OVLBI-ES MEMO NO. 48

REFERENCE TRANSMISSION SYSTEM: DESIGN AND TEST RESULTS

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Summary

This report describes the OVLBI Earth Station reference transmission system, which begins with a hydrogen maser at the Interferometer Building and ends with the delivery of timing reference signals at several frequencies (1 Hz, 10 MHz, 100 MHz, and 500 MHz) to various modules of the station. We concentrate here on the round-trip transmission of the maser reference to the station via optical fibers, including measurement of the two-way delay. Maser-derived 10 MHz and 500 MHz signals are sent to the station, and 500 MHz is sent back over a separate but identical fiber in the same bundle. Generation of the other signals and distribution of all signals to the destination modules is covered briefly; details will be given in the module manuals. The signal transmission and delay measurement make use of modified VLBA modules; the necessary modifications are documented here. Test results are also presented. Using a 250-foot spool of optical cable, it appears that changes in one-way length of ~10ps are determined by the two-way phase measurement with an accuracy of <0.5ps and a measurement noise of <0.1ps (in 3 sec integrating time).

1. SYSTEM DESIGN

An overview of the OVLBI-ES reference distribution system is shown in Figure 1. The hydrogen maser provides 10 MHz and 100 MHz signals to the Reference Transmitter Module (L102-OV), which multiplies the 100 MHz by 5, combines it with the 10 MHz, and sends the composite signal to the laser transmitter. A portion of the 500 MHz signal is used as the main reference to an offset PLL in which a VCXO is locked to 500.0001302 MHz. The laser transmitter (Laser Diode, Inc. model LANA-2013) of a simple type; it uses a bias-current modulated Fabre-Perot laser diode at 1310 nm wavelength to supply about 0.5 mW to the fiber. Since this much power would saturate the detector diode (the fiber loss being only a few dB), an optical attenuator is installed near the laser. This also helps to minimize the effects of reflections in the fiber, which have a tendency to cause intensity noise in the laser output. The transmitter's input matching circuit provides very flat response from about 1 MHz to 1200 MHz.

The single-mode fiber runs continuously from the transmitter at the Interferometer Building to the electronics box at the vertex of the 45-foot antenna. Sections of fiber are joined by fusion splicing where necessary, but connectors are used only at the transmitter and receiver. The optical receiver is a single PINFET device (Laser Diode Model LDPM1000) with a bandwidth of about 1 GHz. Its output is delivered to the Reference Receiver Module (L105-OV) in the vertex rack, where it is split in a power divider. One signal goes to a d.c.-coupled PLL that locks a 500 MHz VCXO with a loop bandwidth of a few hundred Hz; this VCXO provides the high frequency reference to all the station microwave electronics (the first LO synthesizers and the Transmitter). The other signal passes through a 10MHz/1MHz BPF to select the 10 MHz reference, and then the latter is re-timed to the locked 500 MHz reference in a fast GaAs flip-flop (see [1]). The re-timed 10 MHz (now a square wave) is distributed to the station and is also used to lock another VCXO at 100 MHz. This VCXO provides the

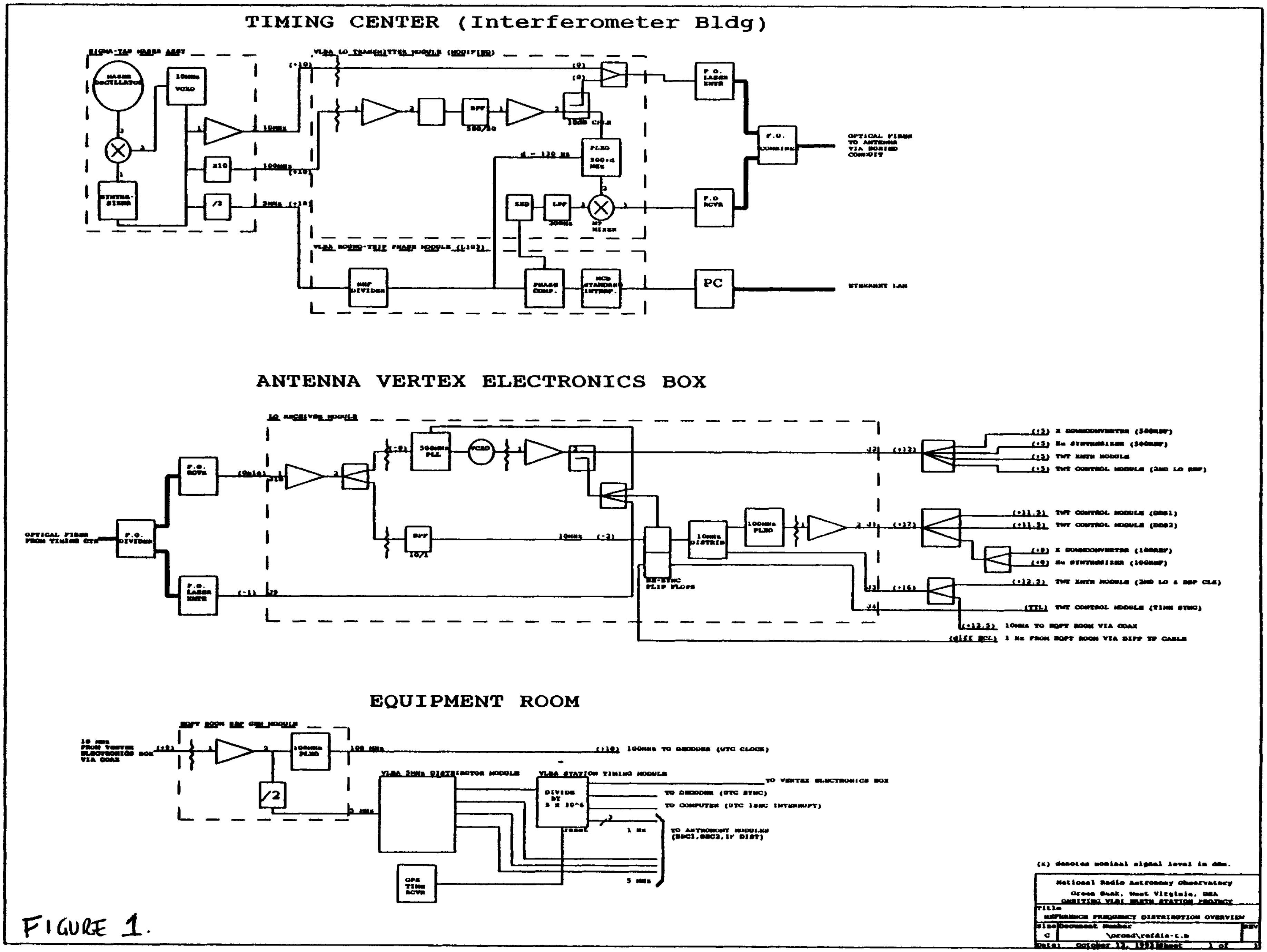

TIMING CENTER (Interferometer Bldg)
ANTENNA VERTEX ELECTRONICS BOX
EQUIPMENT ROOM
PC
(x) denotes nominal signal level in dBm.
National Radio Astronomy Observatory
Green Bank, West Virginia, USA
Title
REFERENCE FREQUENCY DISTRIBUTION OVERVIEW
October 13, 1993

FIGURE 1.

