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CHAPTER 5

The VLBA Receiving System: Antenna to Data Formatter

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Abstract Details of the design and performance are given for that part of the VLBA electronics system located between the output of the feeds and the input to the formatter. This includes low-noise receivers, hydrogen maser and local oscillators, IF and baseband frequency converters, digital samplers and the calibration system.

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5.1 Introduction

The locations of the parts of the receiving system are shown in figure 5.1 on the following page. For receiving bands at frequencies below 1 GHz the antenna feeds are at the prime focus, and the front ends [1] are in a box close to the feeds.

[1] The term "front end" is used to denote the low-noise input stages for each receiving band that are located close to the feed to reduce transmission-line losses. A front end usually has sufficient gain that the later stages have negligible effect on the system noise, and it may incorporate RF amplifier stages, mixers and IF stages.

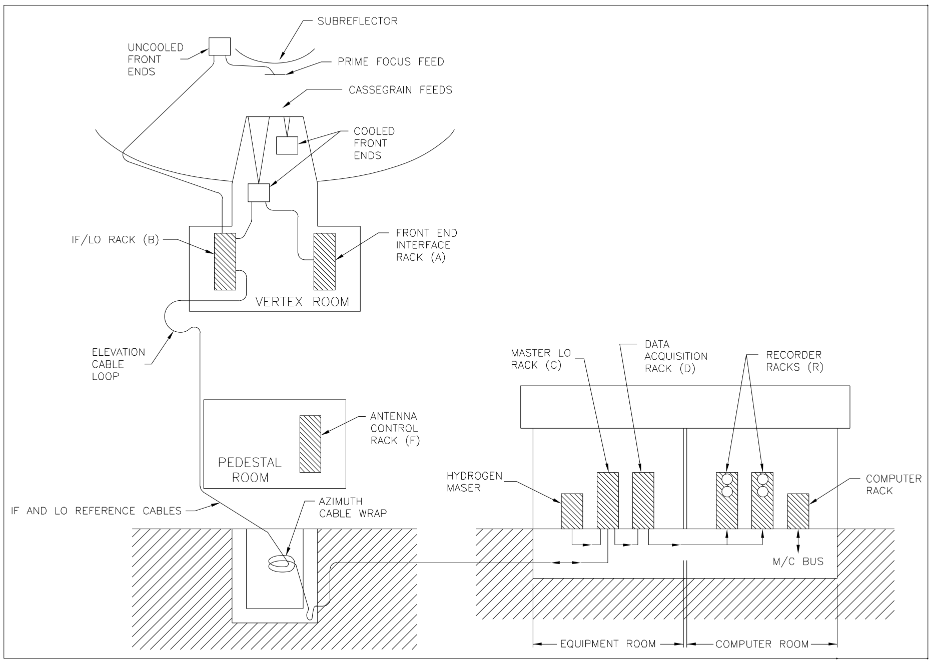

Figure 5.1: Locations of parts of the receiving system on the antenna and in the station building.

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 at 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. The front-end interface rack (Rack A) in the vertex room contains 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. The received signals 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, intermediate frequency (IF) stages, and the local oscillator (LO) system. In this rack the signals are converted to an IF band that extends from 500 to 1000 MHz.

The amplified IF signals are transmitted by coaxial cable from the vertex room to the equipment room of the station building. In the data acquisition rack (Rack D), selected frequency bands within the IF responses are converted to baseband[2] frequencies, sampled and digitized. The baseband responses extend

[2] A "baseband" frequency response is one in which the gain extends uniformly from close to zero frequency to an upper cutoff frequency, i.e. it is essentially a low-pass response. The low frequency cutoff is a small fraction (usually 1% or less) of the upper frequency cutoff.

up to a maximum of 16 MHz, and the electronics contains provision for 16 baseband signals. The bits from the digital sampling are passed to the formatter which is also located in Rack D. The maser frequency standard and the master LO rack (Rack C), are also located in the equipment room. LO reference signals that are required in the vertex room are transmitted by cable from Rack C.

The operation of the antenna and electronics at each site is under the control of the station computer which is located in the computer room of the building. This computer is connected to all subsystems of the electronics through a bus and a series of interfaces that transmit control and monitor data. The tape recorders are also located in the computer room.

5.2 Feeds and Polarizers

The types of feeds used for the various frequency bands have been discussed by Napier (chapter 4). For the two lower frequency bands, 330 and 610 MHz, a Cassegrain feed would be impracticably large. The feeds are therefore located at the prime focus and take the form of crossed dipoles mounted in front of the subreflector. Signals for both bands are received by each dipole, and are then separated by diplexing filters. The diplexer outputs represent orthogonal linearly polarized signals for each band. The linearly polarized signals are then converted to the equivalent circularly polarized signals, which are preferred for most interferometric observing. The polarization conversion is performed in quadrature hybrid networks in which the linearly polarized signals are combined after appropriate 90° phase shifts have been introduced.

For the frequency bands above 1 GHz, Cassegrain feed horns are located on a circle at the top of the feed cone, as shown by Napier (figure 4.5 on page 70). The rotation of the subreflector, as well as adjustment of its position along the antenna axis for focusing, are performed under computer control. The outputs of the feeds are circular waveguide orifices, and from these the signals pass to polarizers which are passive waveguide devices that produce outputs corresponding to opposite circularly polarized components. For the frequency bands from 2.3 to 23 GHz, septum polarizers (Ege and McAndrew 1985) are used. For the 1.5 and 43 GHz bands the polarizer is an orthomode junction, used in conjunction with a quarter-wave phase shifter in the feed horn. Since any loss at the receiver input can add to the system temperature, the polarizers for bands with cooled receivers (i.e., those for frequency bands above 1 GHz) are also cooled. For bands from 1.5 to 4.8 GHz the polarizers are fairly large metal structures, and are cooled only to the first-stage refrigerator temperature of 50 K so as not to overload the refrigerator capacity. For the bands at 8.4 GHz and above the polarizer is sufficiently small that it can be attached to the 15 K second stage of the refrigerator.

