OVLBI-ES MEMO NO. 14

PERFORMANCE MEASUREMENTS OF THE GREEN BANK 45-FOOT (13.7-M) ANTENNA

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I. INTRODUCTION

The subject antenna is a parabolic reflector constructed for the NRAO by Electronic Space Systems Corporation (ESSCO) in 1972. It was designed to be transportable, i.e., it can be disassembled, moved, and re-erected with a minimum of alignment while maintaining a specified accuracy. The antenna was originally assembled at ESSCO in Massachuestts, and has been transported three times: from the factory to Green Bank (1972) for acceptance testing [1]; from Green Bank to Huntersville, WV (1973) where it spent most of its useful life as an element of the Green Bank Interferometer; and from Huntersville back to Green Bank (1988). It is known that the last assembly of the antenna after the return to Green Bank resulted in a major disturbance of the surface alignment. Consequently, a complete re-alignment of the surface was carried out by optical methods in October 1990 [2].

Careful measurements of the antenna performance have been made at several epochs. These have included determination of the aperture efficiency and determination of the (blind) pointing accuracy by observation of known radio sources. The results of the efficiency measurements are summarized in Table 1 and discussed in detail below. Until July 1990, the only receiver available for such tests was the interferometer 2.3/8.4 GHz room-temperature system, which allowed only total power radiometry at these frequencies. In summer 1990, the author constructed a beam-switching receiver for 14.9 GHz to allow accurate measurements at this frequency.

II. APERTURE EFFICIENCY MEASUREMENTS

The orginal specification for the antenna included an rms surface accuracy of 0.8 mm, which implies an aperture efficiency contribution at 15 GHz of 0.78 [4]. To obtain the total efficiency, the effects of illumination, spillover, blockage and polarization mismatch must be included; these depend on the feed arrangement. Our baseline plan for the feeds includes cassegrain, dichroic optics for which an overall efficiency of 0.77 at 15 GHz is estimated [5]. The feed leg and focal package blockage is 6.6%, giving a blockage efficiency of 0.872. Allowing 0.95 for polarization and miscellaneous losses then gives a total efficiency of 0.49. Link budgets of the OBLBI application assume a worst-case efficiency of 0.35 at 15 GHz, which requires a surface efficiency of 0.55 or a surface accuracy of 1.23 mm.

The surface is known to be worse than the original specification, for several reasons: (i) it is not clear whether the specification was ever met; (ii) the panels have deteriorated somewhat over the years; and (iii) the last re-assembly in Green Bank did not achieve the proper alignment of the panels. The latter error has now been corrected to first order (see Appendix B). To verify that the surface accuracy is now adequate to support the OVLBI application at 15 GHz, direct measurements have been carried out by observing strong radio sources.

*The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

Table 1: APERTURE EFFICIENCY MEASUREMENTS

Date	Freq. GHz	Aperture Efficiency Total (meas.)	Feed (calc)	Blockage (assumed)	Surface (calc.)	Surface rms error mm (calc.)
11/72	8.1	0.38+-.03	0.7	0.872	0.62+-.04	2.1+-0.2
12/73		...Moved GB to Huntersville				
9/88		...Moved Huntersville to GB				
2/90	8.1	0.39+-.03	0.7	0.872	0.64+-.04	2.0+-0.2
10/90		...Surface re-aligned				
10/90	8.1	0.49+-.02	0.7	0.872	0.80+-.03	1.35+-0.2
11/90	14.9	0.39+-.03	0.767	0.872	0.58+-.04	
12/90	14.9	0.40+-.01	0.767	0.872	0.59+-.015	1.16+-.03
5/91	11.9	Holographic Measurement (see Section IV)				1.35

Measurements were carried out at 8.1 GHz in 1972 [1], during acceptance testing at Green Bank; again in 1990 [2] after the return to Green Bank from Huntersville; and finally late in 1990 after re-alignment of the surface. All of these measurements used essentially the same feed and receiver, a total-power system with a room temperature parametric amplifier. While these data are of historical interest, they are not immediately relevant and details will not be given here. But it is worth noting that a substantial improvement was found after re-alignment.

In late 1990 measurements were made at 15 GHz using the receiver described in Appendix A. It is a prime-focus, beam-switched radiometer using a room-temperature HEMT amplifier. The measurements involved comparing the receiver output power due to a known radio source with that due to hot and cold loads (ambient and liquid nitrogen temperatures, respectively) placed over the feed. The loads were used to determine the effective noise temperature at the feed aperture of a solid-state noise source built into the receiver. The latter was then switched on and off rapidly (about 20 Hz) during the observations; simultaneously, the receiver input was rapidly switched (10 Hz) between on-axis and off-axis feeds. In this way, the antenna temperature due to the radio source is determined absolutely, provided that the hot and cold loads are accurately characterized and that the noise source is stable between the times of calibration and observation.

The strongest radio sources in the sky were used, as listed in Table 2. Some of these are variable; their flux densities at the epochs of observation were not accurately known, and they were not used in the efficiency estimates. Others, especially the strongest ones (Cas A and Tau A), are large in angular size and are partially resolved by the 6-arcmin beam of the antenna; an approximate correction was made for this (the "resolution factor" in Table 2), but for Cas A and Tau A the uncertainty in this factor dominates the uncertainty in the resulting efficiency estimate. Variable emission from the atmosphere also affects the measurements (although the beam switching is intended to minimize this), so that good weather is needed for the most accurate results. In view of these considerations, the most reliable data is that on Cyg A and Vir A, where the resolution uncertainty is small, in good weather. The data on these sources lead to the final efficiency estimate of $0.40 \pm .01$ given in Table 1.

Table 2: DETAILS OF 15 GHZ EFFICIENCY MEASUREMENTS

Source	Flux at 14.9 GHz (Jansky)	Angular Size (arcmin)	Resolution factor assumed	Antenna Temp. Ideal (K)	Antenna Temp. Measured (K) [1]	Aperture Efficiency [2]
Cas A	317.3	3.0	0.80	16.99	5.25+-.05	0.39+-.01
					5.39+-.03	0.39+-.01
Cyg A	93.3	1 x 2	0.95	5.00	1.7 +-.1	0.36+-.02
					1.85+-.03	0.39+-.006*
Tau A	464.7	3 x 5	0.706	24.9	7.71+-.1	0.44+-.01
Vir A	27.49	<1	1.00	1.472	0.57+-.02	0.39+-.014
					0.58+-.04	0.39+-.03
					0.61+-.02	0.41+-.014*
3C273	Variable	<1	1.00	---	0.66+-.1	
					0.33+-.1	
3C84	Variable	<1	1.00	---	0.73+-.03	

Notes: [1] Multiple measurements on the same source were made on different days; differences in errors mainly due to weather.
[2] Errors in efficiencies do not include uncertainty in resolution factor.
* Measurements believed to be the most reliable.

