the front end. A quarter-wave plate in the throat of the horn, in combination with the orthomode junction, provides the required opposite circularly polarized components at the junction outputs. The feeds for the 2.3 to 23 GHz bands use septum polarizers made by Atlantic Microwave, Inc. These have circular waveguide inputs that match the output of the horn, and coaxial outputs for opposite circularly polarized components. The polarizer for the 43 GHz band has a circular waveguide input and rectangular waveguide outputs, and incorporates a quarter-wave plate and an orthomode junction. The principal specification on the performance of the polarizers relates to the ellipticity of the response. This is defined as the ratio of maximum to minimum power from one output as a function of the orientation of a linearly polarized signal applied to the circular input port. The specified maximum ellipticity varies from one band to another but is never more than 1 dB.

Simultaneous reception on two different frequencies is required for certain types of observations and can be achieved by means of a dichroic reflector. A plane dichroic reflector is mounted in front of the lower frequency feed of the desired pair. The screen is at 45° to the axis of the feed, and it is transparent to radiation at the frequency of the feed. The dichroic screen reflects radiation at the higher frequency, and this is then directed into the second feed by means of an elliptical reflector as shown in Fig. 2.3. One way of making a dichroic screen is to use a pattern of crossed dipoles that are resonant at the higher frequency. At the resonant frequency, the dipoles reflect radio waves, but at a lower frequency they have essentially no effect on the radiation. Dichroic screens on the VLBA use this scheme, the dipoles being etched from a copper-clad dielectric board. The initial construction of the VLBA includes dichroic components for one feed pair, 2.3 and 8.4 GHz, for which simultaneous observations are required in geodetic studies to correct for ionospheric effects. Dual frequency observations can also be made using the 330 and 610 MHz bands with one of the Cassegrain-feed bands. However, since the focus positions of the subreflector are different for the prime focus and Cassegrain feeds, only the lower frequency Cassegrain bands, for which the focusing is less critical, can be used in this mode.

The bandwidths of the feeds are in some cases wider than those of the polarizers and receivers. The 2.3 GHz feed will cover the radio astronomy band at 2.69-2.7 GHz with very little loss in efficiency, and the 4.8 GHz feed will cover the OH lines at 6.02 GHz. However, in most cases the response of the polarizer limits the width of the band that is instantaneously available.




PROFILES IN PLANE CONTAINING AXES OF THE TWO FEED HORNS

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| | | | |
|---|---|---|---|
| TITLE | DUAL FREQUENCY SYSTEM 2.3 & 8.4 GHz | | |
| PROJECT | CDL | | |
| DESIGN | ART | COMPUTER DRAWING | VLBA\58001\Z001 |
| DRAWN | DGS 6-3-92 | MATERIAL | |
| SHEET | 1 OF 1 | FINISH | |
| SCALE | NONE | DWG. NO. | C58001Z001 REVISION |

**Figure 2.3 The dichroic reflector dual-frequency scheme for the 2.3 and 8.4 GHz feeds.**

## 2.2 Front-Ends

The term "Front-End" refers to the low-noise amplifier package that is the first part of the electronic system to receive the signal from the feed. In the 330 and 610 MHz frequency bands, the system temperature is dominated by the contribution from the sky (galactic background radiation), so there is very little advantage in using cooled input stages in the front-ends, and no refrigerator is used. To avoid temperature variations, all RF components are mounted on a chassis that is thermally insulated from the exterior front-end box and held at 45 ± 1°C by a temperature control system using heating resistors mounted on the chassis. The amplifiers use HFET transistors and the overall gain is less than 30 dB to avoid possible intermodulation effects from interfering frequencies at these heavily used frequencies. The signals are transmitted by coaxial cables from the front-end location near the prime focus to Rack B, where filters to limit the passbands are inserted.

Figure 2.4 shows a block diagram of the 8.4 GHz front-end, which is typical of front-ends for bands above 1 GHz. The polarizer is mounted as part of the front-end unit, and the two output signals corresponding to left and right circular polarization pass through directional couplers that allow calibration signals to be added, and are then amplified in low-noise HFET amplifiers. These low-noise amplifiers are designed and constructed within NRAO. The polarizer, couplers and amplifiers are located in an evacuated dewar as indicated by the inner broken line in Fig. 2.4. These components are cooled to approximately 15 K by a closed-cycle helium refrigerator (CTI Model 22) to minimize thermal noise associated with losses and the noise of the transistors. The cooled amplifiers are followed by ambient temperature post-amplifiers which are commercially-available units. The gain of the cooled amplifiers is approximately 34 dB and that of the post-amplifier is 18 dB, providing an overall gain of 52 dB.

As shown in Fig. 2.4, noise at two different power levels, as well as the calibration pulses, can be injected through the calibration couplers. The lower level noise power is adjusted so that it produces an overall increase of approximately 10% in the system temperature. The high-level noise source is intended for use only for observations of the sun, the noise level from which dominates all other sources of system noise. For the 8.4 GHz frequency band, the noise level from the high-level source is 24 dB greater than from the low-level one. For each frequency band, the high-level source is included in one or two front-ends only: since the sun controls the system noise temperature for solar observations, the system temperature should be the same for all antennas and it is only necessary to measure it at one of them. When in use the noise sources are modulated on and off by a squarewave of frequency 80 Hz, and the amplitude of the component at this frequency within the signal channel is measured by a synchronous detector in the baseband section of the receiving system. The gain and system temperature are thereby monitored.

The front-end parts that are not within the dewar in Fig. 2.4 are located in a card cage which is part of the front-end package. The post-amplifiers and their circulators, as well as the noise sources, are mounted on cards. Other cards carry the HFET current control circuits, and temperature and vacuum monitor components. The pulse calibration signal (also sometimes

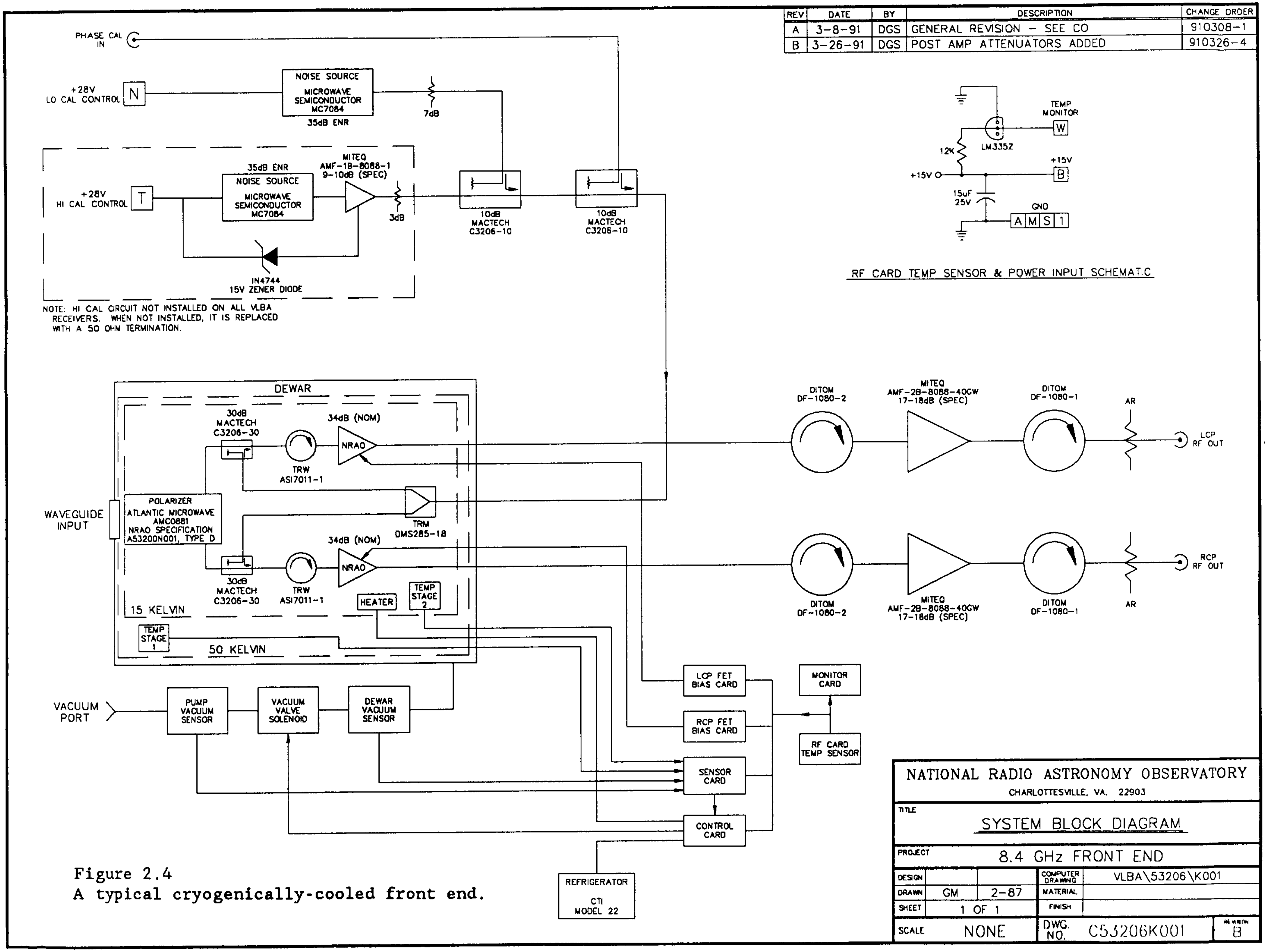


Figure 2.4
A typical cryogenically-cooled front end.

referred to as the phase calibration signal) is generated externally. All monitor and control functions interface with the Front-End Interface modules in Rack A through two 32-conductor cables. Attenuators (indicated by "AR" in the figure) are selected as required to set the overall gain to 46 dB for each channel at the band center.

The other cryogenically-cooled front-ends are similar to the 8.4 GHz unit discussed above, and the most important differences are listed in Table 2.3. In the 1.5 and 2.3 GHz front-ends, the refrigerator is the CTI Model 350 unit with cooling capacity 2-3 W at 15 K: for comparison the equivalent capacity of the Model 22 refrigerator is 1 W. The larger capacity is required to handle the much larger mass of the lower frequency polarizers. The polarizers for the 1.5, 2.3, and 4.8 GHz front-ends are thermally connected to the second stage of the refrigerator which cools them to 50 K. For higher frequency bands, the thermal capacity of the polarizer is small enough to allow cooling to 15 K by connection to the second stage of the refrigerator, of which the cooling capacity is lower than that of the first stage. Also, front-ends for 1.5, 2.3, and 4.8 GHz contain a filter between the cooled amplifier and the post-amplifier to define the passband. At higher frequencies the probability of strong interfering signals near the edges of the bands is much lower, so the bandpass-defining filters can be located later in the signal chain. They are therefore placed in the converter modules, which are in Rack B, where the temperature stability is expected to be a little better than in the feed cone.

In the 23 and 43 GHz front-ends, the signal is converted to a first IF near 9 GHz. This intermediate frequency is high enough to provide good image rejection with the wider bandwidth amplifiers used at the higher observing frequencies. The first mixer for these two receivers is located in the front-end unit to avoid having to transmit the signals to Rack B at frequencies at which long runs of coaxial cable become difficult to use. The LO signals for these frequency conversions is in Rack B (2-16 GHz Synthesizer Module No. 3). In the 43 GHz front-end, the mixer unit contains a frequency tripler for the LO.

## 2.3 Converter Modules

Signals from the front-ends are converted to an IF of 500-1000 MHz in Converter Modules in Rack B. Figure 2.5 shows a block diagram of the 4.8 GHz Converter Module as a typical example. The two incoming signals from the two polarizations can be interchanged by a transfer switch. This switch is used mainly for diagnostic purposes. If one signal is exhibiting abnormal characteristics, throwing the switch should indicate whether the problem is before or after the switch. The signals pass through filters that define the tuning range, and then go into mixers that are fed with a tunable LO signal from another module. The bandpass filters at the LO inputs to the two mixers are to prevent cross coupling of RF or IF signals between the two polarization channels. The IF passband is defined by filters that have a bandwidth of 550 MHz at the -1 dB points. The amplified IF signals are split into two equal components, one of which goes to the station electronics room and the other goes to the front panel of the module to provide a monitoring point.

TABLE 2.3. Characteristics of VLBA Front-Ends.

| NOMINAL FREQUENCY | FREQUENCY BAND | RECEIVER NOISE TEMP. | REFRIGERATOR MODEL (CTI) | PHYSICAL TEMPERATURE OF POLARIZER | FIRST IF | PASSBAND-LIMITING FILTERS |
|---|---|---|---|---|---|---|
| 330 MHz | 312-342 MHz | 70-90 K | | 300 K | 0.5-1.0 GHz | 312-342 MHz[1,2] |
| 610 MHz | 580-640 MHz | 70-90 K | | 300 K | 0.5-1.0 GHz | 596-626 MHz[2,4]<br>609-613 MHz[2,4] |
| 1.5 GHz | 1.35-1.75 GHz | 5-15 K | 350 | 50 K | 0.5-1.0 GHz | 1.27-1.83 GHz |
| 2.3 GHz | 2.15-2.35 GHz | 5-15 K | 350 | 50 K | 0.5-1.0 GHz | 2.0-2.8 GHz |
| 4.8 GHz | 4.6-5.1 GHz | 10-20 K | 22 | 50 K | 0.5-1.0 GHz | 4.5-5.2 GHz |
| 8.4 GHz | 8.0-8.8 GHz | 10-20 K | 22 | 15 K | 0.5-1.0 GHz | 7.92-8.88 GHz[1,2] |
| 10.7 GHz | 10.2-11.2 GHz | 35-55 K | 22 | 15 K | 0.5-1.0 GHz | 10.1-11.3 GHz[1,2] |
| 14 GHz | 12.0-15.4 GHz | 20-45 K | 22 | 15 K | 0.5-1.0 GHz | 11.8-13.0 GHz[1,2,4]<br>12.8-14.0 GHz[1,2,4]<br>13.8-15.0 GHz[1,2,4]<br>14.8-15.6 GHz[1,2,4] |
| 23 GHz | 21.7-24.1 GHz | 40-60 K | 22 | 15 K | 9.4-9.9 GHz | 9.3-10.2 GHz[1,3] |
| 43 GHz | 41.0-45.0 GHz | 35-65 K | 22 | 15 K | 7.9-8.9 GHz | 7.7-9.1 GHz[3] |

[1]Frequencies refer to bandwidth at -1 dB (otherwise -3 dB).
[2]Filters are in Converter Module (otherwise within front-end unit).
[3]Filters are in first IF band.
[4]Filters selectable by computer control.

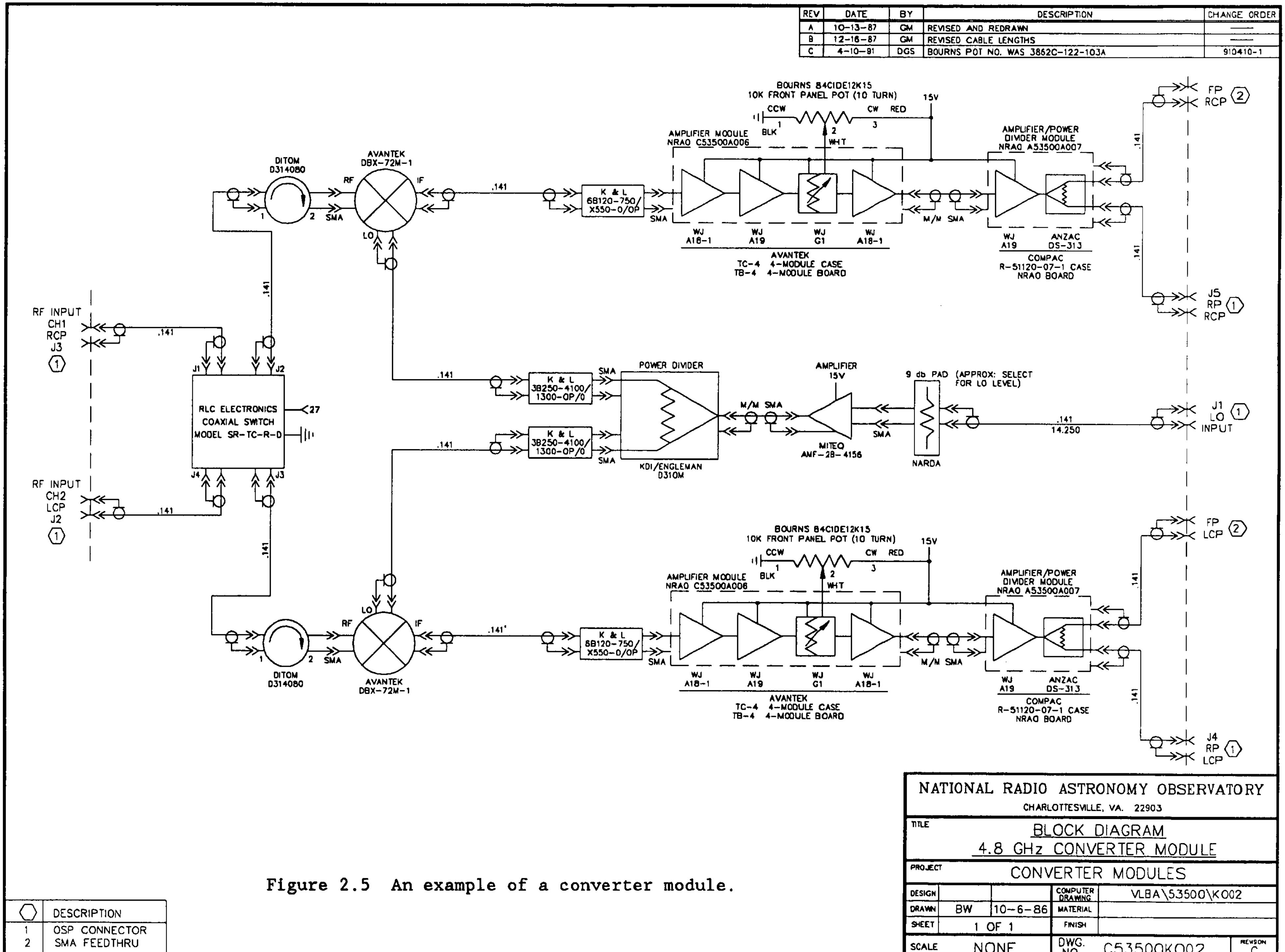


Figure 2.5 An example of a converter module.

The gains of the IF stages can be manually adjusted by potentiometers on the front panel, and the required level at the output of the converter modules is -67 dBm/MHz, *i.e.*, -40 dBm in the 500 MHz bandwidth.

Converter Modules for the different bands differ in some details from the one shown in Fig. 2.5. The 330 MHz converter uses a fixed LO frequency of 500 MHz because the bandwidth of the front-end is less than the 500 MHz bandwidth of the IF and can be accommodated with a single LO setting. For the 610 MHz band, the module that follows the front-end is called the 610 MHz Filter Module since the front-end band lies within the 500-1000 MHz IF, and the input and output frequencies of the module are identical. The 608-614 MHz radio astronomy band was originally allocated to television as channel 37. Because of the occurrence of strong signals in nearby channels, a steep-sided filter is needed for this VLBA receiver. In the 610 MHz Filter Module, the center frequency is converted down to 110 MHz by a 500 MHz fixed LO and then down to 10 MHz using a 100 MHz fixed LO, with appropriate filtering to suppress image responses. The signal is filtered by an eight-pole filter of bandwidth 4 MHz centered at 11 MHz, and then converted back in two corresponding steps to the 610 MHz band.

In the 14 GHz converter, a set of four switchable filters is used at the inputs to break down the input band, which is 3.4 GHz wide, into four bands each less than 1.2 GHz wide, and to select one of them. This enables a frequency conversion to the 500-1000 MHz IF to be made without signals from the front-end entering the unwanted image response. An alternate method of eliminating the image response would be to use a higher frequency first IF, as is done for the 23 and 43 GHz bands. However, it is desirable to retain the possibility of making simultaneous observations in the 14 and 43 GHz bands, and if a first IF greater than 500-1000 MHz were used for both these bands it would be necessary to provide four independently tunable LO signals at each antenna. There are three such tunable LO signals (from 2-16 GHz Synthesizer Modules) at each antenna, and providing the switched filters for the 14 GHz band was a less expensive solution than providing an additional LO module.

For the 23 GHz band (21.7-24.1 GHz), the first IF must be greater than 8 GHz to allow use of the standard LO module (2-16 GHz Synthesizer) that tunes up to 16 GHz. Such a high frequency also allows adequate separation of the signal and image responses. The frequency should also be chosen to avoid responses of the form (2xLO-IF) and (3xLO-IF) from falling within the front-end band. A satisfactory choice is an IF of 9.4-9.9 GHz with settings of the first LO in the range 12.1-14.4 GHz and the second LO at 8.9 GHz. This IF band is close enough to 8.4 GHz that the same converter module can be used for the 8.4 and 23 GHz bands. These two bands are ones for which simultaneous observation is not required. The combined 8.4/23 GHz Converter has inputs from both front-ends and two single-pole, double-throw coaxial relays to select between them. The 8.4 GHz band is routinely used for geodetic observations, in which it is desirable to spread the frequencies of the baseband channels (see later in this section) as widely as possible across the observing frequency band. To facilitate this, it is possible to feed the two mixers with separate, independently-tunable LO signals, and feed the signal from the right-handed polarization channel into the RF ports of both mixers.

This flexibility makes the 8.4/23 GHz Converter Module one of the more complicated of the converter modules.

The 43 GHz front-end uses a first IF band centered on 8.4 GHz, and a second pair of inputs, designated ALT (alternate), are included in the converter module. The alternate inputs are intended for a future front-end that requires a first IF near 8.4 GHz, possibly for 86 GHz. The 43 GHz/ALT Converter Module is similar to the 8.4/23 GHz Module except that it does not contain the facility to feed the RF inputs of the two mixers with the same first IF signal and the LO inputs from separate LO sources.

## 2.4 IF Transmission

The overall analog signal path is shown in Fig. 2.6. This includes the IF and baseband stages and the switches and cables in the path from Rack B in the antenna vertex room to the electronics room of the station building. There are four coaxial cables, labeled A, B, C and D, bringing IF signals from the antennas, enough to accommodate two frequencies and two polarizations simultaneously. The System Block Diagram for the Antenna (in the pocket at the back of the report) shows four one-by-six switches, S1 to S4, that select the IF signals to be transmitted to the electronics building. S1 and S2 carry signals from one set of front-ends, and S3 and S4 carry signals from the remaining ones. Note that when observing with two frequencies simultaneously, one frequency has to be from the S1/S2 set and one from the S3/S4 set. The assignment of frequencies to switches was made taking account of the pairings most likely to be required for simultaneous observations. Transfer switches S5 and S6 allow cables A and B or and/or C and D to be interchanged, so that in the event of failure of one cable, a pair that remains good can be switched to whichever signal band is the more important for a particular observation. When all transfer switches, including those within the converter modules, are in their normal (unenergized) positions, cables A and B carry right-handed circular polarization and C and D carry left-handed. The switches can all be set remotely through the station computer. The cables from the vertex room to the electronics room are 3/8-inch foam-filled semi-rigid coaxial type, with lengths of flexible coaxial cable at the azimuth cable wrap and the elevation loop of the antenna. The attenuation from the vertex room to the building is approximately 7.5 dB at 500 MHz and 14 dB at 1 GHz.

## 2.5 IF and Baseband Signals in the Station Building

In the electronics room of the station building, the cables terminate at Rack C in amplifiers with a gain slope across the passband that compensates for the differential attenuation of the cables. From these amplifiers the signals go to IF Distributor Modules in Rack D, as shown in Fig. 2.6. The IF Distributors provide computer-controlled step attenuators for level setting, further gain, and a level monitoring detector. Two of these modules are required to handle the four IF signals, and each IF output then goes to an eight-way power divider. The outputs of the power dividers provide signals to eight Baseband Converter Modules.

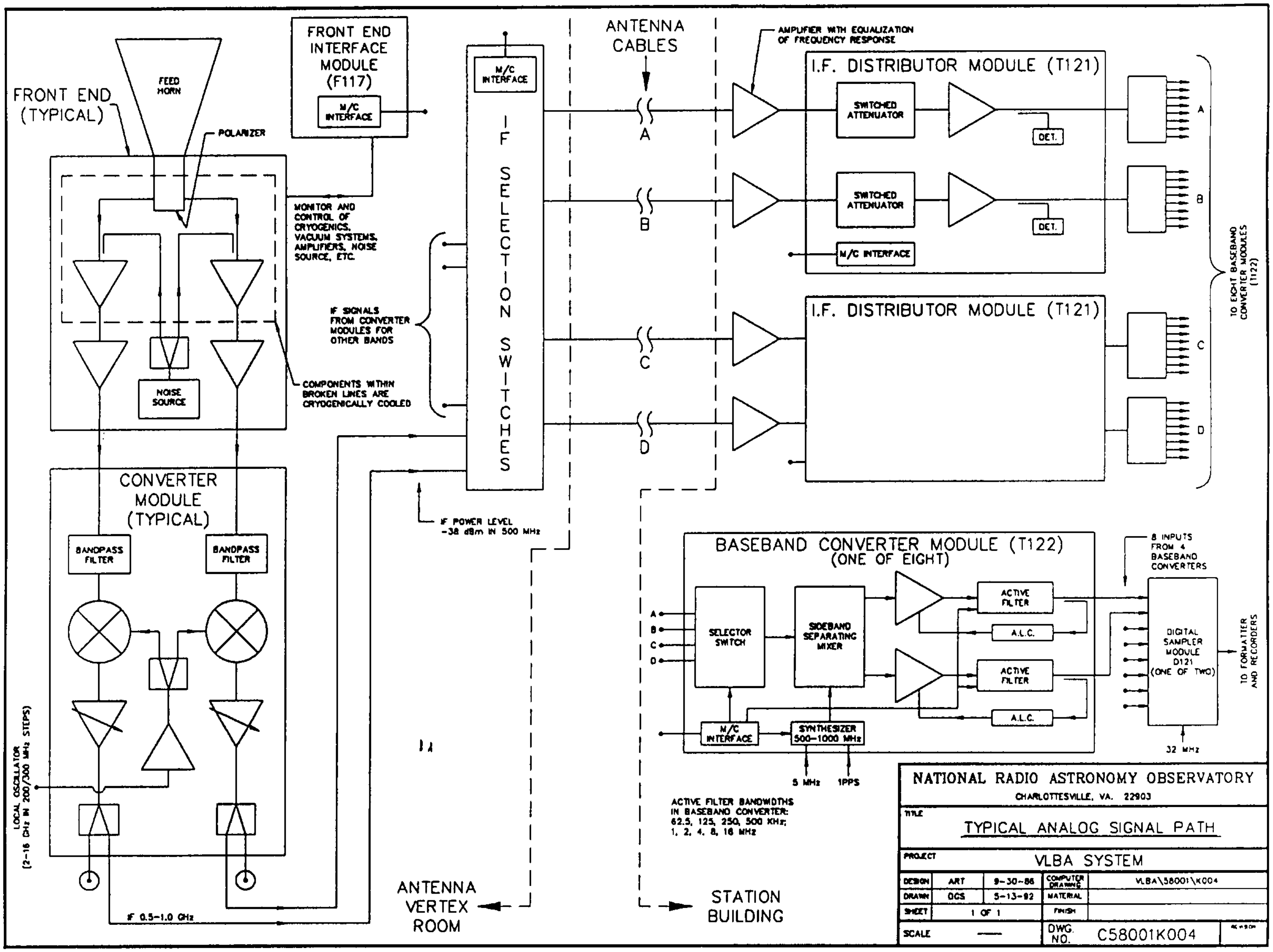


Figure 2.6 Typical analog signal path at RF, IF, and baseband frequencies.

