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A Study of Technical Issues and Tradeoffs in the Design of the New Green Bank Telescope

NRAO Technical Study Group[1]

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I. Introduction

The collapse of the 300-foot radiotelescope on November 15, 1988, was a serious loss to astronomy. Discussions of a new, large aperture radiotelescope for the NRAO, which had been going on over the preceding few years, then acquired more urgency and led to a scientific workshop at Green Bank December 2–3, 1988. At that meeting [1], the scientific impact of the loss of the 300-foot telescope was analyzed and the specifications of a replacement were discussed. Some of the scientific disciplines presented apparently conflicting requirements—*e.g.*, the largest possible collecting area at low frequencies for pulsars, *vs.* operation at frequencies as high as 115 GHz for spectroscopy. Moreover, it seemed that some of the desired characteristics of the new instrument would require extensions of the state of the art in large antenna design—*e.g.*, reducing far sidelobes and standing waves to the absolute minimum, suggesting an unblocked aperture. There was thus some uncertainty over how to optimize the tradeoff of the major parameters of size and frequency limit, and also over the technical feasibility of some of the goals.

A technical study group consisting of NRAO engineers and scientists was formed in mid-December 1988 to investigate these issues. The objective was to estimate quantitatively the performance achievable with various designs, along with their costs. This was to be done in a short period of time, using the limited manpower available from people who have other full-time responsibilities. These limitations have precluded a fully comprehensive study, but the effort has nevertheless yielded some significant results, as presented in this report.

As a result of the Green Bank Workshop, certain minimum requirements and desirable characteristics became clear, and these formed the starting point of our work. A summary is given in Table 1. The requirement for a 100 m class instrument that works efficiently at 5 GHz merely indicates that the new telescope should be at least as capable as the 300 ft. We take "100 m class" to mean that the *effective area* should be no less than that obtainable with other telescopes of that size; *e.g.*, the Effelsberg telescope achieves about 3,700 m^2 at 5 GHz and the 300 ft. achieved about 2000 m^2.

The great interest in improving, relative to existing telescopes, the far sidelobe response (for rejection of interference, both natural and man-made) and the standing waves within the antenna (for accurate spectroscopy) has led us to consider an antenna with no aperture blockage. Since such an antenna is radically different from a symmetrical one, the two are considered separately in this report. Many considerations for symmetrical antennas, which are discussed first, apply also to the unblocked case and these will not be repeated.

II. Axially Symmetrical Antennas

A. Cost *vs.* Size and Minimum Wavelength

Von Hoerner [5] has shown that the accuracy with which a large structure can be kept in a given shape while being tilted is limited by gravity in proportion to D^2 and by thermal

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Table 1: Requirements For a New Large Radio Telescope	
Basic Assumptions:	
1.	"100-m class" (effective size)
2.	Upper frequency limit > 5 GHz
3.	Full sky coverage (minimum elevation $\leq 10°$)
Strong Desires by Some Astronomers:	
1.	Much larger size (120–150 m)
2.	Much higher frequency limit ($\lambda/16$): 23 GHz, 43 GHz, or 86–115 GHz
Important Additional Parameters:	
1.	Very accurate pointing ($< \theta_{HP}/10$ at λ_{min})
2.	Very low sidelobes (10–20 dB below CCIR Recommendation 509)
3.	Very low backscatter to feed
4.	Beam scanning (10–20 beamwidths) and beam switching (Items 2, 3 suggest an unblocked aperture.)

gradients in proportion to D, where D is a measure of its size; and that the proportionality constants depend mainly on constants of the materials. This is illustrated in Figure 1. For the moment we assume that a reflector antenna has a minimum usable wavelength determined only by the accuracy of the main reflector surface[2].

Some attempts to estimate the cost of large reflector antennas have assumed a power law relationship of the form

$$C = C_0(D/D_0)^{\alpha}(\lambda_{min}/\lambda_0)^{\beta} \tag{1}$$

where C is the cost of an antenna of diameter D and wavelength limit λ_{min}, and C_0 is the cost of a similar antenna of diameter D_0 and wavelength limit λ_0. Exponents $\alpha = 2.6$ and $\beta = -0.7$ seem to fit actual cost data for some existing antennas of (see, *e.g.*[2]). However, the use of such a scaling formula to estimate the cost of a new, very large antenna is full of difficulties. First, as von Hoerner points out [3], different structural members scale in mass (and hence cost) as D^1 to D^4. Some elements, like servo electronics, have constant cost. Further, the cost can vary by a factor of 1.5 to 2.0 depending on "fanciness"; cost estimates for JPL and for NRAO of antennas with the same *basic* specifications seem to differ by this amount due to special requirements imposed by JPL. For these reasons, a single-term power law relation is at best a rough approximation to the cost dependence on size.

The cost dependence on wavelength limit is even more complicated. In the following discussion, we consider the wavelength limit imposed by various effects, and then consider the cost implications of specifying a particular wavelength limit.

The first requirement on the antenna structure is that it survive in strong winds. If the reflector is a solid surface (rather than mesh), then the structure required for survival is independent of the wavelength limit. For a mesh surface, the wind loading may be somewhat less (proportional to $1/\lambda_{min}$), but this may be insignificant in the stow position; since we are interested in $\lambda \leq 6$ cm, we assume a solid surface. If the structure is built only for survival,

[2]In this report, "wavelength limit" λ_{min} will by convention mean 16 times the rms deviation of the main reflector from its ideal shape.

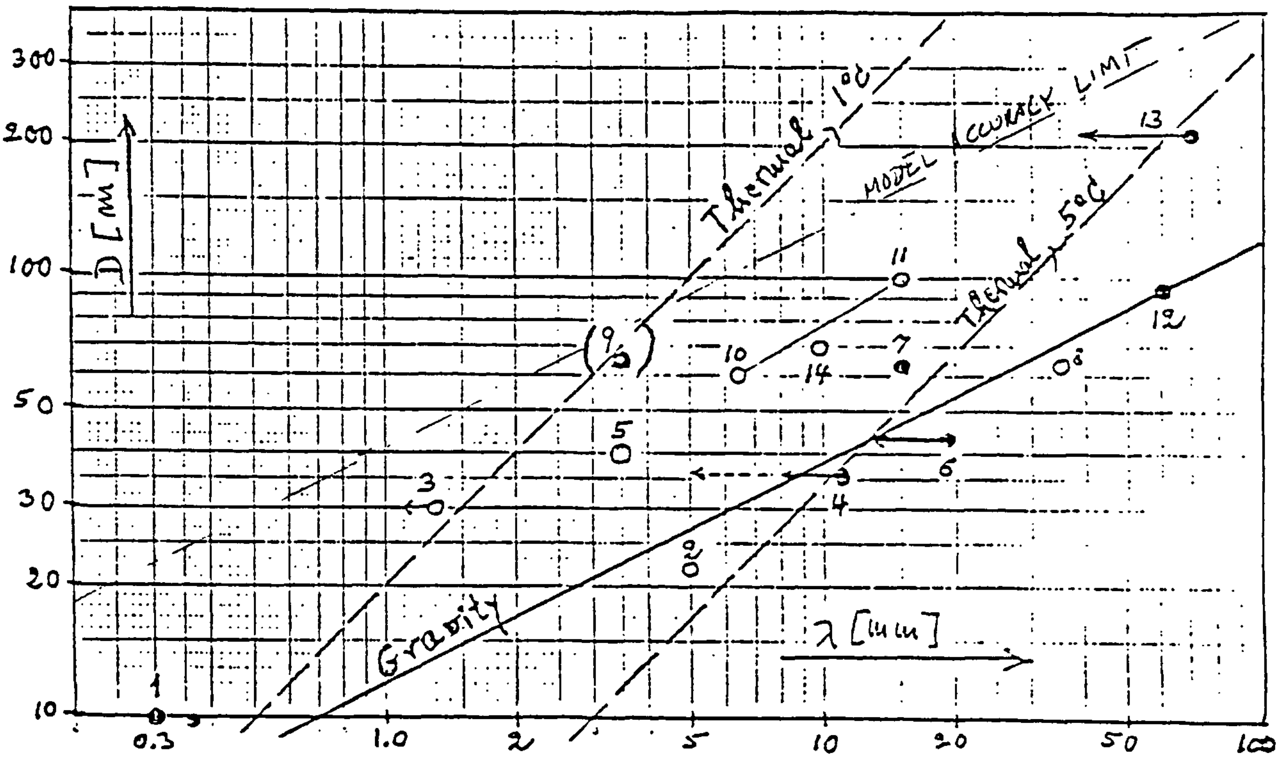

Fig. 1. Radio telescopes, and natural limits for simple design.
D = diameter,
λ = shortest wavelength (16 times surface rms),
Arrows = improvements.