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 at an output of the polarizer, as measured when a linearly polarized signal is applied to the circular input port and the position angle of the linear polarization is rotated. The ellipticity is typically less than 0.5 dB, but can be as high as 1 dB towards the edges of those bands for which the width is greater than 10% of the center frequency.

5.3 Simultaneous, Multi-Frequency Observations

Simultaneous reception in the 2.3 and 8.4 GHz bands is required for certain types of observations and is achieved by means of a dichroic reflector, as described by Napier (chapter 4). The two prime-focus bands can also be used simultaneously. In addition, the receiving system allows the possibility of simultaneously recording signals from the two prime-focus bands and from one of the Cassegrain-feed bands. However, the optimum focusing point for the prime-focus feeds requires an axial repositioning of the subreflector by approximately 55 cm from the optimum focus point for Cassegrain feeds. Thus with Cassegrain focus adjustment the defocusing of the prime-focus feeds would be about half a wavelength at 330 MHz. This would be expected to reduce the aperture efficiency by a few dB, but may be acceptable for some observations. At 610 MHz the loss in aperture efficiency would be substantially greater.

5.4 Front Ends for Bands Below 1 GHz

The signals received by the dipole feeds in the 330 and 610 MHz bands are brought to the front-end box located close to the prime focus by two coaxial cables with matched electrical lengths. The diplexers and hybrids used to separate the signals and produce circular polarization are located within the box. In the 330 and 610 MHz frequency bands the noise contribution from the sky (the galactic background radiation) makes a larger contribution to the system temperature than at higher frequencies, so there is less advantage in using cooled input stages. The RF components are mounted on a chassis that is thermally insulated from the exterior front-end box and held at 45$\pm$1°C by a temperature controlled heating system, to avoid temperature related gain variations. The amplifiers use GaAsFETs (gallium-arsenide field effect transistors) and the overall front end gain is less than 30 dB to avoid possible intermodulation effects from interference in this heavily used part of the spectrum. Provision is made for the insertion of calibration signals in the form of switched noise and pulses (described in section 5.9 on page 87) at the receiver inputs.

The signals from the front-end box are transmitted by coaxial cables to Rack B in the antenna vertex room where filters to limit the bandwidths to 30 MHz are inserted. To bring the signals into the main IF band of 500–1000 MHz, the 330 MHz signals are converted to a band at 830 MHz using a 500 MHz LO frequency. The 610 MHz signals require no frequency conversion to bring them into the IF band. However, the assigned frequency band at 610 MHz was originally the channel 37 television band, and there are likely to be strong television signals in adjacent channels at some sites. A special narrow-band filter module has therefore been provided. In this module the signals are converted from a center frequency of 611 MHz to 111 MHz using a 500 MHz LO, and then from 111 MHz to 11 MHz using a 100 MHz LO, with appropriate filtering to suppress image responses. The wanted signals are then passed through an eight-pole filter with a bandwidth of 4 MHz at -3 dB. They are then converted back to the 610 MHz band using the same LO frequencies as in the down-conversion. Inserting the filter at a relatively low frequency allows a steep-sided response to be achieved: the filter bandwidth is 5.9 MHz at -30 dB and 8.4 MHz at -60 dB. Two such filter units, one for each polarization, are provided at each antenna, and they can be bypassed to allow the use of a 30 MHz bandwidth.

5.5 Front Ends for Bands Above 1 GHz

Figure 5.2 on the next page shows a block diagram of the 4.8 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 (see section 5.9 on page 87). The signals are then amplified in low-noise HFET (heterostructure field-effect transistor) amplifiers designed and assembled at NRAO (Pospieszalski 1992). The polarizer, couplers, and amplifiers are located in an evacuated Dewar. Signals from the feed pass through a waveguide window in the Dewar wall, and there is a small gap between the wall and the polarizer to provide thermal insulation. The refrigerator is a two-stage unit operating on the Gifford-McMahon cycle using a recirculating helium system with a compressor mounted on the base of the antenna. The temperatures of the two stages are approximately 50 K and 15 K. Cooling the amplifiers to 15 K reduces the noise of the transistors and the thermal noise associated with losses. The cooled amplifiers are followed by ambient temperature post-amplifiers which are commercially available units. The gain of the cooled amplifiers is approximately 32 dB and that of the post-amplifiers is 20 dB, providing an overall gain of 52 dB.