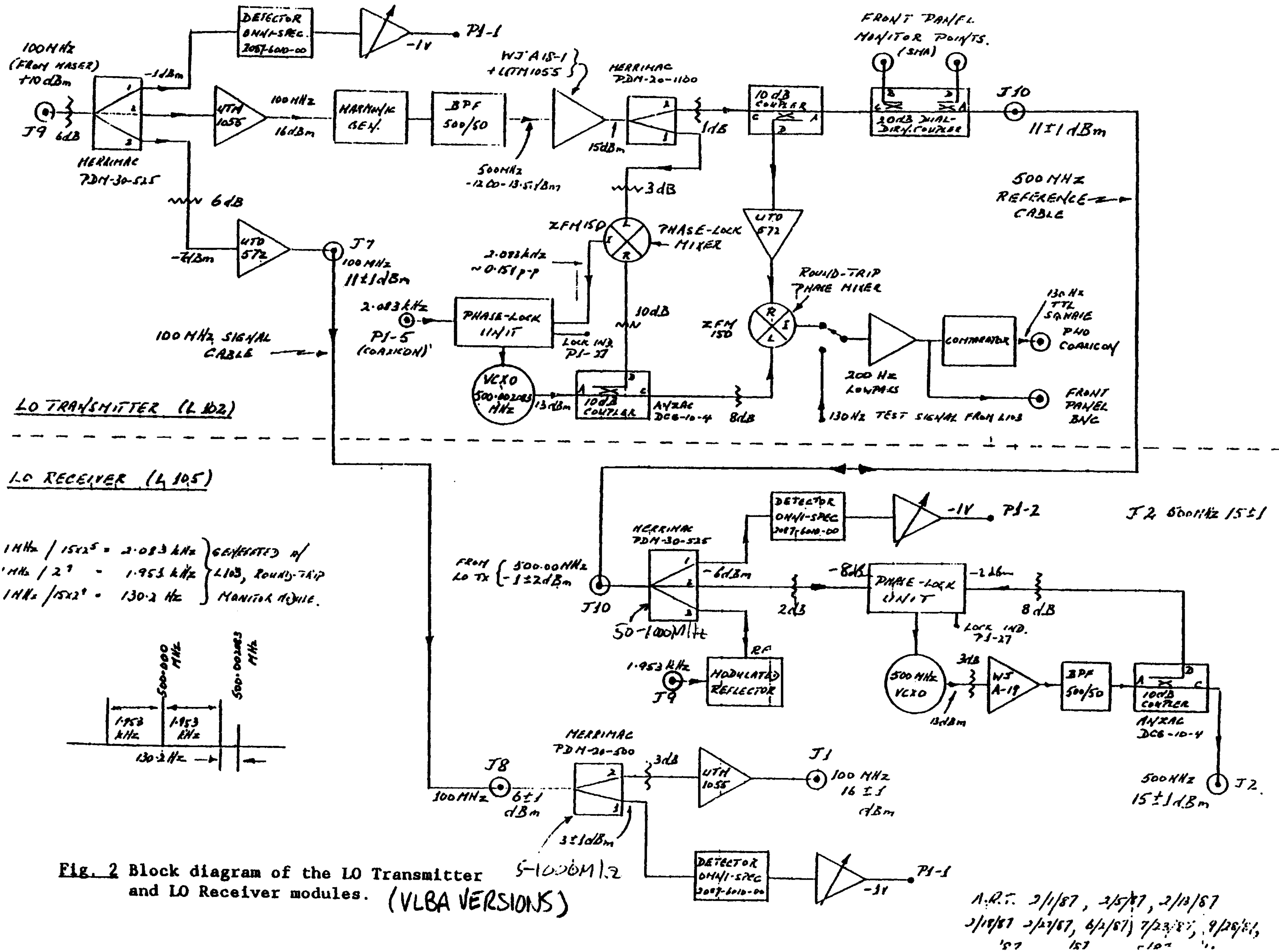


Fig. 2 Block diagram of the LO Transmitter and LO Receiver modules. (VLBA VERSIONS)

100 MHz reference to the station. The 10 MHz reference goes to the Two Way Timing Control Module (OV1) and via coax to Rack L in the Control Building. There it is again multiplied to 100 MHz using a PLXO and it is also divided down to 1 Hz. Provision is made to synchronize the phase of the divider to UTC. These 1 Hz and 100 MHz signals are needed by the station computer and the Decoder, both in Rack M. The 1 Hz reference is sent back to the vertex via cable, where it is re-syncronized to the 500 MHz and 10 MHz in another fast flip-flop. This signal allows the Two Way Timing residual phase measurements to be aligned with UTC.

Meanwhile, the 500 MHz reference from the locked VCXO is also sent to a laser transmitter where it is used to modulate another 1310 nm optical signal for sending back to the Interferometer Building. This return path is nominally identical to the outgoing one, using a second fiber in the same bundle for all segments. [Fig. 1 actually shows another option for the design, not yet thoroughly tested. This is to use the same fiber in both directions by wavelength-division multiplexing. In that case, the return signal would be at 1550 nm. In fact, the tests reported below actually used a 1550 nm laser for the return path, although via a separate fiber.] At the Interferometer Building, the optical signal is detected in a PINFET and returned to the L102-OV module, where it is mixed with the offset 500 MHz VCXO's output to produce a 130.2 Hz difference signal whose phase is proportional to the two-way path length. That phase is measured digitally in the Round Trip Monitor module (L103-OV) and the results are available on the MCB. [We envision use of a small PC at the interferometer building to collect data from the L103-OV module and make it available to anyone -- including the OVLBI station computer -- over the ethernet. This PC could also service similar hardware supporting other users, such as the GBT. However, if the station computer's MCB is extended to the Interferometer Building, then it could read the data directly.]

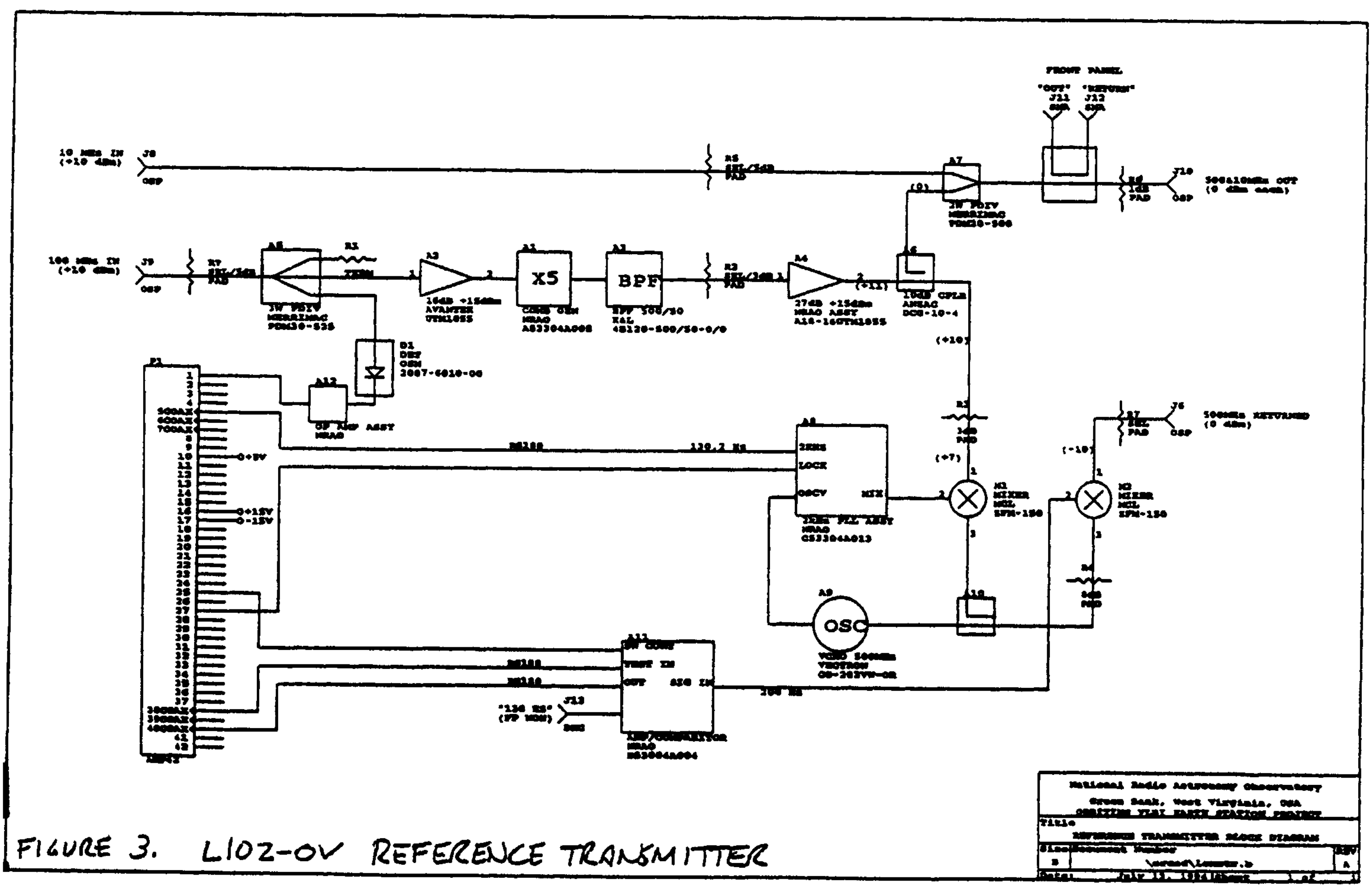


FIGURE 3. L102-OV REFERENCE TRANSMITTER

2. MODIFICATIONS TO VLBA MODULES

The L102-OV, L103-OV and L105-OV modules that handle most functions of the reference distribution system are modified versions of the VLBA modules L102, L103, and L105, respectively. Block diagrams of the L102 and L105 (from [2]) are reproduced in Figure 2. Here we describe the modifications. Detailed design data and parts lists for the new components will be given in module manuals, to be prepared later.