Limits from:
Gravitational deformations for conventional backup.
Thermal deformations for steel and white paint,
unshielded, for rms temperature differences
at night (1°C) and in sunshine (5°C).

Telescopes:

1 Bonn-Arizona SMT	6 NRAO 140-ft	10 Effelsberg, center
2 Crimea	7 Goldstone	11 Effelsberg, all
3 Pico Veleta	8 Parkes	12 NRAO 300-ft
4 Haystack	9 NRAO 65-m design	13 Arecibo
5 Nobeyama		14 Usuriisk

(• USA, o Overseas)

Figure 1: Natural limits for simple telescope designs, from [4].

the amount of surface deflection under operational winds will determine the wavelength limit (neglecting gravitational and thermal deflections, which we consider separately); or, conversely, the desired operating wavelength will set the maximum operational wind. The limits can be improved by stiffening the load-bearing part of the structure.

For a sufficiently large antenna, a structure built for a fixed survival wind will deflect more under gravity than under a fixed operational wind. Under certain assumptions, von Hoerner [5] finds that this occurs for $D > 100\,\mathrm{m}$ if the survival and operational winds are 50 and 10 m/s, respectively; and further that the wavelength limit for $D = 100\,\mathrm{m}$ is 8 cm under these conditions. Under no-wind conditions, the wavelength limit can be improved by stiffening the load-bearing part of the structure against gravity (which also improves the wind limit); but a point is soon reached where the weight of further stiffening causes as much gravitational deflection as it resists. Under von Hoerner's assumptions, this gravitational wavelength limit is $\lambda_g = 6\,\mathrm{cm}$ at $D = 100\,\mathrm{m}$. The stiffening required to approach this limit is very expensive, with the total structural mass proportional to $\lambda_g/(\lambda_{\min} - \lambda_g)$.

Fortunately, the gravitational limit can be surpassed without additional mass. Two ways to do this are considered in some detail later. The wind limit can be improved, if necessary, at the cost of more structure, but we tentatively assume that if the structure is built only for survival, then the wind limit is acceptable (operation at the shortest wavelengths requires waiting for low wind).

Once gravity and wind are overcome, the wavelength limit is determined by thermal deflections and reflector manufacturing errors. Overcoming the thermal limit is also discussed later, but for a steel structure with $D = 100\,\mathrm{m}$ and maximum temperature difference of $\Delta T = 1\,\mathrm{C}$ (probably achievable at night) the limit is about $\lambda_T = 5\,\mathrm{mm}$.

We then conclude that the cost of the mechanical structure depends almost entirely on its size and not on the wavelength limit. The remaining costs which do depend on $\lambda_{\min}$ are *panel manufacturing, panel setting,* and *pointing control.* Pointing control may determine the ultimate wavelength limit; it is considered in detail later. Panel manufacturing cost is a nearly piecewise constant function of surface accuracy, increasing sharply when the limit of a particular manufacturing technique must be surpassed. Using aluminum skin and stiffeners shaped to a machined mold (as in the VLBA and VLA), panel rms errors of 0.125 mm are now routine, corresponding to a wavelength limit (from this cause alone) of 2 mm. A factor of two improvement in panel accuracy now seems possible at the same cost per unit area as the VLBA panels. For $D = 100\,\mathrm{m}$ the panel cost is then less than 25% of the structure cost and less than 10% of the total cost (as shown in the next subsection), so we assume that this panel type will be used. Of course, better panels could someday be installed if it becomes justified.

We finally conclude that *the cost of an antenna in the size range of interest depends very weakly on the wavelength limit and is determined almost entirely by the size.*

B. Specific Cost Estimates

We have obtained specific budgetary cost estimates from several sources for 100 m diameter, axially symmetrical antennas. These estimates are not all based on the same specifications and assumptions, and a breakdown of the cost elements is not available in all cases, so a comparison is not simple. The available data are listed in Table 2. The NRAO estimate was computed by L. King by scaling the VLBA design item by item to 100 m. Without any additional stiffening, this resulted in a wavelength limit of 2 cm, mainly from gravitational deflections.

All estimates exclude receivers, feeds, and computers. Some special items are listed separately; these are expected to improve the wavelength limit substantially, and are discussed in the following subsections of this report.

Table 2: Cost Estimates For a 100 m Symmetrical Antenna

Item	NRAO	Vendor A (1)	Vendor B (2)	Vendor C (3)	Scaling dependence
Structure	19.8	22.0	20.0		$D^{2.6}$
Panels, < 0.125 mm rms					
tooling	1.9	incl	2.0		D^1
fabrication	6.0	5.0	5.1		D^2
Design and drawings	2.7	4.3	2.0		D^1
Drives and controls	7.3	2.4	incl		$D^{1.3}$
Miscellaneous	4.1	0.6			D^2
Subreflector	1.0(4)	1.0	1.0(4)		$D^{1.5}$
Foundation	1.7	6.4	4.1		$D^{2.5}$
Ship, install, test	4.4	9.4	6.0		D^2
Management	1.3	2.0	incl		D^1
Subtotal	50.3	53.1	40.2	38.5	
Special items:					
Active surface control	3.5(4)	3.5	3.5(4)	3.5(4)	$D^{1.5}$
Thermal stabilization	1.0(4)	1.0	1.0(4)	1.0(4)	D^2
Pointing stabilization	1.0	1.0(5)	1.0(5)	1.0(5)	D^0
Total	55.8	58.6	45.7	44.0 M$	

Notes:
(1) Vendor A estimates $\lambda_{\min} = 5.7$ mm in 8 m/s wind with active surface control, 15.4 mm without [6].
(2) Active surface control assumed [27].
(3) Details not given.
(4) Estimated by Vendor A, adopted for others.
(5) Estimated by NRAO, adopted for others.

The last column in Table 2 gives the NRAO estimate of the scaling dependence appropriate to each cost element. This makes it possible to get reasonable estimates for sizes other than 100 m. Applying this to the NRAO estimate gives totals of $28.6M for $D = 70$ m and $86.9M for $D = 125$

In all cases, we assume that an industrial contractor would take major responsibility for both design and construction, but this must be preceded by a preliminary design, and some engineering support would be needed throughout the project. A budget for this plus the necessary eletronic instrumentation is given in Table 3.

Table 3: Estimate of Instrumentation and Support Costs

Project management	1.9 M$
Preliminary design	0.5
Electronics and software development	2.8
Receivers, feeds and instruments	0.8
Control computer	0.2
Analysis computer	0.5
Total	6.7 M$

C. Surpassing the Gravitational Limit

The estimated gravitational deflections of the 100 m antennas considered in the preceding section result in a wavelength limit of 1.5–2 cm, which already surpasses von Hoerner's gravitational limit of 6 cm. This is because the latter considered total deflections from a nominal shape, whereas we consider only deviations from the best fit focus location; that is, the designs are partially homologous. We know of two ways to reduce further the residual deflections and improve the wavelength limit: approach a fully homologous design; or install motorized surface adjusters at sufficiently many points so that the surface can be reset continuously as a function of elevation. We now discuss the limitations of these techniques.

Homologous designs have included the IRAM (15 m and 30 m) and Nobeyama (45 m) millimeter telescopes, the MPIfR Effelsberg (100 m) telescope, the NRAO 65 m design (never built), and the Bonn-Arizona submillimeter telescope (10 m, not yet built). The performance of the existing telescopes exceeds the gravitational limit by factors of 3 to 5; in most cases the performance is then limited by thermal effects or surface fabrication accuracy, so the reduction factor for gravitational residuals may actually be greater. Nevertheless, the approach to perfect homology is always limited by the accuracy of computer modeling of the structures and by tolerances of fabrication. It is estimated that the total deflection in large structures can be modeled to an accuracy of 5–10%; this is good enough to put the gravitational deflections well below the thermal limit for small antennas, but for sizes exceeding about 80 m the computer modeling errors will dominate the residuals. In addition, there are practical limits to homology, even if the models were perfect; large numbers of different-sized members are needed in the backup structure, and these are expensive to fabricate. Thus, recent designs have intentionally been only partially homologous (including the VLBA antennas and the JPL 70 m upgrades).

The other method to reduce the gravitational residuals is continuously to re-adjust the surface. Motorized adjusters at all support points of each panel can in principle remove all deflections except those of the panels themselves. The latter can be made smaller than the manufacturing error by keeping the panels sufficiently small. The adjustment algorithm may be based on either (1) calculated deflections from a computer model, resulting in the same limitations imposed on homologous design; (2) occasional "calibration" measurements of deflections; or (3) real-time measurements of deflections. At present, we are not confident that a sufficiently accurate method of real-time measurements exists, so we base our performance estimates on a combination of (1) and (2): calibration measurements based on holography would be used to provide corrections to the computer model. Eventual development of techniques for accurate real-time measurements would allow further improvements.

