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Ka-Band (32-GHz) Performance of 70-Meter Antennas in the Deep Space Network

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Two models are provided of DSN 70-m antenna performance at Ka-band (32 GHz) and, for comparison purposes, one at X-band (8.4 GHz). The "baseline" 70-m model represents expected X-band and Ka-band performance at the end of the currently ongoing 64-m-to-70-m mechanical upgrade. The "improved" 70-m model represents two sets of Ka-band performance estimates (the X-band performance will not change) based on two separately developed improvement schemes: The first scheme, a "mechanical" approach, reduces tolerances of the panels and their settings, the reflector structure and subreflector, and the pointing and tracking system. The second, an "electronic/mechanical" approach, uses an array feed scheme to compensate for lack of antenna stiffness, and improves panel settings using microwave holographic measuring techniques. Results are preliminary, due to remaining technical and cost uncertainties. However, there do not appear to be any serious difficulties in upgrading the "baseline" DSN 70-m antenna network to operate efficiently in an "improved" configuration at 32 GHz (Ka-band). This upgrade can be achieved either by a conventional mechanical upgrade or by a mechanical/electronic combination. An electronically compensated array feed system is technically feasible, although it needs to be modeled and demonstrated. Similarly, the mechanical upgrade requires the development and demonstration of panel actuators, sensors, and an optical surveying system.

I. Introduction

This report provides two models for 70-meter DSN antennas, each for Ka-band (32 GHz) performance, and, for comparison, one for X-band (8.4-GHz) performance. The first model, the "baseline" or 1990 version, models the expected antenna efficiency at the completion of the now ongoing 64-m-to-70-m upgrade. Though the upgrade for all three DSN 64-meter antennas is scheduled for completion prior to the 1989 Voyager encounter with Neptune, one upgrade may be delayed until after encounter – hence the label "1990 model." The model shows that the baseline 70-meter efficiency will exceed

75% at X-band, but be less than 30% at Ka-band at the 45-degree rigging angle (and substantially less as the antenna elevation differs from that angle).

The second model, the "improved" or 1995 model, describes the expected antenna efficiency after a further upgrade is made (around 1995) to accommodate Ka-band with improved efficiency. The 1995 model does not improve X-band performance noticeably, but increases the Ka-band performance in two ways – the maximum efficiency is increased to above 50%, and this efficiency is achieved over a wide range of elevation angles (from 10 degrees to 90 degrees).

The 1995 Ka-band model is based on two possible approaches to improving the antenna: (1) a "mechanical" approach that provides improved performance by stiffening the antenna and by improving panel settings using advanced surveying techniques, and (2) an "electronic/mechanical" approach that uses an array feed scheme to compensate for lack of antenna stiffness, and improves panel settings using microwave holographic measuring techniques.

The differences in the results of the two approaches are small in performance, though perhaps large in costs. However, cost data are preliminary. Therefore, although a 1995 model is described in this report, the actual approach to obtain that model is not specified.

This report reflects the best engineering judgment available during the summer of 1986. Subsequent analyses will reflect later judgment as Ka-band performance estimates continue to evolve.

II. Baseline, or 1990, Model

At the completion of the currently ongoing 64-m-to-70-m upgrade, the "baseline" antenna efficiency at both Ka-band and X-band is expected to be as shown in Table 1. Figure 1 shows gain versus elevation performance at the above two frequencies for the 70-m antenna.

The results in Table 1 and Fig. 1 are based on the following assumptions: (1) the surface panels will be rigged at a 45-degree elevation angle, (2) a 20-mph (32-km/h) wind is assumed to be blowing, and (3) a temperature range of 40°F (22°C) on the antenna structure is assumed. The surface panel rms manufacturing error is expected to be 0.008 in. (0.020 cm), and the accuracy of the panel settings is assumed to be within 0.015 in. (0.038 cm). Aperture phase error caused by small-scale atmospheric turbulence is included, but no atmospheric attenuation contribution is included (this is considered a space loss parameter). The assumed CONSCAN "tracking" accuracy of 0.002 degrees may represent a somewhat optimistic view, making performance of the "baseline" antenna at 32 GHz as shown in Table 1 and Fig. 1 somewhat optimistic.