The feed used for these measurements was separately characterized on an antenna range, and the illumination efficiency was calculated from those measurements. This allowed the surface efficiency and accuracy to be calculated (Table 1). The final result, 0.60, exceeds our requirement of 0.55.

III. Pointing Measurements

The absolute or "blind" pointing accuracy of the antenna has also been measured using the 15 GHz receiver and known radio sources. An automatic observing program makes repeated measurements of the switched power at 9 different positions surrounding the expected position of a source and uses this to calculate the two-dimensional offset between the actual and expected positions. The positions used are (−5,−1,0,+1,+5) units of offset in each axis, where one unit is about equal to the −3 dB half-beamwidth. By using several radio sources over many hours, coverage of a large part of the sky is obtained (Figure 1).

The expected source positions include corrections for known, small misalignments of the antenna mount and for atmospheric refraction. This is done by adding corrections to the true azimuth and elevation of the source, according to

$$\Delta e = W_1 + W_2 \cos a + W_3 \sin a + W_4 \cos e + W_5 \cot e$$

and

$$\Delta a \cos e = W_6 \cos e + (W_7 \cos a + W_8 \sin a + W_9) \sin e + W_{10},$$

where a, e are the azimuth and elevation, respectively; $\Delta a, \Delta e$ are the corresponding corrections; and $W_1 \ldots W_9$ represent the magnitudes of various effects. W_1 and W_6 are encoder

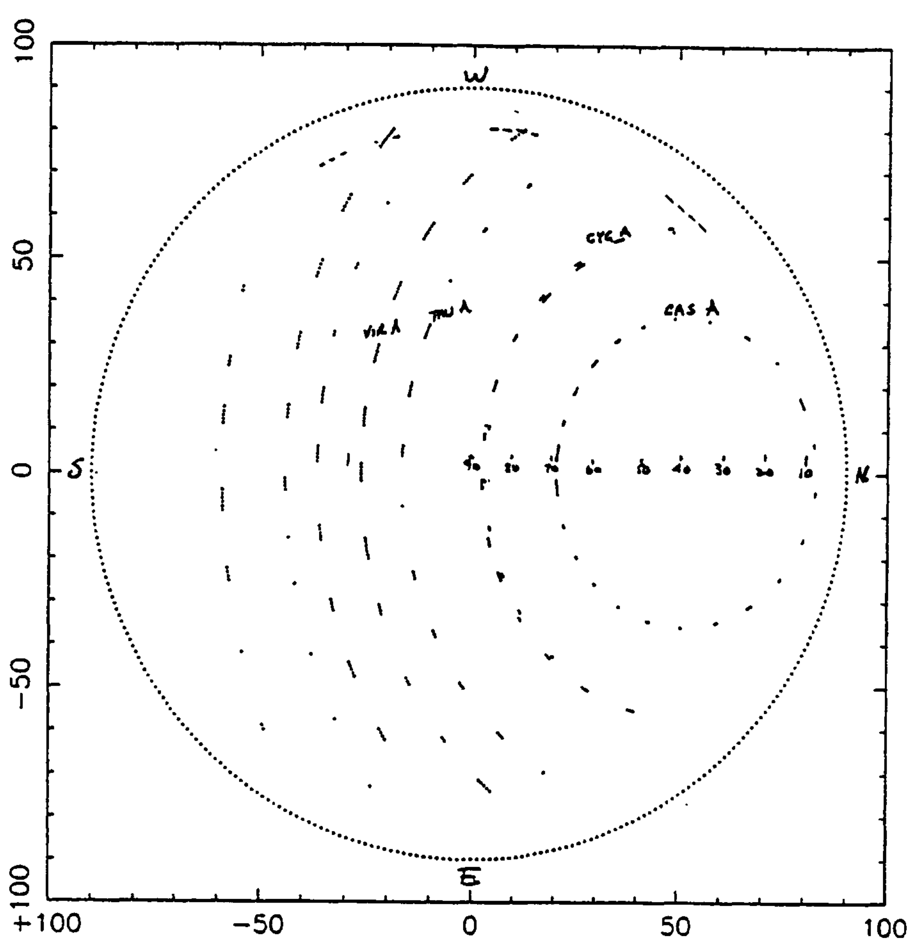


Figure 1. Sky coverage of a typical set of pointing observations.

offsets; $W_2 = W_8$ and $W_3 = -W_7$ are the two components of azimuth axis tilt from vertical; W_9 is the non-perpendicularity of the azimuth and elevation axes; W_{10} is the non-perpendicularity of the beam and elevation axes; W_4 represents gravitational sag with elevation; and W_5 is the (first order) atmospheric refraction. The coefficients are determined experimentally by fitting the above formulas to a set of pointing offset observations. Except for the refraction term, they are expected to be very stable.

The pointing offset measurements are subject to several sources of error. First, they will be quite inaccurate if the error is not a small fraction of the beamwidth (less than about 1/3 of the FWHM). Thus, better results will be obtained after several iterations have refined the coefficients used to calculate the expected positions. Second, the system noise produces errors that are negligible for sufficiently strong sources, but we have had to use some marginal sources in order to get good sky coverage. And third, fluctuations in the atmospheric emission during the time of a measurement can produce errors; typically, 30 sec of integration is used at each of the 5 positions along each axis, so about 2.5 minutes is needed to complete an elementary scan. The beam-switching receiver (with a throw of about 62 arcmin, or 10 beamwidths) cancels much of the atmospheric fluctuation, but it can nevertheless be the dominant source of error in poor weather.

The results of many of the measurement runs are summarized in Table 3. Shown are the rms residuals of a least-squares fit of the pointing formulas to the whole data set. In some cases, the daytime and nighttime measurements were analyzed separately. Histograms of the residuals for the March 8 data are given in Figure 2.