Some limitations and difficulties with this technique are: (1) it has not yet been attempted on a large antenna, although there is some relevant experience (the IRAM 15 m antennas and the Nobeyama 45 m antenna include motorized adjusters, but no real-time adjustment is done); (2) it is dependent on accurate mapping of the deflections over the surface, and this will limit the achievable improvement (high resolution holography requires precise pointing and long integrations, and thermal effects may change the deflections over the time needed to complete the measurements); (3) a large number of adjusters may be required (several thousand for all panel corners of a 100 m antenna), and their reliability must be very high, resulting in potentially high operating cost. We believe that all of these difficulties can be overcome at the level of 0.2 mm rms residuals ($\lambda_{\rm min} \approx 3$ mm), but more study and engineering is needed.

D. Surpassing the Thermal Limit

The thermal limits shown in Figure 1 are for a steel structure with assumed maximum temperature differences of 1 C and 5 C. The former seems to be achievable at night, especially with moderate wind, and the latter is typical in sunlight if the structure is painted with a diffusive coating. Improvements are possible by reducing the temperature differences, by using lower temperature coefficient materials, and by actively compensating for measured temperature variations.

1. Thermal stabilization. So far, most NRAO antennas have been built without thermal stabilization, other than proper choice of paint.[3] The Australia Telescope antennas ($D = 22$ m) have heavily insulated pedestals and yoke structures, with blowers to circulate ambient air for reducing gradients. The Pico Veleta (30 m) antenna goes further by fully enclosing the reflector backup structure and blowing in temperature-controlled air. In the latter case, the 1 C limit is surpassed even in the daytime (see Figure 1).

Although we have done no detailed studies, it appears that any attempt to actively control the temperature of the antenna structure becomes prohibitively expensive for large D. Power consumption would also be a serious limitation. The 30 m antenna may be the largest size subject to such an approach. However, shielding most of the structure from sunlight seems quite feasible. This would include enclosing the reflector backup structure in lightweight shields. The option of adding forced circulation of ambient air should be considered, but natural convection may be enough to keep the structure nearly isothermal. In this way, the sunlit performance may approach that achievable at night. We still expect a limit of $\lambda_{\min} \approx 5$ mm due to thermal effects for $D = 100$ m, even at night.

2. Low coefficient materials. For small antennas, it is feasible to construct the entire reflector and backup structure from materials having nearly zero temperature coefficient of expansion. The favored material is carbon fiber reinforced plastic (CFRP), because it also has good stiffness and strength-to-weight ratio. CFRP members with invar joints are planned for the Bonn-Arizona SMT. Unfortunately, these materials are 10–20 times more expensive than steel for the same stiffness. Some compromise is possible, with CFRP used only for the most critical members; this has been done for the IRAM 30 m and 15 m antennas, but a large fraction of their structures are still CFRP. For our 100-m class instrument the cost seems completely prohibitive, so we have not further considered this approach.

3. Active surface correction. If motorized surface adjusters are installed to cancel gravitational deformations, then they can also be used to fight thermal deformations if adequate measurements of temperature distribution and a good thermal model are available. We know of no experience with such an approach, and at this time we are unable to estimate how much improvement might be possible.

E. Pointing

A fundamental problem in building increasingly large reflector antennas is that (for a given wavelength) the beamwidth decreases linearly with D while the deformations increase with D, so unless special efforts are made the pointing accuracy as a fraction of the beamwidth becomes rapidly worse for large antennas. The gravitational deformation goes as D^2, but it is repeatable, so that once the pointing error is calibrated as a function of direction, it can be removed. The thermal deformations, which are not so predictable, increase as D, so the error in beamwidths from this cause goes as D^2. Even at $D = 25$ m, thermally induced pointing errors are a major problem; they limit high frequency operation of nearly all radiotelescopes in the daytime. Finally, wind-induced deformations go

[3]VLA antennas have had some insulation added to major elements of the pedestal structure in order to improve pointing performance, and a provision has been made to circulate liquid coolant in the VLBA pedestal for the same reason, but no effort has been made to stabilize the reflector structure; for these antennas with $D = 25$ m, $\lambda_{\min}$ is not thermally limited.

as D^2 (for a fixed operating wind speed and structural stiffness), giving a pointing error proportional to D^3 beamwidths.

Experience at the VLA has shown [7] that most of the sunlight-induced pointing error is due to uneven heating of the pedestal and yoke, rather than of the reflector structure. Therefore, if the orientation of the elevation axis in space (or relative to the stable ground) and its rotation can be continuously measured, then all pointing errors due to the lower structure could be removed, including both wind and thermal causes. (However, removal of rapidly varying disturbances such as wind gusts will be limited by the dynamics of the structure.)

As a step in this direction, sensitive inclinometers have been installed on each end of the elevation axis of some VLA antennas. These provide information about the axis orientation, but cannot sense distortions that cause purely azimuthal pointing errors. The inclinometers' only outside reference is gravity, so they cannot be used during accelerated motion of the antennas, including any significant vibration.

A more promising design was pursued for the NRAO 65 Meter Telescope [8]. Here a gimbled platform at the intersection of the antenna's axes was to be stabilized in orientation by optical measurements from stable reference points on the ground. Two high-resolution angle transducers (inductosyns) would then measure the azimuth and elevation of the elevation shaft relative to the platform. Tests on the critical optical components and servo system showed that the platform could be stabilized to about 2 arcsec in spite of atmospheric fluctuations in the optical path. It might be possible to stabilize such a platform to similar or better accuracy by using gyroscopes, and thereby avoid the need for optical paths.

For a $D = 100\,\mathrm{m}$ telescope to operate at 7 mm wavelength, a pointing accuracy of 1.4 arcsec is needed to be within 0.1 beamwidth. This is well beyond the state of the art unless some of the special stabilization techniques outlined above are used. The development of such techniques will be necessary if the new telescope is to operate at short centimeter wavelengths. Even at wavelengths as long as 3 cm, the required pointing accuracy will be achievable with conventional design only under benign conditions of solar radiation and wind.

F. A Conceptual Design

In order to make the preceding discussion more concrete, we now consider a specific configuration. This is not intended to be a recommendation, but just a sample design that can be analyzed, criticized, and further developed. All the conclusions of this section must be considered preliminary, since no detailed design or analysis has yet been done.

1. Description. The major specifications are given in Table 4, and a concept drawing is given in Figure 2. We have assumed that the two technical innovations discussed earlier will be included, namely motorized surface adjusters and a stabilized pointing reference platform.

We have chosen a paraboloidal main reflector mainly to allow for wide beam scanning by displacing feeds from the secondary focus, thus allowing quasi-optical beam switching and future array feeds. This is discussed further in section IV.B, below, and in [9]. For a discussion of the choice of subreflector size, see [10].

The panel manufacturing accuracy is especially good, but has been chosen for cost effectiveness, based on the most recent experience with VLBA panels. With such a large antenna, much of the cost is in the structure and foundation, so the fractional saving with cheaper panels would be small. More accurate panels would be possible at higher cost.

As discussed earlier (section II.A), the mechanical structure need not be made stiffer

Table 4: Axially Symmetrical Telescope—
Parameters of Conceptual Design

Main reflector diameter D	100 m
Main reflector focal length (paraboloid)	35 m
Subreflector diameter (hyperboloid) d	7 m
Subreflector manufacturing accuracy	.07 mm rms
Effective focal length at secondary focus	430 m
Quadrapod leg geometric shadowing	2.5 %
Panel size	1.6 × 2.3 m
Panel manufacturing accuracy	.07 mm rms
Surface adjustment points	~2,700
Surface adjuster resolution and repeatability	.025 mm
Pointing reference platform stability	1 arcsec rms

than is required for survival in the strongest winds. The design will be straightforward and conventional with the Effelsberg 100 m as a basic guide. The most difficult challenge involves minimizing blockage by the focal support legs. The two most advanced designs in this area are the 70 m and 34 m JPL telescopes. The 70 m quadrupod structure has 3.4% blockage and 1.42 Hz natural frequency, and the 34 m tripod has 2.9% blockage and 1.94 Hz. The cross-sections are 63.5 by 265 cm and 30.5 by 112 cm, respectively. For our 100 m telescope, we have made a preliminary investigation of a design using a tripod (rather than a quadrupod) with a cross section of 90 by 371 cm, as shown in Figure 3(a). This configuration will have 2.5% blockage and 0.77 Hz natural frequency; the latter is rather low for a large, movable structure. The two lowest modes are illustrated in Figures 3(b) and 3(c). An increase of member sizes may increase the natural frequency, and an increase of apex weight may decrease the natural frequency, but both of these effects are insignificant. In order to increase the 0.77 Hz natural frequency and not significantly increase the blockage, a method of putting outriggers at the support points has been used on the JPL 70 m design, as shown in Figure 3(d). The outriggers extend from the feedleg supports to 15% of the length of the feedleg to reduce the unsupported length and increase the torsional rigidity. This has been shown to double the natural frequency for the 70 m legs. Doubling our 0.77 Hz will give a respectable 1.5 Hz, at the cost of a slight increase in blockage.

