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PERFORMANCE OF THE NRAO 45-FOOT ANTENNA AS AN EARTH STATION FOR ORBITING VLBI

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2 February 1990

1. BACKGROUND

The NRAO has proposed to construct and operate, with NASA funding, an earth station at Green Bank to communicate with orbiting radio telescopes doing VLBI. Two such spacecraft are scheduled for launch in the near future: Radioastron, to be launched by the USSR in November 1993; and VSOP, to be launched by Japan in 1994. Although these spacecraft will be in very different orbits and they will have other technical differences, the communication requirements are similar. Each requires a round-trip local oscillator phase transfer loop and a wideband digital downlink (144 Mb/s). The latter presents the most stringent signal-to-noise ratio requirement because of limited transmitter power on the spacecraft. For each spacecraft, this link is expected to use QPSK modulation on a carrier frequency near 15 GHz.

Because of orbit geometry (discussed later) and because of the launch schedule, the Green Bank station will make a much larger contribution to the Radioastron mission; that spacecraft will be visible from Green Bank during most of every orbit. VSOP, being in a lower orbit, requires a world-wide network of several earth stations to provide good coverage. NRAO will be able to complete the station in time for the earlier Radioastron launch, and it will be available to provide supplemental coverage during the VSOP mission.

The present report discusses the suitability of an existing antenna as a major component of this earth station. The antenna is a 45-ft (13.7 m) diameter parabolic reflector constructed for NRAO by Electronic Space Systems Corporation (ESSCO) in 1972 and presently installed at Green Bank. 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 Massachusetts, and has been transported three times: from the factory to Green Bank (1972) for acceptance testing; from Green Bank to a mountain top near 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). How well the alignment has actually been maintained during these moves is discussed in Section 2 below.

The reflector is on an elevation-over-azimuth mount with accurate inductosyns for position readouts and a drive system capable of speeds up to 50° per minute on each axis. A fast servo system accepts digital position commands in a Type-II loop. It is shown in Section 4 below that this allows accurate tracking of each spacecraft, with the possible exception of a few minutes per orbit of VSOP when its pass over Green Bank occurs near perigee.

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Absolute pointing accuracy of the antenna is also discussed in Section 4. It appears that open-loop ("blind") pointing to better than 30 arcsec (0.1 beamwidth at 15 GHz) will be possible over most of the sky. Orbit predictions are expected to be accurate enough so that no autotrack capability is needed. However, contingencies have been considered in case the pointing accuracy or orbit prediction are worse than expected.

2. ANTENNA APERTURE EFFICIENCY

2.1 Specifications and Historical Data

The major specifications for the reflector are given in Table I. The maximum rms surface error (.032 inches or 0.8 mm, including field reassembly after transport) implies an aperture efficiency contribution at 15 GHz of 0.78 [Ruze, 1966]. To obtain the total efficiency, the effects of illumination, spillover, blockage, and polarization mismatch must be included; these depend on the feed arrangement. To simplify the system, NRAO will probably use prime focus optics (although Cassegrain focus operation is possible). A two-mode hybrid feed, with which we have some experience, is then expected to produce a feed efficiency (illumination and spillover) around 0.8 [Thomas, 1971]. The feed leg and focal package blockage is 6.6%, leading to a blockage efficiency of 0.872. Allowing 0.92 for polarization and miscellaneous losses then gives an overall efficiency of 0.50.

Theodolite measurements of the surface profile were made at Green Bank in 1973 before transportation to Huntersville. These gave a surface *adjustment* accuracy with respect to the design parabola (not the best-fit parabola) of 0.26 mm rms; combining this with the estimated panel manufacturing accuracy of 0.30 mm and gravitational deflections of 0.50 mm gives an overall accuracy of 0.64 mm rss, well within the specification. Re-focusing to the best-fit paraboloid will make the error smaller.

2.2 Recent Tests

It is known that the last assembly of the antenna after transportation from Huntersville to Green Bank resulted in a major disturbance of the surface alignment, and no attempt to correct this has yet been made. Visual inspection shows that some adjacent panels have a relative misalignment of about 1 mm. A complete re-alignment of the surface is certainly called for, and is entirely feasible. The necessary fixtures and expertise exist at the NRAO. It is therefore expected that the original accuracy can be re-established.