Several comments can be made about the data. The results at 15 GHz through February

Table 3: POINTING ACCURACY MEASUREMENTS

Date	Freq. GHz	---- Residuals On Sky, rms arcsec ---- Daytime			Nighttime			Combined			Weather
		Az	El	Tot	Az	El	Tot	Az	El	Tot	
90/02	8.1	24	40		18	26		23	38		
90/11/28	14.9							56	87	110	
90/12/14	14.9							34	54	66	CLR
91/02/06	14.9							44	61	77	cloudy
91/02/28	14.9	63	81		23	22	33	47	65	82	CLR -+5
91/03/07	14.9				44	41	62				50SCT 20 -4
91/03/08	14.9	21	37	45	21	25	34				CLR +1

1991 were relatively poor, either because of poor weather or because the on-line pointing coefficients were not yet well determined. We managed to get a good run on the night of February 28; using the coefficients derived from this run on March 8 resulted in the numbers in the last line. These are believed to be a good measure of the performance achievable, but this should be verified by repeating the measurements. Remember that the residuals reported include not only the actual pointing error of the antenna, but also the errors in its measurement; the latter can only make the overall rms worse.

It is clear that the daytime pointing is significantly worse than the nighttime pointing. At night, less than 35 arcsec rms (< 0.1 HPBW) is achieved consistently. The daytime results are more erratic and need further study, but it appears that 45 arcsec rms is now being achieved. If we take 45 arcsec as nominal and 135 arcsec (3 sigma) as the worst case, we get pointing losses of -0.2 dB and -1.7 dB, respectively, at 15 GHz. We will use these values in our link budgets; it turns out that this gives reasonable worst-case margins for both spacecraft. Therefore, although the daytime pointing is less than ideal, it appears to be satisfactory for the application.

Improvements to the pointing are likely once we have a better understanding of it. Not all effects are modeled by the correction formulas; additional terms can be added. The atmospheric refraction term has so far been fixed at the standard-atmosphere value, but we will soon install local temperature, humidity, and pressure sensors that will allow real-time computation of a much better estimate for this term. Daytime pointing is probably affected by differential heating of the antenna tower, leading to a tilt; this can be measured in real time and corrected, if necessary.

IV. Holographic Measurements

Beginning in April 1991, the 15 GHz radiometer was replaced with instrumentation specially designed for "holographic" measurements of the antenna surface. This involves measurement of the complex far-field pattern of the antenna by correlating the signal it receives from a strong source during a raster scan against the signal received at a fixed reference antenna. The Fourier transform of this pattern is the aperture field distribution, and its phase is directly related to deviations of the reflector surface from the desired paraboloid. This is now a well-established technique of antenna measurement [5]. Here our intention is to confirm the radiometric measurements of performance and determine

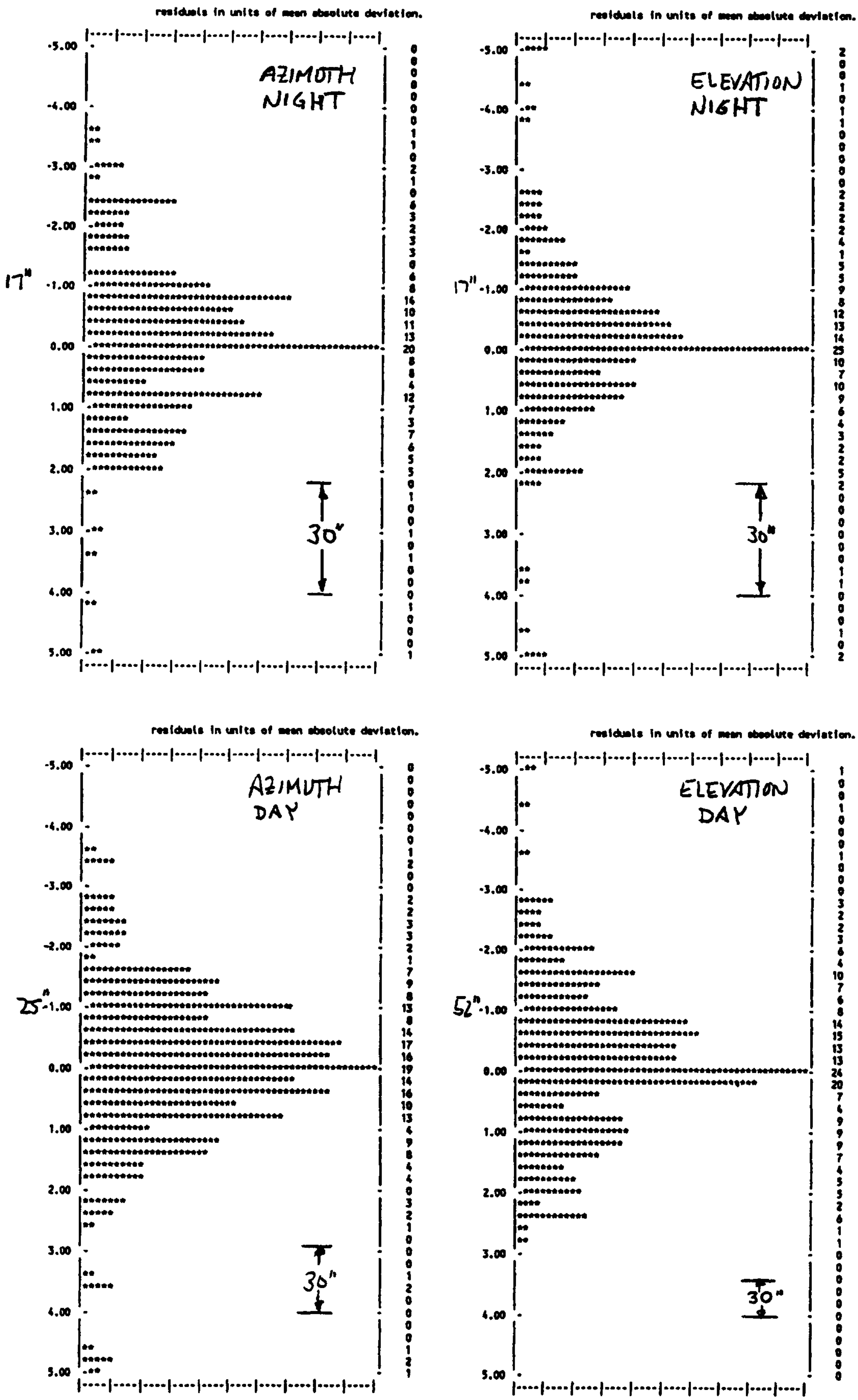


Figure 2. Histograms of residuals from 8 March 1991 pointing observations. Daytime and nighttime data were analyzed separately.

whether any refinement of the surface alignment is justified. This work is continuing, and only preliminary results are reported here.