2. Performance Estimates. Our best estimates of the performance of this antenna are summarized in Table 5. Certain details are discussed below.

Table 5: Estimated Performance of Symmetrical 100 m Antenna

Wavelength limit ($16\,\sigma_{\rm rms}$)	
Ultimate, with perfect compensation	1.6 mm
Without compensation	20 mm
Predicted for initial system	7 mm
Maximum Cassegrain wavelength ($d/20$)	35 cm
Effective area	
Prime focus, $\lambda = 21\,$cm	(59%) 4,600 m^2
Cassegrain, $\lambda = 6\,$cm	(71%) 5,500 m^2
Pointing error, non-repeatable, 7 m/s wind	
With stable reference platform	2 arcsec
Without stable reference platform	14 arcsec

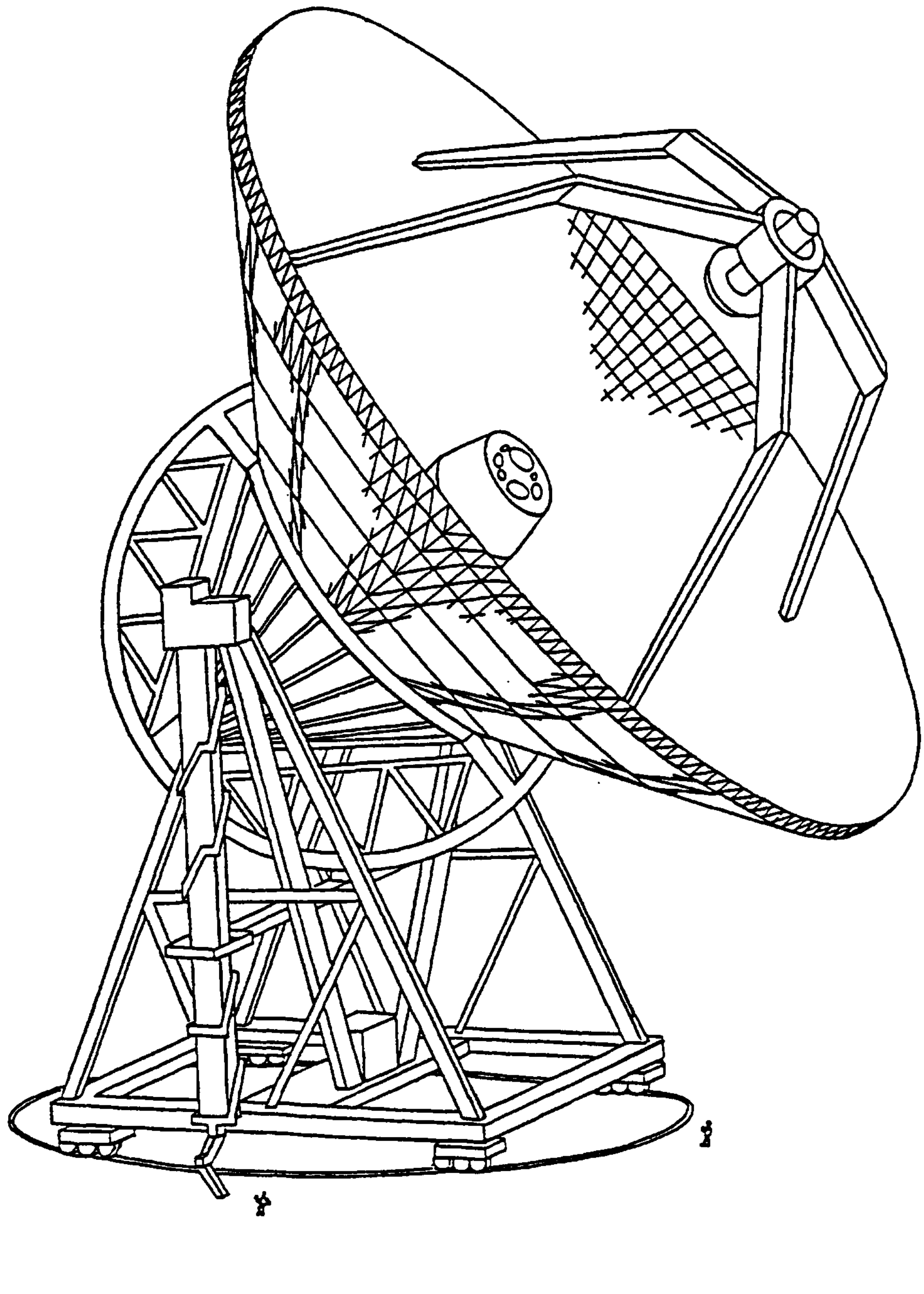

Figure 2: Axially Symmetrical 100 m Telescope Concept

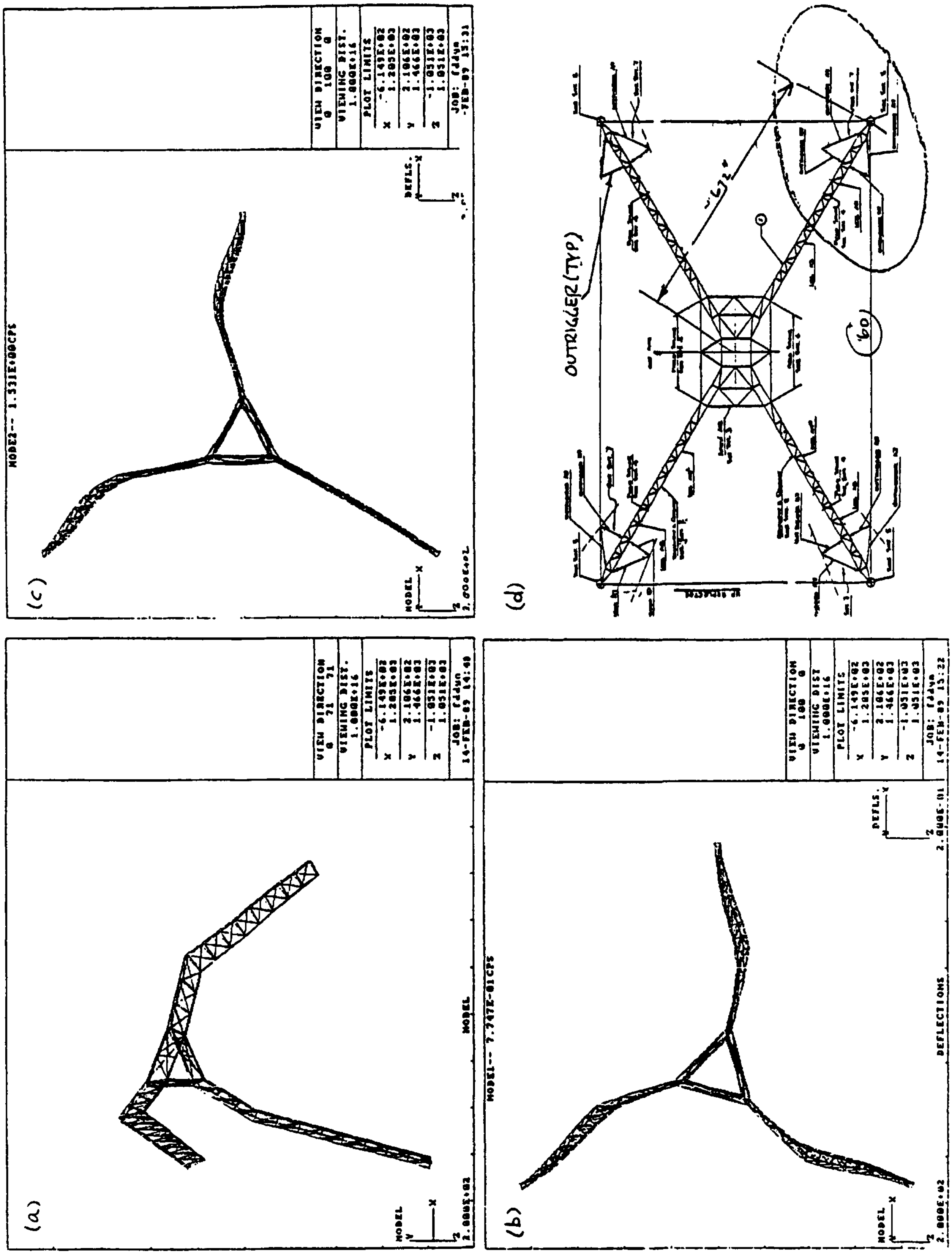

Figure 3: Focal support structure. (a) Proposed tripod geometry. (b) Lowest natural mode at 0.77 Hz, top view. (c) Second natural mode at 1.57 Hz, top view. (d) JPL 70 m quadrupod, showing outriggers at base.