2.1 Reference Transmitter Module, L102-OV

The OVLBI version block diagram is given in Figure 3. The changes from the VLBA version are fairly minor, and while the modified module is not interchangable with the original, it would not be difficult to change it back. The modifications are:

2.1.1 The 10 MHz reference input is added at J8, and a power combiner is installed to add it to the 500 MHz reference at the output, along with pads for adjusting the signal levels.

2.1.2 The returned 500 MHz input is added at J6, and the internal wiring is changed to use it instead of the directional coupler on the single coax line that is used for both directions in the VLBA version. Note that the VLBA uses an offset of 2.1 kHz between the outgoing and returned 500 MHz references, whereas we use exactly 500 MHz in both directions.

2.1.3 The low-frequency reference to the offset PLL is changed from 2.1 kHz to 130.2 Hz by (a) connecting it to a new 130.2 Hz signal brought over from L103-OV via P1-5; and (b) changing the loop bandwidth from 104 Hz to approximately 14 Hz by changing the loop filter components as shown in Figure 4.

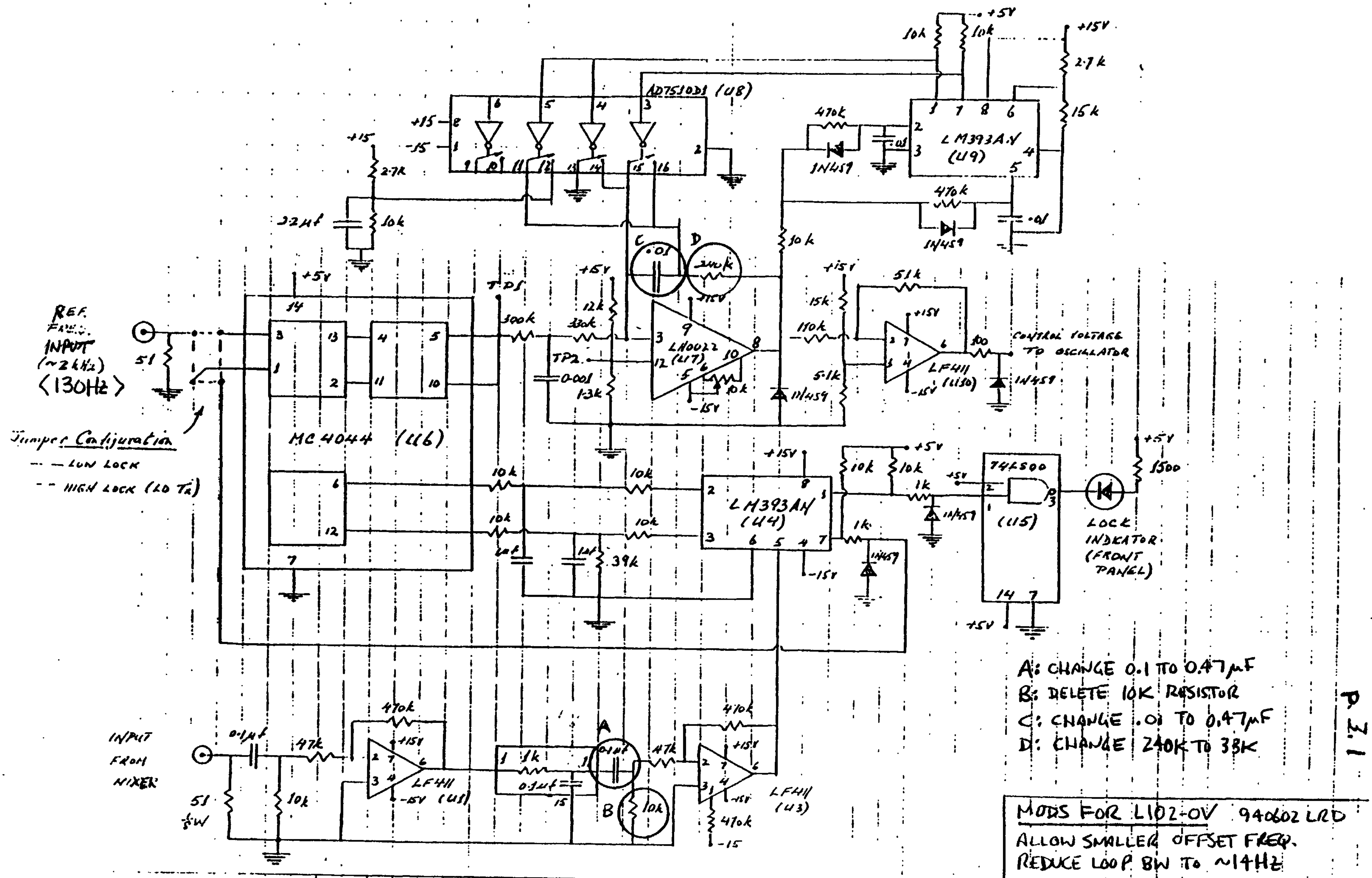
2.2 Round Trip Monitor, L103-OV

The modifications here are very minor and the modified module is essentially interchangable with the original. Details are given in Figure 5. Details of the VLBA design are given in [3]. The changes are:

2.2.1 Add an internal coax cable and make minor changes to the wirewrap board so as to bring the 130.2 Hz reference signal to P11-6. An inter-module cable then brings it to L102-OV.

2.2.2 Replace the external 1PPS reference that controls the timing of the phase detector integrations with an internally generated 1.017 Hz reference. This involves the addition of two MSI logic chips to the wirewrap board.

The second change was made because it is inconvenient to provide the 1PPS reference in our application, but it turns out that it corrected a flaw in the VLBA design and avoided a difficulty that they encountered. The flaw is that their design produced intergrations that are not an integral number of cycles of the 130.2 Hz measurement frequency; counting for the fractional cycle creates an error in the phase measurement except when the phase difference is zero or one-half cycle. The difficulty is that the 1.9kHz and 2kHz references used to offset the 500 MHz are also not multiples of the integrating period, so they need to have their phases reset at the beginning of each integration; this causes a phase glitch in the analog electronics for which a settling time allowance must be made. In our modification, these difficulties are avoided since the integrating time is an integral number of cycles.



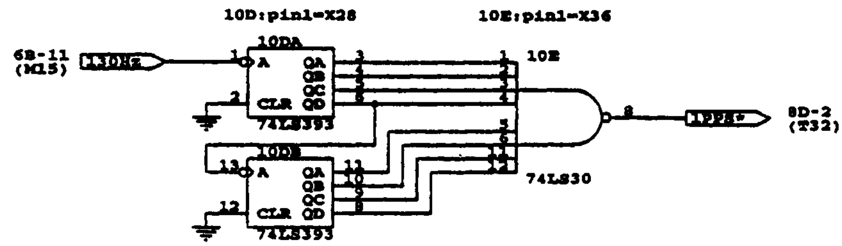
A: CHANGE 0.1 TO 0.47μF
B: DELETE 10K RESISTOR
C: CHANGE .01 TO 0.47μF
D: CHANGE 240K TO 33K

MODS FOR L102-0V 940602 LRD
ALLOW SMALLER OFFSET FREQ.
REDUCE LOOP BW TO ~14HZ

R.T. 5/1/86, 12/19/86, 4/23/87, 6/4/87, 6/30/87, 7/5/89, 8/1/89, 11/6/89.

FIGURE 4.

Circuit diagram of phase lock unit used in the LO Transmitter module. This unit is designed for use with input signals near 2 kHz.