Equipment constructed for similar measurements on other NRAO antennas has been utilized; it is described in Appendix C and in [6-7]. The receivers for the test and reference channels cover the 12 GHz satellite downlink band, and the sources used are geosynchronous communication satellites. The reference antenna is a horn mounted on the prime-focus receiver box but facing outward; although it moves with the main antenna, its beamwidth is broad and corrections for its motion (both in phase and amplitude) are made in the analysis software.

Several sets of observations have been taken using the Satkom K2 satellite, which is at 45 degrees elevation from Green Bank. The observations consist of 64x64-point rasters with a spacing of 0.8 beamwidth. About 7.5 sec is required per point (3 sec to move, 4 sec settling, 0.5 sec integrating), resulting in 8.5 hours total.

The data were analyzed using software developed by R. Maddelena for earlier holographic studies of the 140-foot telescope, and modified by him for this experiment; his help is gratefully acknowledged. Preliminary maps are shown in Figure 3. These are half-tone images of the surface deviation, measured parallel to the beam axis. Figure 3a uses a high-contrast display, showing only those regions that deviate more than 2 mm. Figure 3b gives further detail on the same data at a vertical resolution of 1 mm. Most of the features that exceed 1 mm deviation repeat on separate runs. The blocked area near the center and all of the region outside the rim have been set equal to a constant for the display; but the regions shadowed by the feed legs have not, so these should be ignored. The rms deviation derived from this image (ignoring the blocked regions) is 1.35 mm, which is consistent with the 1.16 mm derived from the 14.9 GHz efficiency (Table 1).

Additional observations and more detailed analyses will be presented in a later report.

References

[1] E. B. Fomalont, "45-Foot Pointing and Efficiency," NRAO internal memorandum to D. Hogg et al., March 8, 1973.

[2] S. Smith and L. D'Addario, "Re-alignment of the 45-ft Antenna in October 1990," NRAO internal report, in preparation.

[3] L. D'Addario, "Performance of the NRAO 45-foot Antenna As an Earth Station for Orbiting VLBI." NRAO internal report, 2 February 1990.

[4] J. Ruze, "Antenna tolerance theory–A review." Proc. IEEE, vol 54, pp 633-640, 1966.

[5] F. Scott and M. Ryle, "A rapid method of measuring the figure of a radio telescope reflector." Mon. Not. Roy. Astr. Soc., vol 178, pp 539-545, 1977.

[6] J. Payne, "Description of the hardware used in the holography experiment." NRAO (Tucson) internal report, December 1983.

[7] H. Fulbright, "Modification of MSE block receivers for use in holography." NRAO (Green Bank) internal memorandum to R. Norrod, August 28, 1986.

(Appendices A, B, and C are not included with all copies of this report. They are available from the author upon request.)

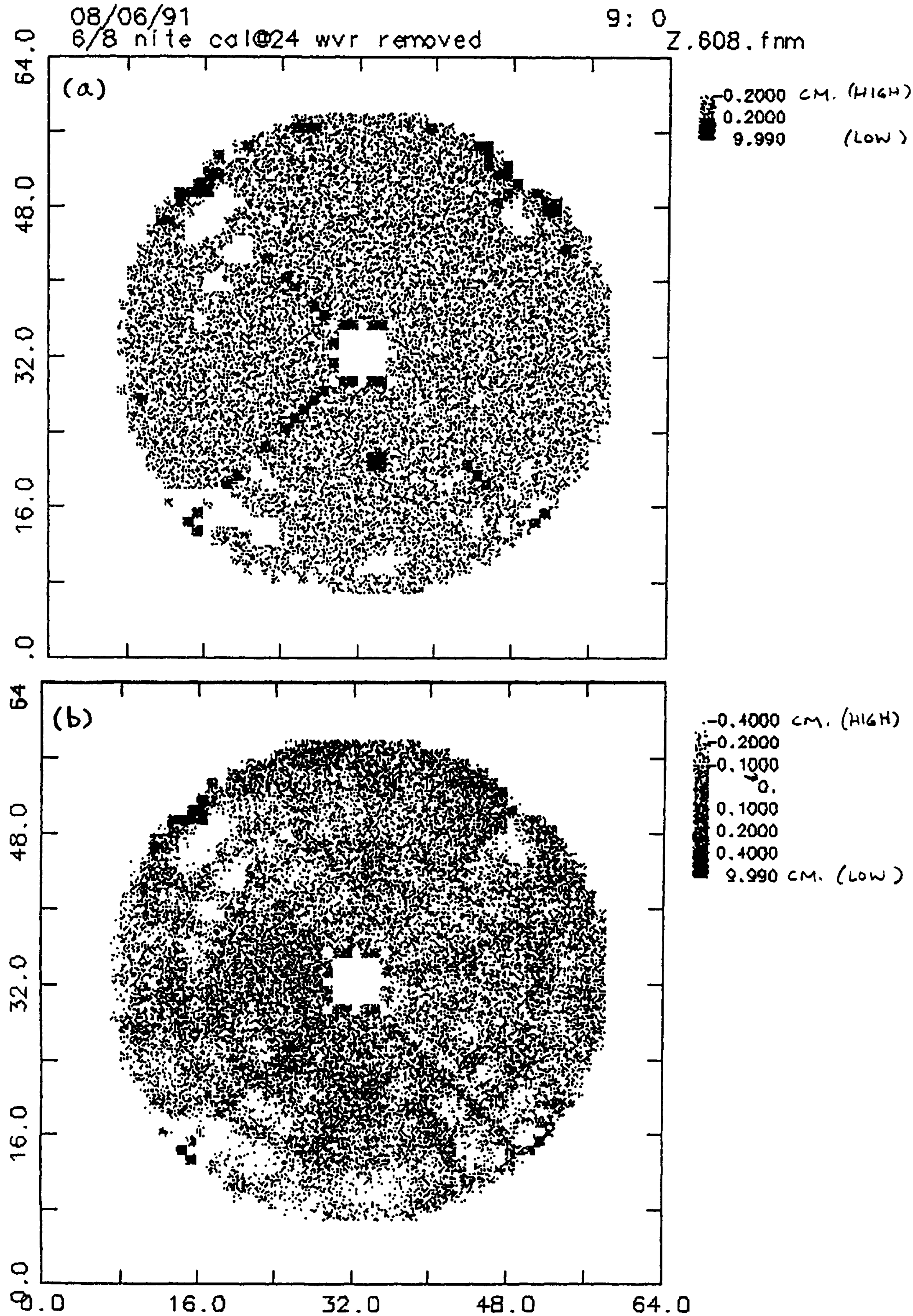


Figure 3. Holographic maps of the antenna surface deviations: (a) deviations greater than ±2 mm shown in black and white; (b) gray-scale to ±4 mm in 1 mm steps.