Nevertheless, a series of astronomical measurements of the efficiency in the present state has been carried out. An available dual-polarization receiver operating at 8.085 GHz was installed as a noise-adding radiometer. This receiver uses room-temperature parametric amplifiers and achieves receiver temperatures of 90 to 110 K. The feed is a simple, circular waveguide horn at the prime focus. A solid-state noise source adds a stable reference signal with 50% duty cycle. Calibration of the system temperature was based on transfer of absolute standards (room temperature and liquid nitrogen temperature absorbers placed over the feed) to the noise source.

ESSCO

TABLE I

ESSCO 45 FOOT TRANSPORTABLE REFLECTOR - SALIENT FEATURES

Reflector Diameter	45 feet
f/D	.37
Focal Length	200 inches
Operating Frequency	Primarily to be used at 2,695 MHz and 8,085 MHz
Reflector Surface Tolerance for 25 mph Wind Load with Gravity Deflections and Including Reassembly in the Field with no Realignment of the Reflector Surface	.032 inches rms max.
Environmental	
Operating	25 mph wind load
Drive to Stow	50 mph wind load
Withstand at Zenith	100 mph wind load
Snow Load with no Permanent Deformation	20 lbs./ft.^{2}
Temperature	-20°F to $+120^{\circ}$F
Material of Construction	6061-T6, 6061-T4 and 6061-T69 aluminum
Weight	10,000 lbs.
Optical Shadowing by Feed Support and Spars	7%

The efficiency measurements are based on observations of a few very strong radio sources of known flux density. The accuracy is believed to be limited by small fluctuations in the system temperature due to the atmosphere, since rapid beam-switching was not possible. The results are summarized in Table II.

TABLE II: 8 GHZ EFFICIENCY MEASUREMENTS

Source Name	Flux at 8.085 GHz	Angular Size	Resolution Factor	Antenna Temp.		Aperture Efficiency
				Ideal	Measured	
	Jansky	arcmin	[Note 1]	K [2]	K	
Cyg A	199	2	.968	10.31	3.85 ± 0.2	0.373 ± .02
Cas A	518	3	.931	25.82	10.5 ± 0.3	0.407 ± .03
Tau A	558	3 x 5	.878	26.24	10.2 ± 0.3	0.389 ± .03

Notes:

[1] Resolution factor is estimated as $D_b^2/(D_s^2 + D_b^2)$ where D_b is the angular diameter of the beam (11 arcmin) and D_s is that of the source.

[2] $kT_a(\text{ideal}) = 0.5\ r\ S\ \pi\ D^2/4$, where r is the resolution factor, S is the flux density, and D = 13.7 m is the antenna diameter.

To estimate the surface error from these measurements, we need to remove the feed efficiency and blockage efficiency. The latter is (from geometric optics) about 0.87, and the simple waveguide horn used here is estimated to produce a feed efficiency of 0.70 (this is likely to be an overestimate, hence conservative with respect to estimating the surface error). For a total efficiency of 0.39 (see Table II), this implies a surface efficiency of $\eta_s = 0.638$; under generally accepted assumptions, this is related to the rms surface error σ by [Ruze, 1966]

$$\eta_s = \exp[-(4\pi\ \sigma/\lambda)^2],$$

where λ is the wavelength (3.708 cm for these measurements), which implies $\sigma = 1.98$ mm.

2.3 Predicted Performance at 15 GHz

Taking the above estimate of rms surface error, the same formula implies that $\eta_s(15\ \text{GHz}) = 0.214$. Using a dual hybrid mode feed (efficiency 0.8) and including the blockage efficiency (0.87) and miscellaneous losses (0.92) then leads to an overall efficiency at 15 GHz of 0.137.

In summary, the following performance at 15 GHz is predicted:

	Aperture Efficiency	Effective Area	Gain
In present state	14%	20.2 m^2	58.0 dB
After realignment	50	73.9	63.7

3. NOISE TEMPERATURE PERFORMANCE

The 15 GHz receiver for the earth station will use a state-of-the-art, low-noise design developed at the NRAO. This is based on cryogenically-cooled HEMT amplifiers, and will be a slightly modified version of a receiver already developed for the VLBA. Three such receivers have now been built and tested, and all have achieved receiver temperatures of T_r = 25 to 35 K over a 1 GHz bandwidth. Typical test data for one receiver is shown in Figure 1. These noise temperatures are referred to a room-temperature waveguide flange which bolts directly to the feed (no intervening waveguide). Somewhat lower noise temperatures can be achieved over the smaller bandwidth required by the earth station.