MODIFICATION PROCEDURE -- VLBA VERSION TO OVLBI VERSION

1. Install 74LS393 at 10D and 74LS30 at 10E.
2. Wire as shown here.
3. Remove Coaxicon male connector from pin 39 of AMP connector P11 (rear panel). Secure inside module.
4. WW 1G-5 (4C49) to P1-62 for 130Hz reference to PLL.
5. Install RG188 coax from P1-62 to coaxicon pin at P11-6 (rear panel).
6. Remove wire from 1G-6 to ground; add 1G-6 to 1G-4.

(Items 4..6 may be omitted if supplying the 130Hz to another module is not required.)

MODIFICATION PROCEDURE -- OVLBI VERSION TO VLBA VERSION

1. Remove chip at 10E (74LS30).
2. Re-insert Coaxicon connector at P1-39.

NEW PARAMETERS	
"1PPS" frequency	1.01725254 Hz
Integrating time	2.938560.. sec
Maximum count	14,692,800

National Radio Astronomy Observatory
Green Bank, West Virginia, USA
ORBITING VLBI EARTH STATION PROJECT

Title		
	MODIFICATIONS TO L103 MODULE	
Size	Document Number	REV
A	\orcad\l103mods.sch	
Date:	July 6, 1994 Sheet	of

FIGURE 5 ROUND-TRIP MONITOR MODS

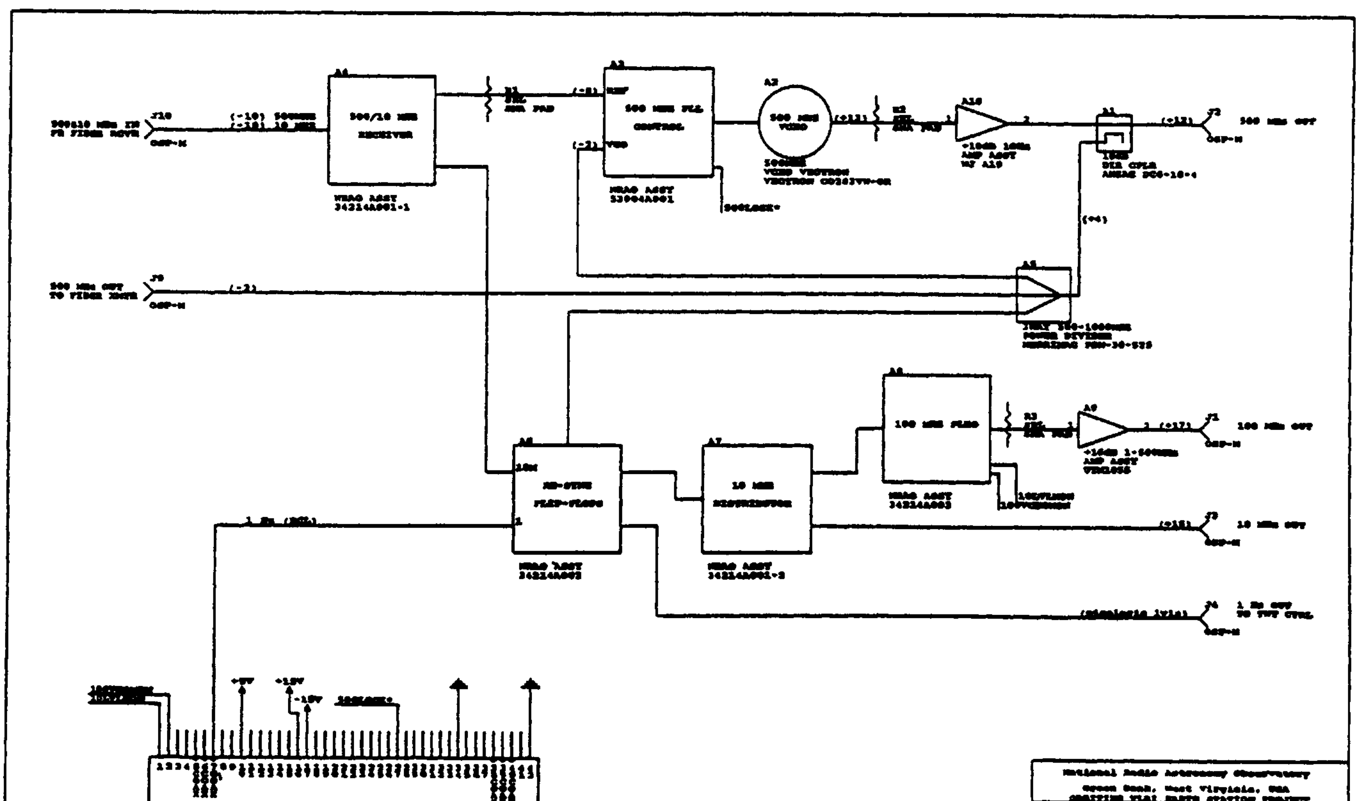


FIGURE 6. REFERENCE RECEIVER L105-OV

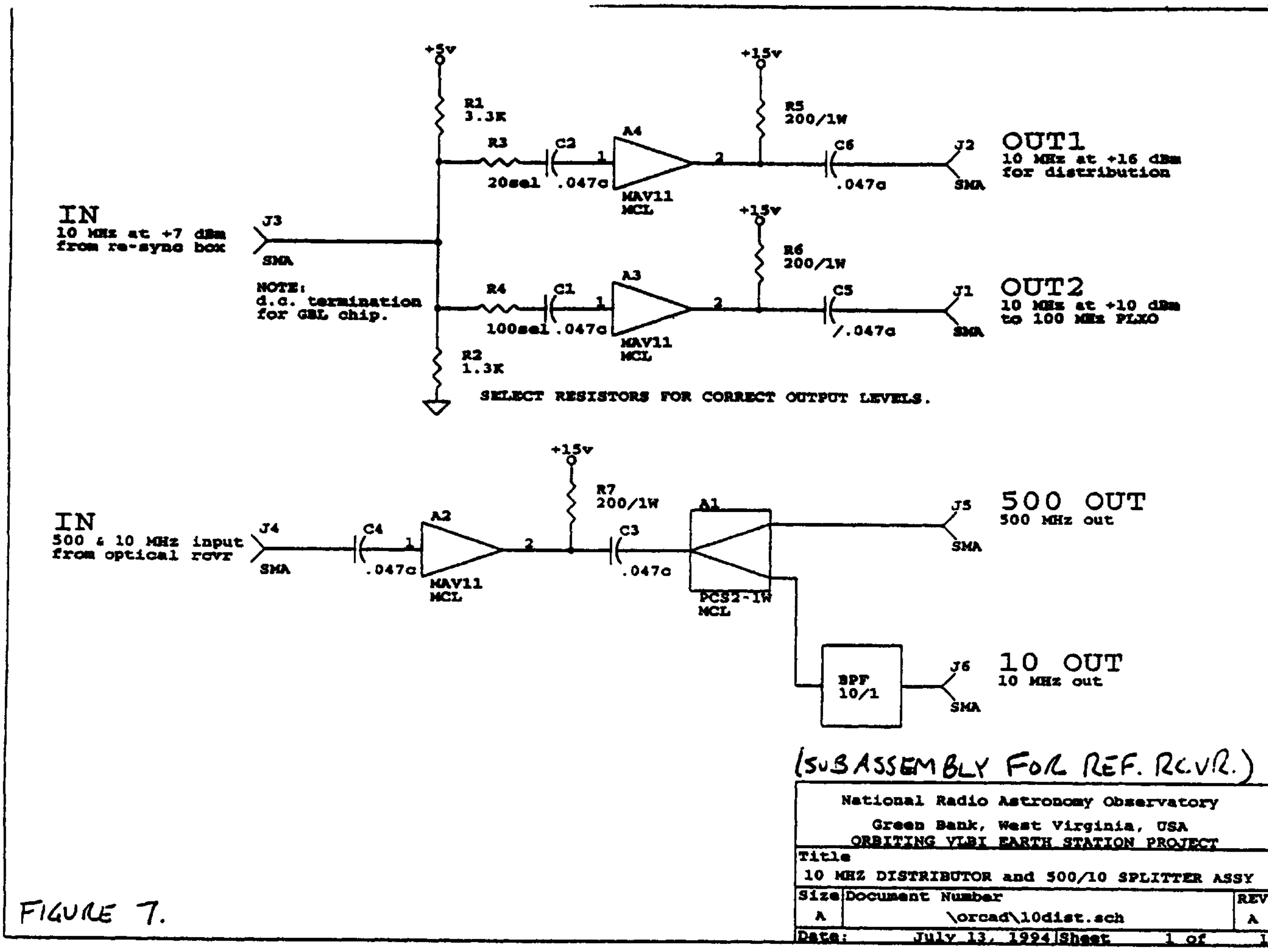
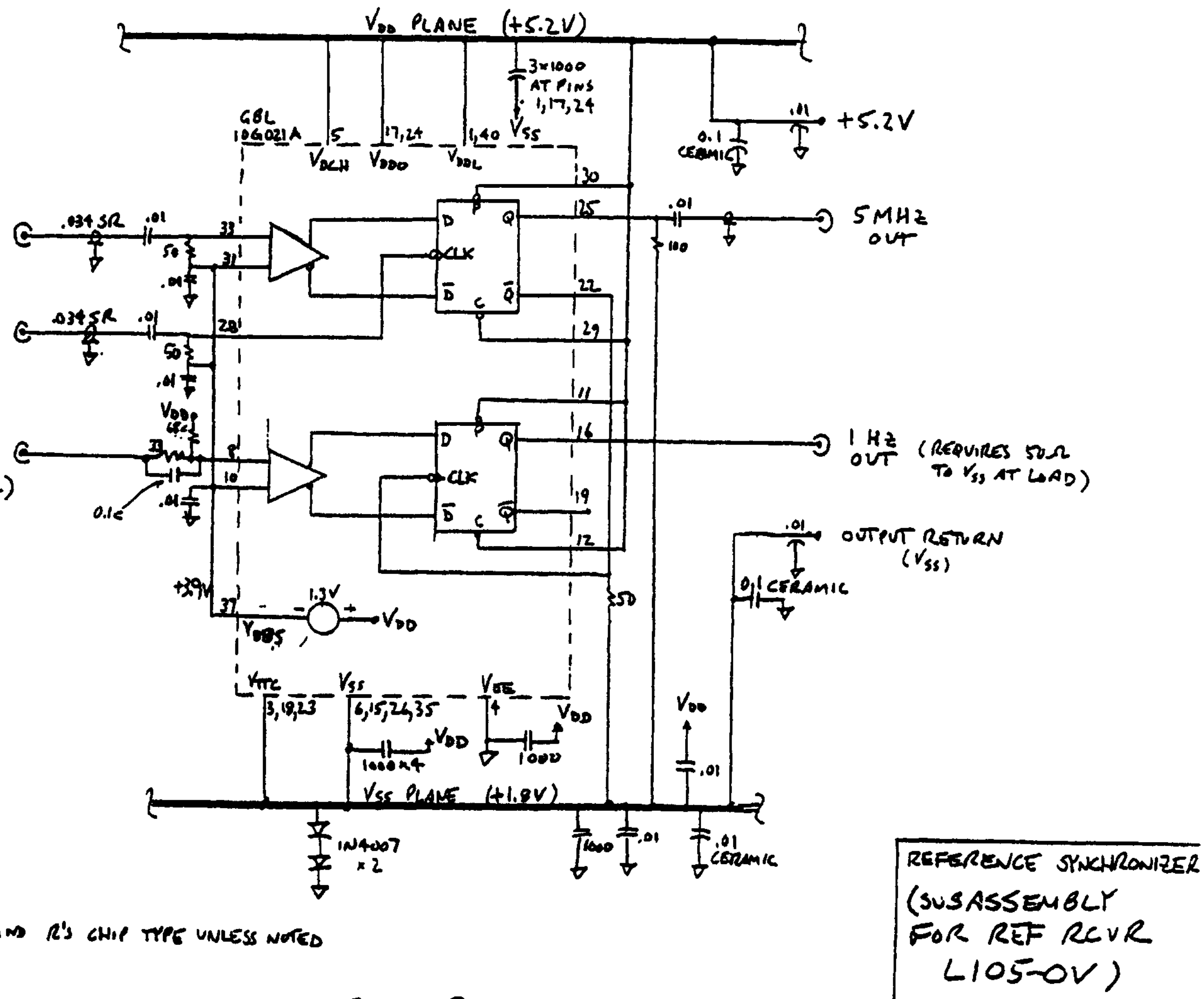


FIGURE 7.



ALL C's AND R's CHIP TYPE UNLESS NOTED

FIGURE 8

If the modified module were used in the VLBA, the changes would be difficult to notice. The first change is transparent, since the new signal uses module pins that are unused in the VLBA. The second change causes the integrations (about 3 sec each) no longer to be synchronous with station UTC, but the VLBA has no apparent need for this feature; besides, the VLBA design has a 3-fold ambiguity in the UTC second on which each integration begins. This change also causes the integrating time, and hence the scale of the raw phase measurements, to be 1.7% smaller; this would require some constants in the VLBA software to be changed by the same factor if full accuracy is to be retained.

