OVLBI-ES MEMO NO. 12

GREEN BANK EARTH STATION: SYSTEM DESIGN PRINCIPLES

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The current top-level block diagram of the Green Bank OVLBI Earth Station is given in Figure 1. The present report will describe this design, with emphasis on the major principles being used. Some details discussed here are subject to change as the design becomes more refined. The reader is assumed to be familiar with the overall functional requirements for this station.

A summary of the main performance parameters of the station is given in Table 1.

I. DESCRIPTIONS OF SUBSYSTEMS

The station can be separated into a few major subsystems: the main reflector antenna, with all its mechanical drives and servos; the feeds and optics; the RF subsystem, including cryogenic front ends and downconverters; the wideband data handling and recording; the two-way timing link electronics; the reference signal generation and distribution; and the real-time control and monitoring subsystem. The remainder of the station hardware may be classified as infrastructure, common to several subsystems: power supplies, packaging, temperature control, equipment building, cables, etc.

The equipment can be further classified according to its present status. Some already exists, including the main antenna subsystem and much infrastructure. Some will be exactly the same as in the VLBA, so that the designs are now complete, although new modules must be constructed. And some requires the development of new designs. These distinctions are indicated in Figure 1.

Main Antenna: The main antenna is an existing 45-ft (13.7 m) diameter paraboloid on an elevation-over-azimuth pedestal supported on a steel tower. It includes drive motors, brakes, an analog servo system with velocity and position feedback, and both manual and computer control interfaces. It also includes a two-axis positioning mechanism at the prime focus. The performance characteristics of this antenna are summarized in section 1.0 of Table 1.

Feeds and Optics: The present plan is to use room-temperature dichroic optics to separate the signals into two bands, which are then processed through separate corregated feed horns and cryogenic front ends. Both feeds would be at the cassegrain focus. Required components include a 1.9 m diameter subreflector, a planar dichroic reflector, an ellipsoidal mirror, and the two feeds. We will attempt to cover the entire space research allocation in each band, namely 7.190-7.235 GHz, 8.4-8.5 GHz, and 13.4-15.35 GHz (secondary); this may be difficult, in