Each Baseband Converter receives inputs from all four IF signals, and selects one by means of a four-way switch. A selected part of the IF band is then converted to baseband using a sideband-separating mixer and a local oscillator that is tunable across the 500-1000 MHz IF band in 10 kHz steps. (The term Baseband refers to an IF band in which the low frequency end is very close to zero frequency and the high frequency end is equal to the bandwidth.) The mixer has two outputs, one for frequencies below the LO frequency and one for frequencies above it. These outputs go to two separate baseband amplifiers which have maximum bandwidths of 16 MHz. The bandwidths of the baseband amplifiers can be varied by factors of two, by means of switched resistors, to cover 16, 8, 4, 2, 1, 0.5, 0.25, 0.125, or 0.0625 MHz. The passband responses are 8-pole Butterworth lowpass, obtained with four amplifier stages, each containing two poles. The output levels of the baseband signals are controlled by ALC loops. Thus, each Baseband Converter produces two output bands with selectable bandwidths, tunable as a contiguous pair over the input IF band. The eight Baseband Converters provide 16 bands of maximum width 16 MHz, *i.e.*, a total bandwidth of 256 MHz. These 16 signals then go to the Sampler Modules where they are digitally sampled. A sampling frequency equal to twice the bandwidth of the analog signal being sampled, *i.e.*, the Nyquist frequency, allows all the information in the continuous signal to be retained. A sampling frequency of 32 MHz, appropriate for the maximum bandwidth, is used in all cases and for narrower bandwidths the redundant samples are discarded later. The digitizing uses either one bit per sample (two-level sampling) or two bits (four-level sampling). In two-level sampling, the output indicates only whether the signal voltage is positive or negative. In four-level sampling, the output also indicates whether the magnitude of the voltage is greater or less than a preset threshold, which is indicated by V in Fig. 2.7. The coding scheme for four-level sampling is shown in Fig. 2.7. It was chosen because it has the property that, with random noise as input, each bit has equal probability of being a 1 or a 0 in all four levels. Random errors that occur in the processing of the bits are then less likely to introduce a bias into the data. Two Sampler Modules are used since each can process eight baseband signals. Four-level sampling of all basebands at maximum bandwidth produces 32 bit streams, each with a bit rate of 32 Mb/s, that is, a total bit rate of 1024 Mb/s. The bit streams go to the Formatter which rearranges the bits as required for the tape recorders.

## 2.6 Local Oscillator and Timing System

A hydrogen maser provides standard frequencies of 5 MHz and 100 MHz and all other LO and timing signals used in the receiving system are derived from the maser outputs. A description of the maser unit is given in Appendix 3. A maser is located in the electronics room of each station building of the array. A block diagram of the timing system is given in Fig. 2.8. A 5 MHz output of the maser drives a frequency divider that produces a series of pulses at 1 sec. intervals, referred to as the 1 pps (1 pulse per sec.) signal. The divider is in the Secure 1 pps Module in Fig. 2.8, which incorporates a battery for power security, and is located in Rack C. The timing of the pulses is set to the seconds of universal time to an accuracy of better than 1 μs using pulses from a GPS (Global Positioning System) receiver.

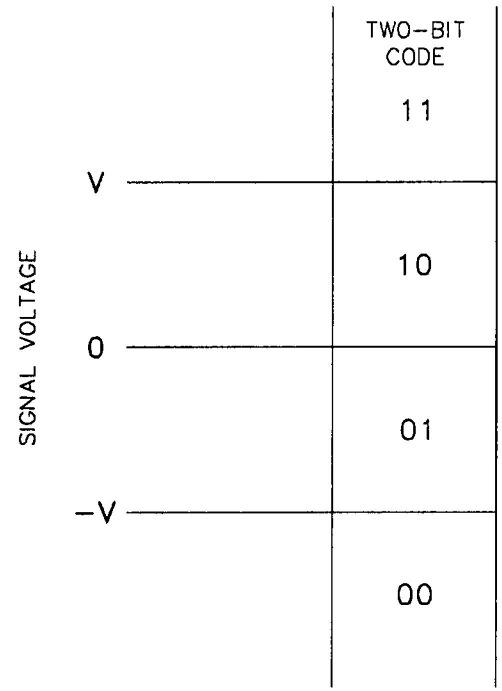


**Figure 2.7** The four-level (two-bit) coding scheme used in the VLBA samplers.

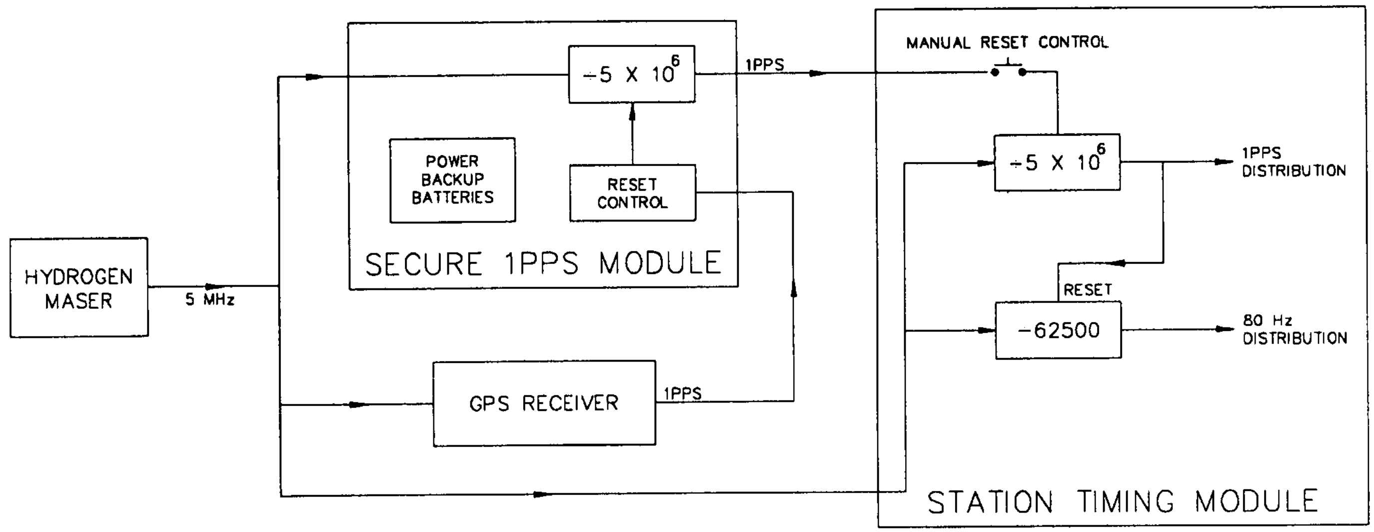


Figure 2.8 The timekeeping system.

| NATIONAL RADIO ASTRONOMY OBSERVATORY | | | | |
|---|---|---|---|---|
| CHARLOTTESVILLE, VA. 22903 | | | | |
| TITLE | TIMING SYSTEM SIMPLIFIED BLOCK DIAGRAM | | | |
| PROJECT | VLBA | | | |
| DESIGN | ART | | COMPUTER DRAWING | VLBA\58001\K006 |
| DRAWN | DGS | 5-14-92 | MATERIAL | |
| SHEET | 1 OF 1 | | FINISH | |
| SCALE | — | | DWG. NO. | B58001K006 |
| | | | REVISION | |

The GPS receiver also uses the 5 MHz maser signal and produces pulses that can be used to reset the Secure 1 pps Module when required. A third 5 MHz signal from the maser drives the Station Timing Module which produces another 1 pps train that can be synchronized to the secure 1 pps signal. The Station Timing Module can be manually reset from the Secure 1 pps output. The redundancy provided by the two 1 pps generators is very important because it allows either one to be maintained operating if the other breaks down or loses synchronization. The Station Timing Module also produces an 80 Hz squarewave output that is used to drive the switched noise sources in the front-ends.

Two other modules produce timing signals for special requirements. These are shown in the System Block Diagram for the Station Building, but not in Fig. 2.8. The 32 MHz Synthesizer generates a 32 MHz clock that is used for the timing of the samplers. In this module a 5 MHz signal from the maser is divided down to 1 MHz and its phase is synchronized to the 1 pps to provide a 1 MHz reference. A 32 MHz VCXO (voltage-controlled crystal oscillator) is phase-locked by dividing its output by 32 and comparing with the 1 MHz reference. The 32 MHz Synthesizer Module also contains buffer amplifiers for distribution of the 1 pps signal. The Output Rate Synthesizer Module produces clock waveforms used in recording the data. For the VLBA recording format, the transport clock frequency that controls the recording bit rate is 9.072 MHz and for the Mark III format it is 9.0 MHz. The recorder also requires a bit-synchronization clock at 21 times the transport clock. The Output Rate Synthesizer contains VCXO's at 190.512 and 189.0 MHz, either of which can be selected as required. The selected oscillator is locked by dividing its frequency to 1 kHz and comparing with a 1 kHz reference obtained by dividing 5 MHz from the maser. The transport clock is obtained by division of the bit-sync. frequency by 21. Dividers by factors from 2 to 32 in powers of 2 can reduce the frequency of both clocks to allow for lower recording rates.

A simplified block diagram of the LO system is shown in Fig. 2.9. The 100 MHz output of the maser is used to provide reference frequencies of both 100 and 500 MHz at the antenna vertex room. The 100 MHz signal is amplified and transmitted by cable to the antenna vertex room. A frequency multiplier generates 500 MHz from the 100 MHz and this is transmitted to the vertex room on a separate LO cable. The phase stability of the 500 MHz signal is especially critical because this frequency is subsequently multiplied to produce the high frequency LO signals needed for the frequency conversions in the front-ends and converter modules. In order to compensate for variations in the electrical length of the 500 MHz reference cable, a round-trip phase measuring system is used. This system measures changes in the phase length of the path out from the station building to the vertex room. A component of the outgoing 500 MHz signal is returned back down the cable from the vertex room by a reflector, the impedance of which is modulated by a squarewave at a frequency of 1.953 kHz. The reflected component thus contains a sideband at 500.001953 MHz, and this is retrieved by a directional coupler in the LO Receiver and converted with an LO frequency of 500.002083 in the round-trip-phase mixer in Fig. 2.9. The reflected component is thereby converted to 130.2 Hz, and this is separated from other components at the mixer output by a lowpass amplifier with a cutoff of 200 Hz. The phase of the 130.2 Hz is compared with a signal at the same frequency generated directly from the 5 MHz

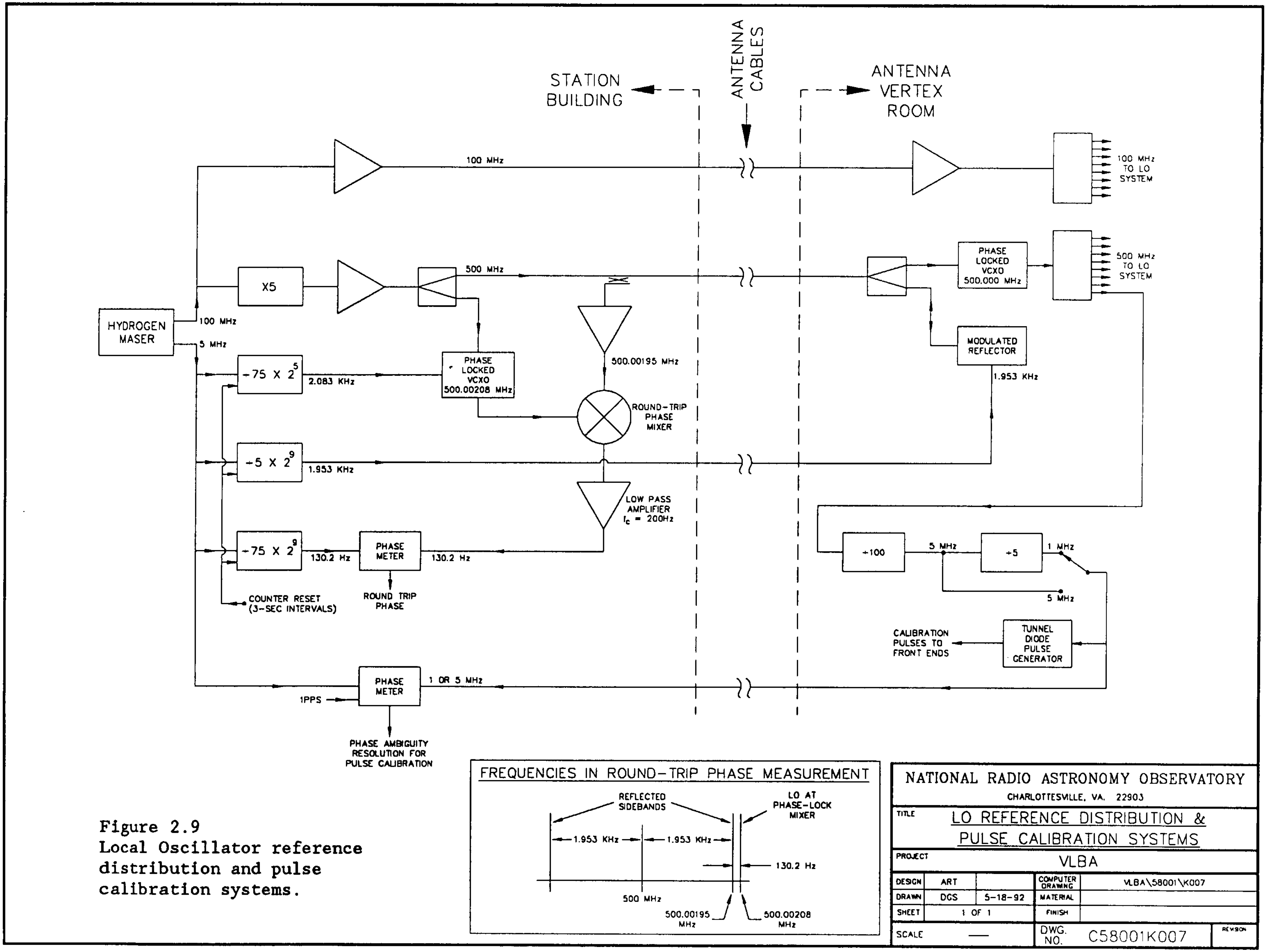


**Figure 2.9**
**Local Oscillator reference distribution and pulse calibration systems.**

maser signal by frequency division. The phase comparison is implemented in a phase meter in which other frequencies required in the round-trip measurement are also generated. The phase change in the 500 MHz signal at the vertex room resulting from a change in the electrical length of the cable is equal to one-half of the phase change measured for the 130.2 Hz component. The 500 MHz output at the vertex room comes from a phase-locked VCXO. The phase-locked loop greatly reduces any sidebands resulting from the modulated reflector that would otherwise contaminate the 500 MHz output.

At the vertex room, frequencies required for the first LO's for the 23 and 43 GHz bands and for the conversions to the 500-1000 MHz IF for 1.5 GHz and all higher bands are generated by three 2-16 GHz Synthesizer Modules. In these units a YIG-tuned oscillator and a doubler provide an output that is tunable over a range of 2-16 GHz. The YIG oscillator is locked by mixing the output frequency with a harmonic of 500 MHz, and comparing the phase of the resulting difference frequency with that of the 100 MHz reference frequency from the maser. Thus, the output frequency of the module can be set to any value between 2 and 16 GHz that is of the form 500N ± 100 MHz, where N is an integer. The resulting frequencies are spaced alternately at intervals of 200 MHz and 300 MHz, and this tunability provides fine enough steps that any required frequency in the front-end band can be set within the 500 MHz bandwidth of the IF. The 100 MHz and 500 MHz frequencies are used as fixed LO's in the 610 MHz Filter Module and the 500 MHz is also used in the 330 MHz Converter.

One other use of the LO reference signals at the antenna is to provide a very stable frequency for the pulse calibration system. In this system a train of pulses at intervals of 1 microsecond or 200 nanoseconds is generated and injected into the receiving front-end. The pulse generator unit was designed by A. E. E. Rogers of Haystack Observatory (see VLBA Acquisition Memo No. 248, 7 Oct. 1991). The pulse train with 1 microsecond intervals (for which the pulse recurrence frequency is 1 MHz) has a comb-type frequency spectrum consisting of a series of lines at harmonics of 1 MHz. Similarly, the pulse train with 200 nanosecond intervals has a spectrum of lines at harmonics of 5 MHz. The lengths of the individual pulses are approximately 25 picoseconds and the line spectrum extends to frequencies greater than 23 GHz. A train of such pulses injected into the front-end input, at a low level that will not cause overloading of any amplifiers, provides a series of calibration lines of known relative phase. After the baseband signals have been digitized, the lines can be extracted by a technique that measures their amplitude and phase. The relative phases of different lines across the receiving passband provide a measure of variations in the time delay of signals through the receiving system, up to the point of the signal extraction. This type of calibration is required for precise geodetic and astrometric measurements. Note that the spectrum of lines with 5 MHz spacing is generated by five times as many pulses as the lines at 1 MHz spacing, and contains one-fifth the number of lines. The individual lines in the 5 MHz comb spectrum are therefore 14 dB stronger than the lines of the 1 MHz comb.

The pulses are generated by a tunnel diode driven by a squarewave at the required repetition frequency. In the vertex room the frequency with the best determined phase is the 500 MHz from the LO Receiver Module, since the phase stability of its cable is measured continuously. The 500 MHz is therefore used to provide the 5 MHz and 1 MHz pulse triggering waveforms by frequency division. In the division process, the phase of resulting waveform is ambiguous within an integral number of cycles of 500 MHz. The ambiguity is not a problem so long as it remains constant, but a change resulting from a power transient, etc. could be misinterpreted as a change in instrumental delay. To prevent such an error, the 1 or 5 MHz waveform is brought down to Rack C in the station building and compared in phase with the 5 MHz and 1 pps from the maser. Note that the cable used to transmit the 1 or 5 MHz from the vertex room need not be particularly stable since it is necessary only to be able to compare the phase with a timing accuracy sufficient to resolve a cycle at 500 MHz.

Other LO frequencies used in the VLBA receiving system are those in the Baseband Converter Modules in Rack D in the station building. These LO's tune from 500 to 1000 MHz in increments of 10 kHz. To generate them an oscillator is locked to harmonics of 10 kHz by dividing its frequency by the required harmonic number, and then comparing the phase of the resulting waveform with a 10 kHz reference derived from the maser. To obtain the 10 kHz reference signal, the 5 MHz and 1 pps signals are fed to the Baseband Converters where the 5 MHz is divided by 5000 and the 1 pps is used as a time reference to establish 10 kHz phase.

## 2.7 The Formatter

The formatter takes the digital data streams from the two sampler modules in Rack D and rearranges them into the data streams required for input to the tape recorders. In the process header information, parity bits, etc. are added. The two sampler modules can process a total of 16 basebands, each sampled at 32 Mb/s, with a maximum of two bits per sample. The corresponding maximum data rate is 1024 Mb/s. A VLBA tape recorder has 36 heads recording in parallel, of which 32 are for data and four for other system requirements. The maximum recording rate is 8 Mb/s per track, or 256 Mb/s for 32 tracks. Two tape recorders will handle a total data rate of 512 Mb/s, just half the maximum output of the Baseband Converters. The formatter therefore selects the data as required and produces up to 64 data streams and eight system streams for the 72 tracks of the two recorders. An important feature of the VLBA formatter is that it allows a wide selection of format parameters, chosen values for which are loaded into the formatter from the control computer during initialization. These include the length of a frame, the length and definition of the header, whether or not data are lost when the header is written, multiplexing or demultiplexing of data streams onto recording tracks, the implementation of longitudinal parity, cross-track parity, a CRCC correcting code, a track (or "barrel") roll of the data streams relative to the recording tracks, and other features. The standard format chosen for VLBA observations is defined in Specification A56000N003. The Mark III VLBI format is also commonly implemented with the VLBA formatter. The formatter was designed by J. I. Levine of Haystack Observatory.

A simplified block diagram of a formatter is shown in Fig. 2.10. It is built in a VME chassis and contains six types of modules in the form of VME boards as well as a MVME117-4 computer. The board types are referred to by the following names:

Digital Switch (DS)
Header Control (HC)
Transport Driver (TD)
Timing and Control (TC)
Data Buffer (DB)
Quality Analysis (QA)

The input data from the samplers first go to a 32x32 crosspoint switch in the Digital Switch Board. This switch connects the 32 input bit streams into the 32 data tracks for one recorder. One input stream can be reproduced on more than one output track if required, but any track can be connected to only one input stream at this point. The 32 track streams then go to a multiplexer and demultiplexer. The maximum output bit rate for the recorder tracks is 8 Mb/s, so for baseband bandwidths of 8 or 16 MHz the bit stream must be demultipexed into two or four streams, or more if the tape recorder is running at less than the maximum rate. Similarly, if the baseband bandwidths are small, as in certain spectral line observations, data from several input streams can be multiplexed onto one output stream. For narrow bandwidths, the 32 Mb/s sampling rate results in redundant samples which can be discarded at this point. The 32 Mb/s clock is also divided down to the appropriate frequency for the output bit stream. Some special formats for testing can also be implemented. Each Digital Switch board also contains circuitry for extracting eight pulse calibration signals from the bit streams. These can be assigned one to each data stream or two or four at a time to the same stream. An early version of the Digital Switch Board used an analog switch and was known as the A/D Buffer Board. It did not have the extraction circuitry for the calibration lines. A/D Buffer Boards are being replaced in the VLBA, but some may remain in use in other VLBA-type systems.

The data streams next go to the Header Control Board, and are clocked into a FIFO (first-in, first-out) array of dimensions 36x1000. The bits are clocked out with a higher speed clock to allow extra bits for parity or headers to be added. This second clock is known as the transport clock because it governs the bit rate of the data recording. The transport clock is generated in the Output Rate Synthesizer Board described in section 2.6 above, which is in the Data Acquisition Rack. For the Mark III format, the transport clock rate is 9/8 times the input clock to allow for one longitudinal parity bit per 8 data bits. With this format, data are lost when the headers are added. The standard VLBA format is a non-data-replacement type and the transport clock is faster by a further small factor to allow for headers that do not overwrite data. The Output Rate Synthesizer can generate the transport clock frequency for the Mark III format or for the VLBA format. The four system tracks are inserted just after the FIFO. They can be used to carry data streams for test purposes, or cross track parity bits which are added in the next board. Some, but not all, of the header bits are inserted at this point. The first 36 bits of the header are the sync word, and time and auxiliary data are also included in the header. In the VLBA format, some

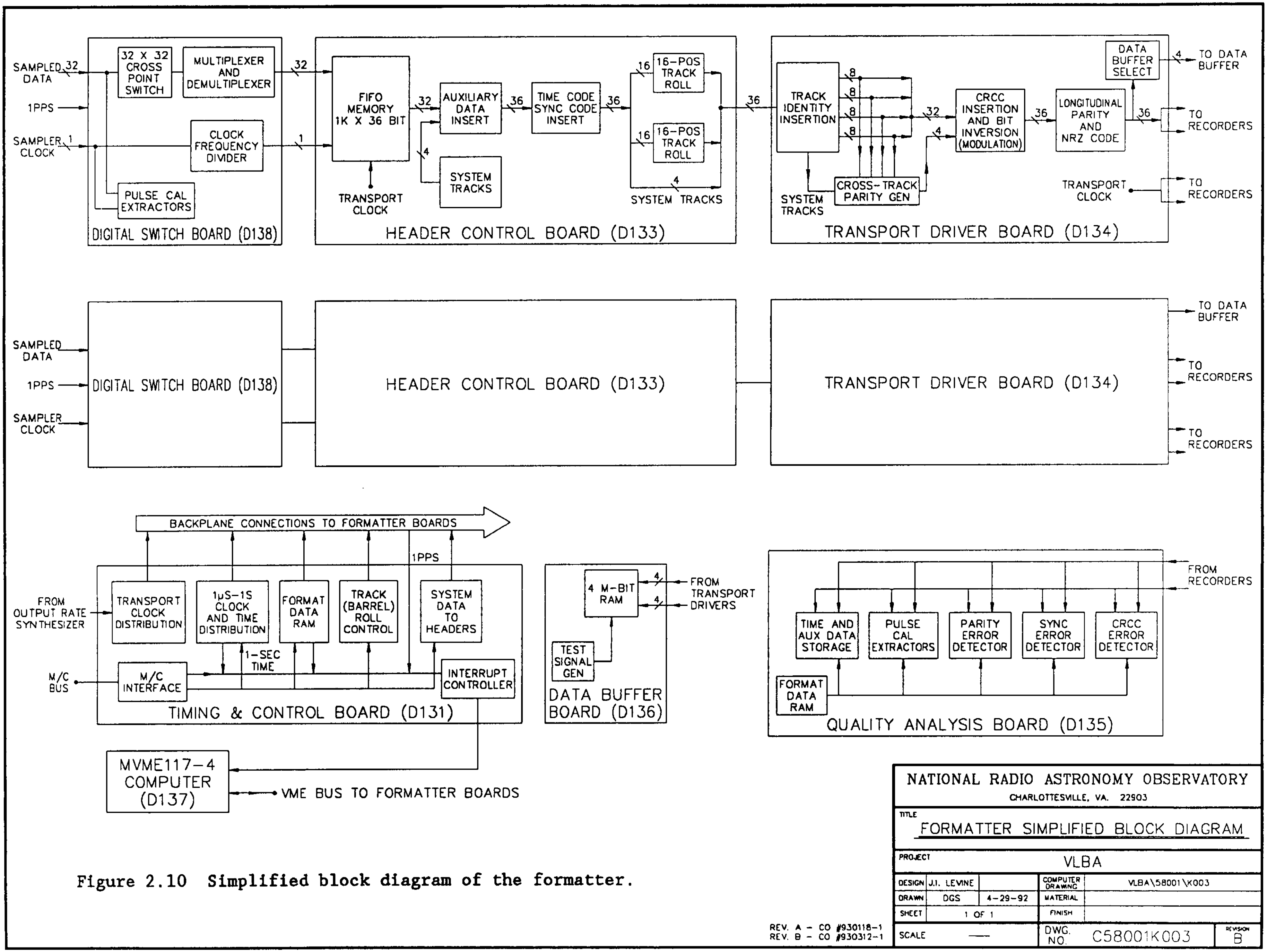


**Figure 2.10 Simplified block diagram of the formatter.**

header-type data go at the end of the frame. Next, the track (barrel) roll operation is performed. In this operation, the assignment of data streams to recording tracks is rotated periodically within a group of tracks. The purpose of this rotation is to distribute any loss of data resulting from a bad write or read track equally over a number of data streams. Each data stream within a selected group steps periodically through each of the tracks assigned to that group. There are eight possible roll modes to choose from, some based on groups of eight tracks and some on sixteen. A step of the roll occurs at the end of each frame or at the end of a group of frames.

The bit streams then go to the Transport Driver Board where track identity data are inserted into the headers. Cross track parity is generated and can be recorded on one of the system tracks. Note that if one parity bit is generated for each eight tracks, the four system tracks are completely filled. Next, cyclic redundancy check characters (CRCC) are generated. In the VLBA format, this is done only for the time information in the headers. Longitudinal parity is then added, and the bit coding is changed to a non-return-to-zero (NRZ) form in which a one is represented by a transition and a zero by the absence of a transition. To facilitate clock recovery during a string of zeros, a periodic inversion of the data is inserted at the same point as the CRCC code. These inversions and the track roll transitions are removed on playback of the tapes at the correlator. The outputs of the board consist of the 36 data streams for the recording heads and the transport clock waveform. These go to the two recorders in parallel.

There are two of each of the three boards described above in each formatter. Each Transport Driver output is connected to the inputs of both tape recorders. Switches in the recorders select the inputs to be recorded. In some cases, both recorders are run simultaneously for maximum bandwidth recording, and, in other cases, the recorders are used alternately so that no observing time need be lost in changing tapes. Each formatter contains one each of three other kinds of boards, which are described below.

The Timing and Control Board performs a number of functions involving timekeeping and storing the format definition information. A clock in the board keeps time in the range microseconds to seconds, the coarser time information being provided by the control computer. The board also distributes the transport clock generated by the Output Rate Synthesizer. It generates control waveforms for the track (barrel) roll functions and converts system status information into serial data that are included in the headers. The Timing and Control Board contains the format data RAM which holds up to 65,535 16-bit words. Each word specifies one bit of the output data frame: the maximum frame length is thus 65,535 bits. However, the standard VLBA format uses only 22,680 bits per frame. The format data control the frequency of the transport clock, the size and content of the headers, the use of parity and CRCC codes, etc. The board also contains the interrupt controller that processes interrupts, including the 1 pps station sync. and passes them on to the computer.

The Data Buffer Board allows extraction of sample quantities of data that can be transmitted to the correlator by monitor and control data lines to check that the system is operating. It contains a 4 Mb RAM buffer which can be filled from one, two, or four tracks, the tracks being returned from the output of the Transport Driver Board. The Data Buffer Board also contains a test generator that can be used to fill the RAM for certain tests.