Note that this module uses a 5 MHz reference input from which the other frequencies are generated by dividers. Our system does not need 5 MHz for any other purpose, but since it is readily available from the Sigma Tau maser (which produces it internally by dividing the 10 MHz by 2) we included it without change. However, this module should work perfectly well if the 5 MHz input is replaced by 10 MHz; this would double the measurement frequency (to 260.4 Hz) and halve the integrating time (to approximately 1.5 sec), but the measurement resolution and scale would remain unchanged. On the other hand, the L102/-OV module passes the signal through a 200 Hz LPF, so this filter would have to be replaced.

2.3 Reference Receiver, L105-OV

This module has been extensively modified from the VLBA version, which is described in [2]. The modified module is not at all compatible with the original, nor easily changed back. A block diagram of the OVLBI version in given in Figure 6. The main circuitry retained from the VLBA (without change) is the 500 MHz VCXO and PLL. Various passive components (dividers and couplers) were retained, but they were re- arranged. The modulated reflector was deleted, but several major new subassemblies were added, including:

2.3.1 Input signal amplifier/splitter - an assembly containing amplifiers, a power divider, and a BPF for separating the composite 10MHz/500MHz signal from the optical receiver into its two components. See Figure 7.

2.3.2 Re-synchronizer - a box containing a high-speed GaAs dual D flip flop chip, and used to re-synchronize both the 10 MHz reference and the 1 Hz reference to the 500 MHz. The underlying concepts, design details, and test results for this device were given in [1]. See Figure 8.

2.3.4 10 MHz distributor - divider, level-setting resistors, and amplifiers for distribution of the re-synchronized 10 MHz. Constructed in the same box as the input signal amplifier/splitter. See Figure 7.

2.3.5 100 MHz PLXO - box containing a harmonic generator, VCXO, and phase lock circuitry for generating the 100 MHz reference from 10 MHz. See Figure 9.

3. TEST RESULTS

The test setup is illustrated in Figure 10. Whereas the optical fiber from the Interferometer Building is not yet available, a crystal oscillator was substituted for the hydrogen maser in these tests. The oscillator was a good quality, 10 MHz, ovenized unit that forms the time base of a commercial microwave counter. The 100 MHz reference is then supplied by locking a VCXO to the tenth harmonic of the 10 MHz reference.