A. RF Loss (Degradation) Factors

The efficiency of a paraboloidal antenna is determined by both RF and mechanical factors, and by other factors (as shown in Table 1). Among the RF factors are those that cause loss when feed pattern characteristics are not ideal. These include the property of the energy source (feed) to illuminate only the reflectors while minimizing the energy that radiates elsewhere, and the property of the combined feed and subreflector to illuminate the parabola uniformly, making maximum use of the entire reflector surface. Ludwig (Ref. 1) and Potter (Ref. 2) have described these loss factors in detail.

B. Mechanical and Other Loss Factors

The uncertainty in the performance of the antenna at Ka-band due to the RF factors described above is outweighed by mechanical factors such as blockage and surface tolerance, and other factors such as pointing errors, wind, thermal effects, and atmospheric turbulence. The ground antenna effective aperture would remain essentially constant with increasing frequency were it not for aperture phase distortion – the so-called "Ruze" effect (Ref. 3) – which becomes serious as the standard deviation of these phase distortions approaches 1/12 of the wavelength. Mechanical deflections, manufacturing tolerances, wind, thermal effects, and small-scale atmospheric turbulence (Ref. 4) result in additional more-or-less random phase errors whose associated aperture efficiency loss factor, η_s, is given by

$$\eta_s = e^{-(4\pi\sigma/\lambda)^2}$$

where

σ = standard deviation of the one-half pathlength error

λ = wavelength

Using the above Ruze formula, various statistically independent factors responsible for phase error (and thus loss of aperture efficiency) can be calculated and tabulated. That is, for each independent factor i, there is an associated standard error, σ_i, and efficiency loss factor, η_{si}. Further, the total efficiency loss factor, η_{st}, is the product of the individual loss factors, and the total standard error, σ_t, is the rms of the individual standard errors. This is the basis for the development of Table 1.

The determination of Fig. 1 follows a similar line of reasoning, with the phase error being introduced by gravitational effects and atmospheric turbulence – a function of the elevation angle. This function is extracted from the works of Levy[1] and Potter (Ref. 4).

These figures differ slightly from a similar model developed last year (Ref. 5), essentially because of a higher expected efficiency, as less power is now expected to be contained in modes with azimuthal (m) variation unequal to 1 (i.e., modes that do not radiate on the antenna axis).

III. Improved, or 1995, "Mechanical" Model

The kernel of the "mechanical" approach for the improved model is to reduce tolerances of the reflector surface panels and panel settings, the reflector structure and subreflector, the pointing and tracking system, and those due to thermal effects. The net effect of these improvements is shown in Table 2 and Fig. 2.

A. Panels and Settings

Bonded panels (rather than the originally planned riveted panels with 0.008-in. rms tolerance) have now been fabricated to provide 0.004-in. (0.010-cm) rms tolerance. A precise setting of the reflector panels can further reduce the rms tolerance from the "baseline" 0.015 in.[2] to either 0.008 in. or 0.005 in. (0.0127 cm). However, the improved setting accuracy depends upon the development of an optical instrument that can be used at a 45-degree antenna elevation position to set the panels. The instrument must provide fully automatic readout, positioning, and ranging. It will require an operator to sight it on a corner cube optical target at the corner of the intersection of the panels. The expected accuracy of this instrument, including operator sighting resolution, will keep the error to within 0.008 in. at a range of 35 m. But an actual optical instrument that will achieve the above is not yet developed, although a prototype of this instrument is in use on the 70-m X-Band Upgrade Project (it must be used only in the zenith position). Corner cube optical targets and ranging instrument prototypes are currently being used, but the accuracy of the ranging and target holders needs to be improved before the accuracy stated above can be ensured.