The Quality Analysis Board performs an error analysis on two data tracks which are selected in the recorder and fed back to the formatter. The inputs are converted from the NRZ code to TTL, and as the data are scanned, 32 bits of time code or auxiliary data can be captured from each header. Synchronization errors, parity errors, and CRCC code errors are counted. The Quality Analysis Board also contains circuitry for extraction of a pulse calibration signal. The extraction capacity is limited to one signal line per baseband channel and the frequency is limited to the sample frequency divided by 8N for 2-level quantization or by 16N for 4-level, where $1 < N < 32,768$ (see VLBA Acquisition Memo No. 108). Note that the extraction capability in this board was included to provide a basic testing capability before the larger and more flexible extraction capability in the Digital Switch Board was designed.

## 2.8 Tape Recorders

The tape recorders that are used to record the data from the Formatter at each antenna site, and to playback the tapes at the correlator, were obtained through Haystack Observatory and are modified Metrum 96 (formerly Honeywell 96) units. The modification includes control electronics designed for VLBI observations as well as modifications to the precision plate and heads to allow handling of thin (16 $\mu$m) tape and 50 kb/i (kilobits per inch) track density. The recorders are described in Appendix 4.

The maximum data recording or playback rate of one recorder is 256 Mb/s, resulting from the 32 data heads writing or reading at 8 Mb/s each. Two recorders running together can thus record 512 Mb/s, which corresponds to the full baseband bandwidth of 256 MHz (16 baseband channels of 16 MHz each) sampled at the Nyquist rate with one bit per sample. The usual recording rate at an antenna, however, is that of one recorder running at 128 Mb/s. This limitation is required because the average recording rate must be less than the playback rate of the correlator, or it would not be possible to reduce all the recorded data. The playback rate is 256 Mb/s, with one playback recorder per antenna. For occasional special projects requiring the highest sensitivity, both recorders at an antenna can be used to provide the 512 Mb/s capacity. More importantly, the availability of two recorders at each site facilitates tape changing and maintenance of recorders.

## 2.9 Monitor and Control System

The VLBA system incorporates a bus with interface units that allows a computer, referred to as the controller, to distribute commands and to gather monitor data. The specification for the bus is given in Spec. No.A55001N001, which is included in VLBA Technical Report No. 12 as an appendix. The bus consists of two lines, each a twisted pair of approximately 100 ohms impedance, in a shielded cable. Data are transmitted serially at a rate of

57.6 kbaud. One line carries outgoing commands from the control computer, referred to as the transmit signal. The other line carries incoming monitor data to the computer, referred to as the receive signal. Thus, the terms transmit and receive are with respect to the controller, not the interfaces at the equipment. Up to 32 interfaces can be attached to a bus. Line branches to interface units can be no more than 20 ft. long, and each line cannot exceed 500 ft. and must be terminated in a 100 ohm resistor.

Messages on the transmit line consist of five bytes of serial data. Each byte consists of a start bit, eight data bits, a parity bit and a stop bit. The first byte has even parity and all others have odd parity. The even parity is used to distinguish the start of a message. Each interface on the bus must receive all messages, decode the addresses, and respond only to those messages with addresses within the block assigned to that interface. The second and third bytes are address-high (ADH) and address-low (ADL), respectively, and the most significant bit of ADH is a 1 for a control message and a 0 for a monitor request message. On the receive line, messages are either a two-byte command acknowledgement or a three-byte monitor data response consisting of an acknowledgement followed by two data bytes. Only the controller can initiate action on the bus. Other devices interfaced to the bus can only respond to commands or requests for monitor data from the controller.

Each interface is assigned a contiguous block of addresses which are not shared by any other interface connected to the same controller. The 15-bit address number allows for up to 32,768 addresses on the bus. A separate address is designated for each monitor or control function, and any particular control or monitor function can be addressed without specification of the interface through which the message is passed. Within the interface to which any function is connected, it is specified by an eight-bit relative address. The relative address is equal to the complete (15-bit) address less the address at the start of the block assigned to the particular interface. The relative address is determined in hardware by the wiring between the interface and the function addressed. The eight-bit length of the relative address limits the number of functions that can be handled by an interface to 256, but simplifies the address wiring to the interface. The address block assigned to each interface is determined in software by the controller, and the address blocks can be reassigned as may be necessary, for example, when new interfaces are added to the system. The values of the first address in the block and the block size in the interface are initialized by the controller.

In all of the VLBA equipment designed within NRAO, a single design of interface board, referred to as the VLBA Standard Interface, has been used. This was developed by D. Weber and W. Koski and is described in detail in VLBA Technical Report No. 12, which includes a specification for the interface (Spec. No. A55001N002A). A useful critical discussion of the design is given by L. D'Addario in VLBA Memo. No. 682. In VLBA equipment designed at Haystack Observatory, *i.e.*, that in Rack D and the Tape Recorder Racks, the interface is in many cases implemented by making use of microprocessors which also perform other functions.

The VLBA Standard Interface includes an analog multiplexer and D/A converter for monitoring of analog voltages. Provision is made for up to eight analog voltages by direct connection to the board, and this capability can be expanded by use of an external analog multiplexer. Two versions of the board have been designed, one with a common ground for the analog inputs and one with differential inputs. Note that there are further constraints that have been introduced in the implementation of the interfaces for convenience in the software. For example, it is possible to use the same address for both transmit and receive messages. By software convention, this usage is limited to readback of a digital command for checking purposes, and the bits in the readback message should correspond exactly to the command message sent. Also, the use of separate addresses for logically unconnected commands is encouraged, even though a message may contain unused bits that could usefully be assigned to other functions.

The standard interface is fairly large, 5.5 x 6.25 inches, and takes 700 mA at 5 V, as well as lower currents at ± 15 V. (The power requirements can be reduced to 650 mA at 5 V and the ± 15 V eliminated if the analog monitoring capability is not required.) The heat associated with the power dissipation, as well as interference at frequencies up to a few hundred MHz commonly generated by digital circuitry, are factors that make the inclusion of the interface undesirable in units that include RF or IF signals and temperature sensitive components such as filters. For these reasons, the interface card was excluded from the card cage of the front-end units, and the monitor and control functions for the front-ends are implemented through interface cards in separate shielded modules (Front End Interface Modules). In cases where the interface module is needed in a module that contains sensitive RF components, a specially shielded design with a separate compartment for the digital circuitry is used (as in the 2-16 GHz Synthesizer Module and the Calibration Pulse Generator Module). Coaxial switches in the converter modules, and in the back plane panels of Rack B, are driven by two modules containing standard interface cards, the Switch Driver and Rack B Interface Modules. Initially, it was suggested that a standard interface might be designed that would be small enough, and have low enough power dissipation, that it could be included in every module. This would enable serial numbers of all modules to be read back, a useful feature for maintenance purposes. Also, monitor and control wiring between modules, other than the bus, would be eliminated. However, at the time of implementation of the VLBA, it appeared that the most practical scheme would be intermediate between the ideal of an interface in every module and the system with all monitor and control through special modules, as in the earlier system developed for the VLA.

## 3 Racks, Bins, and Modules

### 3.1 Racks

Racks in the VLBA system are given reference letters and descriptive names as follows:

Rack A = Front-End Interface Rack (Vertex room)
Rack B = IF/LO Rack (Vertex room)
Rack C = Master LO Rack (Electronics room)
Rack D = Data Acquisition Rack (DAR) (Electronics room)
[Rack E = DAR modified for 14 Baseband Converters][1]
Rack F = Antenna Control Rack (Pedestal room)
Rack R = Recorder Rack (Observing room)

Locations of the racks at an antenna site are shown in Fig. 1.2. Racks A and B are made by NRAO and are designed to be tipped through 90° without damage, as occurs when the antenna is moved in elevation. The other racks are standard commercial types.

### 3.2 Bins

For reference to positions of bins and modules, bins within each rack are designated A, B, C, etc. starting from the top of the rack, and slots within a bin are designated 1 through 12 from left to right as viewed from the front of the bin.

### 3.3 Modules

As used here, the term "module" is not limited to equipment built in NRAO VLA-type modules, but includes any type of unit that may be interchanged for maintenance, such as front-ends. The letters in the type numbers which designate subsystems are based on the scheme outlined in VLA Technical Report No. 31, p. 9-3. These designations are as follows:

D = Digital Signal Processing (includes Formatter)
F = Front-End
L = Local Oscillator
M = Monitor and Control (General)
P = Power Supply
R = Recorder
S = Subreflector Control
T = Signal Transmission, IF, and Baseband

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[1] Not used in the VLBA but installed at some geodetic VLBI antennas for Mark 3 compatibility.

Type numbers begin with 101 to distinguish VLBA modules from VLA modules. Type numbers of modules designed by the Haystack group begin with 121.

Most of the electronics is constructed in modules of the NRAO type developed for the VLA. Details of the modular construction are given in VLBA Electronics Memo No. 78 which is reproduced in Appendix 2. The width of a module is referred to as single, double, etc. in terms of the unit width of 1.375 inches, which is the width of a slot in a bin.

## 3.4 Serial Numbers

All units of types listed in this chapter are assigned serial numbers when made. Serial numbers of units constructed within NRAO or Haystack Observatory begin at 1 for each type of unit and are incremented by 1 for each new unit. They are intended to distinguish between different units of the same type, but not between different types of units. Serial numbers should not be extended to include information on the unit type. An exception to the above has been made in the case of racks. Serial numbers for VLBA racks begin at 101 to distinguish them from VLA racks, which in several cases have the same type designation letters.

A revision letter preceding the numeric part of the serial number should be used to indicate any major modification to the original design. Major modifications are those which make a module incompatible as a direct replacement for any other units of the same type. The practice followed with VLBA modules is to have no revision letter in the serial number for the original design. Thus, for example, if major modifications to a certain type of module were introduced at the third and fifth units, the serial numbers would be 1, 2, A3, A4, B5, etc. When retrofits are made the revision letters of the serial numbers are revised accordingly. When all units of a given type have been brought up to date with the latest modification, the corresponding revision letter is retained in the serial number even though there is no longer any incompatibility between units.

## 4 List of VLBA Modules

A list of VLBA modular units follows, which includes locations and brief descriptions of functions. The number of units of each type refers to the number required per antenna or per recorder rack.

D121 SAMPLER MODULE

Double-width module. Two units, Rack D, Bin C, Slots 5-6 and 7-8.

Each module contains eight samplers that sample the baseband signal waveforms from four Baseband Converter modules at a sample frequency of 32 MHz. The sample voltages are represented digitally by two bits representing four-level quantization. The output of each Sampler module thus consists of 16 bit streams, each with a bit rate of 32 Mb. The two modules digitize the outputs of eight Baseband Converters.

D130 FORMATTER CHASSIS

VME Chassis. One unit, Rack D.

D131 FORMATTER TIMING AND CONTROL BOARD

VME board. One unit, Rack D, Formatter VME Chassis.

A number of functions are performed by this formatter module. These include timekeeping, storing the format definition, distribution of the transport clock, generation of the waveform for track roll control, and processing system status information for inclusion in frame headers. The module also contains an interrupt controller for the VME computer (D137).

D132 A/D BUFFER BOARD (Obsolete)

VME Board. Two units, Rack D, Formatter VME Chassis. Replaced by D138.

Replaced in the VLBA by the Digital Switch Module, D138. D132 had an analog cross-point switch and does not have an extractor for pulse calibration signals as D138 does.

## D133 HEADER CONTROL BOARD

VME board. Two units, Rack D, Formatter VME Chassis.

The Header Control receives the bit streams from the Digital Switch Module. The data are clocked into a FIFO memory by the sampler clock, and out of the FIFO by the faster transport driver clock, to provide space for headers and parity bits. The four system tracks are added and part of the header information inserted. The track roll is performed.

## D134 TRANSPORT DRIVER BOARD

VME board. Two units, Rack D, Formatter VME Chassis.

Bit streams are received from the Transport Driver. Track identity data are added into the headers, cross track parity is generated, cyclic redundancy check characters (CRCC) and longitudinal parity bits are added. The bits are encoded in a NRZ (non-return-to-zero) code and the data waveform is periodically inverted.

## D135 DATA QUALITY ANALYSIS BOARD

VME board. One unit, Rack D, Formatter VME Chassis.

Performs a data quality analysis from two tracks fed back from the recorders. Time code or auxiliary data can be captured from the headers. Synchronization errors, parity errors, and CRCC code errors are counted. The module also contains a limited capacity for extraction of pulse calibration signals, which was included before the extraction system in the Digital Switch Modules (D138) was available.

## D136 DATA BUFFER BOARD

VME board. One unit, Rack D, Formatter VME Chassis.

The Data Buffer allows small quantities of data to be extracted from the recorded data streams and sent to the correlator by data lines to check for correct operation of the system. The module contains a 4 Mb RAM that can be filled from one, two, or four tracks, and the data then transmitted. There is provision for transmission of data from a test generator.

## D137 FORMATTER MVME117 COMPUTER BOARD

VME board. One unit, Rack D, Formatter VME Chassis.

Motorola MVME117-4 computer.

D138 DIGITAL SWITCH BOARD

VME board. Two units, Rack D, Formatter VME Chassis.

The 32-bit streams from the two Sampler Modules go to a 32x32 crosspoint switch in this module. Bit streams are multiplexed or demultiplexed as required and redundant samples can be deleted. Some special formats can be implemented for system testing. The module also contains multipliers that extract the amplitude and phase of the pulse calibration signals. There is provision for simultaneous extraction of eight such signals, one each from each of eight channels, or two or four each from fewer channels. An earlier version of this module, D132, uses an analog switch and has no provision for extraction of pulse calibration signals.

F102 330/610 MHz FRONT-END

One per antenna, on subreflector support structure near prime focus.

This front-end is not cryogenically-cooled. It contains diplexers and quadrature networks to separate the dipole feed outputs into the two bands and forms opposite circularly-polarized components. Further details are given in section 2.2.

CRYOGENICALLY-COOLED FRONT-ENDS

For each of the front-ends listed below, except for 10.7 GHz, there is one per antenna, located in the feed cone of the vertex room. For further details, see section 2.2 and Table 2.2.

F103 1.5 GHz FRONT-END (1.35-1.75 GHz)

F104 2.3 GHz FRONT-END (2.15-2.35 GHz)

F105 4.8 GHz FRONT-END (4.6-5.1 GHz)

F106 8.4 GHz FRONT-END (8.0-8.8 GHz)

F107 10.7 GHz FRONT-END (10.2-11.2 GHz) Note: On Antenna 1 (Pie Town) only.

F108 14 GHz FRONT-END (12.0-15.4 GHz)

F109 23 GHz FRONT-END (21.7-24.1 GHz)

F110 43 GHz FRONT-END (41.0-45.0 GHz)

F111 86 GHz FRONT-END Note: Not implemented as of Dec. 1992

F117 FRONT END INTERFACE MODULE

Single-width module. One unit per front-end, Rack A, Bins D and E, odd-numbered slots.

This module contains a M/C interface card and is shielded to minimize interference from digital circuitry. Two cables, one for commands and one for monitor functions, run from 25-pin D connectors on the front panel to a front-end. Commands control operation of the refrigerator, vacuum pump, and noise calibration signals. Monitor functions include voltages, currents, temperatures, type and serial number of attached front-end, serial number of interface module, and readback of command words. The module operates with any VLBA-type of front-end. Alternate slots of bins D and E are wired to receive Front End Interface Modules. The bin connections are identical at all locations, and the interface module for any front-end will operate from any odd-numbered slot in either of the two bins.

F118 FRONT-END ADAPTER MODULE

Double-width module. One unit, Rack A, Bin C, Slots 1-2.

This module serves as an interconnection between the Front-End Interface Module for the 330/610 MHz Front-End and a special cable that runs to the front-end near the prime focus of the antenna. The D-connector cables used for the front-ends in the feed cone are not suitable for exposure to outdoor conditions. The 330/610 MHz Front-End does not require the full monitoring capacity of the F117 interface, so various other monitor functions are connected to the interface through the adapter module. These include Rack A voltages and temperature, and vacuum manifold pressures. Voltages applied to four BNC connectors on the front panel of the adapter module can also be monitored as a test facility.

L102 LO TRANSMITTER MODULE

Double-width module. One unit, Rack D, Bin C, Slots 9-10.

Local oscillator reference frequencies to the vertex room are transmitted from this module. A 100 MHz signal from the maser is amplified and transmitted on a cable. The 100 MHz is also multiplied to 500 MHz which is transmitted on a second cable. Signals returned on the 500 MHz cable for the round-trip phase measurement are removed by a directional coupler and converted with a frequency of 500.002083 MHz. The required returned sideband is thus converted to 130.2 Hz and is selected out for phase measurement by 200 Hz lowpass amplifier. The 500.002083 MHz is LO is generated by a VCXO that is phase-locked to the 500 MHz with a 2.083 kHz offset. For further details see section 2.6.

L103 ROUND-TRIP MONITOR MODULE

Double-width module. One unit, Rack D, Bin C, Slots 11-12.

Three frequencies are generated by division of 5 MHz from the maser: 2.083 kHz used in locking the VCXO in the LO Transmitter Module, 1.953 kHz used by the modulated reflector in the LO Receiver Module, and 130.2 Hz which is used in phase comparison with the 130.2 Hz signal brought from the LO Transmitter. The phase comparison of the 130.2 Hz waveforms is performed by gating a 5 MHz frequency and counting cycles during 3-second periods.

L104 2-16 GHz SYNTHESIZER MODULE

Shielded triple-width module. Three units, Rack B, Bin A, Slots 10-12 and Bin B, Slots 3-5 and 8-10.

This modules produces LO frequencies in the range 2 to 16 GHz which are required in the vertex room. The output is produced by a 2 to 8 GHz YIG-tuned oscillator and a doubler. The output is mixed with 500 MHz in a harmonic mixer and used to lock the oscillator by a phase-lock loop with an IF of 100 MHz. The lock frequencies occur at (500 x N ± 100) MHz where N is an integer. The 100 MHz and 500 MHz references come from the LO Transmitter Module. The synthesizer module contains a M/C interface for frequency selection by computer. The output level is 3 ± 1.4 dBm, controlled by an ALC loop.

L105 LO RECEIVER MODULE

Double-width module. One unit, Rack B, Bin D, Slots 1-2.

In this module the 100 MHz and 500 MHz signals from the LO Transmitter Module are received and distributed. The 100 MHz is amplified and goes to an eight-way power divider on the back of the rack. The 500 MHz line is coupled to a diode reflector that is modulated by a frequency of 1.953 kHz, and the resulting sideband at 500.001953 is used in the round-trip phase measurement. The 500 MHz frequency that is used in the vertex room the signal is filtered by means of a phase-locked VCXO. The 500 MHz output then goes to an eight-way power divider on the back of the rack.

## L107 SWITCH DRIVER MODULE

Double-width module. One unit, Rack B, Bin B, Slots 1-2.

The Switch Control Module contains a M/C interface card to receive commands, and switch drivers to control the coaxial switches used for RF, IF and LO signals in Rack B. The switches include all those mounted in the back plane of the rack, but not all of those in the modules. The transfer switches that interchange the two inputs of most converter modules are controlled by drivers in the Rack B Interface Module. The Switch Control Module also provides for monitoring power supply voltages in Rack B.

## L108 STATION TIMER MODULE

Single-width module. One unit, Rack C, Bin C, Slot 5.

The 1 pps timing pulses are generated in the Station Timer by dividing a 5 MHz signal from the maser. A button on the front panel provides a manual control for synchronization of the pulses to a series of external pulses. These usually come from the Secure 1 pps Module which is an independent 1-sec. clock that is synchronized to time pulses from a GPS receiver. The Station Timer provides fifteen buffered outputs of the 1 pps. The Station Timer also generates a waveform at 80 Hz which is used for switching the noise sources in the front-ends.

## L109 SECURE 1 PPS MODULE

19-inch wide chassis. One unit, Rack C, Top of rack just below GPS Receiver.

This unit produces 1-sec. pulses by dividing a 5 MHz signal from the maser. The pulses can be synchronized to Universal Time using a GPS receiver. Batteries in the module provide security against failure of commercial power.

## L110 PULSE CAL. GENERATOR MODULE

Double-width module. One unit, special bin in antenna feed cone.

Produces narrow pulse trains with recurrence frequency 1 MHz or 5 MHz for use as calibration signals injected into the front-end inputs. Uses the 500 MHz reference frequency from L105 as timing reference.

## L111 PULSE CAL. MONITOR MODULE

Double-width module. One unit, Rack C.

Measures phase of 1 MHz or 5 MHz pulse timing waveforms from L110 relative to references from the maser to resolve ambiguity in phase resulting from frequency division in L110.

## L121 5 MHz DISTRIBUTOR MODULE

Double-width module. Two units, Rack C, Bin C, Slots 3-4, and Rack D, Bin C, Slots 1-2.

The 5 MHz Distributor provides 15 buffered outputs for a single 5 MHz input. One output is on the front panel. The gain is 0 dB from the input to any one output. The module is used to distribute 5 MHz from the maser and the output level used is 13 dBm.

## L122 32 MHz SYNTHESIZER MODULE

Double-width module. One unit, Rack D, Bin C, Slots 3-4.

This module generates a 32 MHz clock waveform used by the sampler modules and also provides distribution for 1 pps in Rack D. A 5 MHz signal from the maser is divided down to 1 MHz and synchronized with the 1 pps signal to remove phase ambiguities. It is then used to phase-lock a 32 MHz VCXO, the output of which is divided down to 1 MHz for phase comparison. Buffer stages provide 10 outputs for the 1 pps waveform. The module also produces a waveform referred to as synch which consists of a short (31 nsec.) pulse at the second positive-going transition of the 5 MHz after each 1 pps pulse. These short pulses are used to identify samples at the sampler.

## L123 OUTPUT RATE SYNTHESIZER MODULE

Double-width module. One unit, Rack D, Bin C, Slots 9-10.

Frequencies used in the Formatter and Recorder are generated in this module. For recording in the Mark III format, a transport clock of 9 MHz is required at the formatter and a frequency of 9 x 21 = 189 MHz is required at the recorder. For the VLBA format, the corresponding frequencies are 9.072 and 190.512 MHz. The module contains VCXO's for 189 and 190.512 MHz, and either one can be selected and phase-locked. Division by 21 produces the transport clock. For recording at less than the maximum rate, both output frequencies can be further divided in steps of two from 2 to 32.

M101 TEMPERATURE, INCLINOMETER INTERFACE

Double-width module. One unit, Rack F, Bin C, Slots 1-2.

The module provides for monitoring readings of temperature sensors and inclinometers on the antenna, using a M/C interface board.

M102 RACK B INTERFACE

Double-width module. One unit, Rack B, Bin D, Slots 4-5.

The module provides general monitor and control functions in Rack B through a standard M/C interface board. Control functions include energizing coaxial relays in converter modules. Monitor functions include LO power levels, lock status of VCXO in LO Receiver, power supply voltages, and rack temperatures.

M103 UTILITY INTERFACE

Double-width module. Two units; Rack F, Bin C, Slots 11-12; and Computer Rack, Bottom Bin, Slots 11-12.

Monitor and control functions for various building utilities are provided through this module. Examples of these utilities are the air handler, smoke detectors, uninterruptable power system, and temperature monitors. Monitoring inputs accommodate various analog and digital signal types, and command outputs include contact closures, relay energization, and TTL levels. Connection to devices is through a distribution box which is separate from the module. The module contains a M/C interface board and DC power supplies, and requires only 115 V AC input power.

M104 MASER INTERFACE

Double-width module. One unit, Rack C, Bin C, Slots 1-2.

The Maser Interface provides extensive monitoring of pressures, temperatures, voltages currents, etc. in the maser frequency standard, through a M/C interface board. Control functions for the maser are limited to setting of the frequency control digits of the synthesizer.

P101 15 V POWER SUPPLY

Quadruple-width module. Six units; Rack A, Bin B, Slots 1-4 and 5-8, Bin C, Slots 9-12; Rack C, Bin B, Slots 9-12; Rack D, Bin B, Slots 1-4 and 5-8. (For Racks of type D expanded to 14 Baseband Converters, one extra P101 is required in Rack D, Bin A, Slots 1-4.)

Lambda LDS-P-15 linear power supply is used. Current rating is 12 A at 40°C, 10.5 A at 50°C. Front panel meter is 0-15 A.

P102 15 V POWER SUPPLY

Triple-width module. Three units; Rack A, Bin A, Slots 1-3, Bin B, Slots 9-11; Rack C, Bin B, Slots 5-7.

Lambda LDS-X-15 linear power supply is used. Current rating is 5.5 A at 40°C, 4.6 A at 50°C. Front panel meter is 0-15 A.

P103 5 V POWER SUPPLY

Triple-width module. Five units; Rack A, Bin A, Slots 4-6 and 7-9; Rack C, Bin B, Slots 1-3; Rack D, Bin A, Slots 5-7, Bin B, Slots 10-12.

Lambda LRS-53-5 switching power supply is used. Current rating is 25 A at 40°C, 21.5 A at 50°C. Early units used Kepco RMX 05-B switching supply, with current rating 34 A at 40°C and 26 A at 50°C. Front panel meter is 0-50 A.

P104 28 V POWER SUPPLY

Triple-width module. One unit, Rack A, Bin A, Slots 10-12.

Lambda LRS-53-28 switching power supply is used. Current rating is 5.7 A at 40°C and 5.1 A at 50°C. Early units used Kepco RMX 28-B switching power supply with current rating 6.8 A at 40°C and 6.4 A at 50°C. Front panel meter is 0-15 A.

P105 5 V POWER SUPPLY

Quadruple-width module. One unit, Rack D, Bin A, Slots 9-12.

Lambda LRS-56-5 switching power supply is used. Current rating is 77 A at 40°C and 61 A at 60°C.

P106 5 V POWER SUPPLY

Quadruple width module. Used only in Racks of type D with more than 8 Baseband Converter Modules. Replaces P103 in Rack D, Bin A, Slots 5-8.

Lambda LRS-55-5 switching power supply is used. Current rating is 51 A at 40°C and 41 A at 50°C.

P111 MODEL 22 POWER SUPPLY

Chassis mounted on wall of feed cone, one per CTI Model 22 Refrigerator.

Provides 150 V AC for the refrigerator motor. Contains a transformer and a resistive-capacitive network.

P112 MODEL 350 POWER SUPPLY

Chassis mounted on wall of feed cone, one per CTI Model 350 Refrigerator.

Provides 150 V AC for the refrigerator motor. Contains a transformer and a resistive-capacitive network.

R121 RCDR MVME117 COMPUTER BOARD

VME board. One unit per recorder, Rack R, VME Chassis.

R122 RCDR ANALOG I/O BOARD

VME board. One unit per recorder, Rack R, VME Chassis.

R123 RCDR TRANSPORT VME BOARD

VME board. One unit per recorder, Rack R, VME Chassis.

R124 RCDR WRITE VME BOARD

VME board. One unit per recorder, Rack R, VME Chassis.

R125 RCDR MONITOR VME BOARD

VME board. One unit per recorder, Rack R, VME Chassis.

R126 RCDR CLOCK RECOVERY BOARD

VME board. One unit per playback recorder, Rack R, VME Chassis.

R131 RCDR READ INTERFACE

Double-width NIM unit. One per recorder, Rack R, Bin B, Slots 5-6.

R132 RCDR PARALLEL REPRODUCE MODULE

Double-width NIM unit. Two per playback recorder, Rack R, Bin B, Slots 7-8, 9-10.

R133 RCDR WRITE DRIVER

Double-width NIM unit. One per recorder, Rack R, Bin B, Slots 11-12.

R134 RCDR ANALOG CONDITIONER

Triple-width NIM unit. One per recorder, Rack R, Bin A, Slots 10-12.

R135 RCDR INCHWORM CONTROLLER

Triple-width NIM unit. One per recorder, Rack R, Bin A, Slots 4-6.

R136 RCDR HEAD ASSEMBLY

One unit per recorder, Rack R, tape transport plate.

R137 RCDR VACUUM MOTOR

One unit per recorder, Rack R.

R141 RCDR CAPSTAN SERVO MODULE

One unit per recorder, Rack R.

R142 DUAL REEL SERVO AMPLIFIER

One unit per recorder, Rack R.

R143 RCDR REEL SERVO MOTOR

Two units per recorder, Rack R, tape transport plate.