APPENDIX A: Test Receiver For 15 GHz

The 15 GHz receiver used for the efficiency and pointing measurements reported here was built by the author from surplus parts found around Green Bank and Charlottesville (with the exception of the feeds, which were specially made). It was installed in the same front end box used on the 45-ft antenna when it was part of the interferometer; the old receiver had been removed.

A block diagram is given in Figure 4. The receiver is a beam-switched radiometer based on a waveguide circulator whose direction can be electrically switched. A driver was built that achieves up to about 10 Hz switching rate, limited by the inductance of the circulator's coil and dissipation in the driver transistors. The first amplifier is an NRAO 3-stage HEMT covering 12-18 GHz, supplied by M. Pospieszalski. Although designed for cryogenic operation, it achieves a noise temperature of about 110K near 15 GHz; with a fairly noisy next stage and with the switch and waveguide losses, we end up with about 360K receiver temperature at the horns.

The wide-beam feed horns are shown in cross-section in Figure 5. They were scaled from an article in the literature. Their patterns were measured on the Green Bank feed range by G. Behrens, and the resulting illumination efficiency (used in Table 1) was computed from the measurements using the SCOPEFF program by S. Srikanth; these results are shown in Figure 6.

The rest of the receiver consists of filters, mixers, and gain blocks, leading to a near-baseband output of 5-500 MHz. The effective bandwidth is about 300 MHz. The double-conversion arrangement uses LOs at 16.17 and 1.3475 GHz, which are derived from a crystal oscillator in an assembly salvaged from the old interferometer receiver.

APPENDIX B: Surface Re-Alignment In October 1990

The details of this work will be given in a separate report [2], but a summary is provided here. Most of this work was carried our by Sidney Smith.

The alignment was accomplished with an optical theodolite mounted near the vertex, sighting plastic targets installed in special holes drilled in each panel during its manufacture. If the radial position of each target is accurately known, then a measurement of its elevation angle from a point on the nominal axis determines the deviation of the underlying surface point from the nominal paraboloid. To ensure that the radial positions are correct, some special tools were constructed. A ball bearing turntable was mounted near the vertex with its center of rotation on the nominal axis, and an aluminum strap gauge (.062 x 3 inch x required length) was attached to the turntable with its outer end near a panel target hole. The strap gauge lies bent along the panel surfaces, and is made so that a hole near its outer end aligns with a panel target hole when the panel is at the nominal radius. Two strap guages are needed because there are two rings of panels. The panel support screws are attached to the backup structure through slotted holes; using these, the position of each panel was adjusted radially so that a pin would pass through the strap gauge and target holes simultaneously. We were able to get the panels set to the nominal radii within about .060 inch, but we were later able to measure their actual radii to about .010 inch; this is close enough to have negligible effect on the surface error.

The turntable was then replaced by the theodolite, which was aligned so that its vertical axis was along the nominal paraboloid axis. This was done so that the axes would be perpendicular to the plane of a machined aluminum ring (44 inch diameter) that forms part of the structure at the center of the reflector. The panels were then adjusted vertically so that the targets appeared at the correct, pre-calculated elevation angles in the theodolite. There are 480 targets altogether, and each is located above a panel adjusting screw. Later, a separate set of observations of the target positions was collected. The deviations from nominal were .05 inch maximum and about .02 inch (0.5 mm) rms.

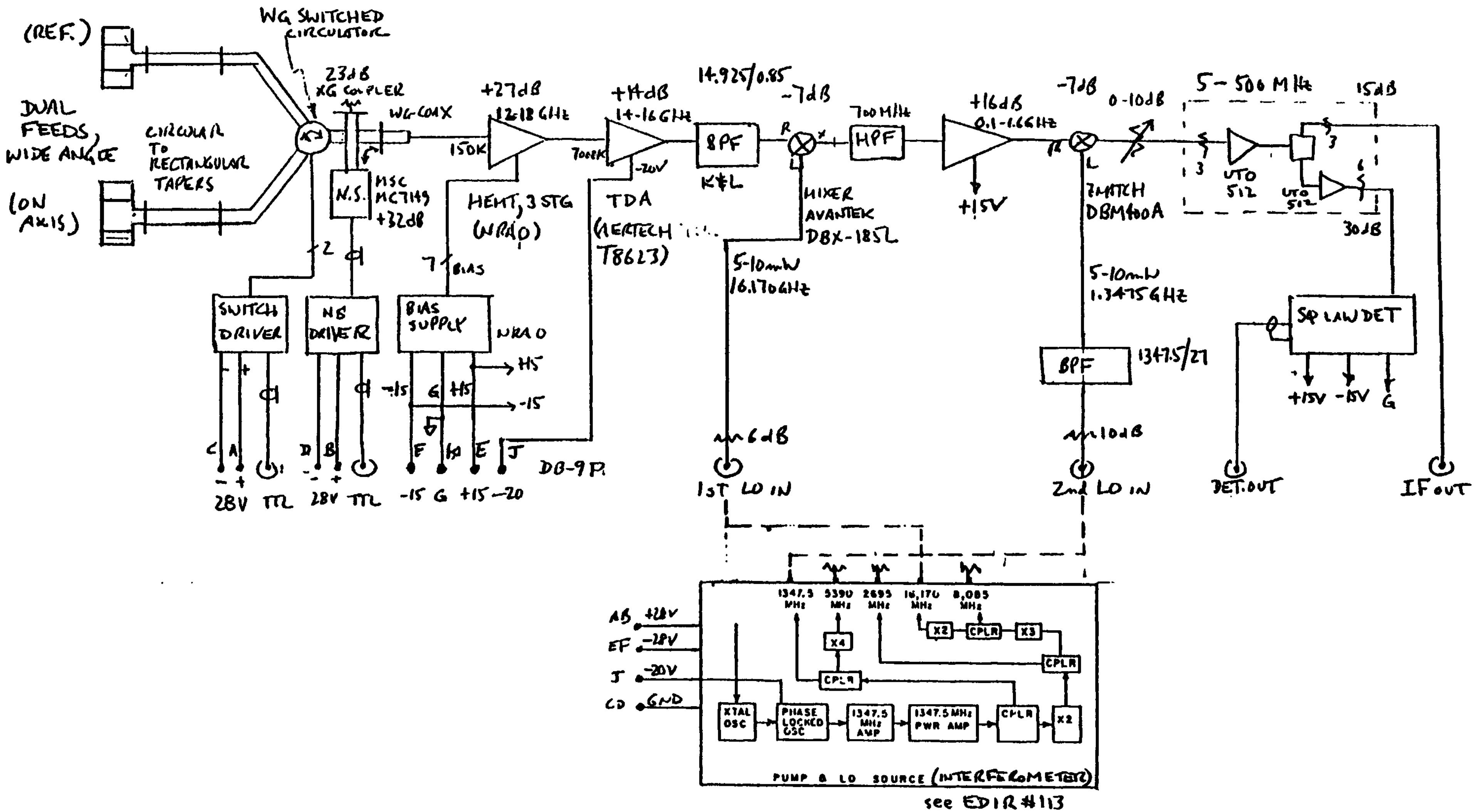
All of the alignment work was done with the antenna at 60 degrees elevation, since this is close to the average elevation expected during operation. All of the work was done at night, and spanned several successive nights.