To estimate the system temperature, we take the spillover efficiency to be about 0.92 with the proposed prime focus, dual hybrid mode feed; and the zenith absorption to be about 1.5% in good weather (allowance for poor weather is made separately, see Section 5 below). Above 68° elevation, all of the spillover falls on the ground, which we take to be at 300 K; below this, an increasing portion falls on the sky, reaching half at zero elevation. This leads to the following model of antenna temperature vs. elevation:

$$T_a = (2.8\ \mathrm{K}) + (4.2\ \mathrm{K}) \csc e + (24.0\ \mathrm{K})\, x$$

where $x = 1$ for $e > 68°$, $x = (1 + e/68°)/2$ for $e \le 68°$, and e is the elevation angle. The terms are the cosmic background, the tropospheric absorption (at an average temperature of 280 K), and the spillover, respectively.

The reasonableness of this model is confirmed by the recent measurements at 8 GHz. A tipping curve measured on 1 February 1990 is plotted in Figure 2, along with the model.

From this analysis, with the receiver temperature taken to be 35 K (probably an overestimate), we expect that the system temperature ($T_{sys} = T_r + T_a$) of this station at 15 GHz will be:

Tsys < 70 K	for	e > 20°
< 98 K	at	e = 5°

CALIBRATION RECORD OF 14.9 GHZ RECEIVER, SERIAL #2, MOD #1
RCP POLARIZATION, TESTED BY CRADY, DATE 03/12/88 TIME 10:58.4
COMMENT: 9DB PAD ON TCAL NOISE SOURCE OUTPUT

15K TEMP = 15.58 50K TEMP = 49.45 300K TEMP = 303.38
AC AMPS = 0.459 DEWR VAC = 15 PUMP VAC = 9939
HEMT LED = 5.15 +15 VOLT = 15.187 TA SENS V= -1.308
CAL VOLT = 28.15 HIGH CAL = 28.16 SPARE = 0.00
FETS: LF1= -.885 LF2= -.775 RF1= -.781 RF2= -.633
CRY0 MODE IS COOL (7) CONTROLLED BY MANUAL. PARITY IS CORRECT

10:59.9 03/12/88 THOT=298.7 TCOLD=80.86 39DB IF ATTEN., 30MHZ BW

F,MHZ	TRCVR	TCAL	HI CAL	SHORT
13900	36.0	8.75	700.7	17.7
14000	31.8	8.66	667.9	18.6
14100	29.4	8.76	652.0	20.6
14200	28.0	7.95	617.0	20.4
14300	26.1	7.25	573.5	20.3
14400	25.3	7.28	594.4	19.0
14500	25.7	6.98	621.7	18.4
14600	25.7	8.06	623.9	18.4
14700	27.6	8.93	641.6	19.0
14800	29.3	8.41	664.7	19.1
14900	28.7	8.39	664.2	19.9
15000	29.5	7.95	656.1	20.3
15100	30.5	7.30	627.3	19.7
15200	28.2	8.03	630.2	19.4
15300	29.1	8.79	619.2	18.4
15400	30.2	8.87	567.1	18.1
15500	30.5	9.33	539.2	18.0
15600	33.4	9.58	570.5	19.0
15700	37.8	9.23	581.5	19.8
15800	48.7	8.30	589.9	24.7
15900	104.7	7.82	633.2	22.6

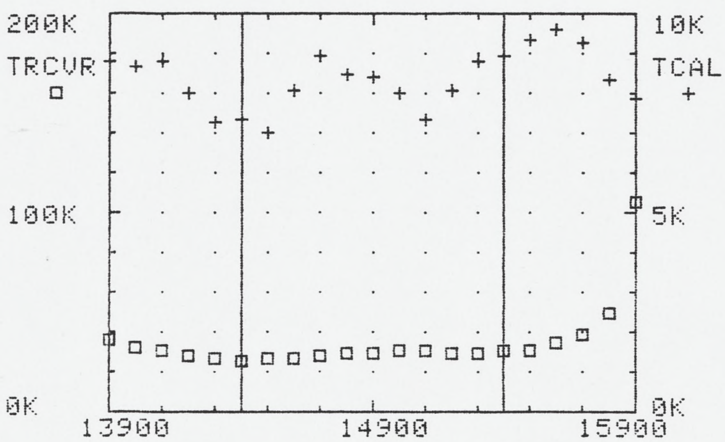

Fig. 1. Typical test data for a VLBA 15 GHz receiver.