2.1. Wavelength Range. Although the subreflector size allows operation at the secondary focus to 35 cm wavelength with low diffraction loss, this requires a rather large feed (about 2 m aperture); restricting secondary focus operation to 20 cm and shorter may be more practical.

The short wavelength limit from surface accuracy is ultimately set by panel and subreflector fabrication tolerances to 1.6 mm. Whether this can be achieved in practice depends on the performance of the real time surface adjustment system and the pointing. Thermal effects on surface accuracy will probably impose a wavelength limit of about 5 mm. Improvement over the uncompensated performance ($\lambda_{\rm min} \approx 20$ mm) by a factor of 2 to 3 can reasonably be expected, so we finally expect $\lambda_{\rm min} < 7$ mm initially, with further improvements over the telescope's life.

2.2. Sidelobes. The far-sidelobe pattern of a symmetrical antenna is determined by scattering from the feed/subreflector support structure. Calculation of the details of this pattern is difficult but a rough estimate of the average sidelobe level can be obtained by assuming isotropic scattering from the blocking structure. If the geometrical blockage weighted by the feed radiation pattern is 3%, the average far-sidelobe level will be about -15 dBi. (This simple method of calculation predicts fairly well the sidelobe level of many existing antennas beyond 50° from the main beam.) The effective blockage at long wavelengths may be as much as 1.5 times (2 dB) higher than the geometrical blockage. Between about 1 and 50° from the main beam the sidelobe level is a combination of isotropic scattering and aperture-plane-blockage diffraction, and these are difficult to compute for a complex antenna. However, measured levels for existing antennas in this angular range fall close to the CCIR reference curve of $32\,\mathrm{dBi} - (25\,\mathrm{dBi})\log(\theta/1\,\mathrm{deg})$, where θ is the angle from the main beam.

2.3. Reflections. An antenna can cause poor spectral baselines through multipath interference of noise from the Sun or because of weak standing waves between the feed and antenna structure which produce a frequency dependence of the antenna gain to sources in the main beam. With current and likely future receiver sensitivities, typical baseline ripples from both causes on current antennas are between 10 and 100 times (10 to 20 dB) stronger than the system noise. Thus, spectral line sensitivity is much more baseline limited than receiver noise limited on the current generation of antennas.

Interference from the Sun can be reduced in direct proportion to the far-sidelobe level: a 10 dB reduction in sidelobes produces 10 times lower baseline ripples. Reducing the feed-reflector standing waves will have little effect on solar interference. Baseline ripple amplitude due to feed-reflector standing waves is proportional to the square of the intensity of the scattered energy returned to the feed from the reflector structure: a 20 dB reduction in return loss of the feed-reflector system produces 10 times lower baseline ripples. Experiments with spoilers on the 300-ft, 140-ft, and Effelsberg 100-meter have shown that the return loss on these antennas can probably be reduced by about 20 dB for prime focus operation, reaching the lower end of the 10 to 100 times improvement desired. Comparable improvements on a Cassegrain antenna will be more difficult.

III. Antennas With Unblocked Apertures

A. Advantages

1. High G/T Ratio. Both the gain and noise temperature are better for unblocked antennas than for symmetrical ones of the same size. Consider a symmetrical antenna with 3% geometrical blockage, which we believe represents the minimum blockage currently achievable. The loss in effective area will be 6–9%, depending on the RF cross section of

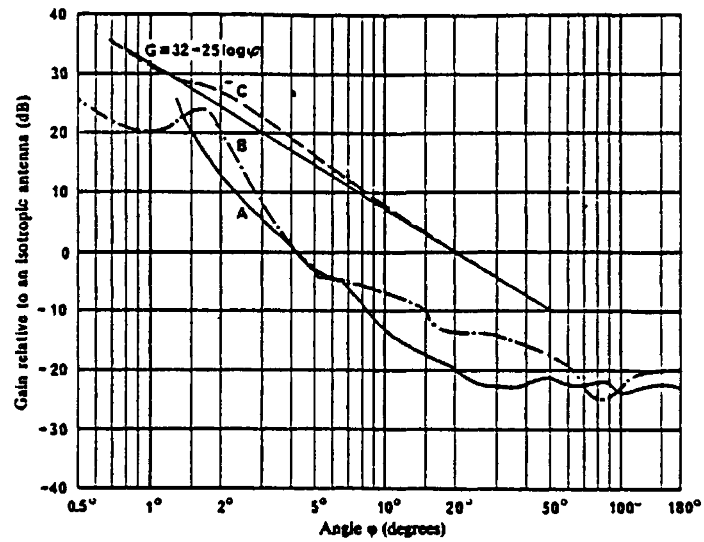

FIGURE 3 — *Measured side-lobe patterns (peak value)*

A: offset Gregorian antenna ($D/\lambda = 66$, 25 GHz, $D = 0.8$ m)
B: offset Cassegrain antenna ($D/\lambda = 750$, 19.5 GHz, $D = 11.5$ m)
C: symmetrical Cassegrain antenna ($D/\lambda = 600$)

Figure 4: Far sidelobe levels compared with CCIR recommendation, from [11].

the blocking structure. The fraction of the resulting sidelobes that is intercepted by the ground will be negligible at the zenith and about 0.5 at the horizon; let us consider 0.3 as a representative value. Then the contribution to the antenna temperature, through the sidelobes resulting from the scatter, is 6–9 K. With the best low noise systems, this is a significant unwanted contribution. With an unblocked aperture both the decrease in gain and the increase in noise are avoided.

2. Low sidelobes for interference protection. Figure 4 shows that the sidelobe levels for an offset reflector antenna can fall to the isotropic level as close as 5 deg to the main beam, whereas for an symmetrical antenna the sidelobes typically remain above the isotropic level for angular distances of about 20 deg from the main beam. Thus, the portion of the sky surrounding an interfering source in which observations are significantly degraded by the interference will generally be smaller for the offset reflector. The value of the improvement depends on the strength of the interfering source, since a sufficiently strong source will be harmful over the whole sky for either antenna type.

3. Protection from interference from celestial sources. Strong celestial sources in the sidelobes, including the Sun, the galactic center, Cassiopeia A, etc., cause significant interference for some observations. Observation of hydrogen line emission at high galactic latitudes without confusion from the galactic plane in the sidelobes is an important example. These effects are reduced in direct proportion to the sidelobe level reduction.

4. Reduction of standing waves on the antenna. Reflections between the feed and the main reflector or subreflector feed are a well known cause of variation in the total power baseline in radio telescopes that incorporate on-axis antennas. The problem has received considerable attention in the past but has not been solved in any completely satisfactory way. A detailed discussion is given in [12]. For a symmetrical dish, it is possible to reduce the dominant reflection from the vertex area by about 20 dB by a spoiler, but at that level reflections from many other parts of the antenna become important, and it is not clear what further progress can be made. In an offset feed antenna the reflection from the vertex is eliminated, and scattering from the support structure is drastically reduced. We are left with only diffraction from the edges of the reflectors, and backscattering from reflector imperfections. (The latter include the edges of the surface panels; if the panels are mounted in the usual way, following the contours of the paraboloidal surface, then the edges follow lines of equal distance from the focus and reflections add in phase.) Little experimental data is available, but a detailed and accurate calculation should be possible. It is expected that the unblocked design should be greatly superior, but a quantitative statement requires further study.

B. Disadvantages

1. Polarization properties. The cross polarization sidelobes of offset feed antennas are usually larger than those of symmetrical antennas. With circularly polarized feeds the beam is offset from the paraboloid axis in a direction normal to the plane of symmetry by a small angle. This effect is often referred to as beam squint, and the squint angles are in opposite directions for opposite polarizations, so the beams are separated by twice the squint angle. Small squints are tolerable for many observations. These polarization effects can be effectively eliminated in two-reflector (Cassegrain or Gregorian) systems by including a compensating offset of the feed from the reflector axis [13] or in a prime focus system by using a special feed [25]. Without compensation, the unwanted polarization effects decrease with increasing focal ratio, and an analysis [14] shows that a focal ratio[4] of ≥ 0.6 should give beam squint < 0.1 beamwidth and linear polarization sidelobes $< -20\,\mathrm{dB}$, which we consider satisfactory.

2. Cost. For a given diameter, the unblocked design is more costly because more panels of different shapes are needed, and because the focus support structure is more cantilevered. This is further analyzed below.