Further precision setting of the reflector panels will require improvements to the Reflector Panel Controller so that individual reflector panel positions can be maintained within a pre-determined location to an accuracy of 0.005 in. (as a function of the antenna's elevation position). The key element of this improvement is a motorized actuator with a transducer that would position the four corners of its supporting panels. The planned approach is to use an open-loop system where either analytical or field-measured data can be used to position the panels, adjusting for effects of gravity on the antenna structure. A central computer would be used to control the 1800 actuators. These same actuators could also be used to compensate for thermal and wind distortions. Currently, the most difficult aspect of wind and thermal distortion compensation is the need for development of effective sensors or algorithms that derive the correct compensation movement for the actuators. Figure 3 is a drawing of a proposed actuator (in place on the antenna). Tailored after commercially available units, this device will fit within the limited space between the existing reflector structure and surface panels.

The gain improvement for the Reflector Panel Controller varies with antenna position. The improvement in gain is near zero at the rigging angle (where the panels are set by the Controller with the antenna at a 45-degree elevation position), and reaches a maximum improvement of 2.8 dB near the antenna zenith or horizon position.

B. Structure and Subreflector

A reinforced reflector structure would improve pointing and reduce wind distortion from 0.011 in. (0.028 cm) rms to 0.006 in. (0.015 cm) rms. In addition, the stiffening would reduce the pointing error caused by 20-mph winds to ±0.002 degrees.

Reduced tolerances are also possible from an improved subreflector. The improved subreflector would be two-pieced machine-cast aluminum, and symmetrically shaped. The improvement in the performance to the desired shape would be 0.006 in. rms versus the existing 0.010 in. (0.0254 cm) rms. The subreflector would be centered on the antenna boresite axis and shaped for optimum 32-GHz performance. The improved surface accuracy is readily achieved because the shape is a curve of revolution, and hence is easier to machine and verify. The current 70-m X-band subreflector is asymmetric in shape and requires (at least) a three-axis milling machine. In addition to the problem of the current subreflector being asymmetric, the vertical travel of the three-axis machine on which it is machined is not sufficient to cover the subreflector height. This requires resetting of the subreflector in order to complete the machining.

C. Pointing and Tracking

Antenna pointing and tracking improvements can be made in a series of progressive modifications, beginning with the tracking system, where there is a positive feedback correction

[1]Levy, R., JPL IOM 3556-84-092, Jet Propulsion Laboratory, Pasadena, CA, Oct. 10, 1984 (JPL internal memorandum); also F. D. McLaughlin, private communcation.

[2]The baseline setting of 0.015 in. relies on holographic measurements taken at a 45-degree elevation angle.

system (CONSCAN). To be able to track and re-acquire a target at 32 GHz requires the following improvements for each stated accuracy (each improvement builds on the previous change):

(1) New 24-bit encoders and associated cabling and software to enable a 0.004-degree accuracy.

(2) The addition of a limited sensor package for measurements of antenna structure (for correction of temperature and gravity effects) to enable a 0.002-degree accuracy. Also needed is four-quadrant wind monitoring and a wind model for pointing correction.

(3) A sensor package to more completely monitor antenna gravity and temperature effects to enable a 0.001-degree accuracy. In addition, gravity panel corrections are required using the actuators for the panels and integrating a predictive wind correction model. Also, an adaptive control algorithm for enhanced antenna control is needed.

(4) An inertial reference to replace the present master equatorial system to provide 0.002-degree pointing acquisition. New systematic error correction software is also required.

D. Thermal

Providing thermal protection to the reflector structure and alidade can reduce the rms tolerance due to this effect from 0.010 in. to 0.005 in. The reflector structure would have insulated panels, enclosing the backside of the reflector structure. The resultant area would be separated into several plenum chambers, ventilated or temperature-controlled to provide uniform structure temperature changes. The alidade legs would be thermally insulated to provide for uniform temperature changes to the alidade structure.