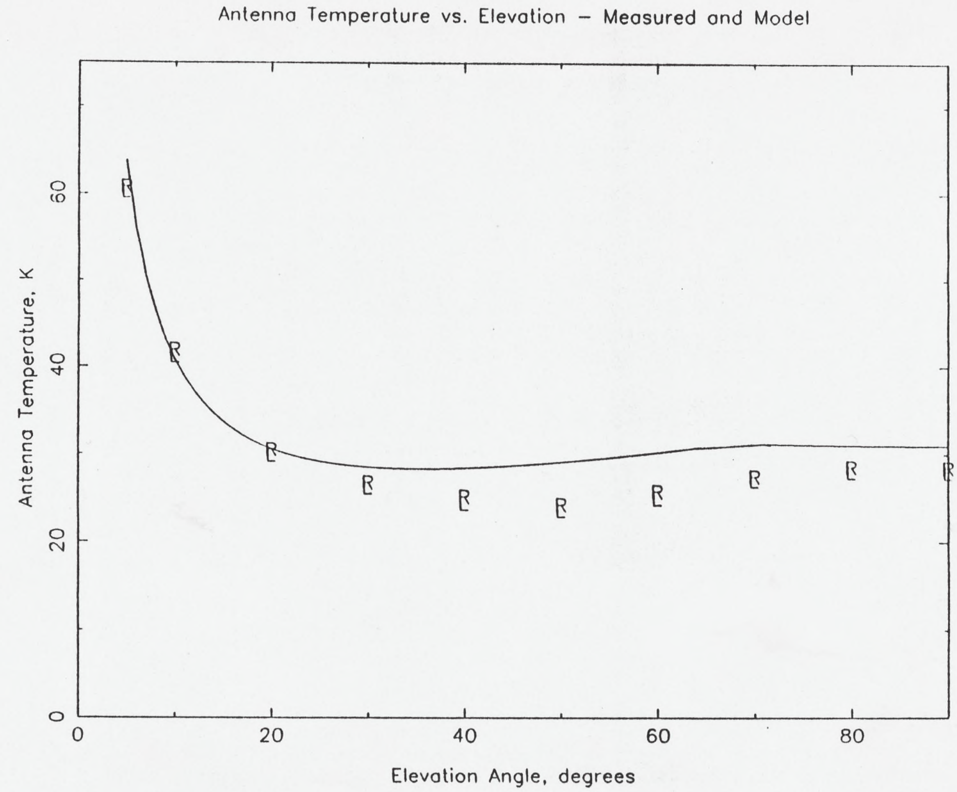

Fig. 2. Antenna temperature vs. elevation model (solid curve) and measurements at 8 GHz (R = right circular polarization, L = left).

4. POINTING AND TRACKING PERFORMANCE

At 15 GHz, the antenna will have a half-power beamwidth of about 6 arcmin; a pointing error of 30 arcsec (.008°) results in a gain loss of 0.3 dB, and an error of 2 arcmin (.033°) gives 1 dB loss. The latter is taken as a firm requirement and the former as a performance goal. Here we show that the requirement will be easily met, and that the goal is expected to be achieved most of the time.

We begin by considering whether "blind" pointing will be adequate, i.e., not relying on any real-time correction based on the acquired signal (in radio astronomy, this is usually the only possibility). In this case, there are several elements of achieving accurate pointing: the spacecraft position must be known *a priori*; the difference between the antenna's electrical axis direction and the direction implied by its shaft encoders (pointing correction) must be known; the antenna's servo system must be capable of responding to position commands fast enough to keep up with spacecraft motion; and there must be an adequate model of atmospheric refraction.

4.1 Orbits and Orbit Prediction

For reasons other than those considered here, the orbits of VLBI satellites will have to be known to high accuracy. The *a posteriori* orbit error is required to be better than 100 m in position and .02 m/s in velocity, and this is believed to be achievable with conventional Doppler techniques. The *a priori* data available in real time may be as much as one week old, during which time the instantaneous position may diverge from its extrapolated value; but if the *a posteriori* requirements are met, then this divergence will be at most 1,000 m in position and 0.1 m/s in velocity [Christensen, 1990].