3. Risk. To our knowledge, the largest unblocked antenna yet built is 11.5 m diameter. Thus in building a very large one we would be breaking new ground, and a very careful and detailed analysis would be required to obtain sufficient confidence in the design.

C. A Conceptual Design

We concentrated on finding an unblocked aperture configuration that would be feasible at 100 m diameter. The offset geometry results in several degrees of freedom not present in the symmetrical case, so that we considered several radically different configurations.

The first major choice is the relationship of the elevation motion axis to the plane of symmetry defined by the beam axis and the (offset) focal point. If these are parallel, then it is possible to arrange for the elevation axis to pass through the focal point, so that the latter is always at the same height above the ground. This was done with the Bell Labs horn reflector antenna [26] (aperture about 6 m square). While this has some advantages, our preliminary study showed that its extrapolation to 100 m size involves severe mechanical problems. Radiation Systems Inc. also considered such an arrangement; while they found it feasible, they have not yet been able to estimate its cost [27].

If the elevation axis is perpendicular to the symmetry axis, then the focal point moves substantially with elevation change, and the feed or subreflector must be supported by an arm that is rigidly attached to the main reflector. At low elevations, this arm is either below or above the reflector. Having the arm below the reflector is advantageous in that any spillover from the primary or secondary is at a higher elevation than the main beam and hence falls mostly on cold sky; most existing offset-feed reflectors use this arrangement, including the Crawford Hill 7 m telescope [28]. However, when extrapolated to 100 m this

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[4]For the offset reflector, we define the focal length to be that of the parent paraboloid, and the diameter that of the constructed aperture.

arrangement is structurally more difficult than having the arm at the top. At low elevations, the arm must clear the ground and the reflector backup structure extends under the elevation axis; this requires that the elevation bearings be both higher and farther apart. For these reasons, we have tentatively selected the top-arm configuration for further study.

1. Description. The selected configuration is shown in Figure 5.

A focal ratio of 0.6 is chosen in order to assure satisfactory polarization performance (see III.B.1) and illumination efficiency [16] at the prime focus. The reflector then has a much shallower curvature than the symmetrical antenna. For the backup structure, the conventional hoop-and-rib geometry is chosen with its center at the middle of the reflector; the shapes of the hoops are ellipses rather than circles (axis ratio 1.12), but otherwise the backup structure looks much like that of a symmetrical reflector. All features of the symmetrical backup structure may be applied, including homology. (Alternative arrangements were considered, including ribs centered on the paraboloid vertex, but these are much less attractive.)

The panels, on the other hand, are arranged in a pattern whose center is at the vertex of the paraboloid. This produces a repetitive pattern along circles, so that the number of differently shaped panels is minimized. There are 48 tiers along the radial direction. Because of the different symmetries of the panel pattern and the backup structure, a complex interface is needed; to reduce this complexity, 250 intermediate substuctures are constructed, each designed to support 16 panels. The equal-softness deflection concept (as in the 65 meter telescope [8]) should be considered for the substructure design. The substructures are then supported at 4 corners by adjusting devices from the backup structure.

The subreflector or the prime focus feed is supported by a long cantilever arm extended over the top edge of the backup structure. The structure is designed to meet the deflection requirements of the operating conditions. Cables may be used to provide additional stiffness if needed. The structure is counter-balanced over the elevation axis. At this time, prior to doing any significant stuctural analysis, this arm is the largest uncertainty in the design. Innovative materials and configuration should be explored early in the design process. The structure may be an integrated part of the backup structure to reduce the vertical deflection.

The counterweight support structure and the azimuth tower structure are similar to the symmetrical antenna.

Just as in the symmetrical concept, we include motorized surface adjustment and a stabilized pointing reference platform.

2. Performance Estimates. The major performance parameters, including minimum wavelength and pointing accuracy, are dependent on the same mechanical considerations as the symmetrical antenna. Whereas we are here using much of the same structure and the same methods, materials, panels, and adjustment system, we expect the performance as is given in Table 5. An obvious exception is the effective area, which will be 6–9% larger because of the absence of blockage, at least at the secondary focus (at the primary focus, about half of this advantage may be lost due to lower illumination efficiency).

However, the reasons for pursuing an unblocked design are reduced sidelobes and reflections. These were discussed in sections II.F and III.B. The unblocked design should provide a substantial improvement, although we are at this time unable give a quantitative estimate.

D. Cost Analysis

In order to estimate the cost of an unblocked design, we first considered each of the major elements of the antenna and estimated the cost of the added difficulties, if any, associated with the asymmetry. We have done this only for the concept of Figure 5. Applying

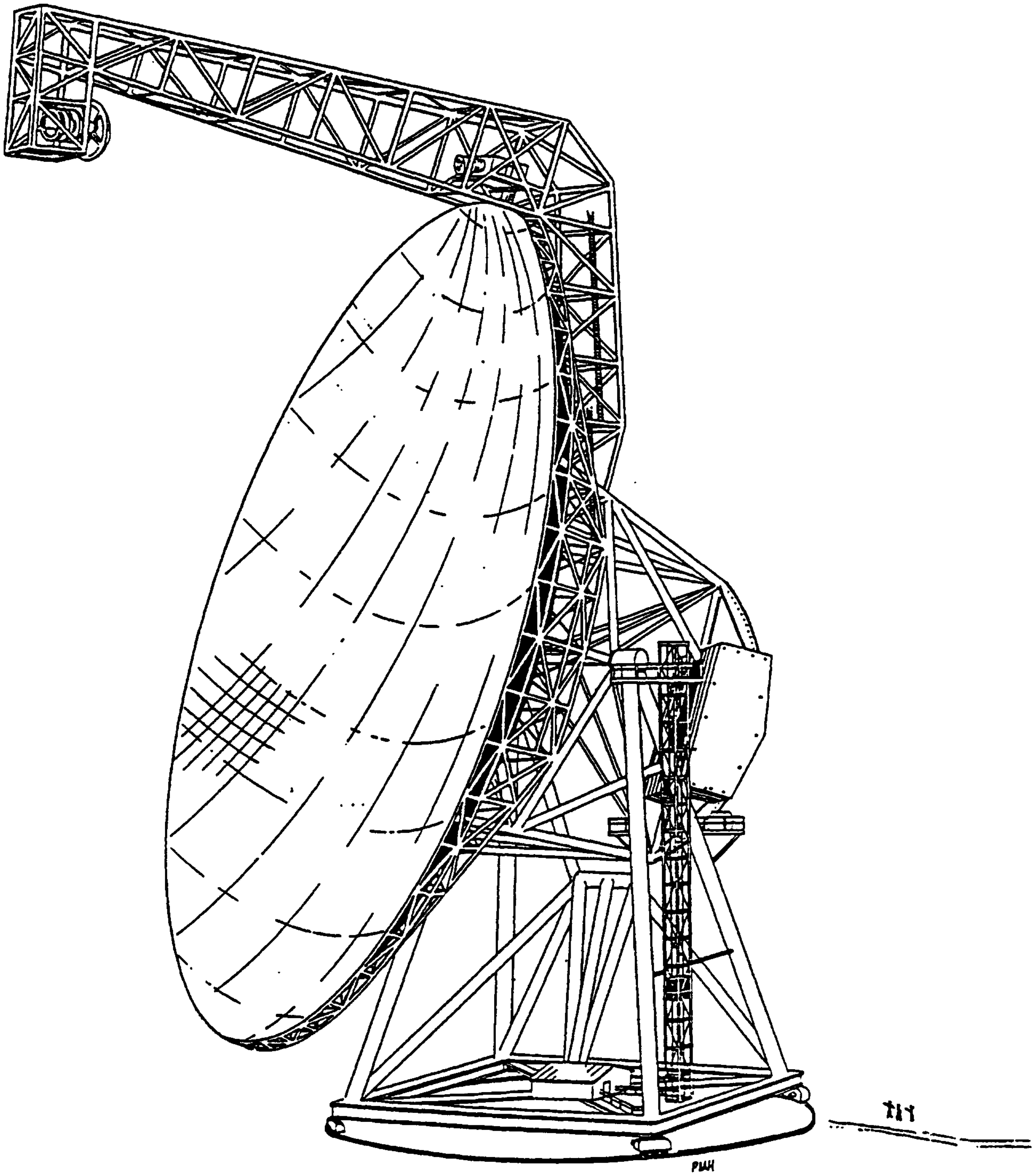

Figure 5: Offset reflector 100 m telescope concept.

this adjustment to the NRAO estimate in Table 2 gives the result in Table 6. The largest uncertainty in this calculation is in the steel structure, and this is due mainly to the focal support arm. Other items are either nearly the same as the symmetrical case or a small fraction of the total. An exception is the panels, which are significantly more expensive because of the larger number of different shapes; but we are able to account for this accurately. Overall, we guess that the estimate is within 25% provided that the estimate for the symmetrical case is within 10%.