Signals from the front ends are converted to an IF of 500–1000 MHz in converter modules in Rack B. Figure 5.2 on the next page also shows a block diagram of the 4.8 GHz converter module. The two signals from the front end can be interchanged by a transfer switch which 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 observable band, and then go into mixers that are fed with a tunable LO signal from a 2–16 GHz synthesizer module (described in section 5.8 on page 83). The bandpass filters at the LO inputs to the two mixers are to prevent leakage 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

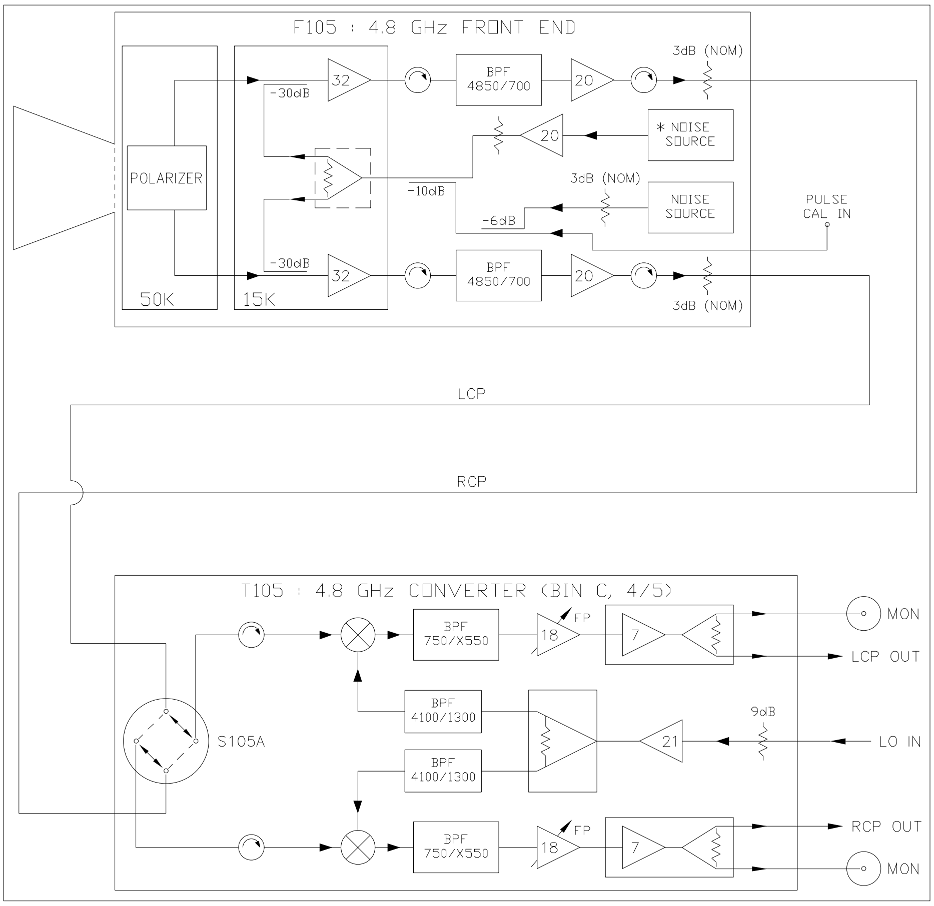

Figure 5.2: Block diagrams of the front end and converter module for the 4.8 GHz band. These units are typical of the receiving system for bands at frequencies greater than 1 GHz. The numbers within the triangular symbols that denote amplifiers are the nominal gains in decibels. The asterisk indicates the high-level noise source used for solar observations.

Table 5.1: Characteristics of the VLBA receiving system

Nominal frequency	Frequency band	Receiver noise temp. (K)	Physical temp. of polarizer (K)	First IF (GHz)	Passband-limiting filters (GHz)
0.330	0.312–0.342	80–120	300	0.5–1.0	0.312–0.342 [1,2]
0.610	0.596–0.626	115–160	300	0.5–1.0	0.596–0.626 [2]
					0.609–0.613 [2,4]
1.5	1.35–1.75	5–15	50	0.5–1.0	1.27–1.83
2.3	2.15–2.35	5–15	50	0.5–1.0	2.0–2.8
4.8	4.6–5.1	10–20	50	0.5–1.0	4.5–5.2
8.4	8.0–8.8	10–20	15	0.5–1.0	7.92–8.88[1,2]
10.7[5]	10.2–11.2	35–55	15	0.5–1.0	10.1–11.3[1,2]
14	12.0–15.4	20–45	15	0.5–1.0	11.8–13.0[1,2,4]
					12.8–14.0[1,2,4]
					13.8–15.0[1,2,4]
					14.8–15.6[1,2,4]
23	21.7–24.1	40–60	15	9.4–9.9	9.3–10.2[1,3]
43	41.0–45.0	35–65	15	7.9–8.9	7.7–9.1[3]

Notes: [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, i.e. after first mixer, and are located in Front Ends. [4] Filters selectable by computer control. [5] The 10.7 GHz band is available on the Pie Town antenna only.

−1 dB points. The amplified IF signals are split into two equal components, one of which goes to the station equipment room and the other goes to the front panel of the module to provide a monitor point. The gains of the IF stages can be adjusted and the required level at the output of the converter modules is −67 dBm per MHz, i.e. −40 dBm in the full 500 MHz bandwidth.

The receiving systems for other bands at frequencies above 1 GHz differ in some details from that described above, and the most important features are listed in table 5.1. Values of the system temperature for each band are given in Napier's table 4.2 on page 63. In the 1.5 and 2.3 GHz front ends the refrigerator has a higher cooling capacity to handle the much larger mass of the lower frequency polarizers.