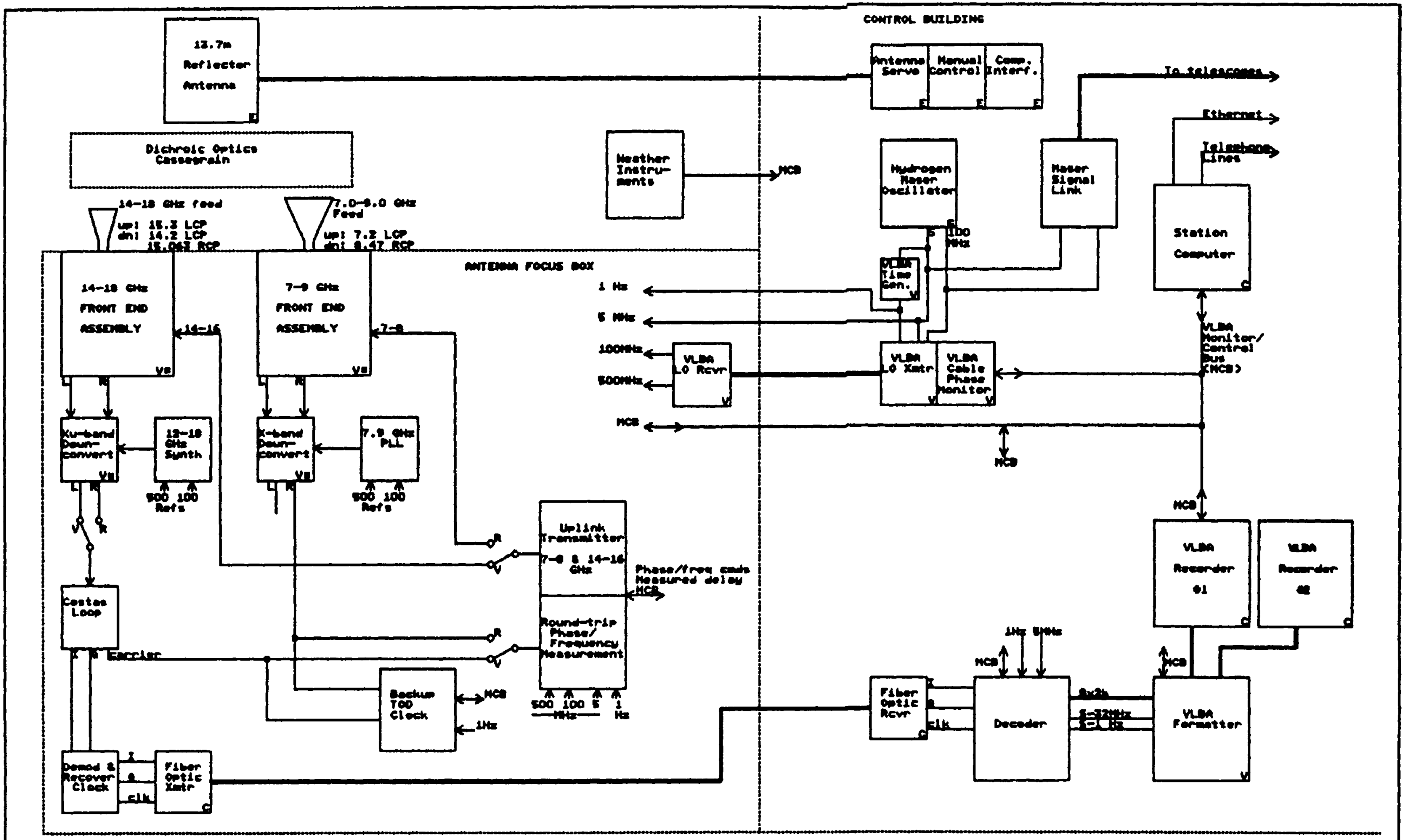

FIGURE 1: BLOCK DIAGRAM

Symbols: C = purchase commercially
V = VLBA design
Vm= modified VLBA design
E = pre-existing

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Title OVLBI EARTH STATION - block diagram		
Size B	Document Number BLOCKDIA	REV
Date:	May 20, 1991	Sheet 1 of

TABLE 1: SUMMARY OF MAIN PERFORMANCE PARAMETERS

	Present Estimate	Worst Case	Units
1.0 Antenna: 13.7 m diameter paraboloid on elevation-over-azimuth mount.			
1.1 Gain at 7.2 GHz	(55%) 57.7	57.2	dBi
1.2 Gain at 8.5 GHz	(50%) 58.7	58.2	dBi
1.3 Gain at 15.0 GHz	(40%) 62.7	62.2	dBi
1.4 Gain at 16.7 GHz	(35%) 62.6	62.1	dBi
1.5 Tracking range			
1.5.1 Azimuth	-162 to +373		deg
1.5.2 Elevation	+3 to +112		deg
1.5.3 Speed, each axis	40	35	deg/min
1.6 Pointing error, absolute, max.			
1.6.1 Elevation > 25 deg	.008	.015	deg
1.6.2 Elevation > 5 deg [1]	.028	.033	deg
2.0 Receivers and Feeds: cryogenically cooled HEMT amplifiers, dichroic Cassegrain optics, corrugated horns.			
2.1 Noise temperature due to receiver alone			
2.1.1 at 8.2 to 8.6 GHz	15	30	K
2.1.2 at 14.5 to 15.5 GHz	25	35	K
2.2 Noise temperature due to scattering and spillover			
2.2.1 at 8.47 GHz	7	10	K
2.2.2 at 15.05 GHz	5	8	K
2.3 Feed and optics loss			
2.3.1 at 8.47 GHz	0.2	0.5	dB
2.3.2 at 15.05 GHz	0.2	0.4	dB
2.4 System temperature in clear weather [2]			
2.4.1 at 8.47 GHz, zenith	41	77	K
2.4.2 at 15.05 GHz, zenith	50	75	K
2.4.3 at 8.47 GHz, 5 deg elev.	72	109	K
2.4.4 at 15.05 GHz, 5 deg elev.	92	117	K
2.5 Polarization mismatch (all freq)	0.2	0.5	dB
3.0 Transmitters: phase and frequency controlled relative to hydrogen maser local standard; phase-continuous tuning.			
3.1 Tuning resolution	0.01	0.1	Hz
3.2 Update rate for phase & freq.	1000	10	Hz
3.3 Power to feed			
3.3.1 at 7-8 GHz	1.0	0.8	W
3.3.2 at 14-16 GHz	0.1	0.05	W

Notes:

[1] At low elevations, pointing error is dominated by refraction.