During these tests, both ends of the optical fiber path were

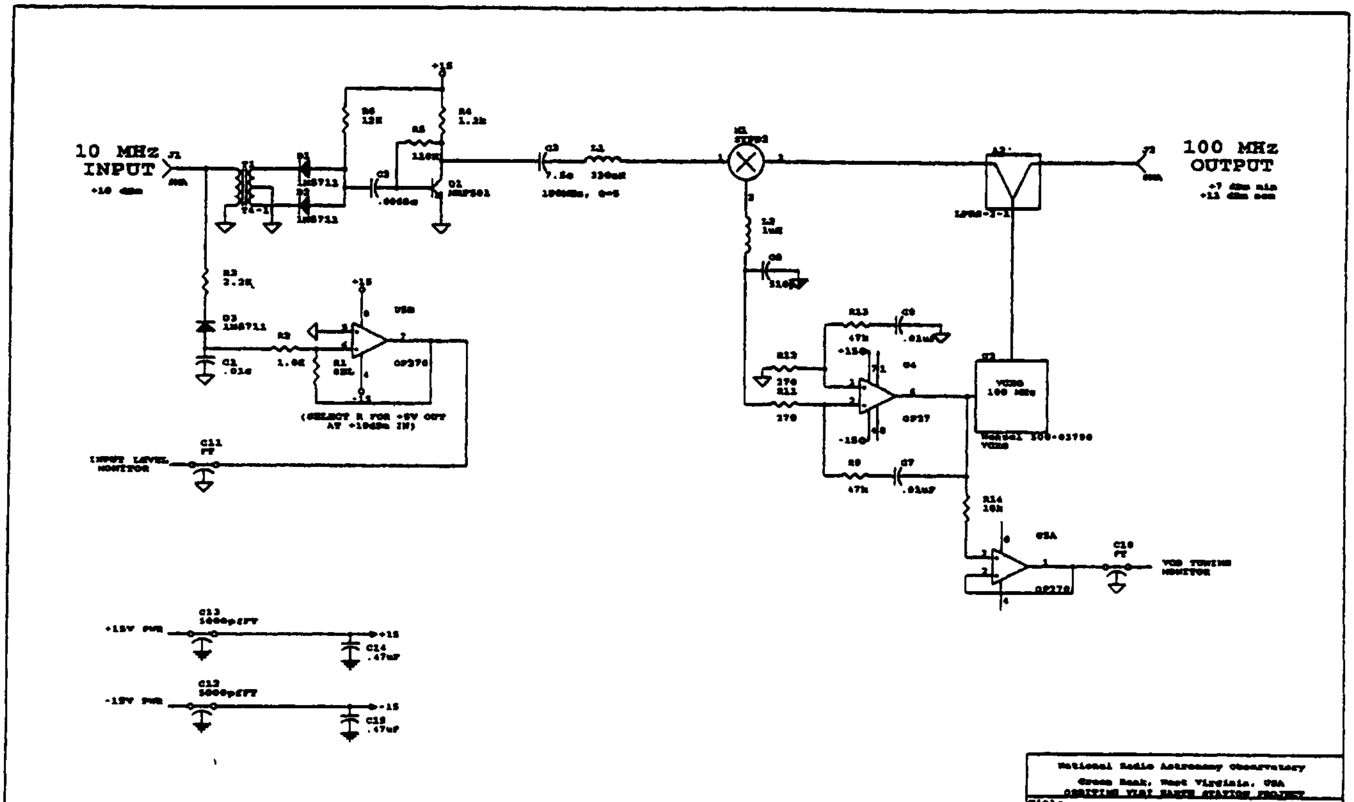


FIGURE 9. (SUBASSEMBLY FOR REF RCVR L105-OV)

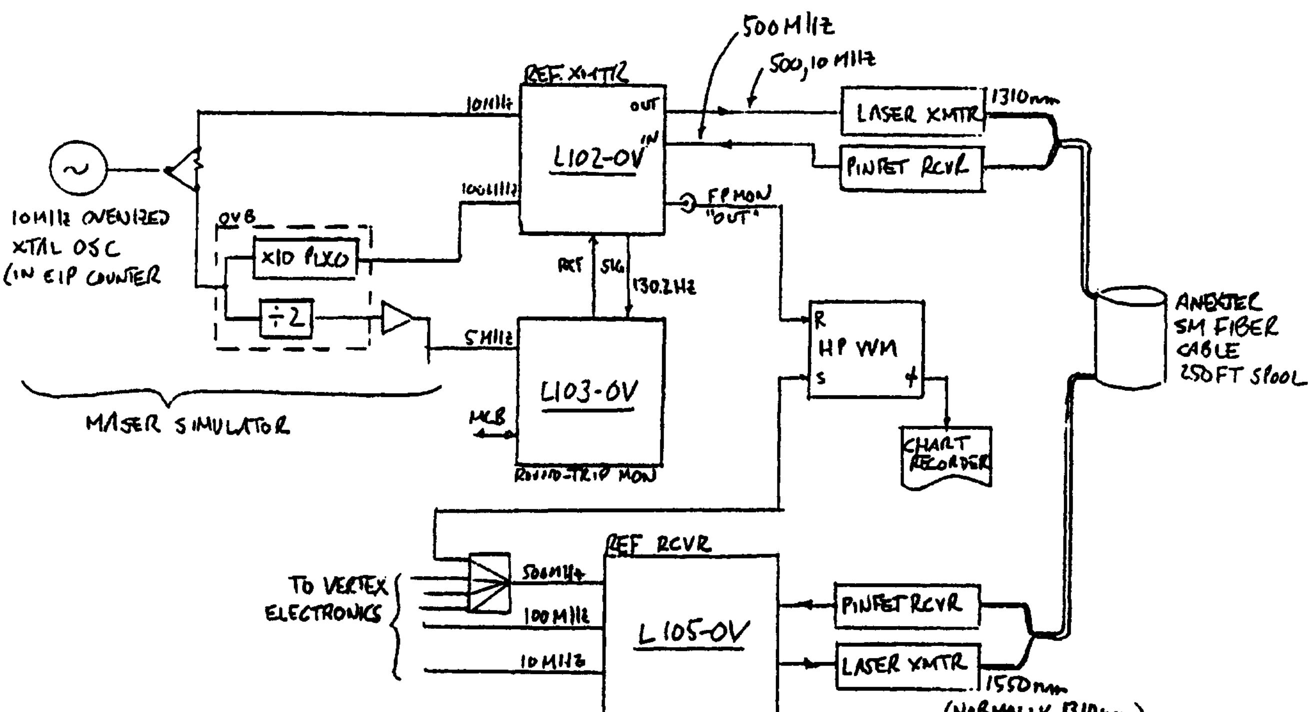


FIGURE 10. TEST SETUP

adjacent to each other in the same room, making it possible to measure the one-way as well as the two-way phase delay. The former was measured by a vector voltmeter and the latter by the digital phase detector in the Round Trip Monitor module (L103-OV).

The optical path consisted of a 250-foot spool of single-mode, loose-tube, 8-fiber cable. Two separate fibers from the one bundle were used. To avoid non-reciprocity due to dispersion, the same optical wavelength should be used in each direction; however, at the time of these tests only one 1310nm transmitter and one 1550nm transmitter were available. The fiber specifications [4] show that the propagation velocities at these wavelengths should be 2.47473e8 and 2.47423e8 m/s, respectively; or 62.9 ps time difference over 250 feet. If the temperature coefficient of delay is 10 ppm/C, then this dispersion would cause a .09 ps difference in the two paths for a 100C temperature change. This is insignificant. Of course, larger errors could occur for longer fiber runs. But in this application (and most others in radio astronomy), only the cable run on an antenna needs to be exposed to large changes of ambient conditions, and this is rarely more than a few hundred feet; longer runs are normally underground.

3.1 Calibration check, one-way and two-way delay

To verify the calibration of the vector voltmeter and the L103-OV phase meter, an SMA M-F adapter was inserted in the outgoing signal line at the output of the optical receiver. This increased the path length by about 2 cm. The following readings resulted:

	---------raw---------		---adjusted---		discrepancy
Adapter	VVM phase	L103	VVM	L103	VVM-L103
OUT	0.0deg(set)	641.1ps	0.0ps	0.0ps	
IN	-13.7	603.8	-76.1	-73.4	-2.7ps
OUT	-0.1	640.8	-0.6	-0.6	0.0

The "raw" L103 reading is from the VLBA "LOMON" screen. The "adjusted" value for the VVM is simply the conversion from phase at 500 MHz to time. The L103 readings were adjusted by subtracting the starting reading, dividing by 1.017 (to correct the VLBA software to the slightly shorter integrating time of L103-OV), and multiplying by 2 (because the path change was in the outgoing path only, and the software assumes reciprocity).

The discrepancy of a few ps is unexplained, but is not serious in our application. It should be noted also that the sign given by the VLBA software seems to be wrong.

3.2 Temperature effects

The system was operated for several days with the 250-foot spool of optical cable on the floor of the trailer and subject to temperature cycling of about 2 C from the air conditioning. The one way phase from the VVM was recorded on a chart recorder, and the two-way phase from L103-OV was recorded by the station computer. A typical record, on two different time scales, is shown in Fig. 11. On the 1-hour scale, the effects are very small and difficult to correlate between the one-way and two-way measurements; however, each showed a peak-to-peak excursion of about 1.4 ps. On the 1-day scale, we find

Time	L103-OV	VVM		
49529.00	642.5ps	+1.0deg		
49529.40	651.0	+2.3		
change	+9.5ps	+1.3deg =	+7.2ps	
adjusted	+9.3		+7.2	discrepancy=2.1ps.