Some other features of particular bands arise from differences in the frequency conversion to IF. The 8.4 GHz band is routinely used for geodetic observations, in which it is desirable to spread the frequencies of the baseband channels as widely as possible across the observing frequency band (8.0–8.8 GHz). To facilitate this it is possible to feed the two mixers in the converter module with separate, independently tunable LO signals, and to feed the signal from the right-hand polarization channel into the RF ports of both mixers. This allows simultaneous observations to be spread over the full width of the band. The 14 GHz band is

Table 5.2: Some features of VLBA receiving bands

330 MHz	First LO fixed at 500 MHz.
610 MHz	Optional filter, 609–613 MHz, to exclude adjacent TV signals. IFs of 330 and 610 MHz bands combined on same cables from antenna to equipment room of site building.
2.3 and 8.4 GHz	Simultaneous observations possible using dichroic reflector.
8.4 GHz	Optional broadband observing mode: both channels of converter module receive RH polarization and have separately tunable LOs.
10.7 GHz	Installed on Pie Town antenna only.
14 GHz	Four switchable filters used (to eliminate image responses).
23 GHz	Two frequency conversions to 0.5–1.0 GHz IF: both first and second LOs are generated by 2–16 GHz synthesizer modules (frequency = $N \times 500 \pm 100$ MHz).
43 GHz	As for 23 GHz, but for first LO the output frequency of the 2–16 GHz synthesizer is tripled. Pulse calibration injected at first IF.

another wide one, designed to cover both the methanol line at 12.178 GHz and the radio astronomy band at 15.35–15.4 GHz. In the 14 GHz converter a set of four switchable filters are used at the inputs to subdivide the input band, which is 3.4 GHz wide, into four bands each less than 1.2 GHz wide. Observations can be made only in one band at a time. This subdivision of the band enables a frequency conversion to the 500–1000 MHz IF to be made without signals from the front end entering an unwanted image response.

For the 23 GHz and 43 GHz bands, two frequency conversions are used to bring the signals to the 500–1000 MHz IF band. For the 23 GHz band (21.7–24.1 GHz) the first IF is 9.4–9.9 GHz and the first LO comes from a 2–16 GHz synthesizer module (see section 5.8 on page 83). The first IF is chosen to avoid spurious responses of the form (2× LO-IF) and (3× LO-IF) from falling within the front-end band. This IF band is close enough to 8.4 GHz that the same converter module is used for the 8.4 and 23 GHz bands. For the 43 GHz band the first IF is 8.0–8.8 GHz and the first LO is obtained by frequency tripling the signal from a 2–16 GHz synthesizer. The first mixers for the 23 and 43 GHz receivers are located in the front-end units. The special features of the various bands are summarized in table 5.2.

5.6 IF and Baseband Signals in the Station Building

The overall analog signal path is shown in figure 5.3 on the next page. This includes the IF and baseband stages, and the switches and cables in the path from the antenna vertex room to the equipment 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

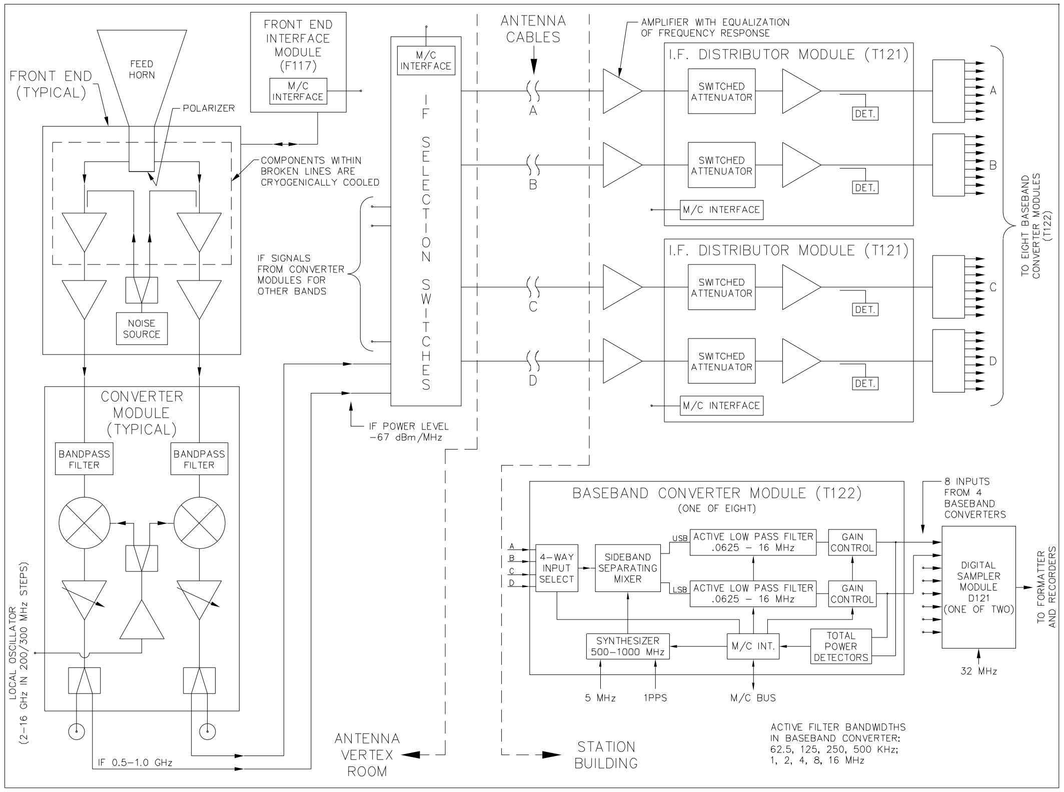

Figure 5.3: Simplified block diagram of the analog signal path at RF, IF, and baseband frequencies.

simultaneously. The 330 and 610 MHz bands share a single pair of IF cables. When all transfer switches, including those within the converter modules, are in their normal (unenergized) positions, cables A and B carry right-hand circular polarization and C and D carry left-hand. The cables from the vertex room to the equipment 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.