IV. Improved, or 1995, "Electronic/Mechanical" Model

Table 3 and Fig. 4 give expected improved performance using "electronic/mechanical" upgrades, i.e., an array feed concept and advanced microwave holographic techniques. Cost factors are included. Figure 5 shows the array concept. The operational principle is described below.

A. Array Feed Concept

In principle, many aperture phasing errors may be compensated for electronically using an array feed. While the surface profile of the 70-m antenna may have sufficient accuracy at X-band, its surface distortion becomes a significant fraction of a wavelength at Ka-band, and the performance will sharply deteriorate. If these distortions can be compensated for by replacing the conventional single feed with an array feed, major performance improvements can be achieved at a fraction of the cost of building a new large-reflector antenna.

Rudge and Davis (Ref. 6) discussed the array feed concept for distorton correction and proposed the use of the Butler matrix and a means of providing adaptive excitation of the feed array. Their analytic and quantitative results, however, are limited to cylindrical reflectors having one-dimensional distortion profiles requiring only linear array feeds. Amitay and Zucker (Ref. 7) analyzed the use of planar array feeds for aberration correction in spherical reflectors. However, their synthesis procedure relies heavily on the circular symmetry of the feed-plane field distribution that exists in this case.

An algorithmic procedure has been developed at JPL to simultaneously provide electronic correction of systematic reflector distribution as well as electronic beam stabilization (Ref. 8). Although the computer code used in the study could be used to optimize general performance criteria (gain, sidelobe levels, and beam shape), this study focused only on gain maximization. For a given feed configuration, reflector f/d ratio, and distortion profile, the algorithm finds the optimum values of the individual feed excitations to maximize the reflector antenna gain in the desired direction.[3]

Once the array feed configuration has been determined, the array excitations must be adjusted to optimize performance. Adjustments to amplitude and phase can be accomplished at RF-with-digital phase shifters and variable power dividers or at some IF frequency using a device such as the Baseband Assembly (BBA). Since it is desirable to have as low a loss as possible, the front-end electronics (feed, low-noise masers) will be housed in a cryogenic front end. Significant trade-off studies have not yet been made to determine whether RF or IF beam forming would be preferred, but as a strawman design, the technique of using a BBA has been selected, and a block diagram is given in Fig. 5. It should be noted that since only seven elements are used, vernier beamsteering cannot be provided for a full ±1 beamwidth pointing error. Further studies are required to provide accuracte estimates of performance.

B. Microwave Holographic Measurements

Microwave holographic measurement techniques are expected to provide 0.015-in. settings by 1990, and 0.008-in.

[3]Numerical results were obtained for the "equivalent" single parabola case showing that good on-axis gain restoration can be achieved with as few as seven elements. For beam stabilization to ±1 beamwidth (BW), 19 elements are required. The dual-reflector case is presently under study.

settings by the 1995 upgrade. Further exploration is required in this area.

V. Conclusions

There do not appear to be any serious difficulties in upgrading the "baseline" DSN 70-m antenna network to operate efficiently in an "improved" configuration at 32 GHz (Ka-band). This upgrade can be achieved either by a conventional mechanical upgrade or by a mechanical/electronic combination. An electronically compensated array feed system is technically feasible, although it needs to be modeled and demonstrated. Similarly, the mechanical upgrade requires the development and demonstration of panel actuators, sensors, and an optical surveying system.

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Table 1. 70-m antenna "baseline" performance estimates[a]