It can be seen that the L103-OV measurements occasionally

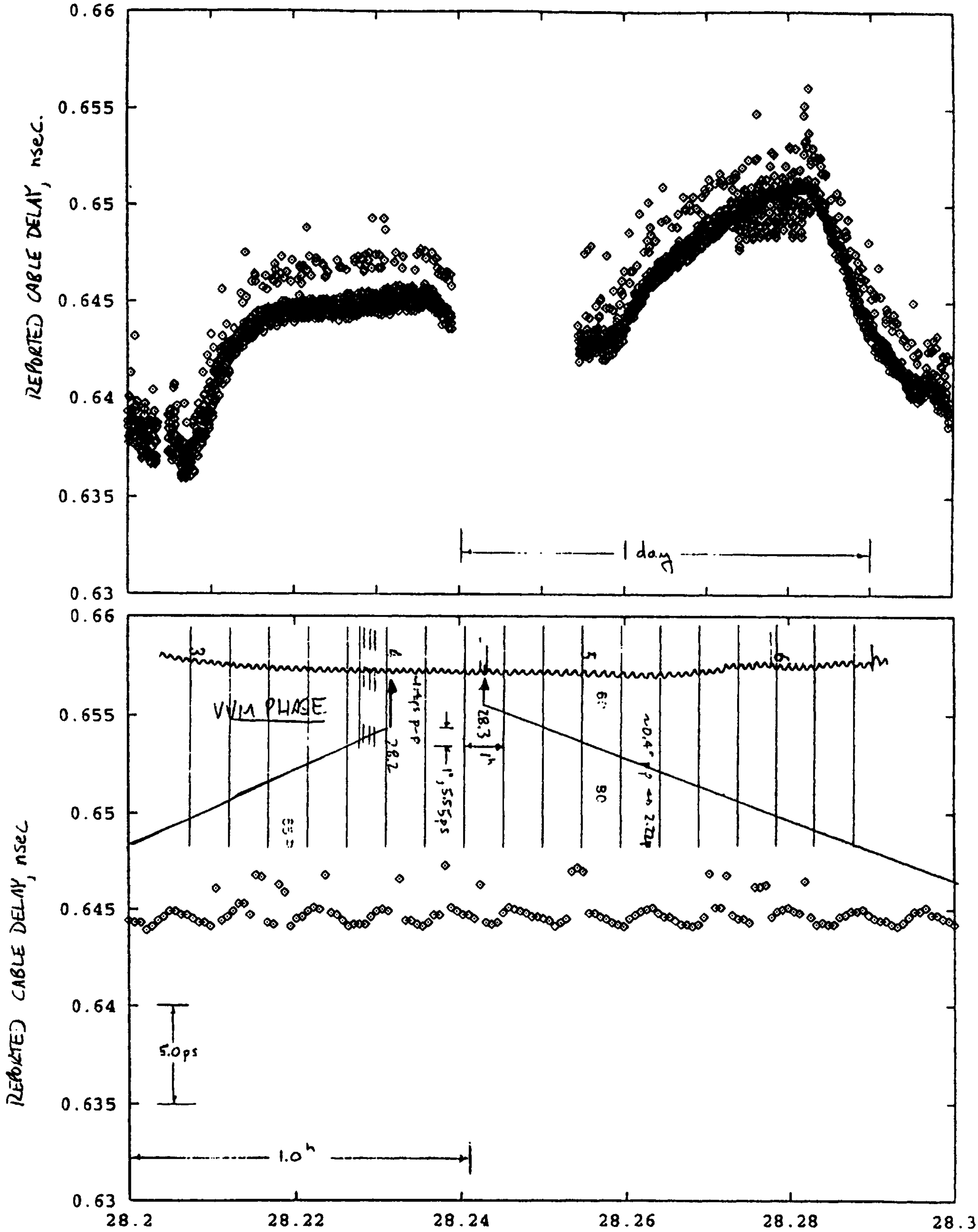

0.66
0.655
0.65
0.645
0.64
0.635
0.63
REPORTED CABLE DELAY, nsec.
1 day
VVLA PHASE
5.0ps
1.0h
REPORTED CABLE DELAY, nsec
28.2
28.22
28.24
28.26
28.28
28.3

FIGURE 11.

deviate by 2 to 4 ps above the dominant trend. This is unexplained; although it is small, it should be investigated.

Later, the system was operated in the same way but with most of the 250-foot spool of cable placed outdoors for about one week, where it was subjected to direct sunlight in the daytime. About 20 feet of cable remained indoors, along with all the electronics. Data collection during working days was sporadic because of tests being done on other electronics and on software, but several days of reliable data were collected. Typical results are plotted in Fig. 12. A few points are worth noting:

a. Tracking between the one-way and two-way measurements seems to be within 2 psec out of 33 psec, or 6%. The discrepancy, if any, is at the limit of these measurements. If the excursions were bigger, as they would be with longer cable runs, we would like this to be better, but in our application only about 1/3 of this cable length (80 feet) will be on the antenna, and much of this will be well protected from ambient conditions. The remainder of the run from the Interferometer Building will be buried. Furthermore, better tracking can be expected when the same wavelength is used in both directions. It therefore seems safe to predict that the cable delay can be corrected to ~1 psec accuracy from the two-way data when in actual operation in the earth station.

b. The total change of 33 psec over 11.2 C is about 11 ppm/C, which is about the expected value for single mode fiber.

c. We continue to observe excursions of about 2 psec P-P due to air conditioner cycling, even though most of the cable is outdoors. This must be due to the electronics. In this test, the vertex rack electronics was not actively temperature controlled (fans on but Peltier system off and rack covers removed), and the reference transmission bin was just sitting on a bench. All of this was at the opposite end of the trailer from the thermostat. Estimated excursions are 1.5C P-P on the 1-hour scale (air conditioning) and 2.5C P-P day/night. This represents a larger than desired temperature coefficient, although it is acceptable if the temperature during operation is held within a 0.5C range, as should be the case.

3.3 Cable bending effects

To simulate the effects of antenna motion on the optical cable in the axis wraps, a portion of the cable was repeatedly unwound from the spool, stretched along the floor, then rewound onto the spool. The cable length involved was 34 feet (about 16 feet out and back, plus a 180 degree turn when stretched, and 10 turns around the 1-foot diameter hub of the spool). Surprisingly, this produced no significant effect on either the one-way or the two-way delay measurement:

Configuration	VVM phase	L103-OV
STRETCHED	+4.0deg	640.1ps
SPOOLED	5.2	640.0
STRETCHED	5.1	641.5
SPOOLED	5.5	642.0

As a further check, a single point in the cable was bent into a 180 degree loop with 4-inch radius; this also produced no measurable effect on the delay.

3.4 Spectra

The close-in noise spectra of various signals in the system were recorded. Some of these are shown in Figure 13. Since all signals in the test setup were derived from the 10 MHz crystal oscillator, the noise performance of that oscillator must be very good