In the equipment room of the station building the cables terminate in amplifiers with a gain slope across the IF band that compensates for the varying attenuation of the cables, which is 7.5 dB at 500 MHz and 14 dB at 1000 MHz. From these amplifiers the signals go to two IF distributor modules in Rack D, as shown in figure 5.3 on the preceding page. The IF distributors provide computer-controlled step attenuators for level setting, further gain, and a level monitoring detector. A power divider provides eight outputs for each IF signal, and these outputs go to eight baseband converter modules.

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 (sometimes referred to as a single-sideband mixer) and a local oscillator that is tunable across the 500–1000 MHz IF band in 10 kHz steps. The mixer has two outputs, one for frequencies below the LO frequency and one for frequencies above it. For a description of the principle of such a mixer see, e.g., Thompson, Moran, and Swenson (1986). The specified rejection of the unwanted sideband in each output is better than 26 dB for intermediate frequencies between 650 and 850 MHz and baseband frequencies above 100 kHz, and better than 23 dB in all cases. The two outputs go to separate baseband amplifiers which have bandwidths that can be individually 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. At the high frequency end the baseband response falls to -3 dB at 90% of the nominal bandwidth. 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. The output levels of the baseband signals are controlled by ALC loops to provide constant power to the sampler inputs.

5.7 Digital Sampling

In the sampler modules the baseband signals are sampled and digitally coded. A sampling frequency equal to twice the maximum bandwidth of the analog signal being sampled, i.e. the *Nyquist frequency,* allows all the information in the continuous signal to be retained. The sampling frequency of 32 MHz is used for all bandwidths, and redundant samples can be discarded in the formatter,

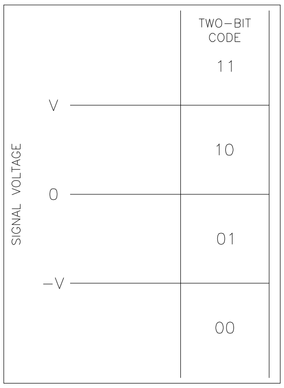

Figure 5.4: Coding scheme used for 4-level sampling.

if desired. 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. The thresholds are indicated by ±V in figure 5.4, which shows the code for four level sampling use in the VLBA. Note that this code has the property that, with random noise as input, each bit has equal probability of being 1 or 0 in all four levels. The code was devised by L. R. D'Addario as an alternative to the use of one bit for sign and one for magnitude: in general the magnitude bit does not have equal probability of being 1 or 0, and with such a scheme random errors in the data transmission can introduce a bias into the magnitude values. Two sampler modules are used since each can process eight baseband signals. Four-level sampling of all basebands at maximum bandwidth would produce 32 bit-streams, each with a bit rate of 32 Mb/s, resulting in a total bit rate of 1024 Mb/s. This is greater than the maximum recording capacity, so in practice the bandwidth and/or bits per sample must be reduced. The bit streams go to the Formatter which rearranges the bits as required for the tape recorders. For a given bandwidth, four-level sampling provides a sensitivity at the correlator output greater than for two-level by a factor of 1.38 (Thompson, Moran and Swenson 1986).

5.8 Local Oscillator and Timing System

A hydrogen maser at each antenna site provides standard frequencies of 5 MHz and 100 MHz, and all other LO and timing signals used in the receiving system are derived from these maser outputs. The masers were made by Sigma-Tau Frequency Standards (Peters et al. 1987) and one is located in the equipment room of each station building.

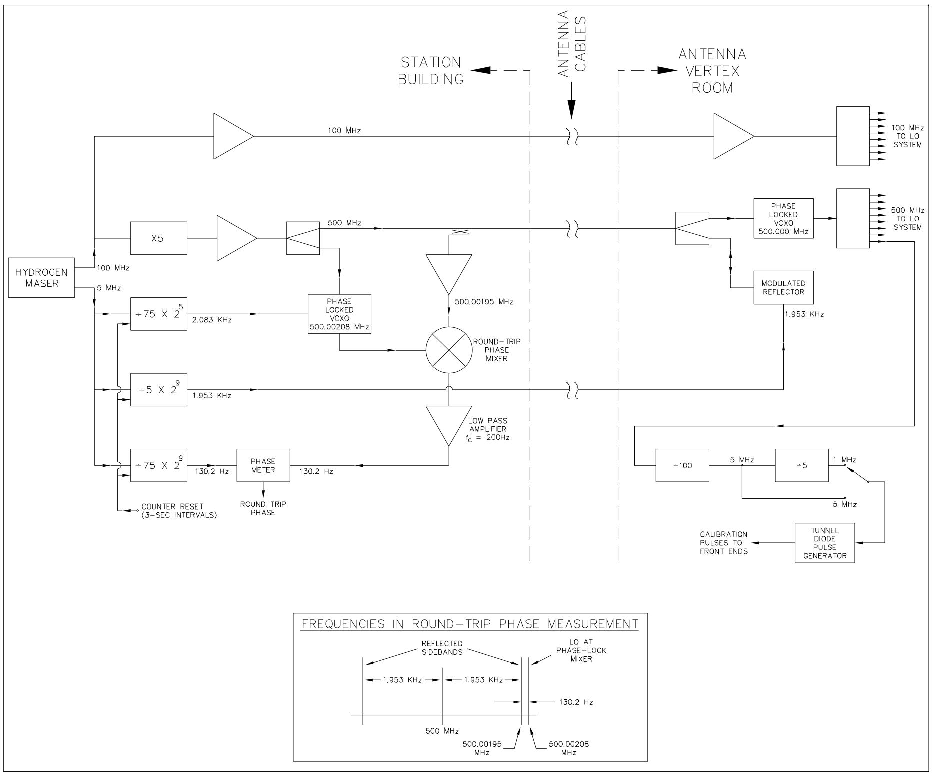

Figure 5.5: Distribution of local oscillator reference frequencies from the maser to the antenna vertex room.