Many of the following results are obtained from computer simulations made by the author at NRAO.

The parameters of the nominal orbits that have been published for Radioastron and VSOP are given in Table III. The Radioastron orbit has a 24-hour period and is designed to remain stable, i.e., its track over the earth will be the same each orbit. While the major parameters are fixed, the Soviets have expressed willingness to make minor adjustments depending on the availability of earth stations in order to optimize coverage. These involve changing only the right ascension of ascending node and the argument of perigee; three possible ground tracks are shown in Figure 3. Orbit A, the nominal one, optimizes coverage from the USSR. Orbit B moves only the longitude so as to increase coverage from the U.S. while maintaining nearly complete coverage from the USSR. Orbit C shifts the argument of perigee in order to allow some (brief) coverage from Australia. The resulting coverage from Green Bank is shown in Table III.

TABLE III: ORBITS AND VISIBILITY

	Radioastron	VSOP	
Semi major axis	42250	16900	km
Inclination	65	46.4	degrees
Eccentricity	0.82	0.56	
R.A. of ascending node (Ω)	TBD	precesses	
Argument of perigee (ω)	215-315°	precesses	
Period	24.00	6.06	hours
Apogee altitude	70500	20000	km
Perigee altitude	1200	1000	km

Orbit	ω	Visibility From Green Bank				
		hours/day with elev > 5°	Range when visible		Max rates	
			minimum	maximum	azim	elev
			km/1000	km/1000	°/min	°/min
RadAst-A	285	17.0	20	76	0.2	0.15
RadAst-B	285°	19.5	10.9	74	0.4	1.3
RadAst-C	215	12.2	9.6	70.5	1.3	2.1
V-apogee	270	8.9	7.7	22.8	1.3	2.1
V-perigee	90	0.25	1.5	1.7	30	8

