25 METER - MILLIMETER WAVE TELESCOPE

REPORT # 3

#4

RADIO TELESCOPES FOR MILLIMETER WAVELENGTH

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Summary

General rules are discussed for selecting the shortest observational wavelength, and for finding the largest possible diameter, for the design of steerable telescopes. The NRAO design of a 65-m telescope for 3.5 mm wavelength is described. This design then is scaled down to smaller diameters, for cost reduction as well as for reaching still shorter wavelengths. Cost and performance are calculated as functions of the diameter. Results are presented for four atmospheric windows of good transparency. Most recommended is a telescope for 2.0 mm wavelength, with 40 m (131 feet) in diameter, at a total cost of 6.3 M$ (1974). Enclosure in a radome is not recommended for this type of design.

INTRODUCTION

What kind of telescopes should we plan for the near future? Science is highly competitive. Either one works at the foremost "frontier of research," at least in one field of activity, or it is no fun, no attraction for really good scientists and students, and not much progress will result. Thus, any new telescope and its auxiliary equipment should be planned in such a way that it will allow a break-through in at least one field of research, being the best of its kind for some special purpose. On the other hand, the telescope should if possible still be a moderately good general purpose instrument, useful for many other tasks. Most urgent scientifically, and still feasible technically and financially, seems at present a break-through in the following two directions:

$$\left.\begin{array}{ll}\text{Optical:} & \text{highest resolution}\\ \text{Radio:} & \text{shortest wavelengths}\end{array}\right\}\text{with telescopes of moderate size.}$$

Regarding optical telescopes, the resolution limit as defined by the atmosphere (about 1 arcsec in good seeing) is already reached by telescopes above 5 inch diameter. Some methods of image improvement are now available or in preparation: First, speckle interferometry (Labeyrie 1970; Gezari, Labeyrie and Stachnic 1972). Second, a computer-controlled image-disector system for automatic guiding, focussing and image-selection (Hoag, Ball and Trumbo 1971).

Third, a correcting plate of several servo-controlled pices (Dyson 1974). Any new telescope design should be prepared for future progress in this direction, by pushing the accuracy and stability of both the mirror surface and the telescope pointing system to their utmost possible limits.

Regarding radio telescopes, a limit to the shortest observational wavelength is given by various deformations of the surface, increasing with telescope diameter. But the actually existing technical possibilities, of constructing moderately large telescopes for millimeter wavelengths, have not yet been exploited; and it is here where future progress is to be expected. The present paper describes these possibilities; it gives a short summary of a recently finished NRAO design for a 65-m telescope for 3.5 mm wavelength, and it describes the possibility of scaling this design to smaller diameters and still shorter wavelengths. There are two reasons for going to smaller diameters: the resulting reduction in cost, and the desire of the astronomers for very short wavelengths.

I. SELECTION OF PURPOSE, SIZE AND WAVELENGTH

Several large radio telescopes are already available, for wavelengths from a few centimeters up (Arecibo, Bonn, Green Bank; see Figure 1), and any duplication would be very costly but not so exciting. Interferometers and arrays are also available or in construction. Most urgent and promising would be to build a medium-large single telescope for shortest wavelengths, for studying molecular spectrum lines, and especially for quasars and active nuclei of radio galaxies, which are the most interesting but still very little understood astronomical objects, showing their most important features at the shortest wavelengths only (variability, violent explosions, abnormal spectra). Furthermore, the telescope should be able to make a short-wavelength sky survey, needed for finding more sources of this most interesting type. Operating at millimeter wavelengths, even a medium-sized telescope will still be the best of its kind, working at the frontier of research in several interesting fields.

Figure 1 shows the telescope size and the shortest observational wavelength of existing important radio telescopes. The figure shows also three natural limits for the design of steerable telescopes. The gravitational limit to the wavelength is defined by the deformation of the telescope surface and back-up structure under its own weight, when the telescope is tilted from one direction to another. This limit can only be surpassed if the telescope is never moved (as the spherical dish at Arecibo), or if a special trick is employed (as the homologous deformations discussed later). The thermal limits shown are defined by thermal deformations, when some parts of the structure have a slightly different temperature from some other parts; these deformations are up to 5 times larger in full sunshine than during a clear night. All three limits are given by material constants and environment, and they depend only little on any special design.