A simplified block diagram of the reference distribution system for the local oscillators is shown in figure 5.5. The 100 MHz output of the maser is used to provide reference frequencies at both 100 and 500 MHz. A frequency multiplier generates 500 MHz from the 100 MHz and these two signals are transmitted to the vertex room on separate coaxial cables. The phase stability of the 500 MHz signal is especially critical because this frequency is subsequently multiplied to produce the high frequency LO signals. In order to correct 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 cable between the station building and 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 square wave 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 and converted with an LO frequency of 500.002083 in the round-trip-phase mixer in figure 5.5. 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 maser signal by frequency division. 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 is filtered by a phase-locked crystal oscillator, which 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 LOs for the 23 and 43 GHz bands, and for the conversions to the 500-1000 MHz IF for all bands higher than 1 GHz, are generated by three 2–16 GHz synthesizer Modules. In these units a YIG[3]-tuned oscillator and a frequency 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 from the maser. Thus the output frequency of the module can be locked to a maser-derived reference at any value between 2 and 16 GHz that is of the form $500 \times N \pm 100$ 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. Tables 5.3 on the following page and 5.4 on page 87 list the settings of the 2–16 GHz synthesizer modules required to cover the nominal frequency bands of the VLBA given in table 5.1 on page 79.

Other LO frequencies used in the VLBA receiving system are those in the baseband converter modules in Rack D in the station building. These LOs 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 10 kHz with a 10 kHz reference derived from the 5 MHz maser signal. One-second timing pulses are used to eliminate ambiguity in the phase of the 10 kHz reference.

The main timing system at each antenna station uses the 5 MHz output from the maser to drive a frequency divider which produces a series of pulses at 1 sec intervals, referred to as the 1 pps (1 pulse per sec) signal. The timing of the pulses is set to the seconds of universal time to an accuracy of better than 1μs using pulses from a GPS (Global Positioning System) receiver. The timing system includes a second divider for redundancy and battery backup in case of power failure. It also produces an 80 Hz square wave that is used to switch the noise sources in the front ends. The station computer counts the 1 pps pulses

[3]Yttrium-iron garnet, a magnetically tunable cavity in which the resonant frequency varies linearly with an applied current over approximately two octaves.

Table 5.3: First LO frequencies for VLBA bands 1.5 to 14 GHz.

Observing band (GHz)	First LO freq. Low Side (GHz)	First Lo freq. High Side[1] (GHz)
1.1–1.6		2.1
1.4–1.9		2.4
2.1–2.6		3.1
4.6–5.1	4.1	5.6
7.9–8.4	7.4	8.9
8.1–8.6	7.6	9.1
8.4–8.9	7.9	9.4
10.1–10.6	9.6	11.1
10.4–10.9	9.9	11.4
10.6–11.1	10.1	11.6
10.9–11.4	10.4	11.9
11.9–12.4	11.4	12.9
12.1–12.6	11.6	13.1
12.4–12.9	11.9	13.4
12.6–13.1	12.1	13.6
12.9–13.4	12.4	13.9
13.1–13.6	12.6	14.1
13.4–13.9	12.9	14.4
13.6–14.1	13.1	14.6
13.9–14.4	13.4	14.9
14.1–14.6	13.6	15.1
14.4–14.9	13.9	15.4
14.6–15.1	14.1	15.6
14.9–15.4	14.4	15.9

Note: [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 5.4: LO Frequencies for VLBA bands 23 and 43 GHz

Observing band (GHz)	First LO freq. (GHz)	First IF band (GHz)	Second LO freq. Low Side (GHz)	Second LO freq. High Side
21.5–22.0	12.1	9.4–9.9	8.9	10.4
21.8–22.3	12.4	9.4–9.9	8.9	10.4
22.0–22.5	12.6	9.4–9.9	8.9	10.4
22.3–22.8	12.9	9.4–9.9	8.9	10.4
22.5–23.0	13.1	9.4–9.9	8.9	10.4
22.8–23.3	13.4	9.4–9.9	8.9	10.4
23.0–23.5	13.6	9.4–9.9	8.9	10.4
23.3–23.8	13.9	9.4–9.9	8.9	10.4
23.5–24.0	14.1	9.4–9.9	8.9	10.4
23.8–24.3	14.4	9.4–9.9	8.9	10.4
40.6–41.1	32.7 (10.9 x 3)	7.9–8.4	7.4	8.9
41.1–41.6	32.7	8.4–8.9	7.9	9.4
41.2–41.7	33.3 (11.1 x 3)	7.9–8.4	7.4	8.9
41.7–42.2	33.3	8.4–8.9	7.9	9.4
42.1–42.6	34.2 (11.4 x 3)	7.9–8.4	7.4	8.9
42.6–43.1	34.2	8.4–8.9	7.9	9.4
42.7–43.2	34.8 (11.6 x 3)	7.9–8.4	7.4	8.9
43.2–43.7	34.8	8.4–8.9	7.9	9.4
43.6–44.1	35.7 (11.9 x 3)	7.9–8.4	7.4	8.9
44.1–44.6	35.7	8.4–8.9	7.9	9.4
44.2–44.7	36.3 (12.1 x3)	7.9–8.4	7.4[1]	8.9[1]
44.7–45.2	36.3	8.4–8.9	7.9	9.4

Note: [1] Harmonics of both 7.4 and 8.9 GHz fall in the band 44.2–44.7 GHz.

and thereby keeps account of universal time.