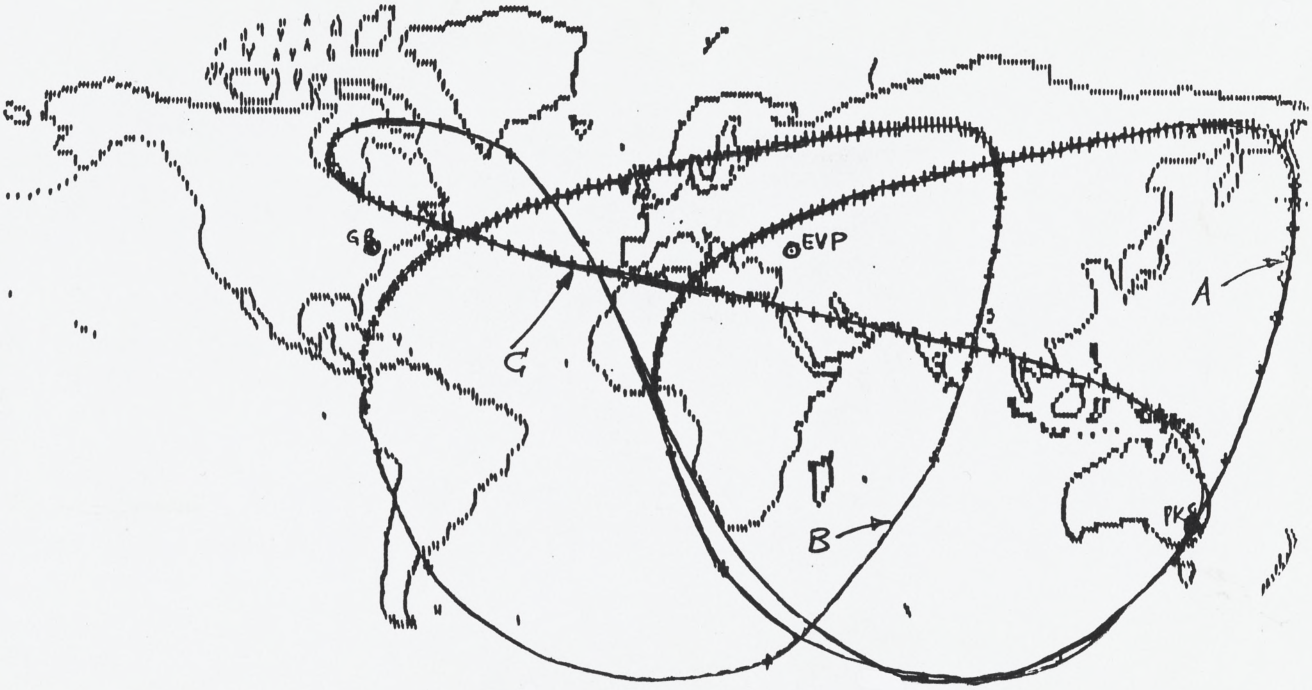

Fig. 3. Radioastron ground tracks for three possible orbits (cf. Table III).

The VSOP orbit is faster (about four per day), and is designed to precess so as to produce good uv-plane coverage in various parts of the sky. The orbit will repeat after about two years. Thus, in alternate years the perigee will be in the Northern and Southern hemispheres. Table III shows the coverage from Green Bank in two extreme cases, when the passes occur near apogee and near perigee.

For Radioastron, the apogee is always in the Northern hemisphere and the range from Green Bank is always about 10,000 km or more. A 1,000-m prediction error then gives a 20 arcsec maximum pointing error, which is negligible for our antenna. And the angular rates required for tracking are no more than a few degrees per minute.

For VSOP, the range is generally 5,000 km to 23,000 km except for the rare pass near perigee. Assuming 1,000-m prediction error, a pointing error of .033° (-1 dB) occurs at 1740 km range. VSOP will be within this range during less than 5% of the worst-case orbit, and such orbits occur during less than 10% of the mission. Furthermore, since the signal-to-noise ratio budget is determined by the maximum range, larger pointing losses can be tolerated during close passes. Angular rates become fairly high during such passes, buth they almost never exceed the tracking speed of the antenna.

4.2 Antenna Absolute Pointing Accuracy

Differences between the actual beam direction on the sky and that implied by angle transducers on the azimuth and elevation bearings are mostly systematic and repeatable. These can be determined astronomically as a function of direction and then corrected during tracking. Residual errors will depend on the accuracy with which the corrections are measured, the number of points measured, the complexity of the interpolation model used, and any non-repeatable effects.

In spite of the long history of use of this antenna, we have so far been unable to find reliable records of experimental determinations of its pointing accuracy. Only enough calibration to ensure sufficient accuracy for its intended use (as an interferometer element at 2.7 and 8.1 GHz) seems to have been done. We have recently begun a new astronomical study of the practical pointing accuracy, the results of which will be described in a later report. Meanwhile, the expected performance based on specifications and experience with other antennas can be discussed.

ESSCO antennas of similar size and design, but intended for use in radomes, have specified non-repeatable pointing errors of .002° (7.2 arcsec). In our exposed configuration, the main additional sources of non-repeatable error are thermal gradients and wind. In an antenna of this size, thermal distortions should be small. For example, the VLA antennas are of the same basic type as this one but are nearly twice as large (25 m); worst-case thermally-induced pointing errors are around .01° (30 arcsec). Von Hoerner's [1967] thermal limit on the surface accuracy of large reflectors implies a pointing error for 5 C gradient of .001° (3.6 arcsec) for 14-m diameter. Wind-induced errors are not immediately known, but the antenna was designed to maintain an overall pointing accuracy of 0.1 beamwidth at 8 GHz (.016°) in 30 mph wind.

One detailed measurement of the pointing error was made during the antenna acceptance tests [Fomalont, 1973]. Astronomical measurements over a wide range of azimuth and elevation were fitted to an 11-parameter model, giving residuals of .008° in azimuth and .014° in elevation. The elevation error may have been dominated by errors in the refraction correction, which was assumed to be (1.1')cot(e). Part of the residuals is due to measurement errors and incomplete modeling; the model included only one term for gravitational deflection, all other terms corresponding to simple mechanical misalignments.

NRAO experience with other antennas includes the 12-m telescope on Kitt Peak, where non-repeatable pointing errors are less than 10 arcsec (3 to 5 arcsec typical); and the VLA 25-m antennas, where these errors are less than 15 arcsec under favorable conditions and 30 sec in strong winds.