APPENDIX C: Holography Instrumentation

A dual channel receiver, IF signal processor, and digital cross-correlator were constructed in 1983 to support holographic measurement of the NRAO 12-m telescope [6] at Kitt Peak. This measurement used the LES-8 satellite at 38 GHz. Later, the same IF chassis and correlator were used with a different front end [7] for measurements of the 140-ft telescope at Green Bank. The latter used communication satellites near 12 GHz. The front end included commercial satellite downconverters and was built into a standard Green Bank prime focus receiver box. Fortunately for us, all of this equipment remained available in 1990, and the receiver box also fits directly onto the 45-ft antenna. An overall block diagram of the system is given in Figure 7, and the front end arrangement is shown in Figure 8.

The digital correlator is capable of integrating for a programmable time up to several seconds, and then its six accumulated values are made available to a computer. Interfaces to a PDP-11 at Kitt Peak and to a Modcomp at Green Bank had been built in, but neither of these was suitable for use at the 45-ft antenna. We therefore added a third interface, using the VLBA Monitor and Control Bus via the VLBA Standard Interface Board. This allowed control and readout of the correlator from the 80286 PC-AT that is used to control the antenna.

It was also necessary to write some additional software for the PC in order to implement the raster-scan observing mode and to write the correlator data to an appropriate file. This is documented in notes maintained with the PC source code. The output data is written into a POPS-like file, for interfacing to the analysis software written by Ron Maddalena for the 140-ft holography.

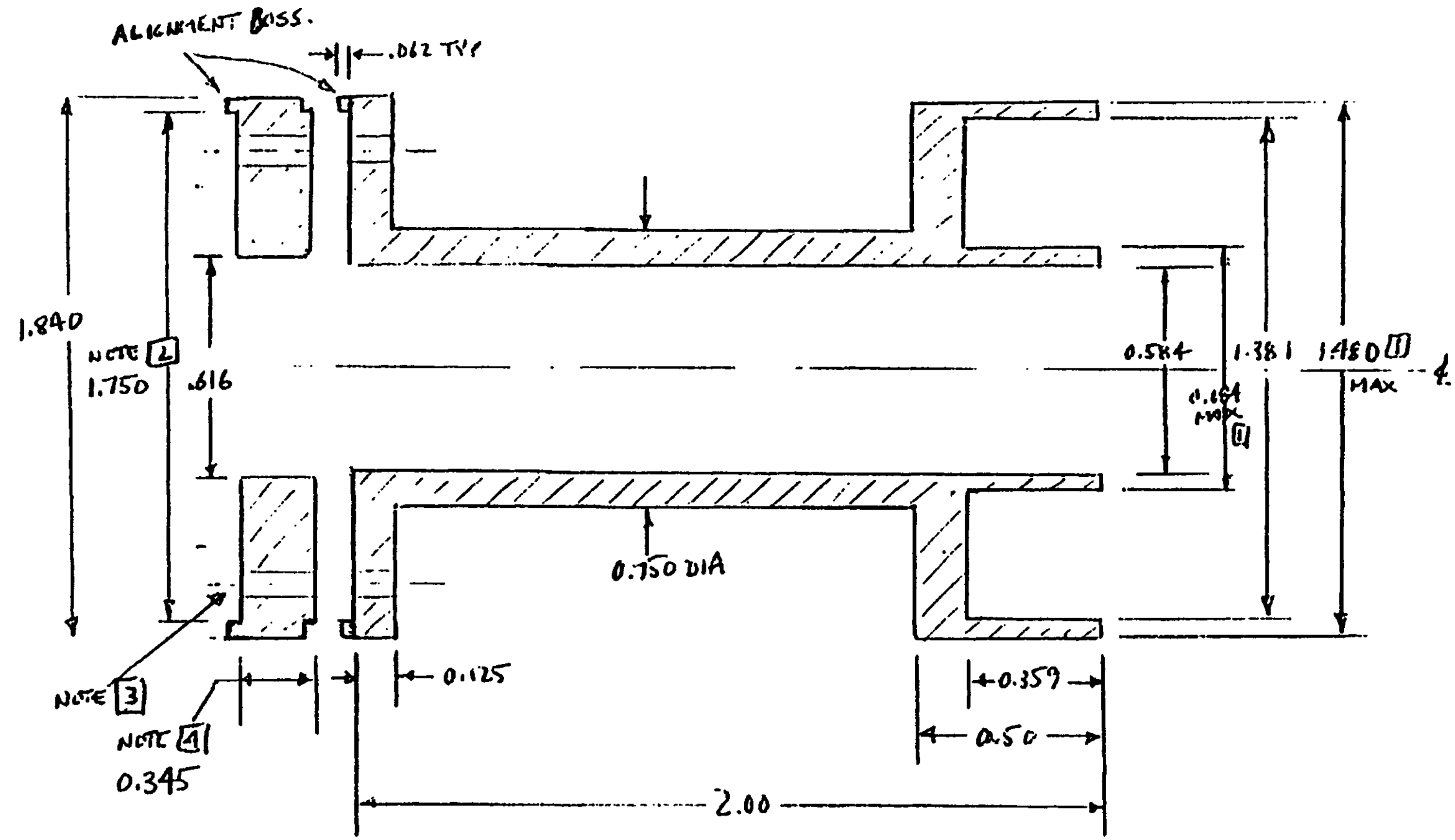


15 GHz TEST RECEIVER

BLOCK DIAGRAM

FIGURE 4

LRD 900722, 724.