5.9 Calibration System

Noise at two different power levels, as well as calibration pulses, can be injected through the calibration couplers at the two inputs of each front end, as shown in figure 5.2 on page 78. The noise sources are switched on and off by a square wave of frequency 80 Hz, and the amplitude of the component at this frequency within the signal channel is measured by a synchronous detector in each baseband converter. The gain and system temperature are thereby monitored continuously during an observation. The lower-level noise power is adjusted so that it produces an increase of approximately 5% in the system temperature during the active half of the switching cycle (i.e. a mean increase of 2.5%). The high-level noise source is intended for use only for observations of the sun, during which the solar noise level dominates all other sources of noise. The high-level source produces an increase of approximately 10% of the system temperature with the antenna pointed at the sun. Since the system noise temperature for solar observations depends upon the sun it should be the same for all antennas, and need only be measured at one antenna to calibrate a solar observation. The noise sources are calibrated by applying hot (ambient temperature) and cold (liquid-nitrogen temperature) loads at the feed apertures.

For calibration of phase and delay variations in the receiving system, a train of pulses at intervals of 1 microsecond or 200 nanoseconds is generated at each antenna and can be injected into the receiving front ends (Rogers, Corey and Nesman 1992). The pulse train with 1 microsecond intervals has a 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 pulses are generated by a tunnel diode driven by a square wave at the required repetition frequency. The rise-time of the individual pulses is approximately 25 picoseconds and the useful 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. In the case of the 43 GHz front end the pulses are injected into the first IF because the calibration lines are too weak at 43 GHz. The lines can be extracted in the later stages of the receiving system by a digital Fourier-analysis technique that measures their amplitude and phase. The relative phases of different lines across the receiving passband provide a measure of the time delay of signals through the receiving system. Such variations are important only in the analog part of the system, since after the samplers the timing is controlled by digital clock pulses. Thus the extraction of the lines is performed in the formatter, which immediately follows the samplers. This type of calibration is particularly important in 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 25 times (14 dB) stronger than the 1 MHz lines. In the vertex room the frequency with the best determined phase is the 500 MHz since the phase stability of its cable is measured continuously. The 500 MHz is therefore used to provide the timing for the 5 MHz and 1 MHz pulse-triggering waveforms. A more detailed discussion of pulse calibration is given by Thompson and Bagri (1991); they describe a preliminary design for the VLBA that differs in some details of the pulse timing control from the system implemented.

5.10 Stability and Accuracy of Measurements

Stability of the gain and phase characteristics is a major consideration in the design of the electronic hardware. Power supply voltages are accurately regulated, and air temperatures in the vertex room and station building are maintained

Table 5.5: Radio astronomy allocations within VLBA bands

VLBA Band	Radio Astronomy Allocated Band	Alloc. Status[1]	Sharing Services, R. A. Lines, etc,
312–342 MHz	322–328.6 MHz	P	Fixed, Mobile, Deuterium line
596–626 MHz	608–614 MHz	P	Region 2
		S	Regions 1,3 except African Broad-casting Area. (Alloc. band was U.S. TV Ch. 37)
1350–1750 MHz	1400–1427 MHz	P (Pas)	Hydrogen line
	1610.6–1613.8 MHz	P	Mobile Sat. Serv. Radio-determination Sat. Serv., OH line
	1660–1670 MHz	P	Fixed, Mobile, Met.Sat., OH lines
	1718.8–1722.2 MHz	S	Fixed, Mobile, OH line
2150–2350 MHz	None		2290–2300 MHz Space Res., Deep Sp., Sp.-to-Earth
4600–5100 MHz	4800–4990 MHz	S	Fixed, Mobile, H_2CO line
	4990–5000 MHz	P	Fixed, Mobile
8000–8800	None		8400–8500 MHz, Space Res., Sp.-to-Earth
10.2–11.2 GHz	10.6–10.68 GHz	P	Fixed, Mobile
	10.68–10.7 GHz	P (Pas)	
12.0–15.4 GHz	14.47–14.5 GHz	S	Fixed, Fixed Sat., Mobile, H_2CO line
	15.35–15.4 GHz	P (Pas)	
21.7–24.1 GHz	22.21–22.5 GHz	P	Fixed, Mobile, H_2O lines
	23.6–24.0 GHz	P (Pas)	NH_3 lines
41.0–45.0 GHz	42.5–43.5 GHz	P	Fixed, Fixed Sat., Mobile, SiO lines

Note: [1] "P" indicates primary allocation; "S", secondary allocation; "Pas", passive band.

constant with a stability goal of ±1°C. Coaxial cables carrying IF or LO signals are buried below ground or thermally insulated to the maximum extent practicable. To minimize the effect of cable flexure at the azimuth cable wrap a support in the form of a spiral spring is used. The relative changes in delay between one cable and another is less than 8 ps over the full azimuth range, which is about an order of magnitude less than was measured when the cables were allowed to flex in an uncontrolled manner. During observations the path length of the 500 MHz reference cable is constantly monitored. The switched noise sources and pulse calibration system can be operated continuously, and the variations in system temperature, gain, and phase recorded are for use in later stages of the signal processing. Details of the VLBA receiving system beyond those included here can be found in Thompson (1993).