We conclude that the required accuracy of .033° (2 arcmin) is easily achieved, at least in moderate winds, and that the goal of .008° (30 arcsec) is very likely to be achieved.

4.3 Antenna Drive Servo Response

The antenna is driven by d.c. servo motors (two per axis, normally producing opposing torques) capable of rates up to 50°/min in continuous winds up to 50 mph. Each axis contains a digitized inductosyn readout with a resolution of $360/2^{18}$ deg (4.94 arcsec). An NRAO-designed servo system [Payne, 1973] implements a Type-II position loop on the difference between the readouts and a computer-commanded position; the error is updated in hardware 20 times per second. The theoretical step response of the loop is given in Figure 4. This type of loop will produce zero error (within the resolution) for constant-position and constant-velocity inputs; an error proportional to angular acceleration occurs, but since the loop is quite fast this is only about 8 sec^{-2} (30 arcsec error at $120°/min^2$).

The largest angular acceleration found in our simulations was $9°/min^2$ (for VSOP near perigee). This should result in a tracking error of only 2.3 arcsec.

The system was designed to track within .0028° (10 arcsec) in 30 mph wind, and actual observations in winds of this strength show no measurable error.

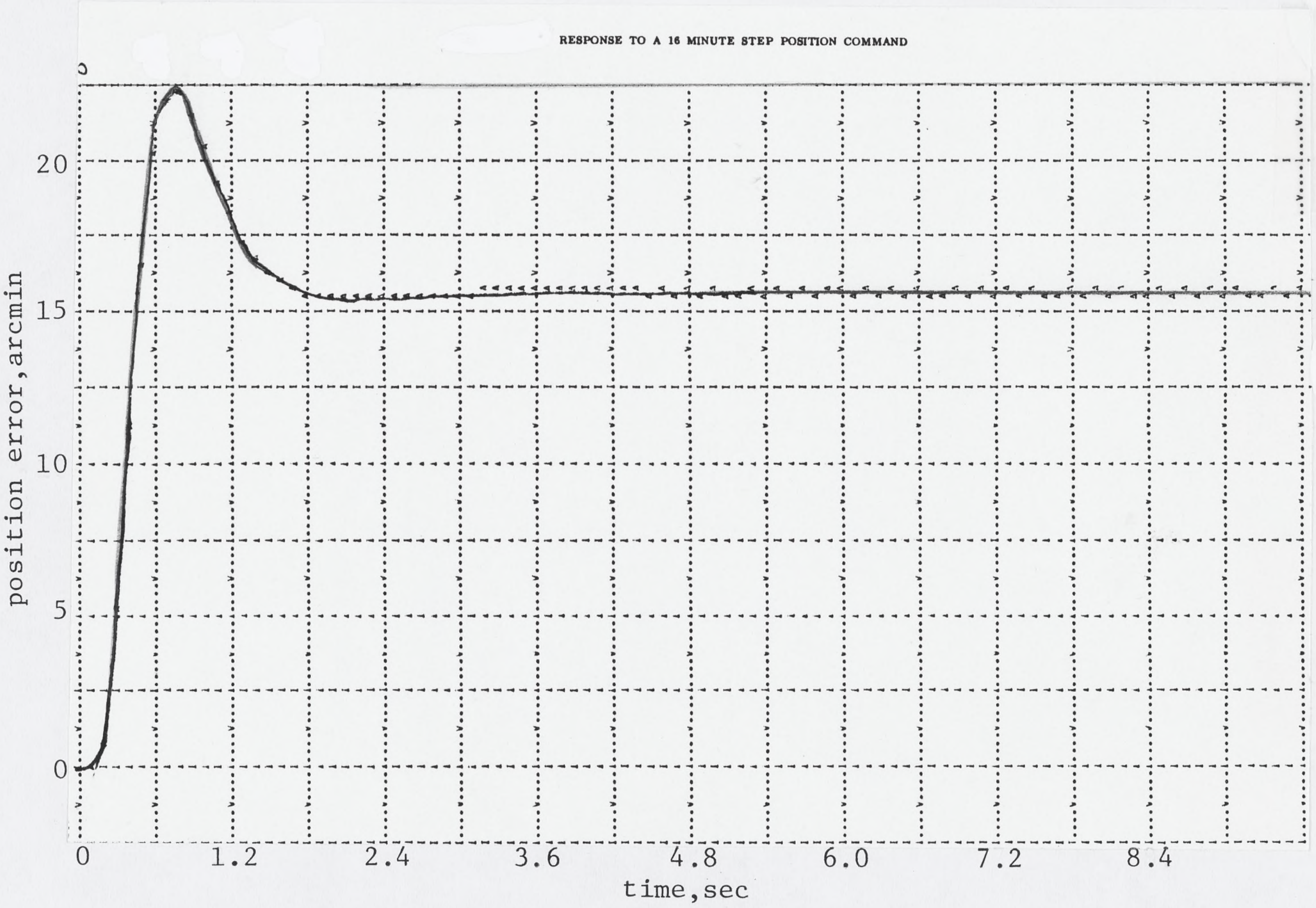

Fig. 4. Antenna drive servo, theoretical response to 16 arcmin step in position.

4.4 Atmospheric Refraction

Below about 25° elevation, the typical atmospheric refraction at Green Bank will exceed our required pointing accuracy of .033°. However, given accurate local measurements of pressure, temperature, and dew point, assumption of a radially symmetric atmosphere allows refraction at 5° elevation to be calculated within about .003° [Green, 1985]. The total refraction is then typically 0.2°, and deviations from radial symmetry might cause model errors up to 10%, leading to a pointing error of .02°; since this is within our requirements, we expect to achieve satisfactory pointing down to 5° elevation.

4.5 Real-Time Pointing Corrections