CIRCULAR CROSS-SECTION

MATERIAL:
BRASS OR ALUM
FINISH:
GOLD PLATE
QTY: 2 REQ'D

NOTES [1] MAKE O.D. OF RINGS AS SMALL AS POSSIBLE, CONSISTENT WITH REASONABLE STRENGTH.

[2] ID OF ALIGNMENT BOSS TO FIT OD OF EXISTING RECT TO CIRC TRANSITION.

[3] HOLE PATTERN TO FIT EXISTING TRANSITION.

[4] DIMENSION TBS. $\lambda_g/4$ AT 14.9 GHz. 0.345".

SCALED FROM DESIGN GIVEN BY KUMAR, MICROWAVES, MAR 1978, P48-50, TO A CENTER FREQ OF 14.9 GHz

15 GHz FEED FOR WIDE ANGLE

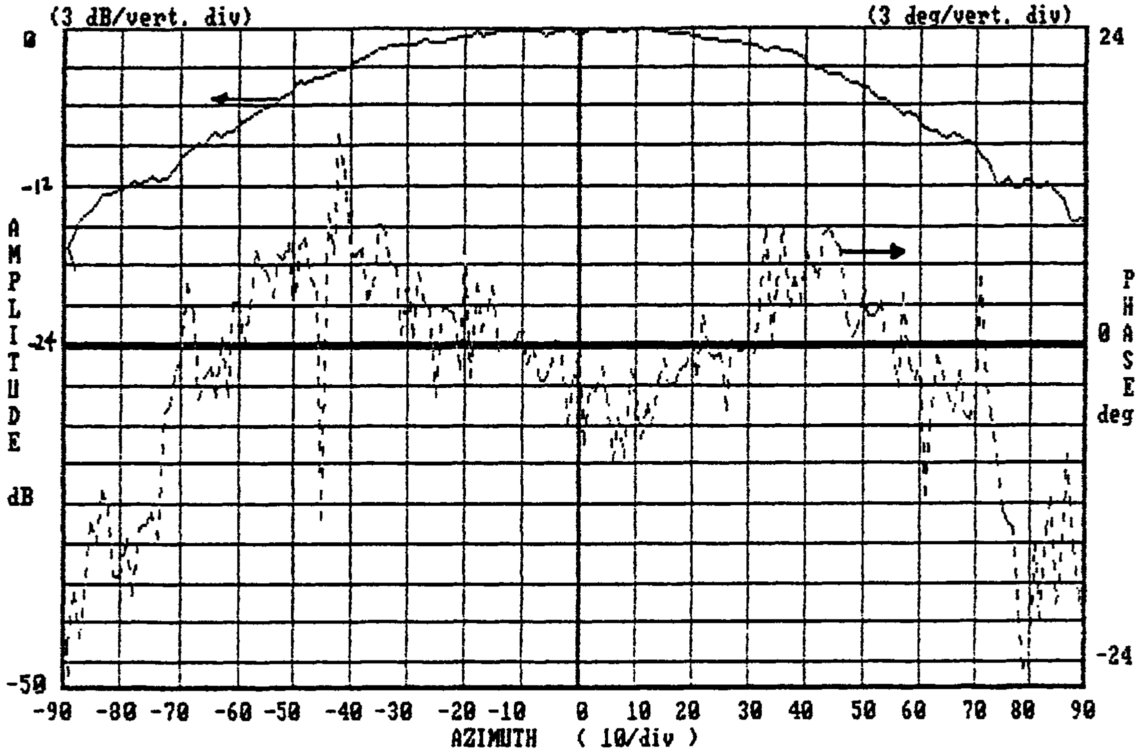
FIGURE 5

LRD 901006
Rev 901015

.616 φ: $\lambda_c = .9676"$ $f_c = 12.198$ GHz
24.577 ..

λ_g(14.9 GHz) = 35.035 mm
$\lambda_g/4$ = .3449"

(a)



FOCUS = PRIME EDGE ILLUMINATION : RIGHT = -9.24 LEFT = -10.88
FEED = Test Feed for 45ft Ant. FREQ = 14.9000 (GHz) PLANE = E
COMMENTS : 45ft test feed type 2
DATE : 11/05/90

EFFICIENCY & TEMPERATURES

(b)

ON A PRIME FOCUS TELESCOPE WITH FOCAL RATIO = 0.370
FREQUENCY = 14.900 Ghz
FEED = Test Feed for 45ft Ant.; COMBINED E & H PLANES
COMMENTS : 45ft test feed type 2

WITHOUT BLOCKAGE :			WITH BLOCKAGE :		
SPILLOVER EFF.	=	0.9246			
TAPER EFF.	=	0.8344	TAPER EFF.	=	0.7298
CROSSPOLAR EFF.	=	0.9957			
PHASE EFF.	=		SCAT. TEMPS. P(J) =		
		0.7030			2.52
		0.9091			0.05
		0.9988			0.08
		0.9400			
		0.7540	TOTAL SCAT. TEMP.	=	3.45
SPILLOVER TEMP.	=	17.01	SPILLOVER TEMP.	=	16.24
APERTURE EFF.	=	0.7672	APERTURE EFF.	=	0.5711

FIGURE 6: Test receiver feeds. (a) Measured pattern. (b) Calculated efficiency.