R144 RCDR CAPSTAN SERVO MOTOR

One unit per recorder, Rack R, tape transport plate.

R145 RCDR FAN MODULE

One unit per recorder, Rack R, back of rack at bottom.

R151 RCDR ANALOG POWER SUPPLY

Full rack width chassis. One unit per recorder, Rack R.

R152 RCDR DIGITAL POWER SUPPLY

Full rack width chassis. One unit per recorder, Rack R.

R153 RCDR HONEYWELL POWER SUPPLY

One unit per recorder, Rack R.

Regulated power supply.

R154 RCDR SYSTEM POWER DISTRIBUTION MODULE

One unit per recorder, Rack R.

R155 RCDR VME POWER DISTRIBUTION MODULE

One unit per recorder, Rack R.

R156 HONEYWELL UNREGULATED POWER SUPPLY

Full rack width chassis. One unit per recorder, Rack R.

Unregulated power supply.

S101 F-R CONTROL MODULE

Double-width module. One unit, Rack F, Bin A, Slots 3-4.

The module controls the focusing and rotation motions of the subreflector mount. Contains servo motor controls, etc. Receives commands from computer through M/C interface board in S104.

S102 APEX INTERFACE

Double-width module. One unit, Rack F, Bin A, Slots 1-2.

Contains circuitry that interfaces with angle-measuring resolvers, focus position readouts, brake status indicators, etc. through optically-isolated cable connections. Position information passed on to S101 to complete servo loops.

S103 F-R SWITCHING MODULE

Quadruple-width module. One unit, Rack F, Bin B, Slots 9-12.

Provides various functions for the focus-rotation system including high-power brake control, resolver references.

S104 F-R INTERFACE

Double-width module. One unit, Rack F, Bin A, Slots 5-6.

Contains a M/C interface board that provides monitor and control connections between the station computer and Focus-Rotation modules S101, S102, and S103.

S105 F-R POWER SUPPLY

Quadruple-width module. One unit, Rack F, Bin A, Slots 9-12.

Provides +5 V and ±15 V as required to S101, S102, S103, S104. Also has front panel controls for manual adjustment of F-R positioning.

T101 330 MHz CONVERTER MODULE

Double width module. One unit, Rack B, Bin D, Slots 11-12.

Receives two outputs from the 330 MHz front-end and upconverts the frequency band to 812-842 MHz using a fixed LO frequency of 500 MHz. Amplifies to the level required for transmission to Rack C in the station building.

T102 610 MHz FILTER MODULE

Triple width module. One unit, Rack B, Bin D, Slots 6-10.

This unit provides filtering of the band 609-613 MHz with a steep-sided bandpass response to reject signals from neighboring TV channels 36 and 38. The two outputs from the front-end are downconverted in two steps with local oscillators of 500 MHz and 100 MHz from 609-613 MHz to 9-13 MHz. They are then filtered by an eight pole filter with bandwidth 4 MHz, and reconverted back up to 609-613. The circuitry within the modules that provide the frequency conversions and the narrow band filtering can be bypassed, providing an overall bandwidth of 30 MHz for observations in cases where the nearby TV channels are not used.

T103 1.5 GHz CONVERTER MODULE

Double width module. One unit, Rack B, Bin C, Slots 8-9.

The outputs of the 1.5 GHz front-end covering 1.35-1.75 GHz go to this module where they are converted to the 0.5-1.0 GHz IF. The LO signal comes from a 2-16 GHz Synthesizer Module. The complete input band can be covered by using LO frequencies of 2.1 and 2.4 GHz. The IF signals are amplified and transmitted by cable to the station building.

T104 2.3 GHz CONVERTER MODULE

Double width module. One unit, Rack B, Bin C, Slots 1-2.

The outputs of the 2.3 GHz front-end, which covers 2.15-2.35 GHz, are converted to fall within the IF band 0.5-1.0 GHz using an LO signal from an L104 module. An LO frequency of 3.1 GHz is appropriate. The amplified IF signals are transmitted to Rack C in the station building.

T105 4.8 GHz CONVERTER MODULE

Double width module. One unit, Rack B, Bin C, Slots 4-5.

The outputs of the 4.8 GHz front-end, which covers the band 4.6-5.1 GHz, are converted to 0.5-1.0 GHz in this module. The LO signal comes from an L104 module and LO frequencies of 4.1 or 5.6 GHz can be used. The amplified IF signals are transmitted by cable to Rack C in the station building.

T106 8.4/23 GHz CONVERTER MODULE

Double width module. One unit, Rack B, Bin A, Slots 4-5.

The input can be switched between the outputs of either the 8.4 GHz front-end or the 23 GHz front-end, for conversion to the 0.5-1.0 GHz IF. The module contains special features that allow separate LO inputs from two 2-16 GHz Synthesizer Modules, and both mixers to be fed from the right-hand circular polarization signal. These features are required for geodetic and astrometric observations in the 8.0-8.8 GHz band. The module also provides a second conversion for signals from the 23 GHz front-end. Further details are given in section 2.3.

T107 10.7 GHz CONVERTER MODULE

Double width module. One unit, Rack B, Bin A, Slots 1-2.

Note that the 10.7 GHz front-end and T107 module have been implemented on the Pie Town antenna only. The input bands from the front-end cover 10.2-11.2 GHz. LO frequencies of 9.6 and 9.9 GHz allow coverage of the bottom part of the band and 11.6 and 11.9 GHz allow coverage of the top part. These frequencies avoid placing the LO within the front-end passband. The amplified IF signals go to Rack C in the station building.

T108 14 GHz CONVERTER MODULE

Double width module. One unit, Rack B, Bin A, Slots 8-9.

As explained in section 2.3, the 14 GHz Converter contains four switchable filters for each of the two input signals to suppress image responses in converting directly from the front-end input frequency to the 0.5-1.0 GHz IF. The passbands of these filters are:

| | |
|---|---|
| 11.8-13.0 GHz | 13.8-15.0 GHz |
| 12.8-14.0 GHz | 14.8-15.6 GHz |

These bands are approximately 1 GHz wide. The band covered by the front-end is 12.0-15.4 GHz.

T110 43 GHz/ALT CONVERTER MODULE

Double width module. One unit, Rack B, Bin C, Slots 11-12.

The output of the 43 GHz front-end, which covers 41-45 GHz, is in the band 7.9-8.9 GHz to which it is converted by a mixer in the front-end. In the T109 module, the signal is converted to a second IF of 0.5-1.0 GHz. The two inputs can also be switched to two auxiliary terminals which were added to handle a future front-end, possibly for 86 GHz. As in other converter modules, the IF signals are amplified and go the selector switches for connection to the cables to Rack B in the station building.

T121 IF DISTRIBUTOR

Double width module. Two units, Rack D, Bin D, Slots 1-2, and 3-4.

The inputs to an IF Distributor are two IF signals in the frequency range 0.5-1.0 GHz that come from Rack B via Rack C. The IF Distributor provides level adjustment by computer-controlled attenuators, gain, and a level monitoring detector. The outputs of the two IF signals go to eight-way power splitters at the rear of Rack D from which they feed the inputs of the Baseband Converters. Two IF Distributors are required to accommodate the four IF bands that come from the antenna.

T122 BASEBAND CONVERTER

Double width module. Eight units; Rack D; Bin D, Slots 5-6, 7-8, 9-10, and 11-12; Bin E, Slots 5-6, 7-8, 9-10, and 11-12.

The Baseband Converter selects two contiguous bands from an IF signal and converts them to baseband for sampling. The module receives inputs from all four IF channels and can select any one by means of a four-way switch. The IF signal then goes to a sideband separating mixer and is converted to baseband by an LO that tunes across the 0.5-1.0 band in 10 kHz steps. The two mixer outputs corresponding to the upper and lower sidebands go to separate baseband amplifiers which have lowpass responses, the bandwidths of which can be varied in factors of two from 62.5 kHz to 16 MHz. The output levels are controlled by ALC loops. The detected signal levels are also synchronously detected at 80 Hz to extract the component from the modulated noise source at the front-end. The two baseband outputs go to inputs of the Sampler Module. The Baseband Converter contains a microprocessor which has a number of functions including M/C interfacing and synchronous detection.

## 5 Local Oscillator Frequencies

The frequency settings of the three 2-16 GHz Synthesizer Modules (L104) in the vertex room must be chosen to convert the desired range of observing frequencies to the 500-1000 MHz IF band. For the 330 MHz and 1.5, 2.3, 4.8, 8.4, 10.7, and 14 GHz bands, there is one frequency conversion in the vertex room, *i.e.*, before signals reach the Baseband Converter Modules, and for the 23 and 43 GHz bands, there are two such frequency conversions.

For the 330 and 610 MHz bands, the LO frequencies are fixed. For the 330 MHz band, the intermediate frequencies are equal to the observing frequencies plus 500 MHz. For the 610 MHz band, the intermediate frequencies are equal to the observing frequencies.

For the 1.5, 2.3, 4.8, 8.4, 10.7, and 14 GHz bands, the possible LO settings and the corresponding observing frequency bands are given in Table 4.1. As a result of the discrete tunability of the 2-16 GHz Synthesizer Modules which generate the LO's, the observing frequency bands listed cannot generally be chosen to fit exactly within the nominal frequency bands of the front-ends shown in Table 2.3. Thus, to cover the front-end bands completely, it is necessary in most cases to use some LO settings for which only a part of the IF band is used. For front-end bands at 4.8 GHz and above, there are two possible LO settings, one above the observing frequency and one below it. When the higher setting is chosen, the spectrum of the IF band is reversed relative to the observing band, *i.e.*, the high end of the observing band is converted to the low end of the IF band, and vice versa. In choosing between possible LO settings, it is a good precaution to avoid, when possible, cases in which LO frequencies or their harmonics fall within the chosen observing bands. The likelihood of this occurring is increased when simultaneous observations are made in two frequency bands. If such frequencies do fall within observing bands, harmful interference will not necessarily result, but should be checked for. For the 14 GHz band, the filters at the input of the converter module must be appropriately selected.

For the 23 and 43 GHz bands, there are two LO settings, and possible values for these are given in Table 4.2. There is generally more than one combination of the settings for the two LO's for any given observing band. However, the choice is narrowed by the limits on the first IF bands imposed by filters in the front-ends. These limits are 9.3-10.2 GHz for the 23 GHz band and 7.7-9.1 GHz for the 43 GHz band. For the first LO of the 43 GHz band, the output frequency of the 2-16 GHz Synthesizer Module is tripled in the mixer assembly. Again, it is a good precaution to choose LO frequencies so that neither fundamentals nor harmonics fall within observing bands, although this is not always possible.

The final step is to choose LO frequencies and bandwidths in the Baseband Converter Modules so that the desired parts of the IF bands fall within the baseband responses.

TABLE 4.1. Local Oscillator Frequencies for Observing Bands 1.5-14 GHz.

| OBSERVING FREQ. BAND | FIRST LO FREQUENCY | |
|---|---|---|
| | Low Side | High Side[1] |
| 1.1-1.6 GHz | | 2.1 GHz |
| 1.4-1.9 GHz | | 2.4 GHz |
| | | |
| 2.1-2.6 GHz | | 3.1 GHz |
| | | |
| 4.6-5.1 GHz | 4.1 GHz | 5.6 GHz |
| | | |
| 7.9-8.4 GHz | 7.4 GHz | 8.9 GHz |
| 8.4-8.9 GHz | 7.9 GHz | 9.4 GHz |
| | | |
| 10.1-10.6 GHz | 9.6 GHz | 11.1 GHz |
| 10.4-10.9 GHz | 9.9 GHz | 11.4 GHz |
| 10.6-11.1 GHz | 10.1 GHz | 11.6 GHz |
| 10.9-11.4 GHz | 10.4 GHz | 11.9 GHz |
| | | |
| 11.9-12.4 GHz | 11.4 GHz | 12.9 GHz |
| 12.1-12.6 GHz | 11.6 GHz | 13.1 GHz |
| 12.4-12.9 GHz | 11.9 GHz | 13.4 GHz |
| 12.6-13.1 GHz | 12.1 GHz | 13.6 GHz |
| 12.9-13.4 GHz | 12.4 GHz | 13.9 GHz |
| 13.1-13.6 GHz | 12.6 GHz | 14.1 GHz |
| 13.4-13.9 GHz | 12.9 GHz | 14.4 GHz |
| 13.6-14.1 GHz | 13.1 GHz | 14.6 GHz |
| 13.9-14.4 GHz | 13.4 GHz | 14.9 GHz |
| 14.1-14.6 GHz | 13.6 GHz | 15.1 GHz |
| 14.4-14.9 GHz | 13.9 GHz | 15.4 GHz |
| 14.6-15.1 GHz | 14.1 GHz | 15.6 GHz |
| 14.9-15.4 GHz | 14.4 GHz | 15.9 GHz |

[1]For LO settings on the high-frequency side of the observing band, the high end of the observing band appears at the low end of the IF band and vice versa.

TABLE 4.2. Local Oscillator Frequencies for Observing Bands 23 and 43 GHz.

| OBSERVING FREQ. BAND | FIRST LO FREQ. | FIRST IF BAND | SECOND LO FREQUENCY | |
|---|---|---|---|---|
| | | | Low Side | High Side |
| 21.5-22.0 GHz | 12.1 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| 21.8-22.3 GHz | 12.4 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| 22.0-22.5 GHz | 12.6 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| 22.3-22.8 GHz | 12.9 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| 22.5-23.0 GHz | 13.1 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| 22.8-23.3 GHz | 13.4 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| 23.0-23.5 GHz | 13.6 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| 23.3-23.8 GHz | 13.9 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| 23.5-24.0 GHz | 14.1 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| 23.8-24.3 GHz | 14.4 GHz | 9.4-9.9 GHz | 8.9 GHz | 10.4 GHz |
| | | | | |
| 40.6-41.1 GHz | 32.7 (10.9 x 3) GHz | 7.9-8.4 GHz | 7.4 GHz | 8.9 GHz |
| 41.1-41.6 GHz | 32.7 GHz | 8.4-8.9 GHz | 7.9 GHz | 9.4 GHz |
| 41.2-41.7 GHz | 33.3 (11.1 x 3) GHz | 7.9-8.4 GHz | 7.4 GHz | 8.9 GHz |
| 41.7-42.2 GHz | 33.3 GHz | 8.4-8.9 GHz | 7.9 GHz | 9.4 GHz |
| 42.1-42.6 GHz | 34.2 (11.4 x 3) GHz | 7.9-8.4 GHz | 7.4 GHz | 8.9 GHz |
| 42.6-43.1 GHz | 34.2 GHz | 8.4-8.9 GHz | 7.9 GHz | 9.4 GHz |
| 42.7-43.2 GHz | 34.8 (11.6 x 3) GHz | 7.9-8.4 GHz | 7.4 GHz | 8.9 GHz |
| 43.2-43.7 GHz | 34.8 GHz | 8.4-8.9 GHz | 7.9 GHz | 9.4 GHz |
| 43.6-44.1 GHz | 35.7 (11.9 x 3) GHz | 7.9-8.4 GHz | 7.4 GHz | 8.9 GHz |
| 44.1-44.6 GHz | 35.7 GHz | 8.4-8.9 GHz | 7.9 GHz | 9.4 GHz |
| 44.2-44.7 GHz | 36.3 (12.1 x 3) GHz | 7.9-8.4 GHz | 7.4[1] GHz | 8.9[1] GHz |
| 44.7-45.2 GHz | 36.3 GHz | 8.4-8.9 GHz | 7.9 GHz | 9.4 GHz |

[1]Harmonics of both 7.4 and 8.9 GHz fall within the band 44.2-44.7 GHz.

APPENDIX 1. VLBA Sites

| CODE | LOCATION | N LATITUDE (°, ′, ″) | W LONGITUDE (°, ′, ″) | ELEVATION (m) |
|---|---|---|---|---|
| PT | Pie Town, NM | 34 18 03.61 | 108 07 07.24 | 2371 |
| KP | Kitt Peak, AZ | 31 57 22.39 | 111 36 42.26 | 1916 |
| LA | Los Alamos, NM | 35 46 30.33 | 106 14 42.01 | 1967 |
| FD | Fort Davis, TX | 30 38 05.63 | 103 56 39.13 | 1615 |
| NL | N. Liberty, IA | 41 46 17.03 | 91 34 26.35 | 241 |
| OV | Owens Valley, CA | 37 13 54.19 | 118 16 33.98 | 1207 |
| BR | Brewster, WA | 48 07 52.80 | 119 40 55.34 | 255 |
| HN | Hancock, NH | 42 56 00.96 | 71 59 11.69 | 309 |
| SC | St. Croix, VI | 17 45 30.57 | 64 35 02.61 | 16 |
| MK | Mauna Kea, HI | 19 48 15.85 | 155 27 28.95 | 3720 |

VLBA Electronics Memo No. 78

(860822)

Electronics Packaging
A. R. Thompson
August 22, 1986

Most of the electronics of the VLBA is packaged in one of three forms: (1) metal modules that plug into rack-mounted bins, (2) circuit cards that plug into rack-mounted cages or bins, and (3) special-purpose units. The modules comprise the most general-purpose form of packaging, and are used for a large part of the analog and smaller digital subsystems. Cage-mounted cards, which may be of the wirewrap or multi-layer printed type, are used mostly in digital subsystems such as the formatter and correlator. These subsystems are large enough that the size and type of the card and their connectors should be chosen for most efficient construction of the particular electronic design. Special purpose units are typified by the front ends, in which all of the components that must be mounted in the vicinity of the feed are designed into a highly compact package. For the cards and special-purpose units, arbitrary specification of styles and dimensions is not likely to be helpful, and this memorandum is therefore concerned mostly with recommendations for modules and connectors. Some of these considerations have already been discussed in VLBA Electronics Memoranda Nos. 47, 51, 52, 53, 66, 67a, and 69. Cables are discussed in VLBA Electronics Memo No. 64. The main purpose of such recommendations is to minimize, as far as possible, the number of different types of metal parts, connectors, etc. for efficiency in procurement and maintenance. With a few exceptions, which are noted below, the VLBA packaging recommendations are based on those used for the VLA which are described in VLA Technical Report No. 31.

## Modules and Bins

The modules and bins follow the design developed for the VLA in 1974. The front panel dimensions of the modules are the same as those of the commercially-available NIM (Nuclear Instrumentation Module) series, but the modules are longer and more ruggedly constructed. Dimensions of the VLA bins and modules are given in VLA Specification A13050N2, Rev. A, which is reproduced in VLA Technical Report No. 31, pp. 9-8 to 9-9. VLBA bins and modules differ mainly in the use of the OSP type coaxial connectors rather that the OMQ type of the VLA modules. Both OSP and OMQ are blind mating connectors manufactured by Omni-Spectra. The OMQ type is no longer available, and is replaced by the OSP type which is a superior design. The back panels of the modules and bins that carry these coaxial connectors have been redesigned for the VLBA. A list of drawing numbers for the VLBA bins and modules is given in Appendix A. These drawings refer to blank modules, i.e. they do not include holes or other details specific to a particular electronic design. Omni-Spectra part numbers for the OSP connectors are as follows:

4503-7941-00 Bulkhead plug for .141 SR coax (module)
4503-7985-00 Bulkhead plug for .085 SR coax (module)
4533-7388-02 Bulkhead plug for flexible coax (module)
4506-7941-02 Flange mount jack, floating, for .141 SR (bin)
4506-7985-02 Flange mount jack, floating, for .085 SR (bin)

The OSP connectors should be used for high frequency signals (up to 18 GHz), and any signals for which the phase stability is particularly critical. For other signals, including power and the monitor and control (M/C) bus, one of the Amp connectors listed in Table 1 should be used. Of these, the 42-pin mixed connector is the preferred one for general use. It contains 36 holes for signal pins, of which both crimp and wire-wrap types are available. The same holes will accommodate coaxial connectors of the AMP Subminiature Coaxicon series: from experience at the VLA these are not recommended. The mixed 42-pin connector also contains six larger holes which accommodate high current pins (used in VLBA power-supply modules) and coaxial connectors of the AMP Miniature Coaxicon series. The latter can be used for signals up to about 1 GHz for which the less precise electrical length of the mated connectors (as compared with that of the OSP connectors) is acceptable. The pin and socket designation for Miniature Coaxicon connectors is shown in Fig. 1. In cases where a large number of signal pins are required (e.g. for the output lines of the Switch Driver Module) the AMP 50-pin connector can be used, either in addition to, or instead of, the mixed 42-pin connector. If more power pins or miniature coaxicons are required the 20-large-pin connector can be used. These three connector blocks (the 42-mixed-pin, 50-small-pin and 20-large-pin types) are of the same overall dimensions and all require the same sized mounting holes in the bin and module panels. Usage of these three types alone would therefore be a simplification and they should cover all VLBA requirements. The 34-pin and 14-pin connectors listed in Table 1 have been used in modules in the VLA, mainly in cases when it was necessary to get a particular number of connections in the small back panel of a single-width module. They can be used on VLBA modules also, if this proves to be necessary.

A complication that has arisen in the use of the various types of AMP connectors described above involves the mating tolerances of the module- and bin-mounted parts. The pin lengths must be chosen to allow a sufficient range in the spacing of the two parts of the connector over which reliable contact is made. The signal pins are available in a number of lengths, as shown in Figure 2. In addition, for most of the connectors tested in Table 1, the module-mounted block that holds the pins is available in two different versions. These differ in the position of a shoulder that holds a spring clip which locks the pin into the block. Thus the pin length protruding from the front of the block is different in the two versions. To add to the potential for confusion, many of the AMP catalogs list only a subset of the available pins and blocks. The mechanical design- of the VLA modules was based on the use of the 42-pin mixed AMP connector (largely because this is the connector commonly used in the NIM series modules). The mechanical tolerances of the metal parts (as specified in the drawings listed in Appendix A) result in a gap of 0.05 ± 0.05 inches between the front surfaces of the module- and bin-mounted blocks (see also VLA drawing D1305P1). This gap is satisfactory when the long-type signal pins (see Fig. 2 and Table 1) are used with the 42-pin module-mounted block or the shallow-block design of the 14-, 34-, and 50-pin connectors in Table 1. The protrusion of the pin outside the front face of the block, in sample units that I have measured, is 0.31 inches for the 42 pin connector and 0.40 inches for the 50 pin connector. With the deep block design the measured pin protrusion on the 50 pin connector is only 0.24 inches. In the construction of the VLA, the deep block design was used for the 14-, 34-, and 50-pin connectors (perhaps because the shallow design was not available, or not in the catalog at hand, at that time). The long pins did not give reliable contacts when used with the deep blocks, and to overcome this the long-long pins (see Fig. 2 and Table 1) were substituted. The long-long pin was originally designed to be used as a special ground pin for situations in which it is required to connect the ground before the other pins. Consequently the range of available types of long-long pins is very limited. The long-long wire wrap pin in Table 1 was a special design made by AMP for NRAO. It consists of a 85931-3 wire-wrap post inserted and crimped in a 204219-1 long-long crimp pin. The pin protrusion with deep blocks and long-long pins is, as I measure it, the same as that with shallow blocks and long pins.*

In conclusion, it is recommended that for the 42 pin mixed connector, the one specified in Table 1 be used with the long-type pins. (Another 42-pin mixed block, AMP No. 202515-3, with pin protrusion similar to that of the 50-pin deep block, is listed in the catalogs. It should not be used for VLBA modules.) For the 14-, 34-, and 50-pin connectors the shallow block with the long pins is recommended. If the deep-block type is used, the long-long pins should be used with it.

In the 20-large-pin block the protrusion of the large pins and miniature coaxicons is the same as that in the 42-pin mixed block. The Mark III VLBI system also uses VLA-type modules and the 20-large-pin AMP blocks, and during development of this system by Alan Rogers and colleagues at Haystack, it was found advisable to reduce the size of the gap by 0.054 inches by milling out a corresponding depth of metal on the panel that supports the bin-mounted half of the connector. For the VLBA,

* The terms 'long' and 'long-long' follow the usage of the AMP literature (see Fig. 2). At NRAO we have commonly used the terms 'short' and 'long', respectively to describe the same pins.

this modification is being used on the parts of the system constructed at Haystack, and in addition the dimensions of the 20-pin blocks are being milled to closer tolerances, as described in VLBA Acquisition Memorandum No. 63. To assure correct mating of all of the types of connectors discussed above, a series of measuring jigs is being designed in Charlottesville to check the length of each bin-slot and module between the connector mating surface and the front panel contacting surface. Use of these jigs will be described in a later memorandum.

Departures from the recommendations made above concerning module connectors should be made only for significant engineering reasons. In such cases the engineer concerned must be responsible for assuring satisfactory reliability and performance. This assurance should include a study of module and connector tolerances, and design of adjustment jigs if necessary.

## Pin Assignments in AMP Connectors

Table 2 gives standard pin assignments for power and M/C bus connectors in the AMP connectors. The use of standard pins is intended to minimize the possibility of damage if a module is inserted into the wrong slot, and to simplify test and maintenance procedures. The power and M/C bus connection should normally be made through a connector in the lower right-hand corner of the module back panel (as viewed from the rear of the module) and the pin assignments in Table 2 apply only to the connector in this position. If only one connector is used it should be on this lower-right position, and if more than one connector is used and one of them is the mixed 42-pin type, the latter should be in the lower-right position.

For power supply modules, the 42 pin mixed connector and the large power-contact pins (0.094 inch diameter) that fit in the six large-sized holes of the 42-pin mixed connector should be used. The current rating of the large pins is 23 amps. Two such pins wired in parallel should be used for each terminal of the 5 volt supply, since the capacity of the 5 volt supply exceeds 23 amps. Pin numbers in the 42-pin mixed connector are as follows:

| | | |
|---|---|---|
| +5 V | pin nos. | 6 and 39 |
| +15 V | pin no. | 5 |
| +28 V or other voltage | pin no. | 38 |
| negative terminal | pin nos. | 40 and 7 |

The usage of a module to supply a positive or negative voltage is determined by grounding the appropriate terminal in the rack wiring. The use of different positions for the positive terminal will prevent damage if a power supply module of the wrong voltage type is plugged into a power-supply slot.

## Guide-Pin Keying of Module Connectors

As a further precaution against possible damage if a module is inserted into the wrong slot, the scheme shown in Figure 3 should be used for the keying of the guide pins and guide sockets at the corners of the connectors. The connector cannot be inserted if these guide screws at the corners of the two parts of the connector do not mate. The figure shows the module connector as seen looking towards the back of the module.

## Racks and Air Flow

The two racks in the vertex room of each VLBA antenna will be of NRAO design and constructed of welded aluminum. Except for some additional panel-mounting holes, they will be identical to the VLA type B racks. Racks in the station building, other than recorder and computer racks, will be Equipto Heavy Duty type, size 170-070-030, with modification according to NRAO drawing No. C13030M2-2, Rev. C. This rack can accommodate seven VLA-type bins.

Temperature controlled air will be blown upwards through each rack, so some space for air flow should be left between modules in the bins. Ducting or side panels will be installed to channel the air through the rack. Modules which produce the most heat, such as power supplies, should be mounted near the tops of racks to minimize the amount of heat transferred to other modules.

## RFI Shielding

The vertex room of the VLBA antenna is shielded as far as is practicable, but it must be assumed that interference generated within the vertex room can be picked up in the antenna feeds. Thus modules containing potentially interfering circuitry, i.e. circuitry that generates or transmits frequency components within the signal bands, should either be of the shielded type, or else all of the potentially-interfering circuitry should be in shielded boxes interconnected with coaxial cable, preferable of the .141 or .085 semi-rigid type. The monitor and control bus and interface card are examples of potentially-interfering circuitry.

The electronics room and observing room of the station building are sufficiently well shielded that unshielded modules can be used for digital circuitry.

## Monitor and Control Bus

The monitor-and-control bus requires two balanced pairs of connectors: one for command (transmit) signals from the computer to the interface units, and the other for monitor (receive) signals from the interface units to the computer. A cable containing two twisted pairs within a single outer shield will be installed in a daisy-chain arrangement from the computer to the units to be connected to the bus. The connectors for use with this cable are the 9-pin D-type with RFI shielded hoods. Since the cable contains signals going in both directions, there is no logical reason to assign a particular sex to any connector. For simplicity the following arbitrary choice has been made: connectors mounted on the cable will be plugs (male) and connectors mounted on the racks or other units will be sockets (female). There will be two sockets wired in parallel at each point where the bus connects with equipment, to allow the cable to be connected and then run on to the next piece of equipment in the chain. At the last unit the command lines of the bus will be terminated by a plug containing 100-ohm resistive loads.