Contributor	X-Band (8.450 GHz)	Ka-Band (Baseline) (32 GHz)
Waveguide Loss	0.984	0.980
Dichroic Loss	0.992	–
Forward Spill	0.964	0.970
Rear Spill	0.997	0.997
Illumination	0.982	0.980
X-Polarization	1.000	1.000
Phase	0.989	0.980
Central Blockage	0.988	0.990
M ≠ 1 Modes	0.996	0.996
VSWR	0.991	0.990
Mesh Loss	0.999	0.998
RF Subtotal	0.887	0.887
Quadripod Blockage	0.9196	0.9196
Panels (0.008 in.)[b]	0.9948	0.9285
Setting (0.015 in.)[b]	0.9820	0.7704
Subreflector (0.010 in.)[b]	0.9919	0.8905
Gravity (30°)[c]	0.9948	0.9285
Thermal[b]	0.9920	0.8905
Wind (20 mph)[b]	0.9903	0.8691
Atmospheric Turbulence (30°) (Ref. 4)	0.9916	0.8864
Pointing (0.002°)[d]	0.9894	0.8568
Mechanical and Other Subtotal	0.854	0.320
Combined Efficiency	0.758	0.284
Relative to 100%	−1.20 dB ± 0.2	−5.47 dB ± 0.5

[a]No atmospheric attenuation contribution is accounted for, as it is considered a space loss parameter.

[b]"64-Meter Antenna Rehabilitation and Performance Upgrade Project, Antenna Mechanical System," Ground Antenna and Facilities Engineering Section's E-Level Design Review (JPL internal document); also F. D. McLaughlin, private communication.

[c]Levy, R., JPL IOM 3556-84-092, Jet Propulsion Laboratory, Pasadena, CA, Oct. 10, 1984 (JPL internal memorandum); also F. D. McLaughlin, private communication.

[d]*Deep Space Network/Flight Project Interface Design Book*, Vol. I, TRK 10, Rev. B, p. 5, JPL Document 810-5, Jet Propulsion Laboratory, Pasadena, CA (JPL internal document), states "blind pointing or open loop pointing of 0.005 degrees and engineering estimates are made here for CONSCAN tracking to be 0.002 degrees (optimistic)."

Table 2. 70-m antenna "mechanical" upgrade performance estimates

Element	Improvement[a]	Quality
Reflector Panels	~0 dB	<0.004 rms
Subreflector	~0.3 dB	<0.006 rms
Quadripod	~0.1 dB	<2.5% blockage
Reflector Panel Setting	~0.8 dB	<0.008 rms
Reflector Panel Control	2.8 dB[b]	<0.005 rms
Thermal Control	0.4 dB	<0.005 rms
Reflector Stiffening (at ≤20-mph wind)	1.0 dB[b]	±0.002°
Tracking/Pointing Control	4.5 dB[b]	<0.001°/±0.002°

[a]Improvement over 70-m X-band.

[b]Varies with antenna position.

Table 3. 70-m antenna "electronic/mechanical" upgrade performance estimates

Contributor	Improvement					Comments
	Efficiency		dB	NRE	Per Antenna	
	(a)	(b)				
RF	0.887	0.887	0.0	0	0	No more improvement after currently scheduled 64-m - 70-m upgrade
Quadripod Blockage	0.9196	0.9196	0.0	0	0	No more improvement after currently scheduled 64-m - 70-m upgrade
Mfg. Reflector Panels (0.008 in.)	0.9285	0.9285	0.0	0	0	No more improvement after currently scheduled 64-m - 70-m upgrade
Mfg. Subreflector (0.006 in. from 0.010 in.)	0.9591	0.8905	0.32	150K	800K	Cost estimate per Ground Antenna and Facilities Engineering Section for new subreflector
Setting (0.008 in. from 0.015 in.)	0.9285	0.7704	0.81		60K	Improved setting with holographic technique
Other Factors	0.8913	0.5458	2.13	2000K	3000K	Electronic phase error compensation using arrayed feed system for distortion correction
Combined Efficiency	0.600	0.284	3.26	$2150K	$3860K	
Relative to 100%	-2.21 dB $^{+0.0}_{-1.5}$	-5.46 dB ± 0.5		+2000K −500K	±1000K	

[a]After proposed upgrade (mechanical and electronic).

[b]At completion of currently scheduled 64-meter-to-70-meter upgrade.