A new design should be located in Figure 1 at the upper thermal limit, labelled "Night." Once a shortest wavelength is chosen, this line then gives the largest possible telescope diameter.

Figure 2 shows the absorption of radio waves in the Earth's atmosphere, as a function of the observing frequency or wavelength. There are several peaks of high absorption, where observation thus is impossible; and in between these peaks are the so-called "atmospheric windows" of smaller absorption, where observations should be planned. Table 1 gives some data for these windows. A telescope design thus must start out with the selection of the shortest wavelength for the telescope in one of these windows.

Table 1

Atmospheric Windows of Maximum Transparency

Frequency range GHz	Attenuation db	Transparency per cent	Wavelength λ range mm	center mm
67 - 120	1.0	79	2.5-4.5	3.5
130 - 160	2.5	56	1.9-2.3	2.1
210 - 300	5.0	32	1.0-1.4	1.2
340 - 440	10.0	10	0.7-0.9	0.8

The choice of the two last windows (at 0.8 and 1.2 mm) could only be recommended for exceptionally good sites, and only if other, larger telescopes were planned as well for a sky survey. Their choice would limit the observations to short periods of extremely good weather, and would limit the telescope to a rather small size, too small for a sky survey, and too much specialized for still being a moderately good general-purpose instrument as demanded. And the first line might be too expensive. The best recommendation then seems to be the second line, with a wavelength of about $\lambda = 2$ mm. From Figure 1 we then read off a telescope diameter of about $D = 40$ m (or 131 feet). With this size, we have by far the best of its kind for short wavelengths, and still a rather good general-purpose telescope for all longer wavelengths.

II. THE NRAO DESIGN FOR A 65-m TELESCOPE

In 1972, a design study was completed at the National Radio Astronomy Observatory, for a new type of radio telescope, of $D \doteq 65$ meter diameter (213 feet), operating at a shortest wavelength of $\lambda = 3.5$ millimeter during clear nights and (5-9 mm in full sunshine). A picture of this design is given in Figure 3.

Design and all cost estimates were done in contract with several well-experienced engineering and construction firms. All results are published in a book distributed by NRAO (Findlay and von Hoerner 1972). This book should be consulted for all details, while the following is only a very rough summary. The construction of this telescope had to be postponed, because another still larger NRAO project was approved meanwhile: The Very Large Array (VLA), to be built in New Mexico, taking up most available funds for the near future. The 65-m design and its details, however, are available for any other institutes who might be interested.

A break-through in telescope design was intended, and several new basic features were employed. First, the principle of <u>homologous deformations</u> as developed by the author (von Hoerner 1967a, 1967b, 1969). If a telescope surface is adjusted to a perfect parabola for one direction in the sky, it must deform under its own weight if tilted to some other direction. But we have shown that it is possible to design the telescope structure in such a way that it deforms from one parabola to another one, thus always giving a perfect mirror for any angle of tilt. This type of design can be roughly approached during a computer study by trial and error, as has been done with good success for the new Bonn telescope of 100 m diameter. Our own design uses a mathematical method which automatically improves a given design during several iteration steps of a computer program, until the remaining deviations from homology are below some prescribed accuracy limit. The program simultaneously fulfills the stability conditions for all structural members, under various survival conditions of highest winds and heaviest snow. The dynamical behavior is analyzed, too. Once a stable homologous design is found, the program then calculates all deviations from homology, as resulting from manufacturing standards and tolerances, and erection errors, as well as from wind and thermal deformations under various conditions. Also these latter deformations were minimized during several design trials.

Second, an *optical reference system* was developed for achieving a high pointing accuracy, based on a suggestion of von Hoerner (1967a). Right at the center of the dish structure, a small movable platform is mounted, which is tied optically to seven beacons on the ground, and which is kept stable and unmoved (against the rotating and tilting telescope) by a closed-loop servo system. The pointing direction of the telescope then is measured against this platform, see Figure 4. In this way, all thermal and wind deformations occurring between the ground and the center of the dish are completely omitted (deformation of the axes, of the whole tower structure holding the dish, of its trucks, rails and the foundations). Detailed experiments made with a prototype of such a platform gave very good results. Future designs should re-investigate the possibility of a gyro-controlled reference platform, which seemed not feasible at the time of our design study.