Following are the recommended part numbers and the pin numbers to be used.

Cable: Belden 9842

| | | | |
|---|---|---|---|
| Pin Numbers: | command signals (+) | red | pin no. 1 |
| | command signals (-) | black | pin no. 2 |
| | monitor signals (+) | white | pin no. 8 |
| | monitor signals (-) | black | pin no. 9 |
| | drain wire | (ground) | pin no. 5 |

Shield for Cable-Mounting Connector: Amp 1-745129-7 (inner)
1-745130-0 (outer)

RFI Gasket for Panel Mounting Connector: Amp 747024-3

9-pin D Connector. For good grounding should have tin-plated steel shell and grounding indents on plug. Units of this type with solder-pot contacts are:

Amphenol 17-12090-00 (socket, female)
Amphenol 17-22090-00 (plug, male)

Similar connectors with different wire contacts (e.g. crimp pins) could be used if preferred.

Nomenclature

Each type of module or other unit of the electronics is given a descriptive name and type number. This scheme is described in VLBA Electronics Memorandum No. 66.

## Indicator Lights

Indicator lights should use the following color code.

1) Lights for which the on-condition indicates normal operation should be green.

2) Lights for which the on-condition indicates the system is not ready for operation or that a fault has occurred should be red.

3) Lights for which either the on- or off-condition may occur in normal operation should be yellow.

The above code should be used wherever possible, particularly for LED indicator lights. Fuse-holder lights on the power supply modules, which are amber to indicate a blown tube, are an exception.

## Acknowledgements

Much of the information on module tolerances and connector problems was gathered by Larry D'Addario. Harry Dill prepared the drawing list in Appendix A.

Table 1. AMP Connector Parts for VLA and VLBA Modules

| | Module Block | Module Hood | Bin Block | Bin Hood |
|---|---|---|---|---|
| 42-pin, mixed | 204186-5 | 202394-2 | 202516-3 | 202579-5 |
| 20-pin, large | 200458-1 | 202394-2 | 200459-1 | 202579-5 |
| 50-pin | 200276-4 (shallow) | 202394-2 | 200277-4 | 202579-5 |
| | 201358-3 (deep) | 202394-2 | | |
| 34-pin | 200837-3 (shallow) | 202434-4 | 200838-3 | 201350-2 |
| | 201357-3 (deep) | 202434-4 | | |
| 14-pin | 201297-3 (shallow) | 201347-4 | 201289-3 | 201363-4 |
| | 201355-3 (deep) | 201347-4 | | |
| Contacts; Long: | | | | |
| Crimp, #14 wire | 201570-1 | | 201568-1 | |
| Crimp, 2 #18 wires | 202725-1 | | 202726-1 | |
| Crimp, #24-20 wire | 201578-1 | | 201580-1 | |
| Crimp, #24-20 wire | 201330-1 | | 201328-1 | |
| Solder Tab | 202236-1 | | 202237-1 | |
| Wire Wrap (.025x.025) | 66460-6 | | 66461-6 | |
| Wire Wrap (.045x.045) | 66471-6 | | 66473-6 | |
| Min. Coaxicon: | | | | |
| RG 188 or twisted pair | 201143-5 | | 201144-5 | |
| High Current: | | | | |
| #14-12 wire | 202422-1 | | 202417-1 | |
| Long-Long Pin: | | | | |
| Crimp, #18-16 wire | 204219-1 | | | |
| Wire Wrap | 601488-5 | | | |
| Guide pin (corner) | 200833-4 | (zinc-plated brass) | | |
| Guide pin (corner) | 202514-1 | (gold plated for grounding) | | |
| Guide socket (corner) | 203964-2 | (zinc-plated brass) | | |
| Guide socket (corner) | 202512-1 | (gold plated for grounding) | | |

| | | | |
|---|---|---|---|
| <u>2 WIDE UNSHIELDED MODULE</u> | | | |
| PANEL, FRONT (2UA) | C53306M013-1 | 1 | B13050M19-1 |
| COVER, PERFORATED (2UA) | C53306M014-1 | 2 | B13050M22-1 |
| PANEL, REAR (2UA) | C53306M015-1 | 1 | B13050M24-1 |
| BAR SUPPORT | C53306M016 | 4 | B13050M23 |
| SIDE PLATE | C53306M017 | 2 | ~B13050M18 |
| GUIDE | B53306M018 | 4 | B13050M4 |
| SIDE PLATE OPTION (SOLID) | B53306M032-1 | 2* | |
| SIDE PLATE OPTION (PERF.) | B53306M032-2 | 2* | |
| PLATE MOUNT OPTION | B53306M033 | 12* | |
| <u>3 WIDE UNSHIELDED MODULE</u> | | | |
| PANEL, FRONT (3UA) | D53306M013-2 | 1 | B13050M19-2 |
| COVER, PERFORATED (3UA) | C53306M014-2 | 2 | B13050M22-2 |
| PANEL, REAR (3UA) | C53306M015-2 | 1 | B13050M24-2 |
| BAR SUPPORT | C53306M016 | 4 | B13050M23 |
| SIDE PLATE | C53306M017 | 2 | ~B13050M18 |
| GUIDE | B53306M018 | 4 | B13050M4 |
| SIDE PLATE OPTION (SOLID) | B53306M032-1 | 2* | |
| SIDE PLATE OPTION (PERF.) | B53306M032-2 | 2* | |
| PLATE MOUNT OPTION | B53306M033 | 12* | |
| <u>4 WIDE UNSHIELDED MODULE</u> | | | |
| PANEL, FRONT (4UA) | C53306M013-3 | 1 | B13050M19-3 |
| COVER, PERFORATED | C53306M014-3 | 2 | B13050M22-3 |
| PANEL, REAR (4UA) | C53306M015-3 | 1 | B13050M24-4 |
| BAR SUPPORT | C53306M016 | 4 | B13050M23 |
| SIDE PLATE | C53306M017 | 2 | ~B13050M18 |
| GUIDE | B53306M018 | 4 | B13050M4 |
| SIDE PLATE OPTION (SOLID) | B53306M032-1 | 2* | |
| SIDE PLATE OPTION (PERF.) | B53306M032-2 | 2* | |
| PLATE MOUNT OPTION | B53306M033 | 12* | |
| <u>6 WIDE UNSHIELDED MODULE</u> | | | |
| PANEL, FRONT (6UA) | C53306M013-4 | 1 | B13050M19-4 |
| COVER, PERFORATED (6UA) | C53306M014-4 | 2 | B13050M22-4 |
| PANEL, REAR (6UA) | C53306M015-4 | 1 | B13050M24-4 |
| BAR SUPPORT | C53306M016 | 4 | B13050M23 |
| SIDE PLATE | C53306M017 | 2 | ~B13050M18 |
| GUIDE | B53306M018 | 4 | B13050M4 |
| SIDE PLATE OPTION (SOLID) | B53306M032-1 | 2* | |
| SIDE PLATE OPTION (PERF.) | B53306M032-2 | 2* | |
| PLATE MOUNT OPTION | B53306M033 | 12* | |

* - Designates parts that are optional. Use of these may require standard parts additional to, or different from, those listed for the particular type of module.

~ - The VLBA parts are similar to the VLA parts, but are not exact replacements. See the drawings for details.

Table 2. AMP Connector Pin Assignments

| Signal | Connector 42* (Mixed) | 20 (Large) | 50 | 34 | 14 |
|---|---|---|---|---|---|
| +5 V power | 10 | 2** | C | C | C |
| +15 V power | 16 | 15** | A | A | B |
| -15 V power | 17 | 14** | E | E | E |
| +28 V power | 29 | | F | F | A |
| -28 V power | 28 | | J | J | P |
| -5.2 V power | 11 | 8** | H | H | R |
| Power ground | 34 | 1** | L, B | L, B | - |
| Signal ground | 42 | | HH | NN | D |
| 117 VAC hot | 33 | | - | - | - |
| 117 VAC common | 41 | | - | - | - |
| MC Bus CMD (+) Red | 8 | 13 | z | EE | N |
| MC Bus CMD (-) Black | 9 | 12 | DD | KK | K |
| MC Bus MON (+) White | 14 | 7 | BB | HH | J |
| MC Bus MON (-) Black | 15 | 6 | FF | MM | M |

* See text for usage of large pins in power supply modules.

** These positions use power pins and all others for this connector use miniature coaxicons. Deviations from this standard mix of the two connector types will result in the need for special extender modules or cables.

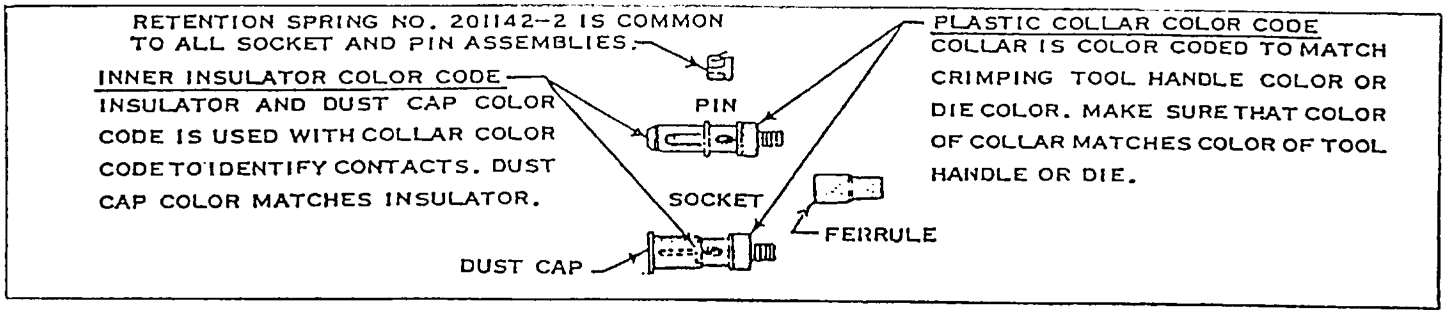


__Figure 1.__ Pin/socket designation for miniature coaxicon connectors. Pins are male with respect to the outer and female with respect to the inner, and they are used in the module-mounted blocks. From Amp Instruction Sheet No. IS 1770.

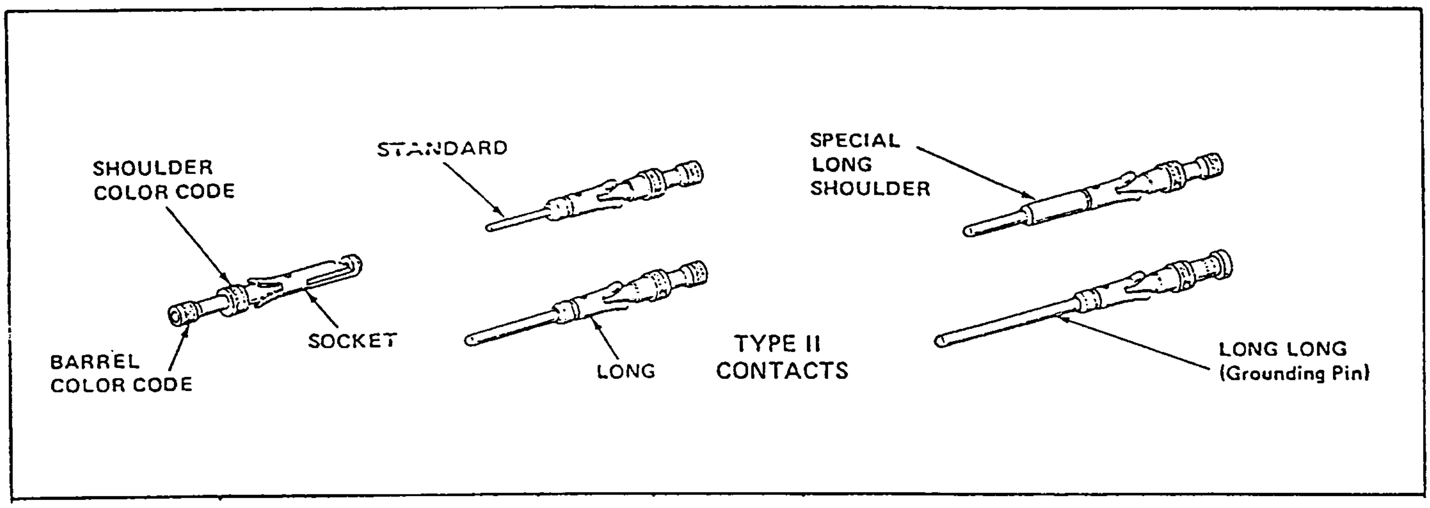


__Figure 2.__ Some pin lengths for AMP series M connectors. From AMP Instruction Sheet No. IS 1379.

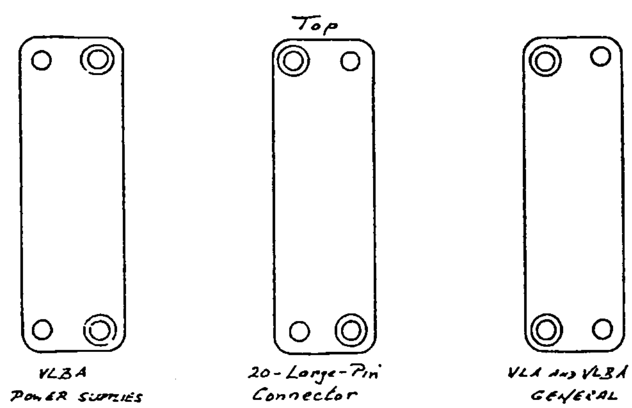


__Figure 3.__ Guide-pin keying scheme. The diagram shows the module connector as seen when viewing the module from the rear.

APPENDIX A, Drawing List for Module Parts

| PART | VLBA DWG # | # PER MODULE | VLA DWG # |
|---|---|---|---|
| 1 WIDE SHIELDED MODULE | | | |
| PANEL, FRONT (1SA) | C53306M021 | 1 | B13050M10 |
| PANEL, REAR (1SA) | C53306M022 | 1 | B13050M15 |
| BAR SUPPORT (BOTTOM) (1SA) | D53306M004-1 | 1 | ~B13050M9-1 |
| BAR SUPPORT (TOP) (1SA) | D53306M004-2 | 1 | ~B13050M9-1 |
| SHIELD (1SA) | B53306M027-1 | 2 | B13050M14-1 |
| SIDE PLATE | D53306M005 | 2 | ~C13050M12 &M13 |
| CONNECTOR SHIELD (1SA) | B53306M028 | 1* | ~B13050M11-1 |
| BAR SUPPORT, TOP (HALF SHIELD) | D53306M004-3 | 1* | ~B13050M9-5 |
| GUIDE | B53306M018 | 4 | B13050M4 |
| 2 WIDE SHIELDED MODULE | | | |
| PANEL, FRONT (2SA) | C53306M023-1 | 1 | |
| PANEL, REAR (2SA) | C53306M024-1 | 1 | |
| BAR SUPPORT, BOTTOM (2SA) | D53306M025-1 | 1 | ~B13050M9-2 |
| BAR SUPPORT, TOP (2SA) | D53306M026-1 | 1 | ~B13050M9-2 |
| SIDE PLATE | D53306M005 | 2 | ~C13050M12 &M13 |
| SHIELD (2SA) | B53306M027-2 | 2 | B13050M14-2 |
| REAR SIDE SHIELD | B53306M006 | 1* | |
| GUIDE | B53306M018 | 4 | B13050M4 |
| 3 WIDE SHIELDED MODULE | | | |
| PANEL, FRONT (3SA) | C53306M023-2 | 1 | |
| PANEL, REAR (3SA) | C53306M024-2 | 1 | |
| BAR SUPPORT, BOTTOM (3SA) | D53306MO25-2 | 1 | ~B13050M9-3 |
| BAR SUPPORT, TOP (3SA) | D53306M026-2 | 1 | ~B13050M9-3 |
| SHIELD (3SA) | D53306M027-3 | 2 | B13050M14-3 |
| SIDE PLATE | D53306M005 | 2 | ~C13050M12 &M13 |
| REAR SIDE SHIELD | B53306M006 | 1* | |
| GUIDE | B53306M018 | 4 | B13050M4 |
| 4 WIDE SHIELDED MODULE | | | |
| PANEL, FRONT (4SA) | C53306M023-3 | 1 | |
| PANEL, REAR (4SA) | C53306M024-3 | 1 | |
| BAR SUPPORT, BOTTOM (4SA) | D53306M025-3 | 1 | ~B13050M9-4 |
| BAR SUPPORT, TOP (4SA) | D53306M026-3 | 1 | ~B13050M9-4 |
| SHIELD (4SA) | D53306M027-4 | 2 | B13050M14-4 |
| SIDE PLATE | D53306M005 | 2 | ~C13050M12 &M13 |
| REAR SIDE SHIELD | B53306M006 | 1* | |
| GUIDE | B53306M018 | 4 | B13050M4 |
| 1 WIDE UNSHIELDED MODULE | | | |
| PANEL, FRONT | C53306M044 | 1 | B13050M1 |
| PERFORATED COVER | D53306M045 | 1 | C13050M7 |
| BAR SUPPORT (TOP AND BOTTOM) | C53306M046 | 2 | B13050M3 |
| PANEL, REAR | C53306M047 | 1 | B13050M2 |
| SIDE PLATE | C53306M048 | 1 | ~B13050M6 |
| FASTENER, PERFORATED COVER | B53306M049 | 2 | B13050M4 |
| GUIDE | B53306M018 | 2 | B13050M4 |

APPENDIX 3

# HYDROGEN MASERS FOR RADIO ASTRONOMY

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PREPRINT

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HYDROGEN MASERS FOR RADIO ASTRONOMY

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Summary

Ten atomic hydrogen masers are being provided by Sigma Tau Standards Corporation for the Very Large Baseline Array (VLBA), a system of ten radio telescopes under construction for deployment in locations stretching from Hawaii to the Virgin Islands. Radio astronomical observations using the method of Very Long Baseline Interferometery (VLBI) are among the most demanding applications of frequency standards, requiring the best stability and spectral purity of signals for the telescope local oscillators to maintain phase coherence at microwave frequencies over intercontinental distances.

Features which improve the stability, operating life, reliability and field utility of the masers include automatically tuned maser cavities using a technique which does not require a separate reference standard, remotely programable phase coherent receiver synthesizers giving fractional frequency resolution of 5 parts in 10 to the 17th, field replaceable vacuum pumps with extremely long life, 32 multiplexed channels of remotely addressable analog instrumental data and redundant AC and DC power supplies with battery back up. The maser is contained in one compact package measuring 46 cm (18 in) wide by 76 cm (30 in) deep by 107 cm (42 in) high, uses less than 75 watts of internal DC power and weighs 238 kg (525 lb), including batteries for 16 hours (max) of operation.

VLBA Requirements

Following is a brief summary of the specifications and performance goals which the VLBA masers must satisfy.

Frequency Stability. In radio interferometry the signals received from distant extraterrestrial sources at each remotely located antenna are heterodyned with individual stable local oscillators and the IF frequencies are recorded magnetically for later cross correlation by computer. The most important requirement for successful results is that the frequency standards driving the local oscillators contribute negligibly to the phase noise over the period of the observations. The wide band phase noise for the VLBA masers is specified to be less than .6 picoseconds rms for the maser 100 MHz outputs and the frequency stability goal is $7 \times 10^{-14}$ for one second measuring intervals, decreasing as the square root of time. For longer term measuring intervals of 1,000 to 10,000 seconds the stability goal is $2 \times 10^{-15}$.

Other Requirements. The VLBA masers are to be used at isolated installations with a minimum of operational attention; all normal operations shall be automatic or be controlled remotely through a Monitor and Control (M&C) interface system. The maser standards must have two 5 MHz outputs with 90 db isolation and two 100 MHz outputs with a minimum of 70 db isolation. The outputs must be controllable in frequency with a resolution of $1 \times 10^{-16}$.

The masers should operate within specification in the temperature range of 17°C to 27°C with a temperature coefficient of less than 3 parts in 10 to the 14th per °C. The sensitivity to ambient magnetic field variations must be less than 2 parts in 10 to the 13th for a change in field of ± 1 gauss. Other effects, such as atmospheric pressure changes, humidity, vibration or powerline variations should not affect maser performance more than 1 part in 10 to the 14th. In general, the masers are to operate in a normal laboratory environment but should be rugged enough and portable enough to withstand commercial shipment. The masers and maser sub-systems must be in one self contained package. The specified power supply is either 22 to 30 volts DC or 105 to 120 VAC with less than 500 watts input.

The VLBA-112 Hydrogen Masers

General Configuration. The Sigma Tau Standards Corporation VLBA-112 atomic hydrogen maser frequency standard is an active oscillator with a natural output frequency of 1,420,405,751.xxxx Hz which is derived from quantum transitions between two of the "hyperfine" levels of the ground electronic state of atomic hydrogen. This is the famous 21 cm line of atomic hydrogen.

The maser operation, in brief, is as follows: Molecular hydrogen is supplied from a small storage bottle and passes via an electronic pressure control servo to an RF source discharge bulb where the molecules are separated into atoms. Atoms emerge from the source through a small elongated hole, the source collimator, and then pass through a magnetic "state selector" which directs a beam of atoms in the correct quantum state to a teflon coated quartz storage bulb. The bulb is located within a microwave cavity which is resonant at the hydrogen transition frequency and CW emission from the atoms is produced by maser action. Power is coupled from the cavity by a small coupling loop and is transmitted to the receiver-synthesizer system through a coaxial cable.

A low noise heterodyne receiver system is used which contains a high resolution frequency synthesizer and a voltage controlled crystal oscillator. Subsequent integral multipliers, dividers and buffer amplifiers provide several well isolated outputs at standard frequencies. To provide the proper environment for maser action to occur and to minimize systematic perturbations of the maser output frequency, the maser is maintained under high vacuum by sputter-ion pumps, which also getter the hydrogen. The cavity is also surrounded by a set of magnetic shields and isolated by a multilevel thermal control system. An axial magnetic field coil provides for control of the internal magnetic field, and a single turn coil placed

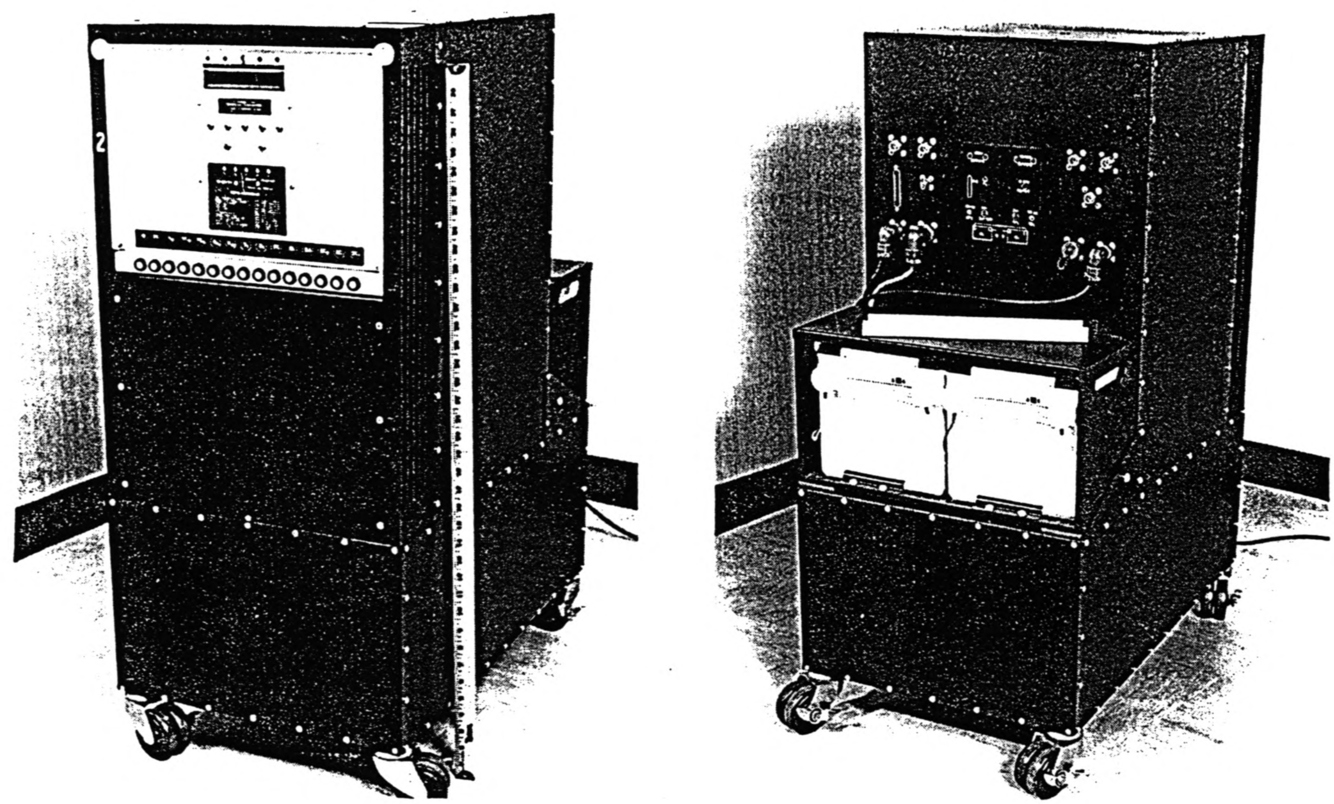

Figure 1. The VLBA-112 Hydrogen Maser.

transversley about the cavity provides a means of measurement of the field by the "Zeeman frequency" method.

One of the unique and important features of the VLBA masers is the incorporation of an automatic frequency control system to maintain the cavity at a constant frequency relative to the hydrogen emission line. This is a stand-alone system and does not require periodic source pressure changes or a separate frequency reference as used in the traditional spin-exchange method of cavity tuning. This system and many other features of the VLBA masers are discussed in more detail in References 2 and 3.

<u>Maser Design Description</u>. Figure 1 is a picture of the VLBA maser and Figures 2 and 3 are line drawings illustrating the arrangement of the parts and controls. These masers differ from previous developmental masers produced by Sigma Tau, described in References 2 and 3, in several ways although they are fundamentally similar. In the present design more attention has been given to electronic packaging, placement of sub-systems and controls in convenient, replaceable modules, more use of printed circuits, and other details to facilitate maintenance and repair. There are two hydrogen ion pumps, each with an estimated life of over 10 years, and a separate ion pump for regions surrounding the source and storage bulb which isolates the "inner" (hydrogen pump) system from vacuum background contaminants. Each pump may be easily changed in the field if need be.

The battery module in the present design is mounted on the maser. Two lead-acid "Maintenance Free" batteries provide up to 16 hours of operation with the masers fully operational. For partially

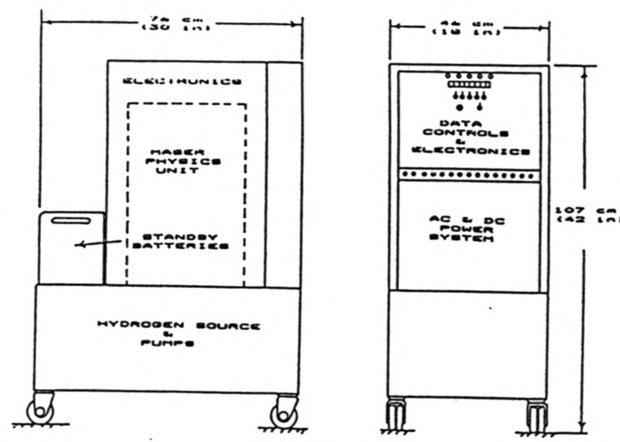


Figure 2

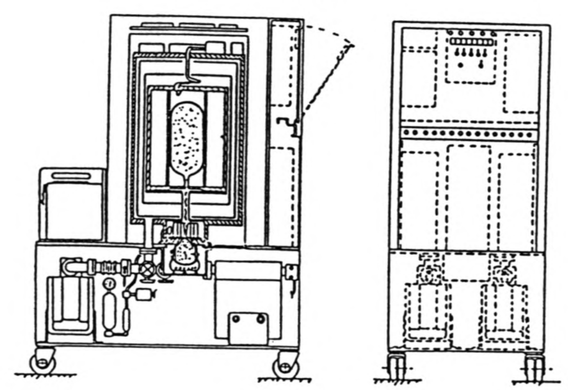

Figure 3

powered operation, such as may be used for long trips and installations, the maser will operate for periods up to a week on batteries with just the ion pumps and the cavity thermal control on; if only the ion pumps are active, about 5 watts of power is used, which will allow several weeks without AC power.