SIMPLIFIED BLOCK DIAGRAM OF HOLOGRAPHY EXPERIMENT

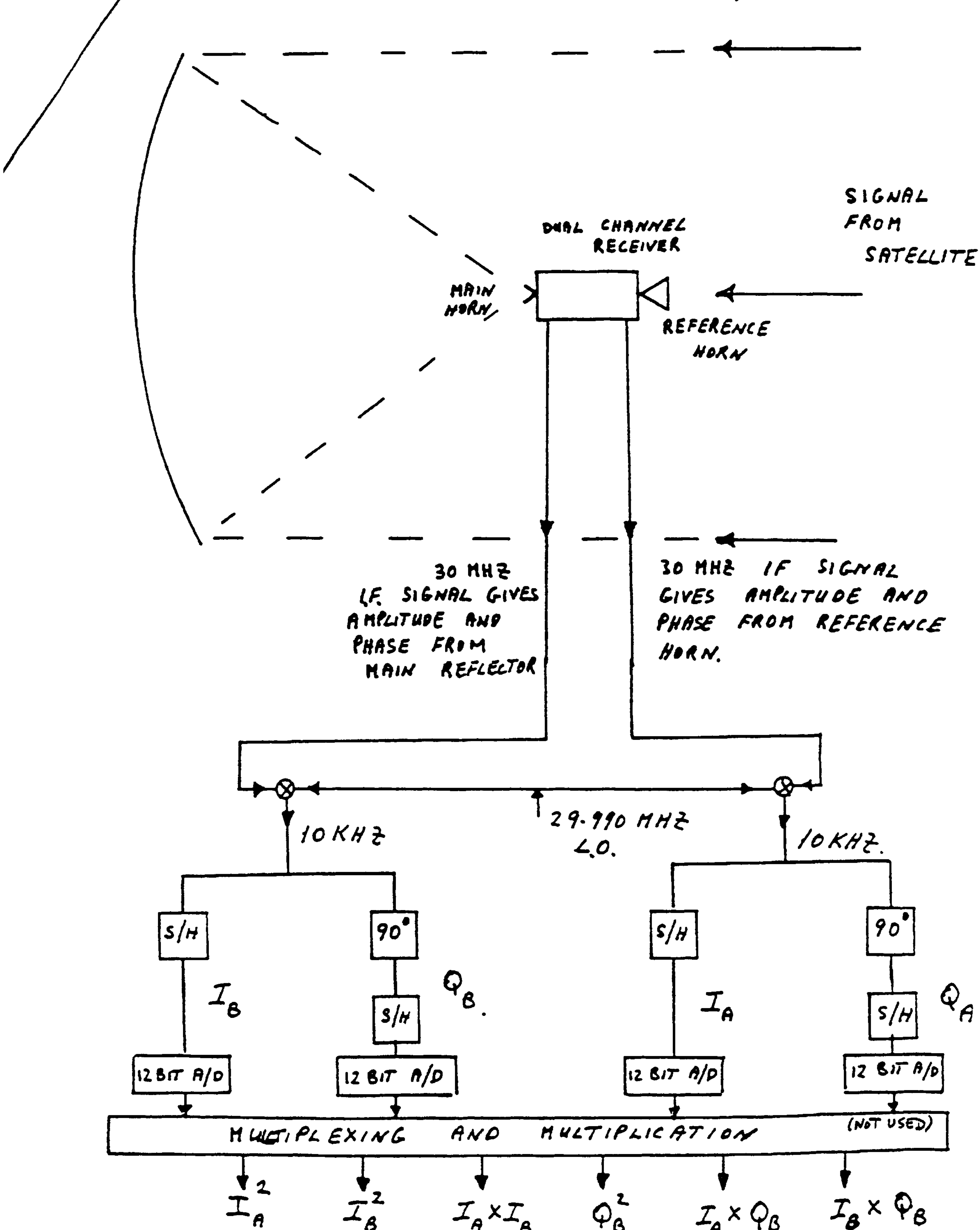
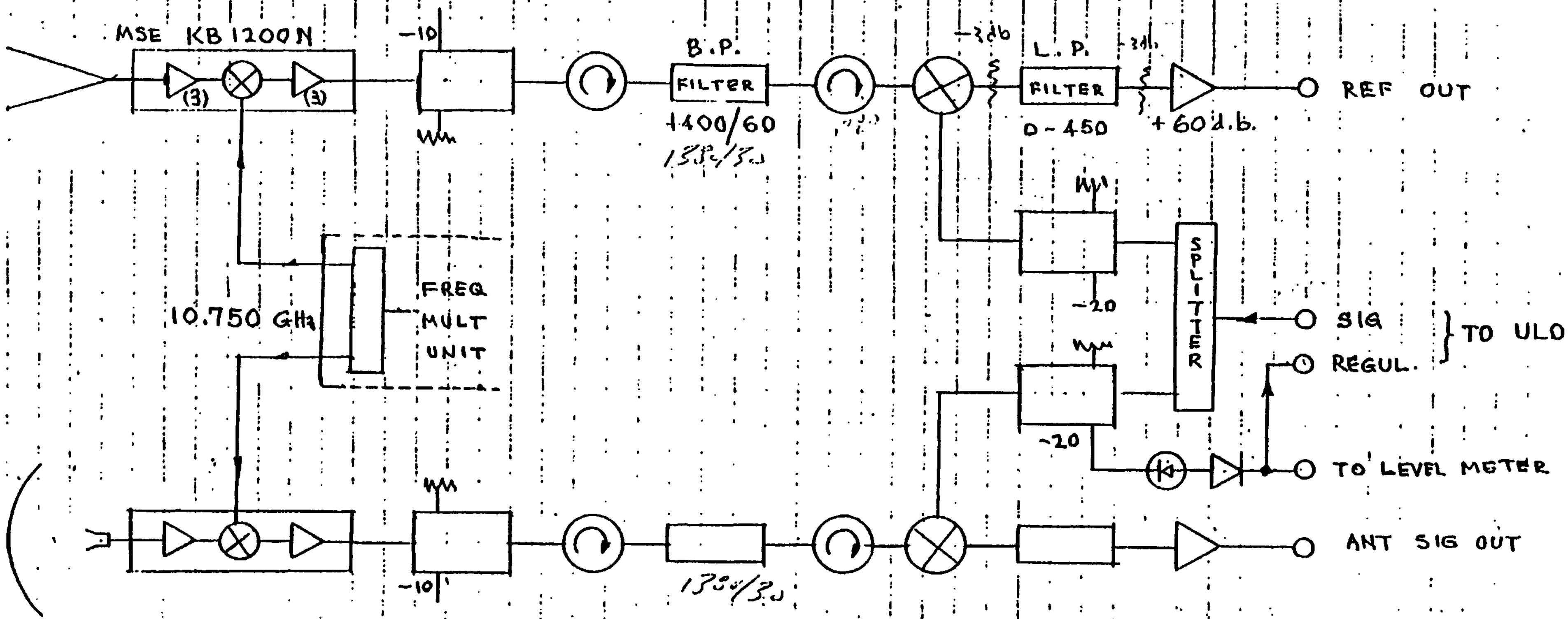


FIGURE 7



-15-

NOTES

(1) B.P. FILTER WILL BE CHANGED TO 1380/30.

(2) CHANNEL GAINS MUST BE ADJUSTED.

(3) COMPUTER SWITCHED GAIN CONTROL MAY BE ADDED IN I.F. LINE(S).

FIGURE 8

HOLOGRAPHIC RECEIVER

H. W. FULBRIGHT
8-29-86