5.11 Observing Bands and Radio Interference

The observing bands of the VLBA are chosen so that, in most cases, they contain bands allocated to the Radio Astronomy Service in the Radio Regulations of the International Telecommunication Union. Such allocations have been made with the aim of protecting important radio lines and providing for continuum observations at intervals no greater than one octave in the frequency spectrum. The bands allocated to radio astronomy that fall within the VLBA bands are given in table 5.5 on the preceding page. Primary allocations are protected from interference by other services sharing the band, but secondary allocations are not. Passive bands are those in which no intentional transmissions are allowed. However, interference can occur in these bands from harmonics and spurious emissions of services in other bands. Column 4 of table 5.5 on the previous page is a simplified list of other services sharing the allocation, and also any radio lines. In the less intensively used parts of the radio spectrum observations can often be made outside the bands allocated to radio astronomy, and hence the VLBA bands are wider than the allocated bands. In the 2.3 and 8.4 GHz bands there is no band allocated to radio astronomy. (The 2.3 GHz front end can operate in a radio astronomy band near 2.7 GHz but the performance of the polarizer is degraded.) The bands 2.29–2.3 and 8.4–8.5 GHz contain allocations to deep space communications in the space-to-earth direction, and large antennas with very sensitive receivers for these bands have been built by the NASA Deep Space Network. During the past two decades observing time has been available for radio astronomy on these antennas, in particular for geodetic VLBI studies. As a result, the use of these bands and nearby frequencies for radio astronomy has now become an established practice.

It is important to be able to estimate the power levels at which man-made signals within the band of a radio astronomy receiver cause harmful interference. In the case of a total power measurements with a single antenna, interference simply adds to the total power level. Thus it begins to degrade the measurement accuracy when it is some significant fraction of the sensitivity level determined by the system noise. For interferometers and arrays the receiving system must be constantly adjusted for the fringe frequencies resulting from the sidereal motion of the radio source and for the different space-path delays of the signals in reaching the antennas. As a result, signals entering the antenna from directions outside the desired field to be mapped (i.e. through the sidelobes) are suppressed to a degree that increases with the spacing of the antennas. In VLBI these effects are even more critical, and the probability of interference from different antennas producing a correlated output is negligibly small. Furthermore, the likelihood of two widely separated antennas picking up the same interfering signal is small. In VLBI the mechanism by which an interfering signal can cause errors is by the addition of an uncorrelated component of radio power, similar to an increase in the system noise at an antenna. This will cause the automatic level control to reduce the system gain so as to keep the power level at the sampler input constant.

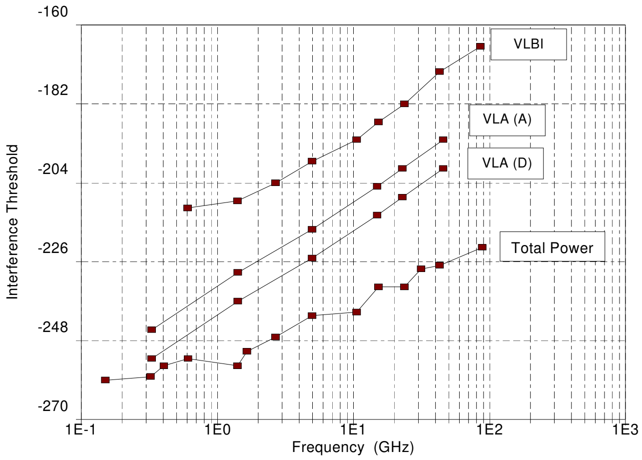

Figure 5.6: Representative values of the harmful threshold for interference received in sidelobes of gain 0 dBi, for various types of radio telescopes. The units of the ordinate are dB (W m^{-2} Hz^{-1})]. Connected-element arrays are represented by the VLA (NRAO) in either its large (A) or small (D) configurations.

In principle this change in gain can be measured by the noise calibration system, but this is difficult if the strength of the interfering signal varies rapidly, as is commonly the case. To keep the resulting amplitude errors below the 1% level, a safe criterion for the harmful threshold of interference is that which results in an increase in the received power equal to 1% of the system noise. The harmful level, S$_H$, expressed as spectral power flux density (W m^{-2} Hz^{-1}), is thus given by

$$A_s \, S_H = \frac{k \, T_s}{100} \tag{5.1}$$

where A_s is the collecting area of the antenna in the sidelobes through which the interference is received, k is Boltzmann's constant, and T_s is the system temperature. For a representative value of As one can take the collecting area of an isotropic radiator, $\lambda^2/4\pi$ i.e. a sidelobe gain of 0 dBi. Thus

$$S_H = \frac{0.04 \, \pi \, k \, T_s}{\lambda^2} \tag{5.2}$$

Harmful threshold levels in terms of power flux density (W/m^2) are obtained by multiplying by the receiver bandwidth used. figure 5.6 shows the plots of the harmful interference threshold as a function of frequency for various types of radio telescopes, using typical values for the various system parameters. In all cases the interference is assumed to be received in sidelobes of gain 0 dBi, and the curve for VLBI is derived from equation 5.2. The decrease in S_H with frequency results from the λ^{-2} dependence of the sidelobe collecting area. Note that the harmful threshold for VLBI is 40 to 50 dB higher than for total power measurements, i.e. VLBI observations are to that degree less vulnerable to interference. Nevertheless, the harmful thresholds for VLBI are small compared with power levels of many communications systems, so interference is by no means rare in VLBI observations. For a more detailed discussion of interference see chapter 14 of Thompson, Moran, and Swenson (1986).

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