Other improvements incorporated into the VLBA masers include a very low noise receiver preamplifier having a noise figure under 1 db, a much heavier copper cavity providing better thermal homogeneity and larger thermal capacity to reduce susceptibility to ambient temperature variations. There are separate ion pump DC-DC converters for each of the three pumps. To insure phase stability, the multipliers and dividers for the 100 MHz and 5 MHz outputs are mounted on a temperature controlled plate with other potentially temperature sensitive components.

Detailed Specification. Following are the Sigma Tau Standards Corporation specifications for the VLBA Hydrogen Masers.

1. Stability, time domain: Figure 8 gives the specified frequency stability in the time domain and also the VLBA goal. The specification is a maximum which applies for realistic environmental conditions, in practice the nominal stability may be much better under ideal conditions.

2. Stability, frequency domain: The stability in the frequency domain, above the 10 Hz bandwidth of the VCO phase locked loop, is characterized by the stability of the crystal VCO. A high stability 10 MHz unit is used with phase noise specified as follows:

| Phase Noise | Offset |
|---|---|
| -120 db | 10 Hz |
| -140 db | 100 Hz |
| -157 db | 1 KHz |
| -160 db | 10 KHz |

3. Wide band phase noise: For purposes of radio astronomy, and several other applications, a useful specification is the wide band rms phase noise expressed in picoseconds such as may be observed at the output of a balanced mixer fed by signals in quadrature from two masers in a bandwidth from one Hz to up to a frequency just below the carriers. (A low pass filter which excludes the carriers must be used.) For the 100 MHz outputs, the specification is .6 ps rms and for the 5 MHz output the specification is 1.4 ps rms.

4. Drift: Included in the stability specification.

5. Settability: The output frequencies are adjustable without phase discontinuity using front panel switches or by external data system control with a resolution of $4.66 \times 10^{-17}$. The maximum continuous adjustment range is limited only by the loop hold-in range of the crystal VCO to over $\pm 5 \times 10^{-9}$. The VCO frequency coarse adjustment may also be used to obtain offsets as large as $\pm 1 \times 10^{-6}$.

6. Reproducibility: Included as the maximum range of stability and environmental specifications.

7. Magnetic field sensitivity: For a ± .5 gauss external field change, the maser frequency will change by less than $\pm 1 \times 10^{-14}$.

8. Temperature sensitivity: Less than $3 \times 10^{-14}$ per °C.

9. Barometic pressure sensitivity: Less than $1 \times 10^{-14}$ per inch of mercury.

10. Operating life and mean time between failure: The hydrogen supply is adequate for over 50 years of operation. The ion pumps have an expected life between changes of over 10 years, and may be easily changed on site. The main failure mode is likely to be due to the expected MTBF of the electronic components and systems, which should be quite reliable.

11. Power supply sensitivity: For nominal line voltage changes or switching to batteries, the frequency will change by no more than $\pm 1 \times 10^{-14}$.

12. Power supply requirements: AC power, 115V rms ± 10%, 60 Hz, 100 watts nominal, 150 watts maximum with automatic crossover to batteries. On batteries, the typical current drain at 24 volts is 2.5 A. If external DC power is used, the requirement is 24 to 28 volts, 2.5 amperes (typical).

13. Standby battery operation: A 40 A-H, 24 volt lead-acid, "maintenance free" battery module is mounted on the maser which when fully charged will last approximately 16 hours. The batteries may be removed from the maser and located remotely if desired. Automatic recharging occurs at about 2 amperes.

14. Instrumentation: Thirty-two channels of analog data are multiplexed and selectable internally or remotely by binary addresses. Up to eight status channels are simultaneously outputed when addressed. An on-board monitor and control interface board adapts to the VLBA M&C system. Minor modification will adapt this system to other communication formats.

15. Automatic cavity tuner: An automatic cavity tuner of the cavity frequency switching type described in References 2 and 3 is continuously in operation, and no operator control is needed. The cavity spin-exchange offset frequency is set after first operation at the factory, but if it is desirable to check and reset the spin-exchange adjustment, it may be done with a digitally set resolution of $1 \times 10^{-15}$ relative to the maser output frequency.

16. Size and weight: The maser is 46 cm (18 in) wide by 76 cm (30 in) deep by 107 cm (42 in) high, including casters. The overall weight is 238 kg (525 lb) including the battery module. The removable battery module weighs 34 kg (72 lb).

17. Nominal maser parameters and calibration factors:

a. Cavity loaded Q: 36,000

b. Operating line Q: $1.8 \times 10^{9}$

c. Cavity/line frequency ratio: $2.0 \times 10^{-5}$

d. Approximate pressure shift ratio at initial pressure settings: 5/1

e. Synthesizer factor: $4.658 \times 10^{-17}$/bit

f. Initial MPG setting: (M = 52300 approximately)

g. Cavity thermal mass: 15,600 w-s/°C

h. Cavity temperature: 50 °C

i. Other oven temperatures: 49 °C

j. Nominal oscillation frequency: 1,420,405,751,775.28 Hz assuming a magnetic field of .7 mg

Sigma Tau Hydrogen Maser Development

There are several particular design developments incorporated in the VLBA hydrogen masers which provide the performance of a "full size" oscillating atomic hydrogen maser in a relatively compact package with operational features that adapt it well to the long lived stable operation required of continuously operating basic time and frequency standards. These include the automatic cavity tuning system, the compact cavity and bulb assembly, an efficient tapered pole state selector, a compact and efficient magnetic and thermal shield configuration, an accessible arrangement of field replaceable vacuum pumps, a compact low pressure hydrogen supply, efficient and compact modularized electronics and a wide range high resolution receiver synthesizer. The cavity configuration, state selector and auto tuner are most important and only these will be detailed more fully at this time.

Cavity and Bulb Configuration. The use of metal cavities with the associated advantages of high electrical and thermal conductivity, thermal homogeneity, mechanical rigidity and ease of fabrication, ease of tuning and mounting stably within the vacuum enclosure has been one well established approach to hydrogen maser design[4,5]. To partially overcome one of the disadvantages of the large size cavity required by the relatively low frequency of the hydrogen hyperfine quantum transition and to improve the stability further, Sigma Tau Standards Corporation has analyzed the effect on the maser oscillation parameters of loading the cavity with a quartz cylinder situated about the maser storage bulb and arrived at an improved cavity and bulb design configuration[3].

Figure 4 illustrates the design. The quartz maser storage bulb is supported within a quartz cylinder which is held between the cavity end plates by spring action of a metal ring situated at the top. The thickness of the bulb and cylinder walls is such that the resultant inside diameter of the cavity is approximately 21.5 cm (8.5 in), rather than the 27 cm (10.3 in) diameter typical of a cavity loaded only with a thin-walled bulb. Analysis of the product of cavity Q x "filling factor" as calculated in Reference 3, Figure 11, gives a value approximately 28,000, which is very good and makes a very efficient design which oscillates easily.

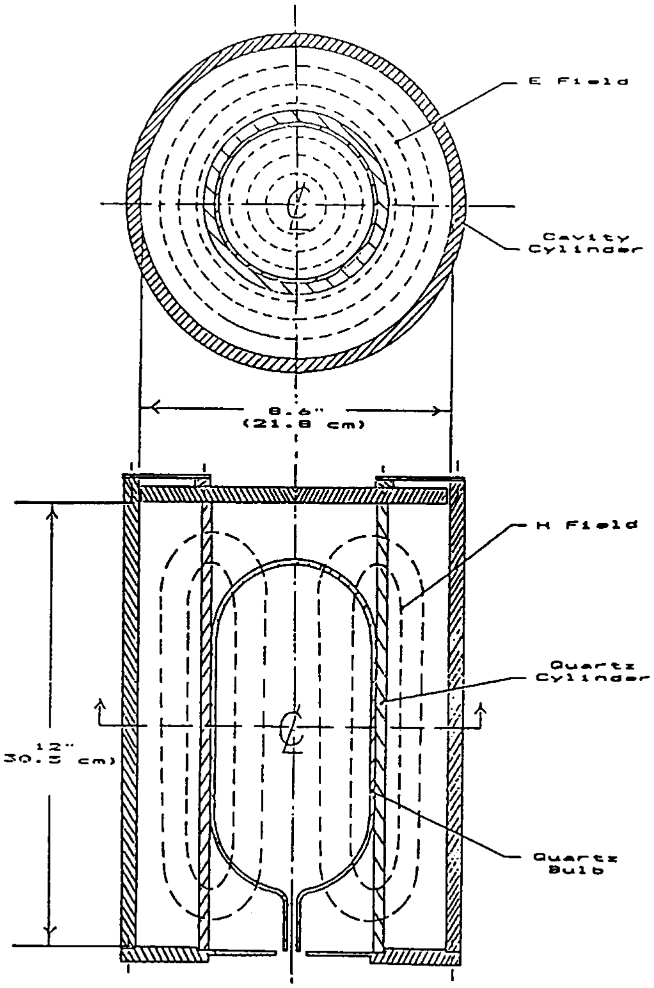


Figure 4. Cavity and Bulb Assembly

State Selector. The service life of pumping elements and the store of hydrogen required for a maser are directly dependent upon the efficiency of the magnetic state selector which selects atoms in the proper hyperfine quantum states and focusses them into the maser storage bulb. A new quadrupole state selector with tapered pole tips was developed at Sigma Tau Standards Corporation which is much more efficient than the straight bore hexapole or quadrupole focussers widely used.

Figure 5 illustrates the state selector design. The entrance aperture is only .5 mm (.02 in) and the magnetic field gradient is very intense, approximately $2 \times 10^5$ gauss/cm at the entrance. This produces a strong acceleration to the atoms and gives a large source "capture angle". A primary practical advantage of this particular design is that the structural segments are adjustable after the magnet is assembled to provide five degrees of freedom for aligning the individual pole tips after assembly; this obviates the necessity of extremely high machining tolerances, which would make the design otherwise impractical. The design of the state selector and the analysis of factors affecting the trajectory analysis of the atomic beam in hydrogen masers is given in Reference 6.

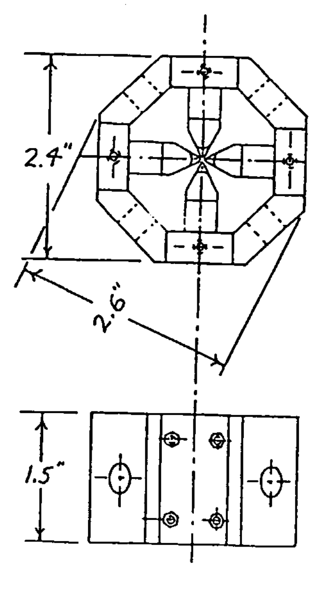


Figure 5. State Selector

Automatic Cavity Tuner. The automatic cavity tuner relates the cavity frequency to the hydrogen emission frequency through a servo system which does not require the transmission of external signals through the cavity or require a variation in beam intensity as used in spin-exchange tuning. A varactor is mounted within the cavity so that the cavity resonant frequency may be modulated electronically; as the cavity frequency changes, the coupling between the radiating atoms and the coupling loop changes, so that there is an amplitude modulation (as well as a phase modulation) of the maser output signal when the cavity average frequency differs from that of the maser signal.

In the cavity servo, a modulation period generator varies the cavity frequency periodically and a synchronous detector senses the amplitude and sign of the cavity offset and corrects the cavity average frequency. Figure 6 illustrates the amplitude variation which occurs when the cavity is detuned. Figure 7 is a block diagram showing the cavity servo system. While there is an undesirable phase variation occuring at the modulation frequency, it is cancelled out by a compensating phase shift inserted ahead of the crystal VCO so in practice the phase shift does not effect the standard output frequency. Reference 3 gives the details of the analysis of this type of cavity servo and also presents experimental result of its use in previous Sigma Tau Standards hydrogen masers.

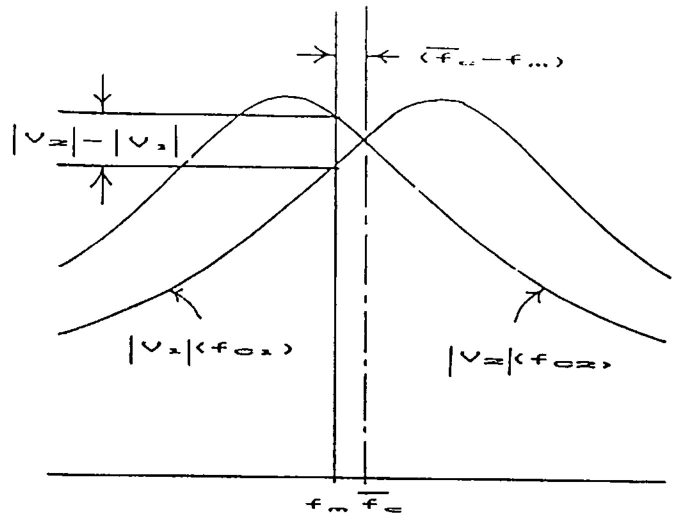

Figure 6. Cavity Frequency Modulation

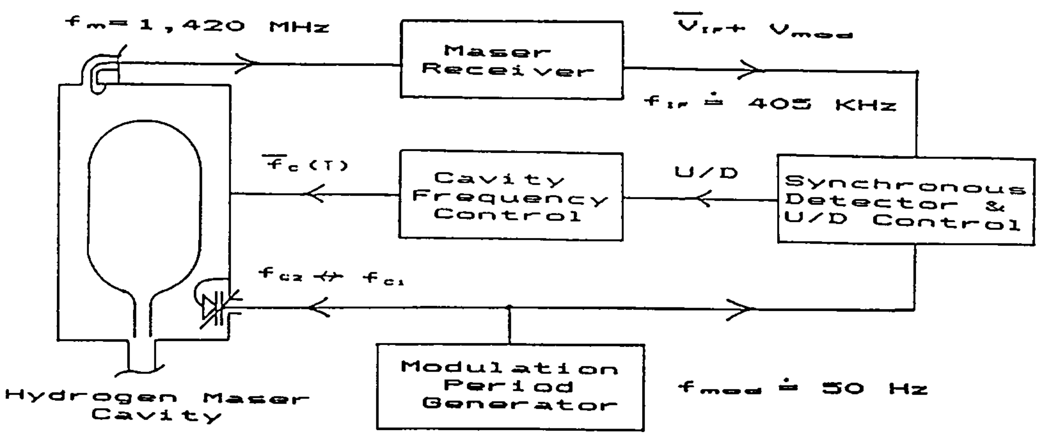


Figure 7. Cavity Frequency Servo

## Performance

The first three of the ten hydrogen masers being produced for the VLBA are scheduled for delivery in July 1987. Construction is nearly completed and preliminary tests of stability have begun.

Stability. The present tests have been made under normal working laboratory conditions in an area where the temperature is held to approximately ± 1 °C by the building air conditioner, with a cycle time of approximately 20 minutes. Figure 8 shows the measured stability for time intervals between one second and 10,000 seconds. The ordinate is the two sample Allan Variance with no dead time. Also shown are the Sigma Tau Standards Corporation stability specification and the VLBA contract goal. Both masers were operating at nominal (low) beam intensity with both cavity auto tuners on.

The data for Figure 8 was obtained by connecting the 100 MHz outputs of two of the masers to a balanced mixer with a one Hertz low pass filter on the output. For measuring times between one second and 100 seconds an offset difference frequency of one Hz was set by the maser synthesizers and a period counter was used to measure the frequency differences. For 1,000 to 10,000 seconds the synthesizers were set for a slow beat frequency and the periods were measured from a strip chart recording.

Figure 9 shows stability data which was obtained, under similar conditions, using equipment supplied by the National Radio Astronomy Observatory (NRAO). In this case the curves were plotted by computer using an NRAO program, with phase measurements derived

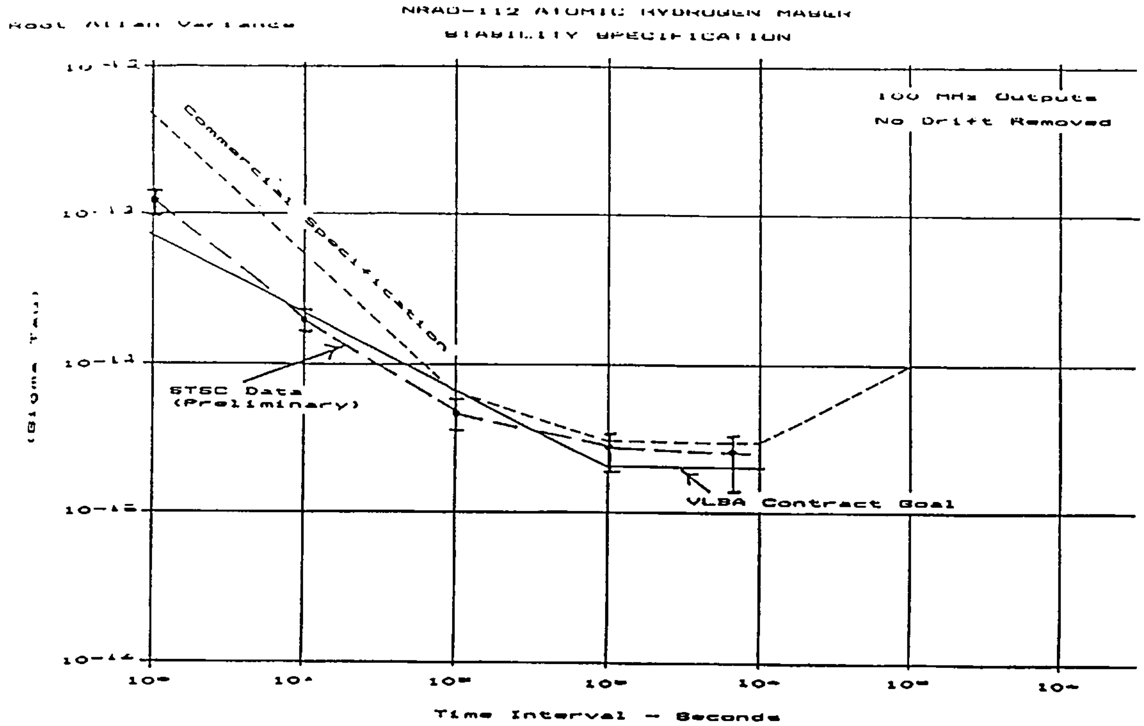


Figure 8.

```
FST PROGRAM OF 05/20/87          EQUAL REFERENCE ASSUMMED
BATCH START 17:57.5 05/24/87     TEMP=20.94C        PHASE=32.6PS
BATCH  END  20:44.3 05/24/87     TEMP=20.94C        PHASE=136.9PS
RUN   START 15:09.9 05/24/87     TLOW=20.48C, THIGH=21.73C
```

| TAU SEC | LAST BATCH SAMPLES | LAST BATCH SIGMA *EXP-15 | CUMULATIVE SAMPLES | CUMULATIVE SIGMA *EXP-15 | TIME ERROR PS |
|---|---|---|---|---|---|
| 1 | 10009 | 129.9 | 20018 | 130.5 | 0.1 |
| 2 | 5004 | 76.1 | 10008 | 76.4 | 0.2 |
| 5 | 2001 | 36.8 | 4002 | 37.1 | 0.2 |
| 10 | 999 | 17.4 | 1998 | 18.3 | 0.2 |
| 20 | 499 | 12.7 | 998 | 13.6 | 0.3 |
| 50 | 199 | 5.8 | 398 | 7.7 | 0.4 |
| 100 | 99 | 4.8 | 198 | 5.2 | 0.5 |
| 200 | 49 | 3.1 | 98 | 3.6 | 0.7 |
| 500 | 19 | 2.3 | 38 | 2.2 | 1.1 |
| 1000 | 9 | 1.5 | 18 | 1.6 | 1.6 |
| 2000 | 4 | 1.5 | 8 | 1.4 | 2.8 |
| 5000 | 1 | 0.7 | 2 | 0.8 | 3.8 |
| 10000 | 0 | 0.0 | 0 | 0.0 | 0.0 |

Figure 9(a). NRAO System Stability Data

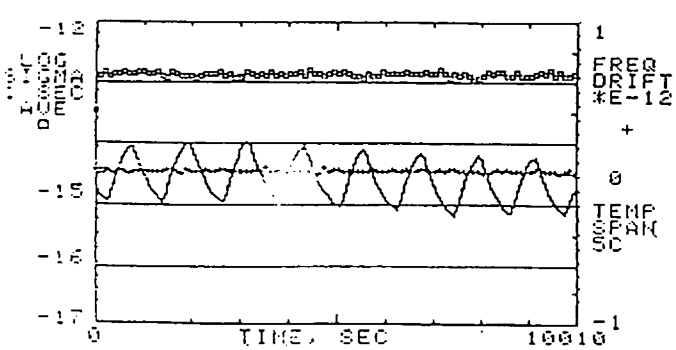


Figure 9(b). Frequency, Drift and Temperature Plot

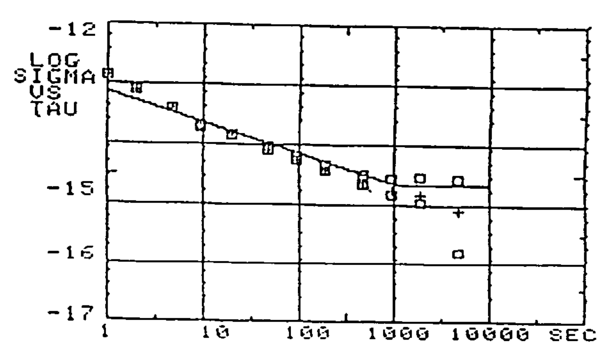


Figure 9(c). VLBA Maser Stability

from the two maser 100 MHz outputs connected to a highly stabilized balanced mixer and voltage amplifier. Figure 9(a) is a copy of the printer output of the data plotted in Figures 9(b) and 9(c). Figure 9(b), in the top trace, shows the one second stability averaged for 100 samples, the second trace gives the room temperature, which illustrates the 20 minute cycling of the temperature; the third trace, which starts at zero in the first batch, shows the relative variation of the two masers's frequencies since the measurement batch was started.

Figure 9(c) is a plot of the stability versus measuring interval in the familiar sigma tau format; also shown (the solid line) is the VLBA contract stability goal. It is noteworthy that the data taken with the NRAO computer equipment agrees very well with the stability plot obtained with counter and strip chart, shown in Figure 8.

In addition to stability in the time domain, the wide band phase noise at 100 MHz has been tested and the results are within the specifications of .6 ps rms.

Much more stability data will be taken under different conditions of operation and for longer times. The masers are still being tested and adjusted to optimize the maser temperature and cavity tuner servo gains and other parameters, however the present data is quite encouraging.

Other Performance Data. Due to the short time since the assembly of the first three masers was completed, other test data is not available at this time. There are several tests which remain to be done before delivery. These include long term stability, magnetic shielding and barometric pressure sensitivity. It is anticipated that the performance will be similar to that of the three earlier masers of similar design described in References 2 and 3, and these met or exceeded the VLBA environmental sensitivity requirements as given in the Sigma Tau Standards specifications given previously.

## Acknowledgements

The authors greatfully acknowledge the support of the National Radio Astronomy Observatory under Contract VLBA-112 as well as the Associated Universities, Inc., and the National Science Foundation.

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APPENDIX 4

# A High Data Rate Recorder for Astronomy

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J. C. Webber
W. T. Petrachenko
H. Allen

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# A High Data Rate Recorder for Astronomy

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*Abstract*—**A magnetic tape recorder has been developed for the special requirements of radio astronomy and geodesy. These requirements include a high data rate, a high bit packing density, and long record times. The current version of this longitudinal recorder used by the very long baseline array (VLBA) records 5.5 Terabits on a 14-in diameter reel of inch-wide tape. A maximum record rate of 256 Mb/s is achieved in the VLBA configuration with one recorder operating at 4 ms and utilizing 32 of the heads in a single stack. Laboratory tests have been made at 1024 Mb/s with 4 headstacks, and we expect to be able to use this configuration for 2048 Mb/s operation at 8 m/s.**

**A future version configured with the same number of new metal-in-gap (MIG) heads and metal evaporated (ME) tape should permit 4096 Mb/s at a doubled transition density of 4.5 fr/$\mu$m. Also, further reductions in trackwidth and tape thickness to less than 10 and 4 $\mu$m, respectively, are projected based on analysis of the tape path mechanics.**

## Introduction

VERY long baseline interferometry (VLBI) [1] is dependent on tape recorders to record signals at remote sites for later playback at a central processor. VLBI has been used to make astronomical images with an angular resolution of better than 100 micro-arc-seconds in the millimeter wavelength bands, a far higher resolution than can presently be achieved with ground-based optical astronomy. An equally important application of VLBI is in long distance geodesy. This is the result of the instrument's ability to measure group delay with subcentimeter precision. Geodetic VLBI has been used to provide direct measurements of tectonic plate motion [2], [3]. In both applications the signal-to-noise ratio is proportional to the square root of the number of bits processed, which gives rise to the requirement for high data rate recording. With high data rates (typically near 100 Mb/s at present) a high packing density is required for economy. The first version of the wideband VLBI recorder became operational in 1979 and is known as Mark III [4], [5]. This recorder is capable of a maximum rate of 224 Mb/s but requires large amounts of tape because it uses fixed heads to record twenty-eight 635-$\mu$m-wide tracks across inch-wide tape, each with a longitudinal density of 1.31 fr/μm or 33.3 kfrpi. *

A higher density version, called Mark IIIA, was developed to improve system performance and efficiency. It is implemented with "density upgrade" kits for the Mark III recorders. These kits were introduced in 1985. The area density of recording is increased by more than an order of magnitude by reducing track width from the original value of 635 to 38 $\mu$m. Modern video tape and narrow-track headstacks and headstack-positioning subsystems developed by Haystack Observatory are used. Mark IIIA machines record a total of 336 tracks, 28 at a time in 12 passes, each lasting 800 s. Thus, one 2750-m tape lasts 160 min when recording at 56-MHz bandwidth (112 Mb/s at one bit per sample), and holds about $10^{12}$ bits. There are presently over 30 Mark IIIA recorders worldwide used only for VLBI data acquisition and processing. Most of these have operated satisfactorily in the high density mode for several years. Processing recorders (playback drives) operate nearly continuously and support both narrow- and wide-track playback. Some of these drives have been in service for over ten years.

For the very long baseline array (VLBA), a new version of the recorder with the layout shown in Fig. 1 has been developed. The same headstacks and positioners are used but with new electronics and provision for the support of four 36-head stacks. The same headstacks are used for reading or writing, and the tape is bulk-erased between recordings. The VLBA recorders have been tested using a longitudinal density of 2.25 fr/$\mu$m (57.15 kfrpi). 448 "data" + 56 "system" tracks are recorded in 14 passes, each lasting 50 min, for a total record time (at 128 Mb/s) of 12 h on a 14-in diameter reel of inch-wide 13-$\mu$m-thick D1-equivalent tape.