The above analysis shows that "blind" pointing should be fully adequate for this application. However, in case the orbit predictions or the absolute antenna pointing do not meet our expectations, it will be very easy to implement "peaking up" algorithms in real time with no additional hardware. In view of the high SNR available on the spacecraft signal, fine adjustment of the pointing will take less than 60 seconds, with the signal falling below required thresholds during less than half this time, and then only if the spacecraft is near maximum range. Since Radioastron passes will last 12 to 19 hours and VSOP passes will typically last 3 hours (but occasionally less), several pointing adjustments per pass may be made with negligible loss of data. This will certainly guarantee meeting the pointing requirement during the remainder of each pass.

5. REQUIREMENTS AND PREDICTED MARGIN

A power budget for the 144 Mb/s Radioastron downlink is given in Table IV. This is the most stringent of the link budgets because Radioastron will have much larger range than VSOP, and because the phase transfer links have much narrower bandwidths. The spacecraft parameters, namely the transmitter power and antenna gain, are based on the latest data from Soviet engineers [Rogal'ski, 1989].

It can be seen that even after a 3 dB allowance for atmospheric absorption (bad weather) and 1 dB for pointing errors (larger than expected), the system provides a margin ranging from 6.6 dB at 5° elevation to 8.1 dB above 20° elevation, assuming that the antenna surface is aligned to its original specifications. Even without realignment, a margin of 2.6 dB is achieved above 20° elevation. Under favorable conditions, available most of the time, the margins will be larger.

TABLE IV: RADIOASTRON DOWNLINK POWER BUDGET

Spacecraft transmitter power (10 W)		+10.0 dBW
Transmitter circuit losses		- 2.0 dB
Spacecraft antenna gain (0.9 m dia., 20% eff.)		+36.0 dB
Spacecraft antenna pointing loss		- 0.5 dB
Atmospheric loss (poor weather)		- 3.0 dB
Propogation loss (75,000 km range, 15 GHz)		-214.5 dB
		-174.0 dBW
Ideal SNR for differential QPSK at BER=5E-4	7.8 dB	
Detector loss	1.3 dB	
Bit rate (144 Mb/s)	81.6 dBHz	
Required P_r/N_o		90.7 dBHz
Required earth station G/N_o		264.7 dB(Hz/W)
Earth station pointing loss (maximum)		1.0 dB
Net required G/N_o on boresight		265.7 dB(Hz/W)

Expected Performance [1]:		Aper.Eff.	T_{sys}	G/N_o dB(Hz/W)	Margin
Before re-alignment	e > 20°	0.14	70 K	268.3	2.6 dB
	e = 5°	0.14	98	266.8	1.1
After re-alignment	e > 20°	0.50	70	273.8	8.1
	e = 5°	0.50	98	272.3	6.6

Note:
[1] $G/N_o = \eta(\pi D/\lambda)^2/kT_{sys}$

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