[2] Including: receiver; feed and optics loss at 290 K; spillover and scattering noise; and sky at 2.8K + T csc e, where T=3K at 8.47 GHz and T=4K at 15 GHz and e=elevation.

which case we will optimize performance for the frequencies actually used by the two spacecraft. Alternative designs are also being studied.

RF Subsystem: Two vacuum dewars with separate 15 K helium refrigerators will house low-noise electronics. The dewars will use the VLBA design for all mechanical and thermal parts, but there will be slight modifications to the circuitry to accommodate the need to transmit as well as receive. The dewars are small enough so that they can be mounted directly under their respective feeds, with no significant waveguide runs. Cooled LNAs will be provided for both right and left circular polarization, although normally only one will be used at a time. The uplink (transmitted) signals will also pass through the dewars, but will be processed there only by passive components. This allows the necessary switches, isolators, and filters to be kept cold, which keeps their losses low and ensures excellent phase stability.

The received signals will all be converted to an IF center frequency in the range 500-600 MHz, using LOs of 7.9 GHz, 13.6 GHz (for VSOP at 14.2) and 15.6 GHz (Radioastron at 15.063 GHz). Other frequencies in the allocated bands can also be accommodated at IFs from 500-750 MHz. The LO frequencies are always of the form N*(500MHz)+-100MHz, and will be synthesized in phase locked loops from references at 500 MHz and 100 MHz. An important aspect of the design is that only one reference, 500 MHz, is multiplied to high microwave frequencies. Special efforts are made to transmit this reference to each synthesizer with precisely controlled phase (see Reference Distribution, below).

Wideband Data Subsystem: The QPSK-modulated IF will be fed to a Costas demodulator and bit synchronizer. The recovered carrier will be available to the Two-Way Timing subsystem (see below). The data streams and clock will then be transmitted to the decoder (using a fiber optic link from the antenna to the control building), where the headers will be separated from the signal samples; header data will be logged and the samples will be sent to the recording system. Sample times occupied by header information will be replaced by pseudo-random noise for recording. The decoder also contains the main UTC clock, driven by the maser; this will establish the relationship of recorded times to UTC. The recording system consists of a VLBA Formatter and two VLBA Recorders. The formatter contains the tape-time clock, which is driven by the received data stream. It also contains a calibration tone extractor and a 4 Mb buffer that can be used for near-real-time fringe checks on strong sources.

Two-Way Timing: The transmitted signal must be rapidly tuned in frequency so as to cancel the uplink Doppler shift. This requires a rapidly programmable, phase continuous synthesizer with a range of about 100 kHz. Since the two spacecraft are on different frequencies (7.215 and 15.3 GHz), and since we want to allow for the use of other frequencies within the Space Research allocations, slower tuning over a much larger range will be provided. The transmitted signal will be generated by 7-8 GHz VCO in an offset PLL, with a doubler inside the loop to cover 14-16 GHz. The references will be a harmonic of 500 MHz and a (low) harmonic of a DDS near 10 MHz; any frequency that is not very near a harmonic of 500 MHz is available. The DDS frequency and phase will be updated frequently by a dedicated microprocessor; the update rate will be programmable, probably up to several kHz. Accurate computations of the required phase and several of its derivatives will be performed once per second by the station computer and downloaded to the microprocessor.

The received downlink signal will be at IF (500-600 MHz), either from the downconverter or from the Costas loop. It is converted to near 10 MHz for phase comparison with the predicted carrier. The latter is generated in a DDS similar to that used for the transmitter, using the same update rate and method. Quadrature phase detectors are sampled at a programmable rate (probably up to 10 kHz) and processed to obtain a continuous measure of time residual. The latter involves keeping track of cycle completions to resolve the 2n\pi ambiguity. The smoothed residual will be provided to the station computer about 10 times per second.