## Longitudinal Tape Transport

The tape transport used for all versions of Mark III and VLBA is a Honeywell Model 96 longitudinal transport with vacuum buffers between servo-controlled reels and capstan drive, and with a tape path as shown in Fig. 2. This transport has the special property that the tape is guided by the rear (inside) edge, which is biased into the "precision plate" by the action of the vacuum. The walls of the vacuum columns are slightly tilted to provide this bias [6]. Fig. 3 shows the computed profiles of the tape in the vacuum buffers. The "front door" serves to seal

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* kilo flux-reversals per inch

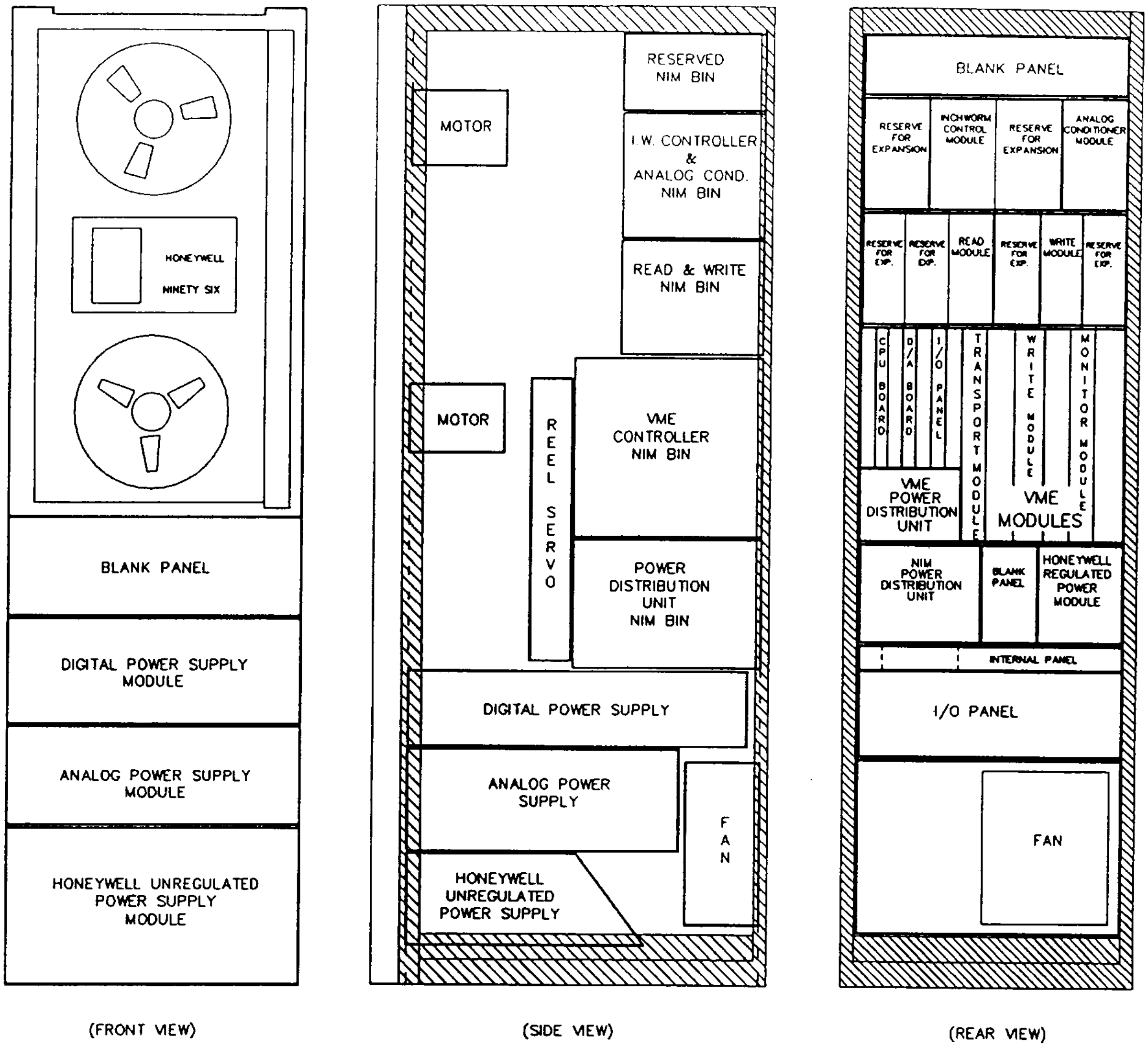


Fig. 1. Recorder rack layout. The overall dimensions are 22" × 29" × 77".

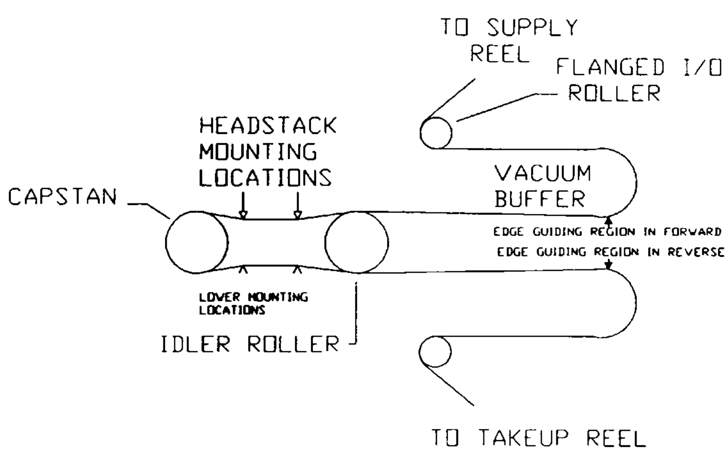


Fig. 2. Tape path in Honeywell Model 96 Transport.

the vacuum and touches the tape edge only in the middle of the turnaround loop. The vacuum buffers serve to isolate both tension and tracking noise from the heads. Although the edge guiding is displaced several inches from the heads (see Fig. 2 for the tape path geometry), the path followed by the tape as it passes over the heads in a given direction is repeatable at the micron level. The tape slitting signature or "edge" noise is low-pass-filtered by the

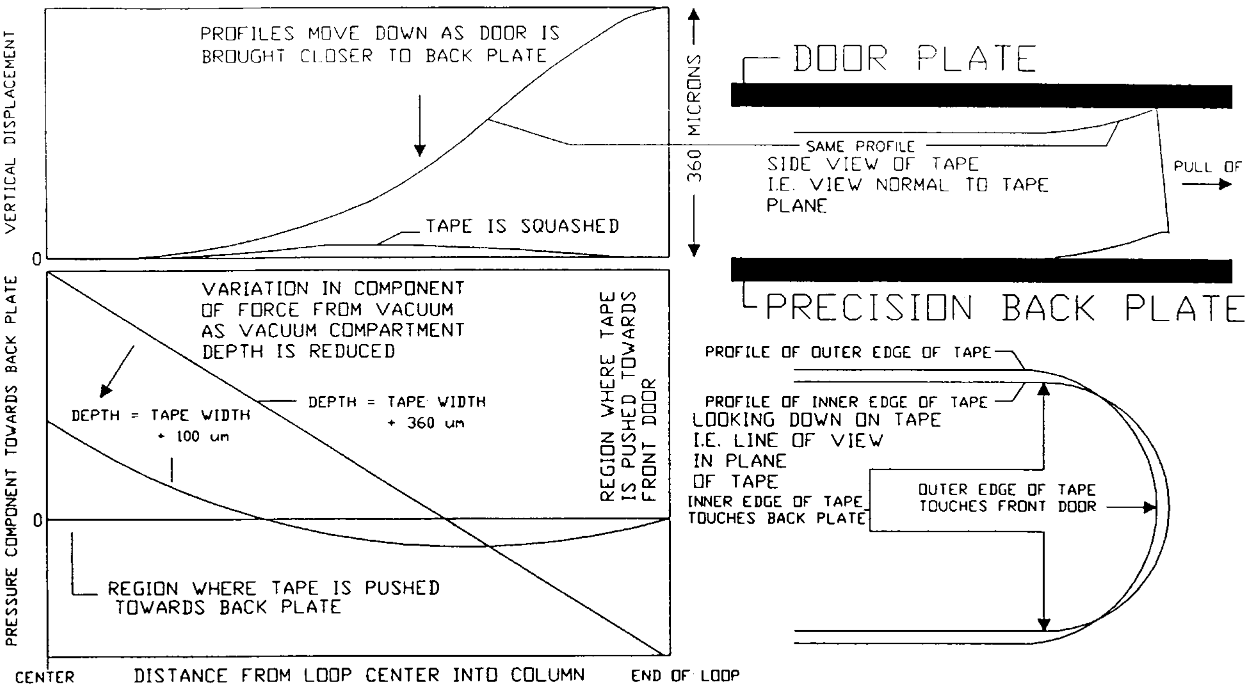


Fig. 3. Computed tape path and edge guiding forces in vacuum buffers show that the tape is pushed towards the precision back plate in the edge guiding region (indicated in Fig. 2) and towards the front door at the end of the turnaround loop. The depth of the vacuum column must be 50 $\mu$m greater than the tape width to avoid "squashing" the tape and less than 360 $\mu$m greater than the tape width to maintain contact with the front door.

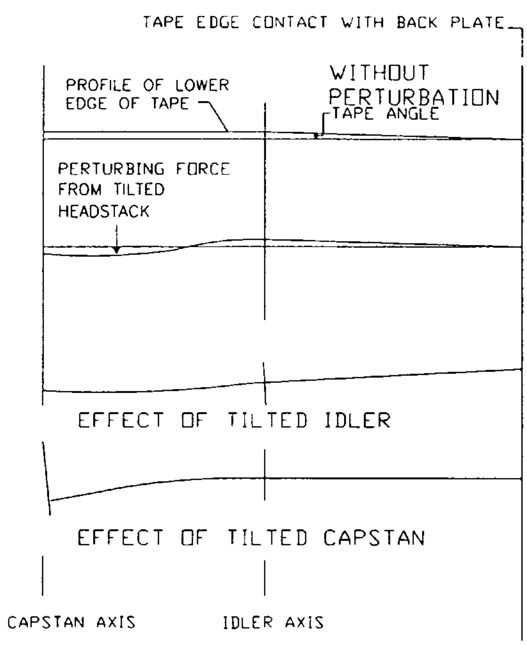


Fig. 4. Schematic illustration of tape path changes, as traced by the profile of the tape edge, in response to perturbations that result from headstack or axis tilts. The mechanical principles used in this illustration assume that the tape edge remains normal to the axis of a rotating tape bearing surface, the tape can pivot about the edge guiding point, forces are balanced by components of tape tension, and that the tape bends as a uniform beam in response to torques. The four cases shown are: unperturbed, a tilted headstack, tilted idler, and tilted capstan.

idler roller. The tilted walls of the column also bias the tape so that it makes a small angle (approximately 100 arcseconds) with the precision plate as illustrated in the top profile of Fig. 4. Small mechanical imperfections or misalignments due to manufacturing variations and wear change this "tape angle" and produce dc tracking differences between transports. These are, however, easily calibrated. The tape loop theory (plotted in Fig. 3) is based on harmonic series expansion of the deviation from a circular arc, which satisfies the following constraints.

1) The tape is bent only in the thickness (easy) direction.
2) The tape arc makes tangential contact with the door.
3) Local tensions are balanced by vacuum pressure.

At 10 in of water vacuum, the force with which the tape is pushed against the precision plate is approximately 0.04 N (0.01 lb) for the 3-degree slope of the vacuum column walls. The net torque due to the wall slope is approximately $4 \times 10^{-4}$ Nm. Detailed calculations for the tape path and other mechanical aspects of the recorder are given in the VLBA Project Memo Series [7]. Fig. 4 illustrates the effect of perturbing forces and axis tilts on the tape path. Table I gives some of the sensitivities to mechanical alignment. Other than a constant bias, tracking signatures between transports are small and are further discussed in the section on performance limits.

## Tape Wrap Angle and Head-to-Tape Contact Pressure

At the nominal operating vacuum of 10 in of water the tape tension is 2.2 N (0.5 lb). The contact arc length on the heads is limited by a step (see Fig. 8) to 300 $\mu$m [8].

TABLE I
DC TRACKING SHIFTS WHICH RESULT FROM TRANSPORT ALIGNMENT ERRORS

| Alignment | Direction | Shift in Forward | Shift in Reverse | Notes |
|---|---|---|---|---|
| Capstan tilt | left | 0.2 $\mu$m/arcsec | 0.2 $\mu$m/arcsec | 1 |
| Capstan tile | up | 0.03 $\mu$m/arcsec | −0.03 $\mu$m/arcsec | 1 |
| Idler tilt | left | 0.5 $\mu$m/arcsec | 0.5 $\mu$m/arcsec | 1 |
| Idler tilt | up | 0.03 $\mu$m/arcsec | −0.03 $\mu$m/arcsec | 1 |
| Capstan taper | | 0.5 $\mu$m/arcsec | 0.5 $\mu$m/arcsec | 1, 2 |
| Idler taper | | 0.3 $\mu$m/arcsec | 0.3 $\mu$m/arcsec | 1, 2 |
| Upper headstack tilt | up | −0.06 $\mu$m/arcsec | 0 | 1 |
| Lower headstack tilt | up | 0 | 0.06 $\mu$m/arcsec | 1 |
| Upper vacuum loop | out | −0.5 $\mu$m/mm | 0 | 2, 3 |
| Lower vacuum loop | out | 0 | −0.5 $\mu$m/mm | 2, 3 |
| I/O roller | | 0 | 0 | 4 |
| Reel table | | 0 | 0 | 4 |
| Front door | | 0 | 0 | 4 |

Notes: 1) A positive tape shift is defined as being away from operator towards precision back plate. 2) A larger diameter near the back plate produces a positive shift. 3) Assuming a tape angle produced by vacuum bias of 100 arcsec. 4) I/O roller, reel table, front door alignments have no effect on tracking.

This "stepped" head contour was introduced by us in 1980 as a high-speed performance maintenance modification to wide-track Mark III read/write headstacks and thereafter incorporated in headstack specifications. The average contact pressure is 48 KPa (7 lbf/in$^2$) for a 10-degree full wrap angle. This contact pressure is adequate to maintain head to tape contact without flying for speeds up to 8 m/s (320 ips). While no detailed analysis has been performed, it is thought that the headstep allows the trapped air to escape and prevent flying. The profile of the tape as it contacts the head can be calculated, ignoring dynamic effects, using the method described by Timoshenko [9] in his chapter on "Beams with combined axial and lateral loads." For 25-$\mu$m-thick polyester-based tape, the stable profile is an arc with radius of curvature of 4.7 mm. For 13-$\mu$m-thick tape, the stable profile has a radius of curvature of 2.8 mm. Fig. 5 shows the computed initial and stable contact profiles for various design parameters based on the solutions of the displacement $y$ for a positive distance $x$ away from the headstep

$$y = ae^{-x/p} \quad \text{when } x \geq 0$$

$$y = bx + cx^2 + de^{x/p} \quad \text{when } x < 0$$

where $a$, $b$, $c$, and $d$ are constants,

$p = \sqrt{(Yt^3W/(12\,T))}$ = "characteristic bending length"
$Y$ = Young's modulus
$t$ = tape thickness
$W$ = tape width
$T$ = tape tension,

which satisfy the boundary condition of continuity at $x = 0$ and half wrap angle equal to $\tan^{-1}(dy/dx)$ at $x = -L$ (where $L$ = headstep half width). Initial contact is assumed to occur only at the edges of the headstep. Stable contours for which $d = 0$ have equal pressure across the head. The following were assumed constant for the calculated profiles:

| | |
|---|---|
| Young's modulus | 4.8 GPa (7 × 10$^5$ lbf/in$^2$) |
| tape width | 1 in |
| tape wrap angle | 10 degrees (full angle) |

The tape tension, headstep width, and tape thickness were varied as indicated on the figure. Good correspondence is observed between the computed profiles of Fig. 5 and the profiles measured with a profilometer.

## HEADSTACK POSITIONER

High track densities are achieved by utilizing a stack of 36 heads separated with a pitch of 698.5 $\mu$m; each head has a trackwidth of 38 $\mu$m. The headstack is moved between recording passes by an amount sufficient to provide a small guardband from the adjacent pass in the same direction. A larger guardband is provided between passes in opposite directions to accommodate the foward–reverse tracking signature, which results mostly from a change in the edge guiding point from upper to lower vacuum buffers (see Fig. 2).

The headstack is moved by an Inchworm® motor (Burleigh 05083-3) and its position is measured using an LVDT (Schaevitz 050MHR). The mechanical principles of the "headblock" assembly are shown in Fig. 6. The term "headblock" is used for the positionable subassembly that includes headstack, the active (motor) portion of an Inchworm® actuator (a piezoelectric tube that looks like a sleeve bearing), the active (transformer) portion of an LVDT (also tube shaped), and the headblock housing, which serves to carry these traveling components. The Inchworm® shaft and LVDT core are fixed while the Inchworm® tube and LVDT transformer move with the headstack.

The mechanical zero of the LVDT is set with opposing screws that locate the LVDT core within the core retainer. The core retainer subassembly is itself retained by the block housing as shown in the partially disassembled view, but the core retainer is fastened to the dual block mount in a completed assembly.

The headblock positioner is designed for a range of ±1.65 mm (in excess of ±2 head pitches) and has measurement accuracy of about 1 $\mu$m.

The scale of the readout can be calibrated by moving the headstack by one head pitch as determined by reproducing a signal previously recorded by an adjacent head. The readout zero offset can be accurately established by recording a single track at a location nominally in the center of the tape and then reproducing this track with the tape flipped over end for end (by exchanging supply and take-up reels). With zero offset, this center track will appear at the same headstack position with the tape flipped.

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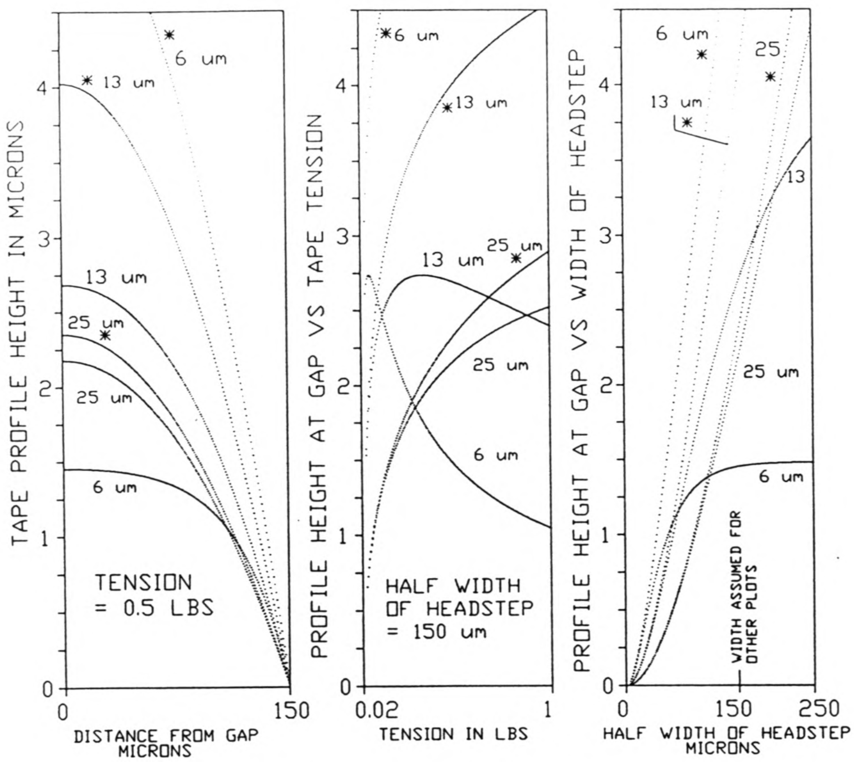


Fig. 5. Computed head profiles worn by the tape. Curves marked with an (*) are those of a stable profile worn after running for a long time with a tape of the thickness indicated. Other curves are those for which the tape initially contacts only the edges of the headstep.

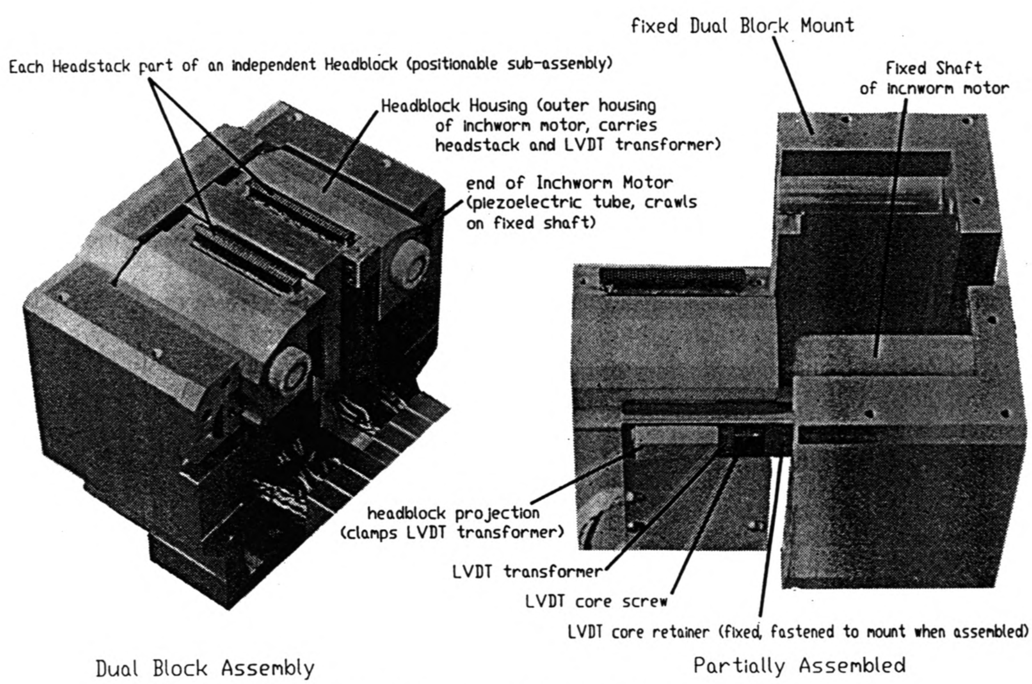


Fig. 6. Head assembly with positioning components.

## HEADSTACK

The headstack is fabricated from an unpatterned single crystal manganese zinc ferrite ''VHS-equivalent'' gapped bar (Hitachi) with 0.33-$\mu$m gap length in which the individual headtips are defined by slotting of the gapped bar with a ''super-precision'' dicing saw. The spaces between headtips are filled with the teeth of calcium titanate spacer combs. The magnetic circuits are completed by bonding a base with 48-turn ''fluxors'' to the ''tip-plate'' formed from the gapped bar. Headstack fabrication is illustrated in Fig. 7. A cross section through one head is shown in Fig. 8:

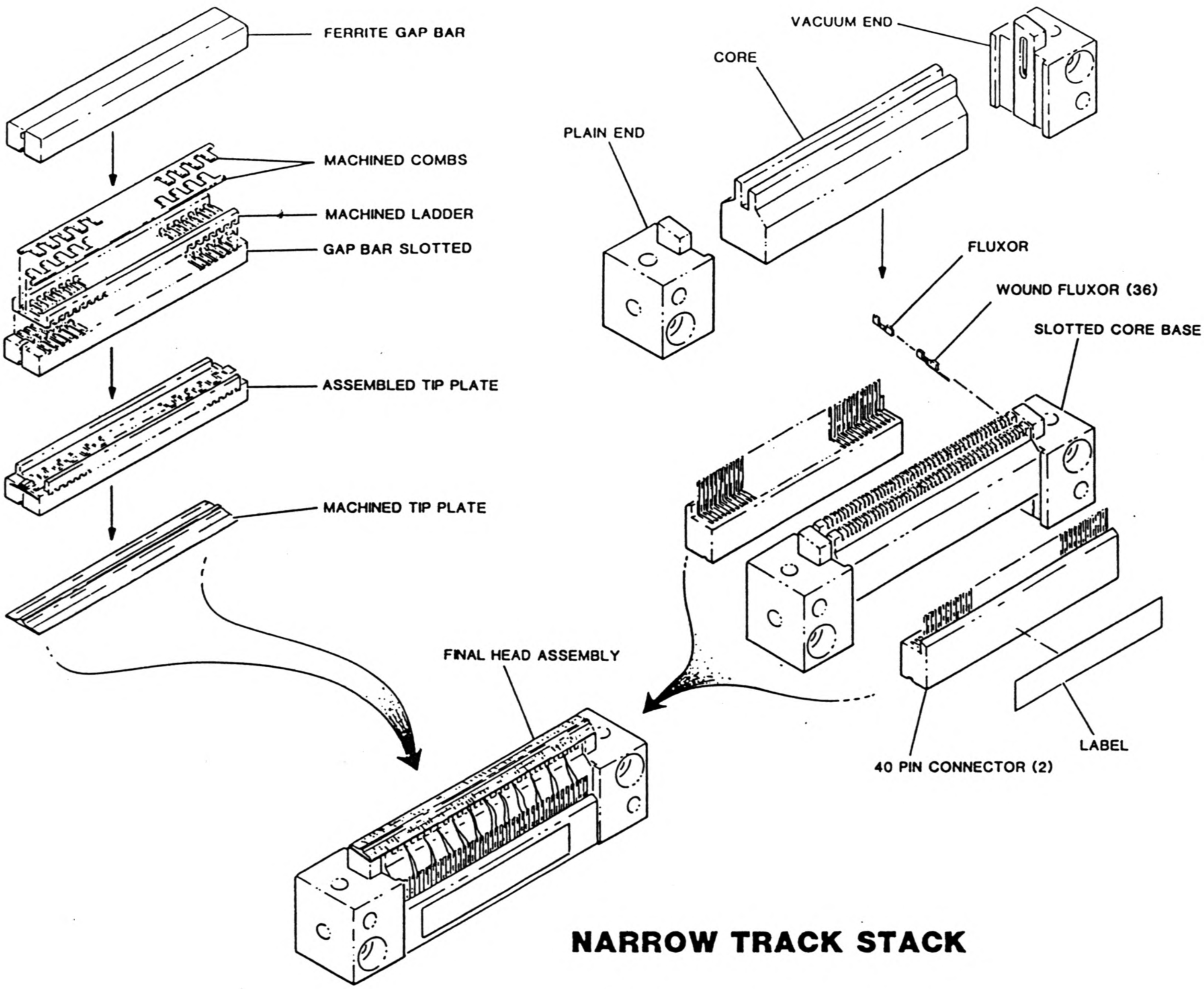


Fig. 7. Headstack assembly. In the final assembly, the "tip" plate and base are bonded to complete the magnetic circuit for each head.

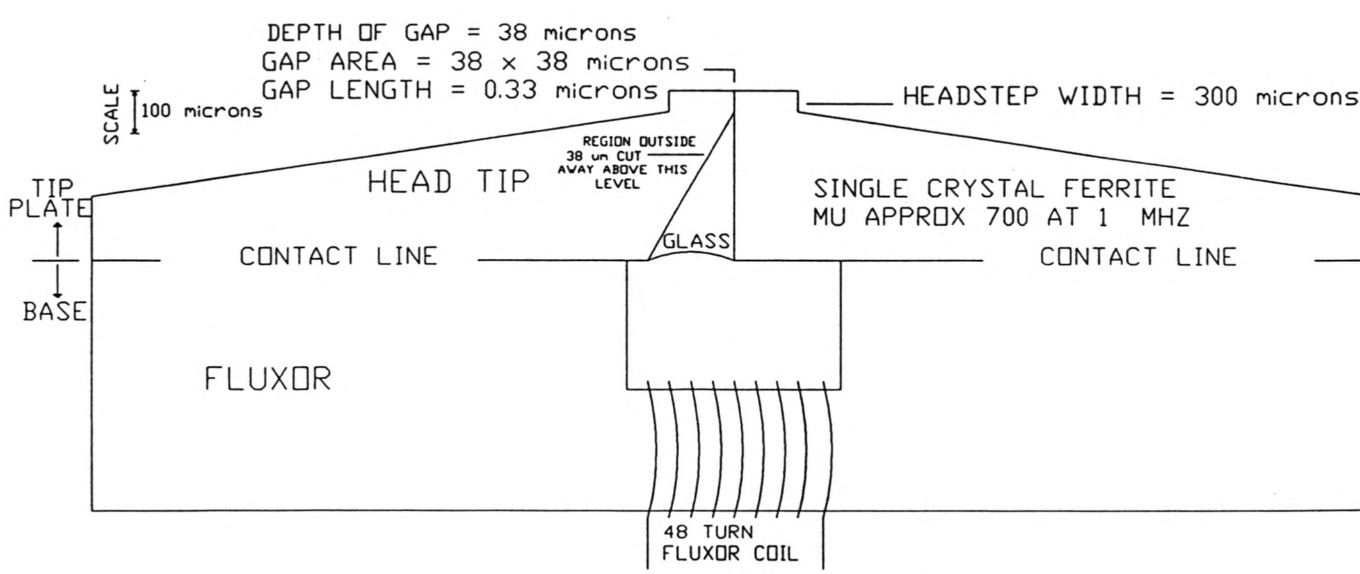


Fig. 8. Cross section of one head in the stack of 36.