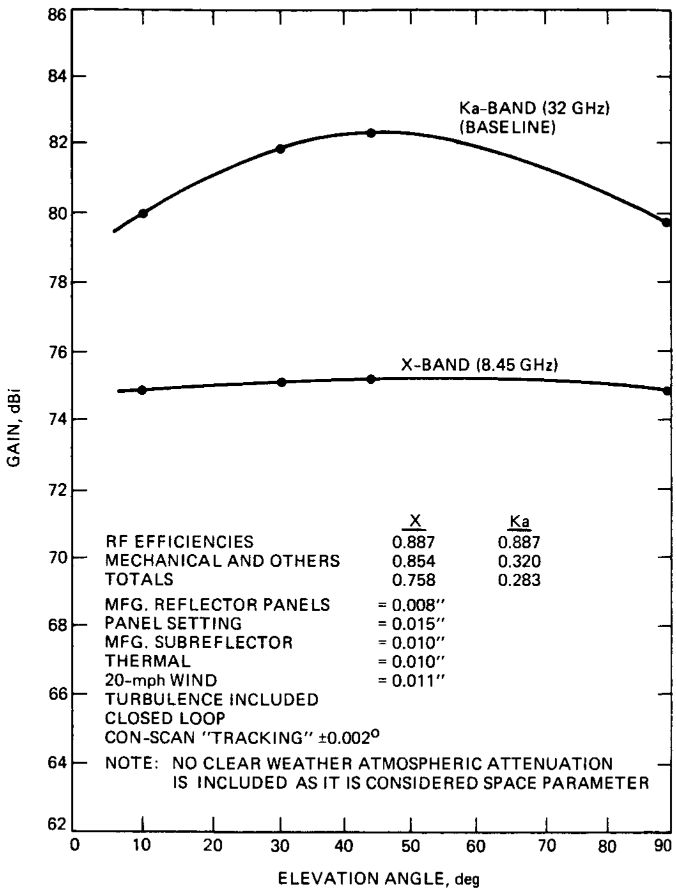

Fig. 1. Predicted antenna "baseline" performance at 64-m-to-70-m upgrade

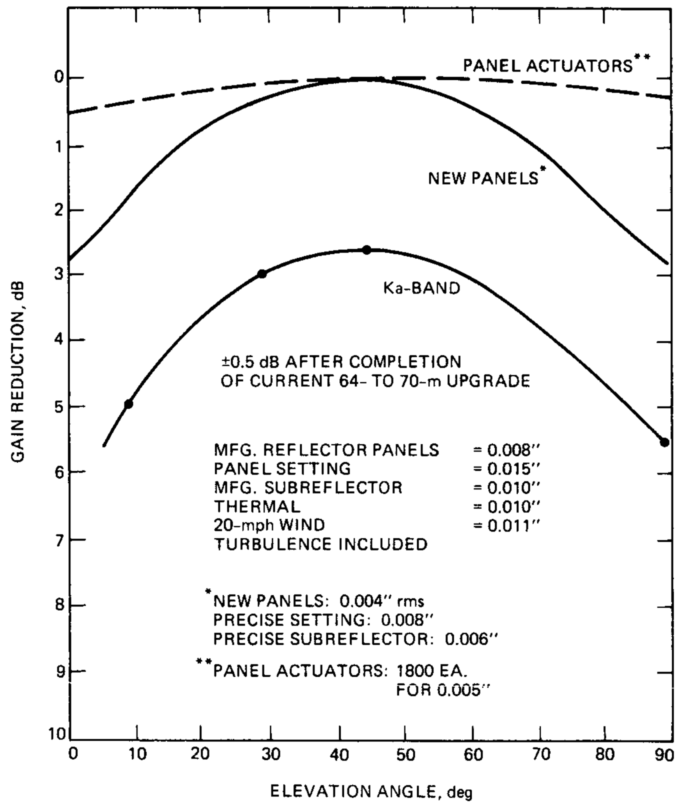

Fig. 2. Antenna gain loss caused by gravity effects for different elevation angles