Table 6: Cost Estimate for 100 m Unblocked Aperture Antenna
(Based on Symmetrical Antenna Costs and Estimated Ratios)

Cost Items	Symmetric	Ratio	Unblocked	Comments
I. Panels				
Tooling	1.9	200%	3.8	Twice as many tools.
Construction	6.0	110%	6.6	More surface area.
II. Engineering and Design				
Structural	1.6	150%	2.4	Complex geometry.
Servo, encoder, gearbox	0.85	100%	0.85	Same as symmetric.
Mgt, documentation	0.23	120%	0.28	More paper work.
III. Construction				
Engineering drawings	0.08	150%	0.12	More drawings.
Steel Structure	19.8	130%	25.8	Complex panel interface and feed support structure.
Servo, encoder	2.0	100%	2.0	Same as symmetric.
Subreflector	1.0	150%	1.5	Asymmetric geometry.
Other mechanical and electrical	9.4	100%	9.4	Same as symmetric.
Management	1.3	110%	1.43	More paper work.
IV. Erection				
	4.4	150%	6.6	More complex structure.
V. Foundation				
	1.7	100%	1.7	Same as symmetric.
Total	50.26		62.38	M$ (1989)

To this estimate must be added the special items from Table 2 ($5.5M) and the instrumentation and support from Table 3 ($6.7M).

IV. Other Considerations

A. Use Of Only Part Of the Surface

It is frequently suggested that a given antenna might be operated beyond its wavelength limit if only the inner part of the surface is used, *i.e.*, the aperture is under illuminated. In this way, the pointing accuracy requirements are relaxed by virtue of the larger beamwidth, and it is then assumed that the inner part of the main reflector can be made more accurate. We have examined this idea and have concluded that it is not an appropriate approach to the design of a new, large reflector. First, the main method of arranging for the inner portion to be more accurate would be to use better panels there, or conversely to use cheap panels in the outer portion for cost saving. This would represent false economy for a 100 m dish because the panels are a small fraction of the total cost; so much money has been used to create the outer portion that it is cost effective to put good panels everywhere. Second, the structural deformations—whether induced by gravity, temperature, or wind—could not be made much smaller in the center without being made larger at the outside; this leads to the equal softness principle of support design, or its extension to the homology principle. (Actually, some stiffening against wind might be possible, but we estimate that it would be insignificant without considerable increase in weight.) If the wavelength limit is determined by the accuracy of active surface adjustment, then this should be equally good at all radii of the dish. Finally, the pointing problem may be significant at the short wavelengths, and this may justify under illumination. But, at least for the parameters of our symmetrical conceptual design, it appears that the pointing accuracy can be made good enough that it does not determine the wavelength limit, at least under nighttime conditions.

There is another reason for under illumination that is often discussed. This involves illuminating not the center but rather an unblocked offset sector of a symmetrical antenna. Such a scheme was planned for the 300 ft telescope. It is useful in experiments where low sidelobes and reflections are critical but the full collecting area and narrow beamwidth of the whole antenna are not needed. For this report, we have preferred to concentrate on investigating the feasibility of constructing a fully unblocked aperture. Sector illumination remains an option on the symmetrical dish for special experiments.

B. Requirements For Multiple Feeds

There are at least three reasons why a new, large aperture radio telescope should be designed to allow operation with multiple feeds. These are: (a) beam switching for removal of atmospheric effects in continuum mapping; (b) use of focal plane arrays to increase the speed with which areas of sky much larger than the antenna beam can be mapped; and (c) use of focal plane arrays to correct for various aberrations in the antenna. We will consider each of these in turn to determine what constraints they place on the beam scan requirements for the telescope and what areas must be available in the primary and secondary focal planes to locate multiple feeds.

Although the following discussion considers mainly an axially symmetrical antenna, the performance of an offset feed antenna with respect to loss of gain and development of coma lobes for off-axis beams is comparable to that of a symmetrical antenna with half the effective focal ratio. This is because an offset feed antenna with focal length $2f$ makes use of approximately the same part of the parent paraboloid as a symmetrical antenna with focal length f. Thus an offset feed antenna with $f/D = 0.6$ is similar to a symmetrical antenna with $f/D = 0.3$ with regard to off-axis performance *i.e.*, the loss in gain can be about 1 dB for a beam three beamwidths off the paraboloid axis [17].

1. Beam switching. At wavelengths shorter than a few cm, continuum imaging of extended objects requires multiple beam observing for cancellation of emission from the first few kilometers of the troposphere [18]. This is also useful for many spectral line observations. The desire (but not requirement) to switch outside the object pushes the beam separation up, but the constraint that the multiple beams overlap significantly within the troposphere limits the maximum beam separation allowed. For example, if $D = 100$ m and if we assume that all the emission comes from a layer 3 km above ground, then we obtain the curves of Figure 6 for the fractional cancellation of the tropospheric emission for various beam throws. If we require a cancellation of 90% at the zenith, then the maximum beam separation is about 8 arcmin and the cancellation falls to 80% at an elevation of 25°; we take this as the extreme case. Emerson *et al.* [18] report acheiving dynamic range ~18 dB under such circumstances at $\lambda = 2.8$ cm. Wielebinski [19] reports that the field of view is limited

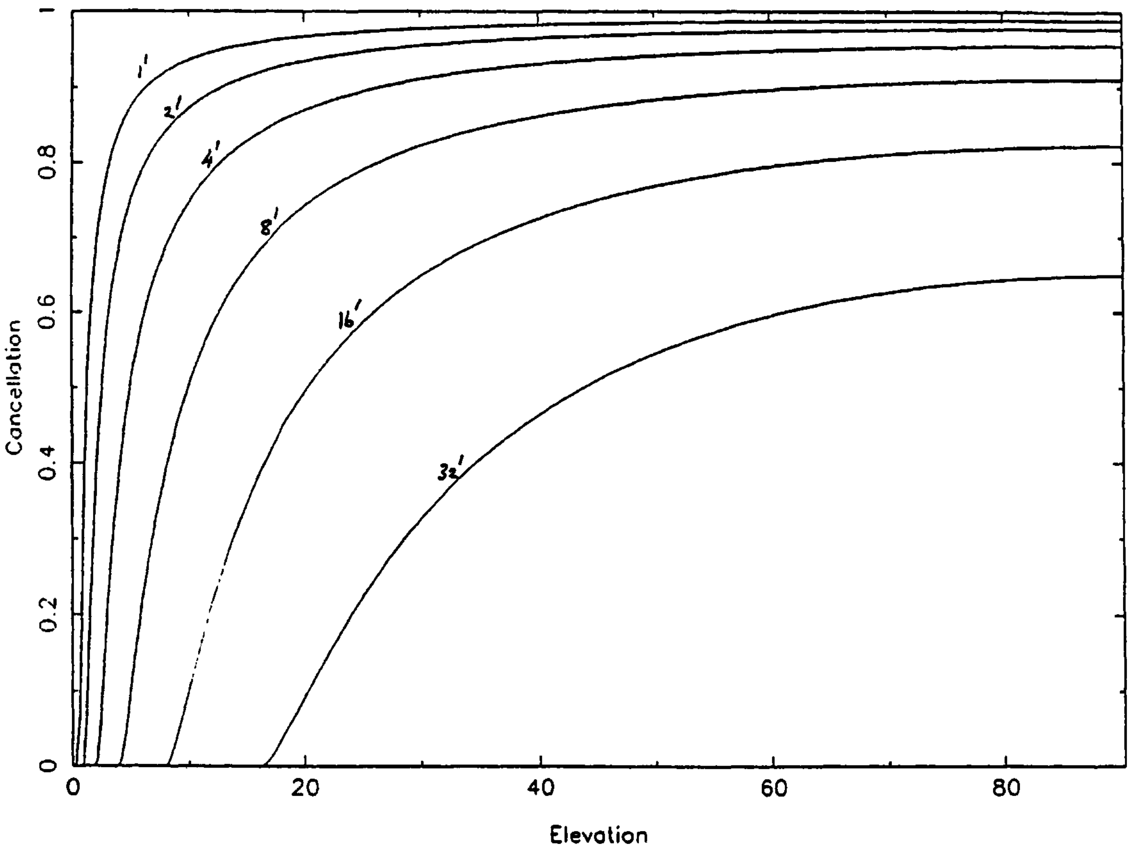

Figure 6: Tropospheric noise cancellation *vs.* elevation angle for various beam throws at $D = 100\,\mathrm{m}$.

to about 5 times the maximum beam separation, or about 40 arcmin in this case. Larger fields of view require larger beam separations and hence poorer cancellation of atmospheric emission. The 8 arcmin maximum beam separation can be obtained by placing beams on opposite sides of the axis, each offset by 4 arcmin. The atmosphere will typically only be a problem at wavelengths less than about 6 cm, where a 4 arcmin offset corresponds to 2 beamwidths for $D = 100\,\mathrm{m}$. At wavelengths shorter than approximately 3 cm, 4 arcmin corresponds to >4 beamwidths, and this will be available with negligible beam degradation only at the secondary focus. For a symmetrical 100 m telescope with a primary focal ratio of 0.35 the 4 arcmin offset is achieved with feed offsets in the secondary focal plane of approximately 50 cm and 75 cm for Cassegrain magnifications M of 10 and 15 respectively. This does not appear to impose a significant constraint on the design of the antenna. The restriction $M > 10$ is suggested here because of the need to keep the subreflector diameter less than $D/10$ to reduce blockage. If the subreflector is made too small, however, the size of the secondary feeds becomes large. For the example above, $M = 20$ requires secondary focus narrow band feeds to have aperture diameters of 17 wavelengths. The Effelsberg telescope, with a subreflector diameter of 6.5 m and a secondary focus 4.7 m above the primary vertex has $M = 13$.