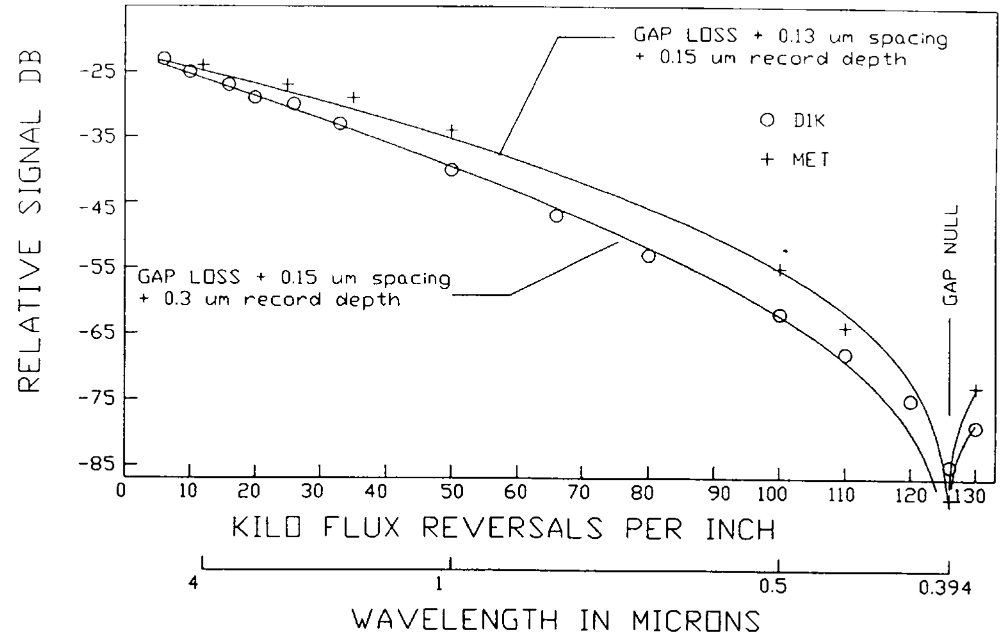


Fig. 9. Head output versus recorded wavelength (for D1K and MET). Measurements are fit with theoretical curves shown (see text).

As in VCR's, the same head design is used for reading or writing. We first used this approach in the original (wide-track) Mark III system after discovering in 1979 that writing with a 0.5-$\mu$m gap read head resulted in a significant ~6 dB increase in 33 kfrpi response compared to that of a standard 2.5-$\mu$m gap record head. Jeffers [10] has analyzed similar findings.

### Transport and Headstack Control Electronics

The transport and headstack are controlled using a combination of commercial and custom VME-based digital electronics. The control intelligence resides in a Motorola 68010 microprocessor. The transport analog control electronics, parts of the standard Honeywell Model 96, are interfaced directly to the VME digital electronics. The headstack Inchworm® motor control and LVDT electronics are custom NIM modules. All transport and headstack motion functions are available via serial communication with the VME computer on board. Operator control screens for recorder diagnostics are provided in the host computer.

### Signal Electronics

The signal electronics are deliberately kept as simple as possible. Write electronics consist of line receivers, signal reclocking flip-flops, and head current drivers. The digital signals for recording are generated in a separate data acquisition rack, which contains VLBI-specific A/D conversion and formatting electronics. Each head is driven by an NRZ-M data stream made up of blocks with a synchronization word, time of day, auxiliary data, and A/D output data. CRC characters and parity bits are recorded along with the data bits from the receiver electronics.

Reproduce electronics consists of preamplifiers, which are close to the heads, postamplifiers, equalizers, dc restoration, comparators, and bit synchronizers. The data acquisition recorders also contain some limited capabilities for decoding the VLBI format so that playback quality checks can be made.

The same head is used for writing or reading by means of a simple single-ended interface circuit. This head interface has no active switch so that when the ac-coupled record signal line goes quiescent (stops toggling) the head automatically defaults to read mode.

### Recording Characteristics and Limitations

The density of flux reversals, which can be supported with a tape whose magnetic and surface characteristics are similar to D1 or S-VHS, is 2.25/$\mu$m (57.15 kfrpi). Fig. 9 shows a "headcurve" measured using Sony D1K tape. The headcurve data were obtained by recording and playing back a constant frequency square wave (with record current optimized at 1-$\mu$m wavelength) over a wide range of tape speed. A good fit to the data was obtained with

record depth $\approx 0.3$ $\mu$m
spacing plus transition length $\approx 0.15$ $\mu$m

for the playback model of Bertram [11] (his equation (59)). With Sony D1K tape a broadband SNR of 18 dB is obtained at 9 Mbit/s per head. Higher densities up to 3 fr/$\mu$m (75 kfrpi) can be achieved but the bit error rate increases from $10^{-5}$ to $10^{-3}$. The better short wavelength response and output of metal evaporated tape (MET), (shown in Fig. 9) would allow reliable operation with densities in the 3 fr/$\mu$m range with the present head. In the future, new heads using a shorter gap and higher saturation materials will be needed to take full advantage of MET at densities of 4–5 fr/$\mu$m or to use metal particle (MP) tape at 3–4 fr/$\mu$m.

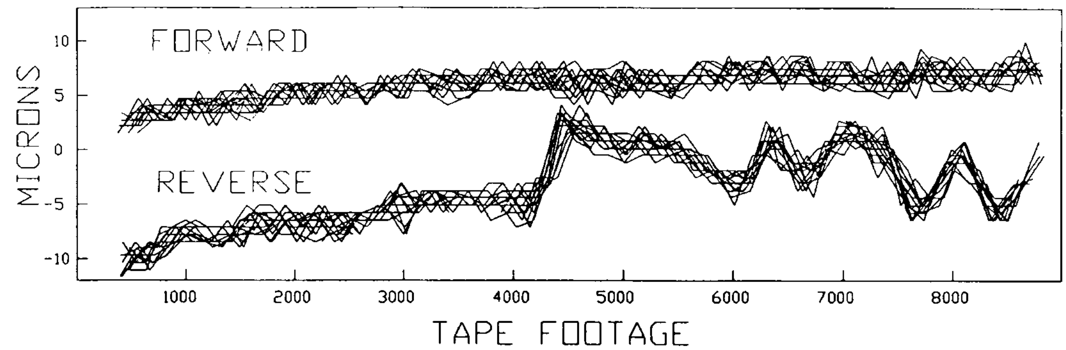


Fig. 10. Tracking signatures determined by peaking on the signal power. This plot was generated from 30 passes taken over 6 h.

*Trackwidth*

The present trackwidth of the VLBA recorder is 38 $\mu$m. Reduction in trackwidth in future versions of the headstack is expected. With MET it should be possible to reduce the trackwidth to 10 $\mu$m. There is no evidence that the longitudinal recorder is limited by head-to-tape contact; head performance is comparable to that in a VHS VCR.

*Tape Speed*

Tests have been made to show that contact recording and playback is maintained with tape speeds up to 8 m/s (320 ips), and that "head flying" (of approximately 0.1-$\mu$m flying height) is observed at 8 m/s only when the tape tension is reduced from 2.25 N (provided by 10 in of water vacuum) to 1.8 N. At 8 m/s and 2.25 fr/$\mu$m a bit rate of 18 Mb/s can be recorded with each head. The longitudinal recorder should be able to work with the same longitudinal densities and trackwidths as rotary machines when operated at comparable head-to-tape speeds and with similar tape.

*Track Density*

The heads record with zero azimuth so that a guardband is needed between tracks to prevent cross-talk between tracks. While the tracking signatures repeat within 2 $\mu$m for passes in the same direction, the differences between tracking in forward and reverse can be as large as 10 $\mu$m, owing to tape slitting variations (the effective guiding edge moves from the upper to the lower loop between forward and reverse) and elastic anisotropy variations in the tape [7], [12], so that a guardband of at least 10 $\mu$m is needed between forward and reverse passes. Fig. 10 shows some tracking signatures made by repeated forward and reverse playback of a track recorded in the forward direction. The small end-to-end tracking drift in the forward direction is the intermachine signature, which results from small alignment differences between the transports used for recording and for playback. Changes in this signature of about the same magnitude also occur if the tape is subjected to environmental changes in shipment. The first time a tape is played after shipment there is often a small tracking difference compared with subsequent passes. This is because at tape speeds greater than about 0.5 m/s there is insufficient time for the tape to relax after being relieved from the stresses of the reel pack. Since this initial tracking shift is small it can be ignored. If necessary, the tracking shift on the first pass can be eliminated by "prepassing" the tape before use. The prepass can be done well in advance since no excessive strains are built up on the tape reel pack unless the tape is subject to large environmental changes. The tracking signature in Fig. 10, from playback of the forward recording in the reverse direction, shows that the elastic anisotropy signature is largely repeatable. The slitting signature is confined to a scale along the tape of a decimeter or less and is not resolved in Fig. 10. Separate tests show the difference in slitting signatures between forward and reverse to be about 10 $\mu$m peak to peak. Fig. 11 illustrates the 14-pass track format presently being used for the VLBA, which has guardbands of 10 $\mu$m between passes in the same direction and 23 $\mu$m between passes in opposite direction, giving an average track density of about 20 per mm. The spacing between passes is under software control. Azimuth recording, as employed by a VCR, could be accomplished by tilting the headstack with respect to the direction of tape motion but would add complexity for only a modest increase in track density.

*Tape Thickness*

The longitudinal transport excels in its ability to handle extremely thin tape without loss of head-to-tape pressure or excessive strain. Head-to-tape pressure for an equilibrium head contour depends only on the tape tension, wrap angle, and headstep width and is independent of the tape flexural strength. Fig. 12 shows the tape strain at various places along the tape path. The pressure between the tape edge and the precision plate is calculated by first estimating the length of flattening for the arc in contact with the plate. Polyester-based tapes as thin as 6 $\mu$m can be handled without exceeding a one percent strain in the tape path. Even thinner tape could be handled by reducing the tension with a corresponding reduction in the headstep width and/or increase in wrap angle to maintain head-to-tape pressure. So far, tests have been made with tape

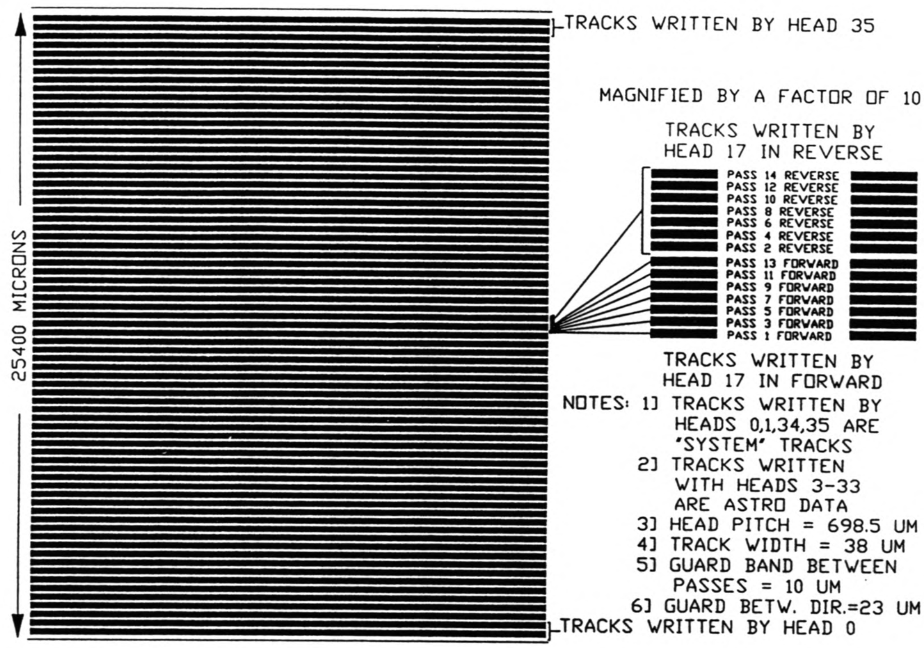


Fig. 11. VLBA longitudinal format. While the head pitch and track width are fixed, the separation between passes is under computer control.

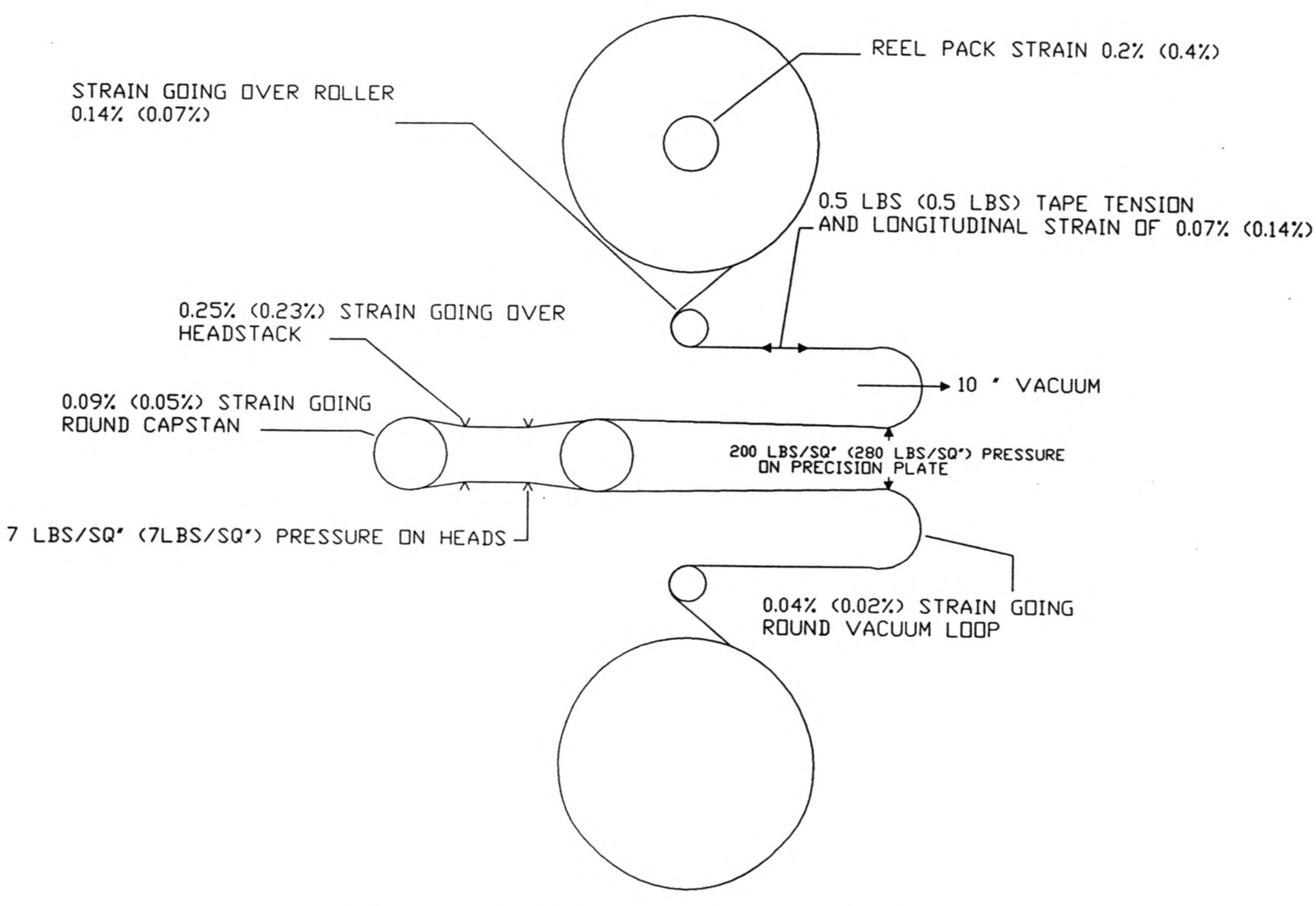


Fig. 12. Calculated strains and pressures on 25-$\mu$m-thick tape as it passes through the transport. The numbers in ( ) are for 13-$\mu$m tape.

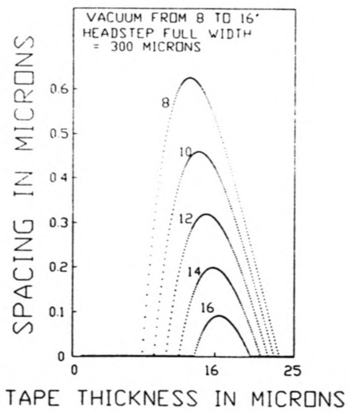


Fig. 13. Calculated initial spacing in making a transition from 25-$\mu$m-thick tape to tape of another thickness. Curves are shown for different vacuum settings for 8 to 16 in of water.

thickness down to 4 $\mu$m (polaramid-base film). However, tapes this thin are not yet generally available and a nominal thickness of 16 $\mu$m has been chosen for initial VLBA use. The interchangeability of tapes of various thickness can pose a problem. There can be loss of contact in going from 25 $\mu$m tape to tapes in the 10- to 19-$\mu$m thickness range as shown in Fig. 13. The curves in Fig. 13 are calculated from the same model used to generate Fig. 5 and represent the difference profile height at the gap for an initial profile using thin tape and a stable profile using 25-$\mu$m-thick tape. Going from a head conditioned with thin tape to a thicker tape poses no difficulty, since initial head-to-tape pressure is higher than the equilibrium value. The difficulty in going immediately from thick to thin tape without conditioning may be overcome in some thickness ranges by changing the tension when the tape thickness is changed. For example, it has been found that a transition can be made from 25- to 16-$\mu$m tape by running the 25-$\mu$m tape at a vacuum of 16 in of water and the 16-$\mu$m tape at 8 in.

### *Reel Size and Packaging*

Though the Honeywell Model 96 transport will handle up to 16-in diameter reels, the 14-in diameter reel is considered to be a more practical size because it is easier to handle and standard shipping containers are available. For applications such as VLBI, in which tape is continually reshipped, we have developed a "self-packing" reel modification in which the flange-to-flange hub width is decreased from 25.90 to 25.45 ±0.05 mm to prevent scatter-wind and hence eliminate edge damage during tape shipping. A 14-in reel holds up to 6580 m (21 600 ft) of 13-$\mu$m tape (54 min at 2 m/s) and weights 5.7 kg including the shipping container.

### *Tribology*

Table II shows the measured head wear rates for various tapes at 4 m/s and 2.2 N tension. The strong dependence of wear rates with humidity was verified for D1K. The humidity dependence was not tested for other tapes but is assumed to be similar. The wear rates were measured by observing the change in spacing loss in making the transition between tapes of different thicknesses. For example, the abrasivity of D1K was measured by observing the gradual reduction in spacing loss in going from a head profile worn with 25-$\mu$m-thick tape to the new profile for 13-$\mu$m D1K tape. In all cases the theoretical model discussed earlier is used to calculate the wear rates. Our actual experience with head wear on the Haystack Mark IIIA VLBI processor is consistent with these results. For example, a head life of about 8000 h is obtained with Fuji H621 tape at 40% relative humidity and an initial depth of gap of 25 $\mu$m. While the use of low abrasivity tape should result in a very long headlife, it is our experience that good head performance cannot be maintained with the exclusive use of tapes whose abrasivity is as low as 3M5198.

TABLE II
MEASURED HEAD WEAR RATES FOR SOME SELECTED TAPES

| Tape | Wear Rate ($\mu$m/h) | Relative Humidity (%) |
|---|---|---|
| Fuji H621 | 0.03 | 60 |
| Sony D1K | 0.004 | 30 |
| Sony D1K | 0.02 | 60 |
| Sony D1K | 0.09 | 100 |
| 3M 5198 | 0.0001 | 60 |
| 3M 5358 | 0.002 | 10 |
| Sony V16B | 0.06 | 60 |
| Fuji PRO S-VHS* | 0.006 | 30 |

*Tested with modified vacuum column width to handle 0.5-in tape.

Tests have been made which show that the headstacks do not suffer from gap erosion, and that the measured effective spacing of 0.15 $\mu$m for D1K must be a combination of magnetic transition length [11], surface roughness and a magnetic dead layer. Studies to determine the relative contributions are still in progress. It is likely that most of the loss is due to the magnetic transition length, which may be reduced in the future with a MIG record head.

## Comparison and Conclusions

Table III gives a comparison of the VLBA recorder with the ID-1 helical scan recorder. The advantages of the longitudinal recorder for VLBI are higher data rate capability and longer record time, the latter due to the higher packaging efficiency of a large reel.

In the future, it is expected that the longitudinal recorder could more easily use very thin tapes than the high-speed rotary recorder.

TABLE III
COMPARISON OF THE ID-1 AND VLBA RECORDERS

| | ID-1 | VLBA |
|---|---|---|
| Recorder type | Helical | Longitudinal |
| Linear data density (bits/$\mu$m) | 1.4 | 2.0 |
| Linear overhead (%, total) | 60.7 | 12.5 |
| Transition density (fr/$\mu$m) | 2.25 | 2.25 |
| Track density** (tracks/mm) | 22.2 | 22.2 |
| Scan speed at 256 Mbit/s (m/s) | 40 | 4 |
| Current max. recording rate (Mbit/s) | 256 | 256 |
| Max. design recording rate (Mbit/s) | 256 | 1024 (4 m/s) 2048 (8 m/s) |
| Bit error rate spec* | $<10^{-10}$ | $<3 \times 10^{-4}$ |
| Taper package | D1-L cassette | 14-in reel |
| Volume (cm$^3$) | 2490 | 2917 |
| Data volume density pkg'd. (Gb/cm$^3$) | 0.4 | 1.9 |
| Filled package weight (kg) | 2.7 | 4.7 |
| Ship. weight: 24 h at 128 Mb/s (kg) | 42.6 | 11.4 |
| Current tape thickness ($\mu$m) | 16 | 16 |
| Planned tape thickness ($\mu$m) | 13 | 13 |
| Capacity with 13-$\mu$m tape (Tbits) | 0.92 | 5.5 |
| Recording time at 128 Mb/s (h) | 2 | 12 |

*For ID-1 the BER is after error correction for VLBA raw BER is given.
**For ID-1 track density is fixed, while for VLBA it is programmable; 22.2 tracks/mm is for 38-$\mu$m trackwidth and 7-$\mu$m guardband.

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**Harry R. Allen** received the B.S. degree in mechanical engineering from the University of Kentucky in 1957. He has been engaged in the development of magnetic recording heads and systems since 1958.

Mr. Allan is a member of the IEEE Magnetics Society and is on the Board of Directors of THIC.

| REV | DATE | BY | DESCRIPTION | CHANGE ORDER |
|---|---|---|---|---|
| D | 8-30-91 | DGS | T102 & T108 REV., 14 GHz DESIGNATION WAS 15 GHz | 910830-1 |
| E | 7-7-92 | DGS | F102, F110, L105, T106, T108 & T110 REV. | 920707-2 |
| F | 3-19-93 | DGS | MINOR REVISIONS | —— |

| REV | DATE | BY | DESCRIPTION |
|---|---|---|---|
| A | 12-90 | ANDREATTA | REDRAWN WITH AUTOCAD |
| B | 3-25-91 | DGS | EXTENSIVE REVISIONS |
| C | 5-8-91 | DGS | ADDED CONVERTER MODULE SWITCH DESIGNATIONS |


## NOTES

1. NUMBERS S1–S14 REFER TO COAXIAL SWITCHES IN BACK PLANE WIRING OF RACK "B". NUMBERS SX–XX REFER TO TERMINALS OF THESE SWITCHES.
2. NUMBERS N1–N21 REFER TO TYPE–N CONNECTORS ON BRACKET AT TOP REAR OF RACK "B".
3. NUMBERS N22–N42 REFER TO TYPE–N CONNECTORS ON BRACKET ON REAR OF RACK "B" IMMEDIATELY BELOW BIN "D".
4. NUMBERS N43–N46 REFER TO TYPE–N CONNECTORS ON BRACKET ON REAR OF RACK "B" AT SIDE OF BIN "A".
5. NUMBERS SHOWN INSIDE THE SYMBOL FOR AN AMPLIFIER REPRESENT THE NOMINAL AMPLIFIER dB RATING.
6. REFER TO DRAWING D58001K002 FOR THE STATION BUILDING ELECTRONIC SYSTEM BLOCK DIAGRAM.
7. X PRECEEDING FILTER BANDWIDTH INDICATES –1dB LEVEL.

* HIGH LEVEL NOISE SOURCE NOT ON ALL FRONT END UNITS OF ANY GIVEN FREQUENCY.

MAY 05 1993

| | | | |
|---|---|---|---|
| VLBA PROJECT | VERY LONG BASELINE ARRAY | NATIONAL RADIO ASTRONOMY OBSERVATORY SOCORRO, NEW MEXICO 87801 | |
| TITLE | ELECTRONIC SYSTEM BLOCK DIAGRAM (ANTENNA ELECTRONICS) | DRAWN BY ANDREATTA | DATE 12-90 |
| | | DESIGNED BY A. R. THOMPSON | DATE 6-24-86 |
| | | APPROVED BY | DATE |
| SHEET NUMBER 1 OF 1 | DRAWING NUMBER D58001K001 | REV. F | SCALE — |

8
7
6
5
4
3
2
1
REV DATE BY DESCRIPTION CHANGE ORDER
A 12-90 ANDREATTA REDRAWN WITH ACAD
B 4-8-91 DGS EXTENSIVE REVISIONS
C 6-2-92 DGS EXTENSIVE REVISIONS
D 7-7-92 DGS EXTENSIVE REVISIONS 920707-1
M104 : MASER INTERFACE (BIN C, 1/2)
HYDROGEN MASER FREQUENCY STANDARD SIGMA TAU CORP.
LOCATED IN STAND ALONE UNIT
L121 : 5 MHz DISTRIBUTOR (BIN C, 3/4)
L109 SECURE 1PPS
GPS RECEIVER
L108 : STATION TIMING (BIN C, 5)
STATION COMPUTER
UTILITY INTERFACE
RECORDER #1
RECORDER #2
FORMATTER INPUT SELECT
COMPUTER ROOM
N20
N21
N18
N1
L102 : LO TRANSMITTER (BIN C 9/10)
PHASE LOCK MON
L103 : ROUND TRIP MONITOR (BIN C, 11/12)
N5
N19
TO VERTEX ROOM
L121 : 5 MHz DISTRIBUTOR (BIN C, 3/4)
TO T122'S, L122 & L123
T122 : BASEBAND CONVERTER (BIN D, 5/6)
T122 : BASEBAND CONVERTER (BIN D, 7/8)
T122 : BASEBAND CONVERTER (BIN D, 9/10)
T122 : BASEBAND CONVERTER (BIN D, 11/12)
T122 : BASEBAND CONVERTER (BIN E, 5/6)
T122 : BASEBAND CONVERTER (BIN E, 7/8)
T122 : BASEBAND CONVERTER (BIN E, 9/10)
T122 : BASEBAND CONVERTER (BIN E, 11/12)
DIGITAL SWITCH D138
HEADER CONTROL D133
TRANSPORT DRIVER D134
TIMING AND CONTROL D131
DATA BUFFER D136
QUALITY ANALYSIS D135
FORMATTER
L123 : OUTPUT RATE SYNTHESIZER BIN C, 9/10
T121 : IF DISTRIBUTOR (BIN D, 1/2)
T121 : IF DISTRIBUTOR (BIN D, 3/4)
D121 : SAMPLER 8 DIGITIZERS 2 BITS EACH BIN C, 7/8
L122 : 32 MHz SYNTHESIZER BIN C, 3/4
IF CABLE TERMINATION PANEL
EQUALIZING AMPLIFIER
EQUALIZING AMPLIFIER (SPARE)
FROM RACK "B" VERTEX ROOM
IF A
IF B
IF C
IF D
RACK "C"
RACK "D"
CASTER BASE
BLANK PANEL
AC POWER STRIP
FORMATTER (VME)
RACK "C"
RACK "D" (DATA ACQUISITION RACK)
NOTE: REFER TO DRAWING D58001K001 FOR THE ANTENNA ELECTRONICS SYSTEM BLOCK DIAGRAM.
MAY 05 1993
VLBA PROJECT
VERY LONG BASELINE ARRAY
NATIONAL RADIO ASTRONOMY OBSERVATORY
SOCORRO, NEW MEXICO 87801
TITLE
ELECTRONIC SYSTEM BLOCK DIAGRAM (STATION BUILDING)
DRAWN BY ANDREATTA DATE 12-90
DESIGNED BY A. E. E. ROGERS DATE 6-27-86
APPROVED BY DATE
SHEET NUMBER 1 OF 1
DRAWING NUMBER D58001K002
REV. D
SCALE —
VLBA\58001\K002