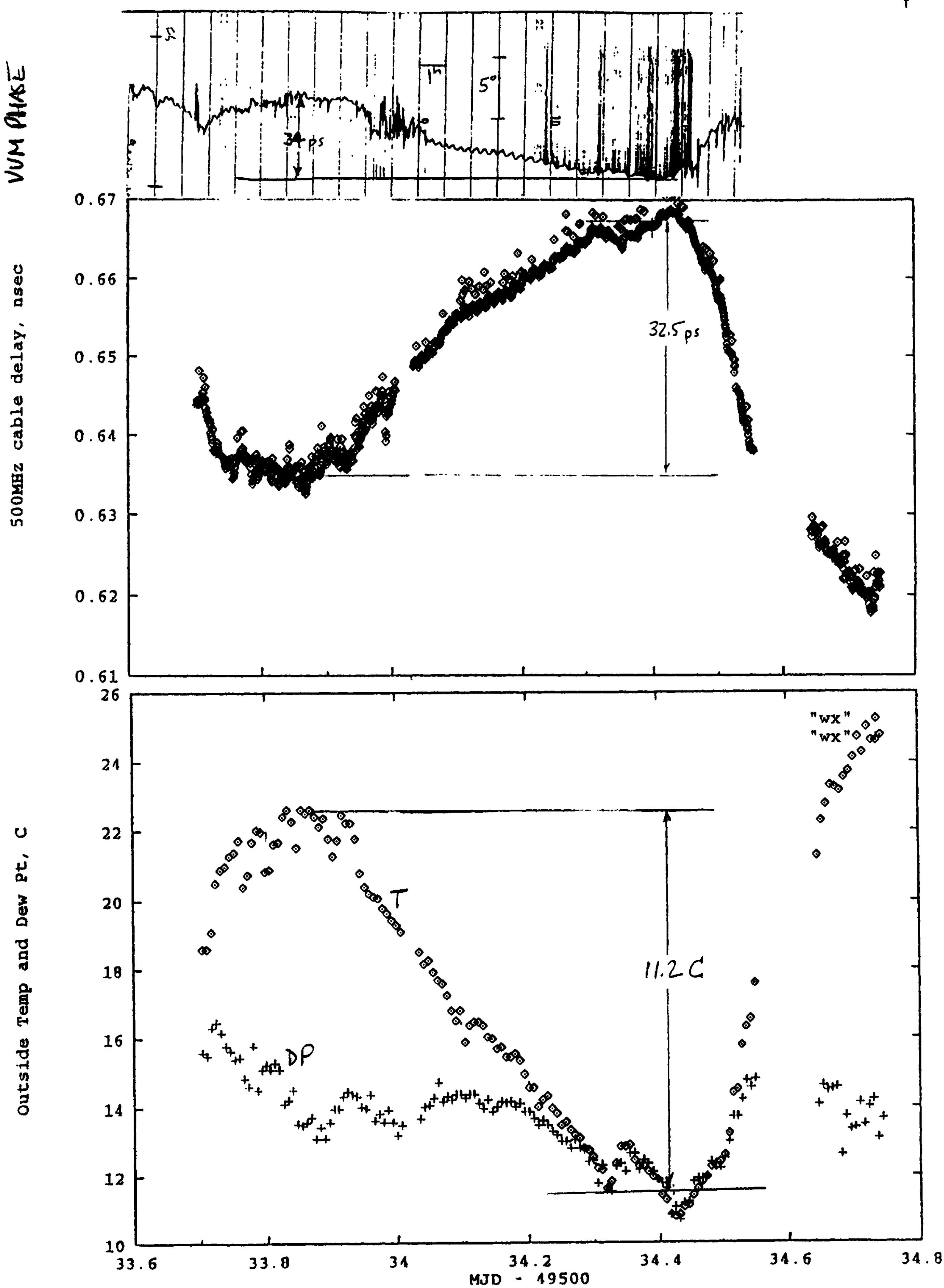

VLM PHASE
1°
5°
34 ps
0.67
0.66
0.65
0.64
0.63
0.62
0.61
500MHz cable delay, nsec
32.5 ps
26
24
22
20
18
16
14
12
10
Outside Temp and Dew Pt, C
"wx"
"wx"
T
11.2C
DP
33.6
33.8
34
34.2
34.4
34.6
34.8
MJD - 49500

FIGURE 12

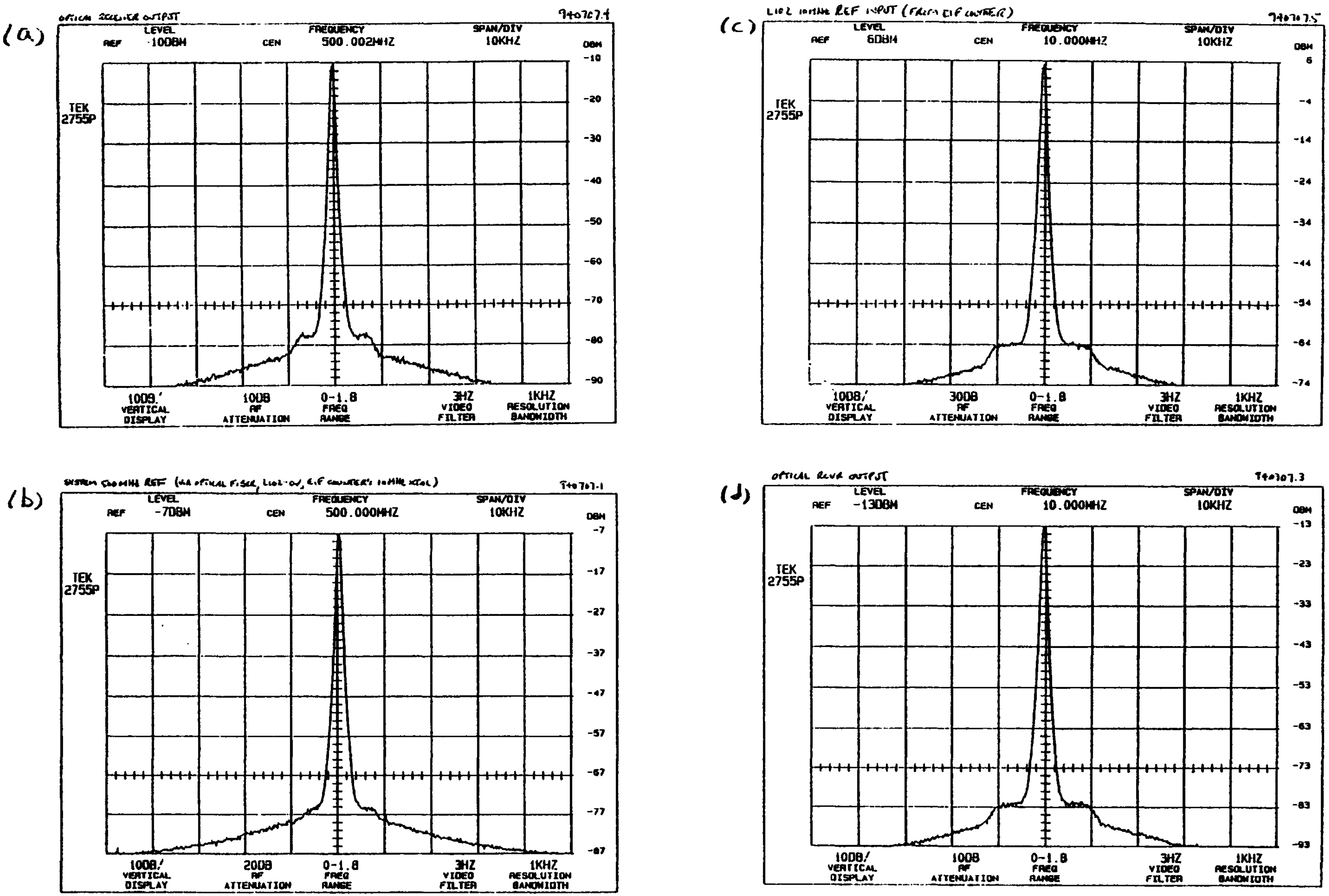


FIGURE 13

P.6.2

if other degradations in the system are to be observed. Fig. 13c gives the spectrum of the 10 MHz oscillator, showing that the noise is about 94 dBc/Hz at 1 kHz offset. After transmission through the optical fiber system (Fig. 13d), little degradation is apparent.

Spectra of the 500 MHz reference (which is quite critical in our system since it is multiplied to microwave frequencies) are shown in Figs. 13a and 13b. At the optical receiver output (where the spectrum is essentially the same as at the optical transmitter input), the noise is accounted for as that of the 100 MHz VCXO after multiplication by 5; the 100 MHz PLL has a bandwidth of a few hundred Hz, so at this resolution the effects of the 10 MHz reference cannot be seen. The system 500 MHz (Fig. 13b) is the output of the PLXO in the L105-OV, which has a bandwidth of 94 Hz [3]; therefore, the spectrum shown is dominated by the noise of the VCXO in that loop.

These results show that there would be some advantage to greatly increasing the bandwidth of the 500 MHz PLXO or using a lower-noise oscillator.

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[3] R. Weimer, "Round Trip Phase Measurement Module," VLBA Technical Report No. 23, Feb 1994.

[4] Corning, Inc., "SMF-28 CPC3 Single-Mode Optical Fiber," product information document PL-11, 5 pages, issued 7/92.