2. Focal plane arrays. As technology develops it will become possible and desirable to utilise an array of feeds and sensitive receivers so that as much as possible of the available field of view of the telescope is observed simultaneously [20]. The maximum number of beamwidths that can be scanned with less than 1 dB of gain loss is given by

$$N = 0.44 + 22\left(\frac{f_e}{D}\right)^2 \tag{2}$$

where $f_e = Mf$ is the effective focal length at the feed. This expression holds for a paraboloid with a -10 dB edge illumination. For a paraboloid with $f/D = 0.35$, the expression gives $N = 3$ at the primary focus and $N = 270$ and 607 at the secondary focus for Cassegrain magnifications of 10 and 15, respectively. Since the number of feeds needed to fill this field is of order $(2N)^2$, it seems likely that the field of view will be limited by the number of feeds that are technically or economically feasible or by the availability of space at the secondary focus. For example, in a 100 m, $f/D = 0.35$ reflector, 50 beamwidths scan at a wavelength of 1.3 cm requires feed offsets of 3.4 m and 5.2 m for Cassegrain magnifications of 10 and 15, respectively. These offsets are large enough that they will have a significant impact on choice of magnification and vertex cabin size. On the Effelsberg 100 m telescope it has been necessary to extend a basically circular vertex cabin into a cross shape (in the shadow of the quadrapod) to accommodate the currently planned total of 22 feeds spread over 7 frequency bands.

3. Aberration correction. Two possible uses of focal plane arrays for correcting aberrations in the telescope are the correction of coma aberration to extend the field of view of the telescope [22] and the correction of reflector profile errors [23]. With the coma correction technique [22] the focal plane field distribution is sampled using an array of feeds and Fourier transformed using a Butler matrix to give the aperture plane field. The aperture plane coma phase error caused by locating feeds off axis can then be removed using phase shifters. Although there is sufficient field of view at the secondary focus that this technique is not needed there, its use at the prime focus may be justified at longer wavelengths because of the compactness of prime focus feeds and arrays. It would be wise to have a usable space in the prime focus plane at least 20 beamwidths in diameter at a wavelength of 21 cm. With the reflector profile correction method [23] the output of a focal plane array is fed into a correlator to provide the focal plane spatial coherence function. Sufficient information is then available to remove the effect of reflector profile phase errors from the focal plane image. Since this technique would only be required at the upper frequency limit of the telescope, the amount of space needed for the focal plane array is likely to be less than that required to accommodate the arrays for lower frequencies and so should not constrain the telescope design.

From the discussion in sections 1, 2 and 3 above it is clear that the telescope should have as large an unaberrated field of view as possible at both the prime and secondary focus. This requirement rules out the use of shaped reflector pairs or a spherical main reflector with Gregorian secondary because of the very limited field of view of these non-parabolic geometries [24]. Although this problem for the non-parabolic reflectors could be solved using a focal plane array and an adaptation of the coma correction technique mentioned above [22], it would be most undesirable to be forced to use a complicated feed array even for the case of atmospheric correction where only two feeds are needed. A parabolic main reflector with a Cassegrain or Gregorian secondary and moderate magnification (in the range 10 to 15) seems to be the best geometry. Subreflector size limitations will drive the magnification higher but feed and focal plane array size will drive it lower.

V. Summary and Conclusions

A. Axially Symmetrical Design

It appears that an axially symmetrical antenna of modern design can be constructed with a 100 m diameter aperture for \$56M (Table 2). This includes the design, fabrication, and erection at Green Bank by an experienced outside company. In addition, about \$7M (Table 3) would be needed over a 4 to 5 year project to cover preliminary design, engineering support of the construction contract, receiver and feed development and fabrication, computers, and software. These cost estimates are believed to be accurate within 10%, but are still very preliminary. At this stage any budget should include a sizable contingency allowance, beyond the usual 10–15%, to allow for uncertainties in the estimate; we recommend adding 20%, for a total budget of \$75M.

Such an antenna would provide performance superior to any existing fully steerable antenna. The aperture efficiency should be > 50% to at least 15 GHz, but we recommend including a system for continuous re-setting of the surface which should extend this performance by a factor of 2–3 in frequency, and perhaps more with future enhancements. The cost estimate includes such a system. Another innovation is also included in order to ensure sufficiently accurate pointing for high frequency operation: installation of an optically (or inertially) stabilized platform at the axis intersection point. This is not a new idea (it was planned for the 65 m telescope in 1972), but we do not know of an implementation on an existing large antenna. For an antenna of this size, the cost is only weakly dependent on the frequency limit; for our purposes, both cost and maximum frequency can be considered to be independently determined by the size.

We have also considered whether a symmetrical antenna, with some unavoidable blockage of the aperture, can have much better far sidelobe levels and standing wave levels than are usually achieved. Careful attention to minimizing blockage should allow it to be limited to 3%, compared to about 6% with many existing telescopes, for a 3 dB improvement. Additional care in the design may reduce sidelobes several dB more, but we do not expect drastic improvements. Similarly, standing waves can be reduced by careful attention to the problem during design, but improvements of several orders of magnitude should not be expected.

For the same design approach and similar performance, a 70 m telescope could be constructed for about \$42M and a 125 m telescope for about \$112M, including the same instrumentation and 20% contingency. Beyond 125 m, the extrapolation from existing experience is large enough that a more extensive study is needed before feasibility and cost can be estimated.

B. Unblocked Design

Clearly, for the same diameter the asymmetrical geometry needed to avoid blockage will be more expensive than the symmetrical one; it will have higher effective area and lower system temperature; and it will have lower scattering sidelobes and standing waves. However, aside from the effective area (which improves directly with the blockage reduction), we have not yet been able to quantify these parameters very accurately.

We have, however, identified what appears to be the most feasible mechanical configuration (Figure 5), in which the elevation axis is normal to the plane of symmetry and the focal point remains above the main reflector for most elevations. This conclusion follows some consideration of alternative arrangements [14]–[16]. In the selected configuration, much of the structure is similar to that of a symmetrical antenna, with the exception of the highly cantilevered focal support tower. Some structural analysis effort will be needed to establish a reasonable design for this tower and to determine its cost and the effect on the performance of the main reflector.

The construction of a 100-m class unblocked reflector antenna would represent a large step in the state of the art of such antennas. The largest yet built (to our knowledge) is 11.5 m. It would be comforting if an intermediate size antenna were available, say 30–50 m, before embarking on a 70–100 m project. Nevertheless, we could recommend that NRAO pursue such a course if (1) a detailed structural analysis shows that it is feasible, and (2) the cost/benefit ratio is favorable. Especially if the chosen configuration retains many structural features of the symmetrical arrangement, the risk appears to be fairly low. Only a short-term study would be needed to establish sufficient confidence in the feasibility, costs, and benefits.

C. Recommended Actions

In order to approach a conceptual design that is as near to optimum as possible, the following near-term efforts are needed. All of these could be completed in about 9 months, at which time it should be possible to begin the major construction effort.

1. Unblocked design structural analysis. A preliminary analysis would lead to increased confidence in feasibility and an accurate (15%) cost estimate. About 4–6 man-months and some computer time would be needed.

2. Unblocked design electromagnetic analysis. It should be possible to determine the diffraction sidelobes and backscattering into the feed for a wide range of frequencies with various arrangements of the optics. Perhaps 1–2 man-months would be needed.

3. Final conceptual design. After the funding level for the project is determined, and with the help of the technical studies mentioned above, the major choices can be made: overall configuration (including symmetrical or unblocked) and final size. The next step would be development of a conceptual design to the point where an RFP could be issued for a final design. This should be mainly an internal effort, with the help of outside consultants; it should require 1–2 man-years of NRAO personnel, but the level of effort should be such as to allow completion in 6 months.

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