Reference Distribution: All timing signals will originate in a hydrogen maser oscillator, which provides 5 MHz and 100 MHz outputs locked to the atomic line. The maser outputs will be used to generate 1 Hz and 500 MHz references. The 1 Hz will be synchronized to UTC via an external time service (LORAN-C, GPS, or VLBI). All four reference signals will be brought from a nearby control building to the antenna-mounted electronics by coax cables [optionally by optical fibers]. The highest frequency reference is most critical; it will be sent both ways on its cable, so that variations in the cable's electrical length can be measured and corrected. All modules of this subsystem are identical to those used in the VLBA.

A system for distributing the maser reference signals to other instruments at Green Bank (GBT and other telescopes) will be provided by other groups at the NRAO; details are TBD at this time. This will allow a phase stable baseline to be established between the ground and space telescopes.

Control and Monitoring: All equipment at the station will be connected to a real-time computer for control and monitoring. The hardware communication will be via the VLBA Monitor and Control Bus (MCB), which is a two-way, multi-drop, serial bus [**ref]. The computer is expected to be an 80386-33 with 80387 coprocessor in a PC-AT architecture. Special application code will be written under an operating system compatible with UNIX but supporting real-time programming. The station computer will be connected to a local ethernet and thence to the Internet; this will be used to support remote control and diagnosis of problems, as well as transfer of files. Operation of the station will be fully automatic, except for the mounting and dismounting of recording tapes. The computer will read and follow one or more schedule files, and will create several log files for each tracking pass. Programs will be run off-line to convert the real-time logs into forms specified for interfaces to other mission elements.

II. DISCUSSION OF DESIGN PRINCIPLES

The two major tasks of the station, namely to demodulate and record the wideband data and to transfer a precise timing reference to the spacecraft, can be considered separately. The first is a rather straightforward communication task, where the performance is mainly measured by the bit error rate. We need only ensure adequate SNR and efficient demodulation and bit synchronization to achieve the desired performance. Care is needed with the time-tagging of data samples, since this is derived from the data stream itself; this is a complicated issue and is dealt with elsewhere (see, e.g., OVLBI-ES Memos 3, 10, and 11). The second task, precise time transfer, requires special efforts in the station electronics design in order to avoid degrading the phase stability of the reference signal. Most of the remarks in this section will be related to these efforts.

A. Compact design. As far as possible, we have kept all of the components that determine the two-way timing inside a small volume with minimal cabling. Thus, both the uplink's phase-locked oscillator and the downlink's phase detector are mounted on the antenna near the front ends, as are all LOs used in the signal paths. The Costas demodulator for the wideband data is also in this package because VSOP uses the recovered data carrier as the timing downlink. All of these critical components are expected to fit in a 1-cubic-meter box. Tight temperature control of this box will be feasible if needed.

B. Careful choice of reference signals. The hydrogen maser must be off the antenna, so its signals must be transferred to the antenna-mounted package. Each reference frequency sent is fixed (not tunable), so any dispersive effects in the transfer are avoided; tuning, to the minimum extent necessary, is implemented by synthesis within the antenna-mounted package. To allow synthesis of all necessary frequencies without ambiguity, a sufficiently low reference frequency is needed (we use 1 Hz); but to avoid excessive multiplication ratios that lead to high phase noise, a relatively high frequency reference is also needed (we use 500 MHz, with intermediate references at 5 MHz and 100 MHz). Only the highest frequency reference is multiplied to microwave frequencies. [Actually, we would have liked to avoid multiplication of any of the others, but available components make it impractical to synthesize the necessary frequencies without using harmonics of a lower reference; so the 5 MHz is multiplied to 10--250 MHz in the second LO synthesizer.] This highest reference is transferred up to the antenna package via a cable whose electrical length is continuously monitored, enabling us to account for the inevitable changes due to temperature and flexing.

C. Wideband design. Low temperature coefficient of phase and delay in all signal paths is obtained by using wideband design techniques. Nearly all RF and microwave components are at least octave bandwidth, even when the signals cover a much narrower range. Filters are used only where clearly needed, and then the bandwidth/(number of poles) is kept as large as possible. Phase-locked loops, which are used extensively, must have their loop bandwidths large enough to track out all of the intrinsic phase noise of the locked oscillator. This often requires selection of oscillators with well-specified noise characteristics.