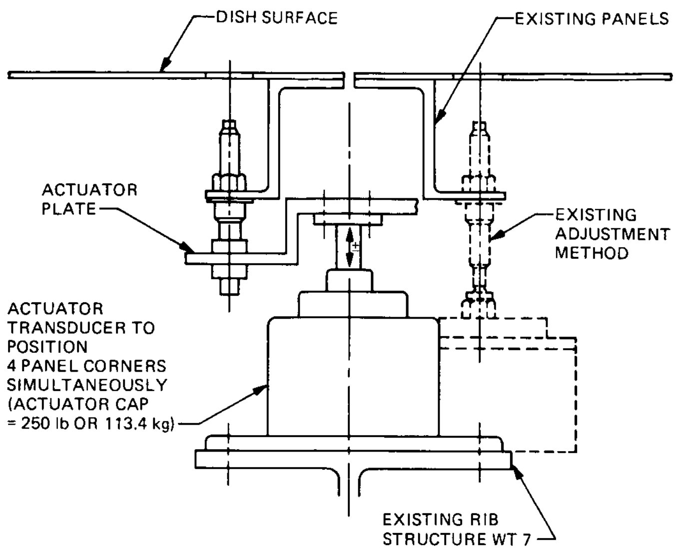

Fig. 3. Reflector panel adjustment, motorized actuator

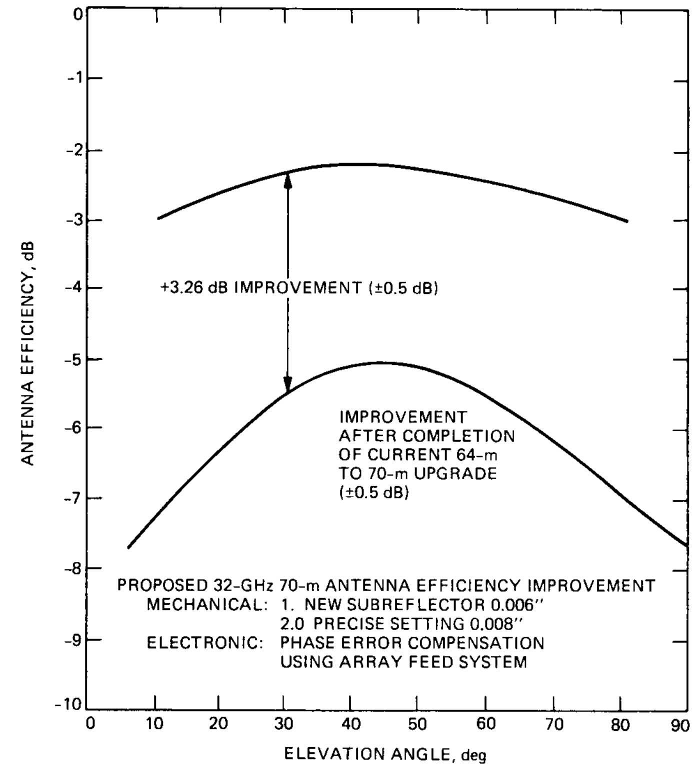

Fig. 4. 70-m antenna performance estimates, "electronic/mechanical" upgrade

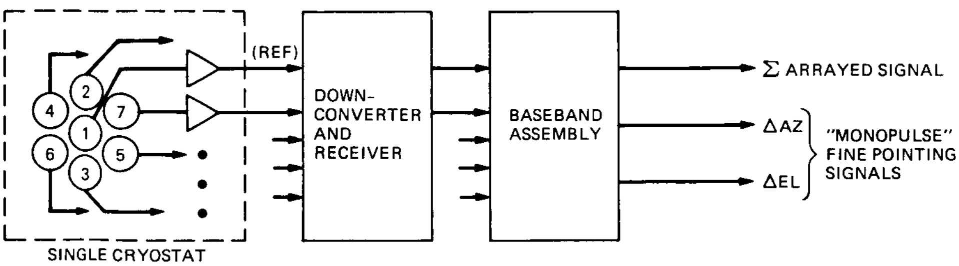

Fig. 5. Array feed concept