D. Avoidance of ALC loops. Automatic level control loops are often used in communication systems, but it is difficult to avoid significant phase variation with gain. In our application, both received signals (timing downlink and wideband data) are delivered to phase detectors whose dynamic range will be greater than 20 dB. This greatly exceeds the signal range expected in any one tracking pass, so ALC loops will not be required. However, the total signal range for all possible tracking passes is about 26 dB (see Appendix A), so some gain adjustment is provided in the downconverters; the gain is set by the computer prior to the tracking pass and is thereafter left fixed.

E. Use of existing designs whenever possible. We make extensive use of designs that are already available within the NRAO, especially from the VLBA. This is made easy because the earth station is, in large part, a portion of a VLBI radio telescope. In some cases, complete subsystems can be adopted without change. In other cases, we adopt the design of small assemblies or modify the design of a module. In addition to electronic hardware, we will also re-use large sections of control software written for the VLBA, especially those used to control the VLBA recording system.

The use of commercially available equipment is considered wherever the required performance can be procured "off the shelf." But commercial contracts for custom designs are avoided because of the cost, delay, and extra administration involved; exceptions to this will be made if in-house expertise is lacking in some critical area.

F. Built-in test facilities and monitoring. Test signal generators will be built into several modules to allow verification of correct performance. Various signals will be brought to front panel connectors to allow local checking with appropriate instruments (oscilloscopes, spectrum analyzers). Extensive monitoring will be provided through the MCB, well beyond that needed for status checking, so as to facilitate remote diagnosis of problems.

APPENDIX A: CALCULATION OF REQUIRED DYNAMIC RANGE AND GAIN

We calculate here the total power expected from each of the downlinks under the extreme conditions of (a) minimum range and minimum loss, and (b) maximum range and maximum loss, for each spacecraft. This determines the absolute gain and dynamic range required in the receivers.

Spacecraft parameters assumed:

Radioastron:	15.06 GHz	10 W QPSK,	37 dB gain	->	EIRP=47 dBW
	8.47 GHz	1 W CW,	24 dB gain	->	24 dBW
VSOP:	near 15 GHz	4 W QPSK,	29 dB gain	->	35 dBW

Earth station parameters assumed:

8.47 GHz: 13.7 m dish, 50% eff -> effective area = 73.7 m^2
15 GHz: 13.7 m dish, 40% eff -> effective area = 59.0 m^2

Losses assumed:

Pointing, polarization, ohmic:	-2.0 dB
Atmosphere:	0.0 dB best to -3.0 dB worst

Calculation:

CONDITION	RECEIVED TOTAL POWER 8.5 GHz	 15 GHz	
Noise only (Tsys=20K,40K; BW=500MHz)	-128.6	-125.6	dBW
Radioastron			
Range 4000 km, minimum loss	-102.4	-83.3	
Range 80000 km, maximum loss	-128.4	-108.4	
VSOP			
Range 2000 km, minimum loss		-86.3	
Range 25000 km, maximum loss		-110.3	
Dynamic range, signal only	26.0	27.0	dB
Max gain for -10 dBm (-40 dBW) signals	88.4	70.3	dB
Gain for -30 dBm noise in 500 MHz	88.6	85.6	dB

Discussion

The Costas demodulator and phase detector should each have a dynamic range of at least 20 dB (10:1 in voltage). The dynamic range expected on any one tracking pass will be much less than the maximums given above; simulations indicate that the worst case is about 17 dB for Radioastron (range varying from 9000 to 70000 km). Therefore, operation without ALC loops is possible. Some gain adjustment will be needed at the start of each pass, but it can then be left fixed.

There will typically be 45 dB of gain in the front end before any frequency conversion; no gain adjustment is needed ahead of this point, since the levels are always well below saturation. Allowing 10 dB for mixing and filtering losses, we will need 51 dB of IF gain for 8.5 GHz and 35 dB at 15 GHz. This should be adjustable downwards by 30 dB in steps of 1 to 2 dB by means of a computer-controlled attenuator at IF.

To allow for doing astronomical observations using the VLBA IFD and BBCs, we need the noise level to be brought up to -30 dBm in 500 MHz. This requires about the same gain at 8.5 GHz, but about 15 dB more at 15 GHz.