Third, two different new types of surface plates of very high accuracy were developed, by NRAO and a construction firm; both prototypes were manufactured and tested, with good results. Fourth, new methods for measuring and adjusting the surface on the telescope were developed and tested, with results even better than first anticipated.

Fifth, a special Cassegrain (secondary mirror) system was developed, to allow simultaneous observations with a very large number of separate receivers. This will be extremely important for any large telescope at short wavelengths, because of the resulting small beamwidth, for finishing a much-needed millimeter sky survey within reasonable observation time.

Performance calculations and cost estimates are given in Tables 2 and 3. Both have been done with the utmost care and with independent counter checks, and both are considered to be on the conservative side.

III. SCALING THE 65-m DESIGN TO SMALLER DIAMETERS

If the cost of the present NRAO design (11 M$ for 1974) is considered too high, or if still shorter wavelengths are desired by the astronomers, then the whole design can be scaled down in proportion, to some smaller diameter D, needing only a small amount of redesigning

Table 2

Performance of the 65-m Telescope Under Various Climatic Conditions

	Wind Velocity Miles/Hour	Surface Accuracy (1σ) mm	Tracking Accuracy (1σ) arc seconds	λ_{min} (mm)		λ_{min} mm (GHz)
				Surface	Tracking	
Clear Night	0	0.215	3.2	3.45	2.35	3.45 mm (87)
	6	0.200	2.0	3.20	2.15	3.20 mm (94)
	12	0.205	2.4	3.30	2.55	3.30 mm (91)
	18	0.215	3.9	3.45	4.20	4.20 mm (71)
Sunny Day	0	0.475	8.7	7.60	9.30	9.30 mm (32)
	6	0.260	3.8	4.15	4.05	4.15 mm (72)
	12	0.230	3.1	3.70	3.30	3.70 mm (81)
	18	0.230	4.2	3.70	4.50	4.50 mm (67)

Table 3

65-Meter Telescope Cost Estimate (1972 dollars)

		Thousands of $
Fabrication of reflector and tower structure, including counterweight		1,475
Fabrication of intermediate structure		441
Erection of complete telescope		1,080
Surface plates, installation and adjustment		1,540
Azimuth trucks, gear boxes and motors		340
Pintle bearing		50
Elevation bearings		95
Elevation gear, gear boxes, drive motors		190
Foundation and track		146
Feed and subreflector supports, subreflector instrument cabins		250
Optical position reference system		460
Servo control system		500
Telescope control computer, including software		200
Ladders, walkways, hoists, cable trays		42
Telescope cabling		100
Painting, start-up and test		200
Site preparation		634
Project management and engineering		450
		8,193
Add 15% contingency	Total	9,422

for some of its details. The main question then is how the cost and the performance will vary as functions of D.

Regarding the cost, we will assume that the cost of each single item of Table 3 varies in proportion to some power n of the diameter, $C \sim D^n$, but with different powers n for different items. For all more massive items, for example, the weight and thus the cost will vary as D^3, or $n = 3$, while for less massive members the wall thickness must be kept constant, giving only $n = 2$, whereas the smallest members even keep their diameter constant, or $n = 1$. For a conservative estimate, however, no variation with $n = 3$ was adopted. In detail, we use the following values:

$n = 2$, for: fabrication of reflector and tower structures; azimuth and elevation gears, motors and trucks and bearings; telescope erection and painting. The subtotal cost from Table 3 for all these items is 3.44 M$ for the 65-m design and for 1972.

$n = 1$, for: intermediate (panel) structures, surface plates (getting more expensive per area for higher accuracy); foundations and tracks; feed legs and Cassegrain mirror, ladders and cabling; site preparation. The subtotal is 3.15 M$.

$n = 0$, (no change) for: optical reference system, servo system; on-line computer; design and construction management. Subtotal = 1.61 M$.

The total cost for a telescope of diameter D then is calculated as:

$$C = 3.44(D/65)^2 + 3.15(D/65) + 1.61$$

to which 15% is added for cost escalation up to 1974, and another 15% for contingency. The resulting cost is plotted as a function of D in Figure 5.

Regarding the performance, a similar procedure was applied to the surface deformations, assuming an rms error $\Delta z \sim D^n$ for each single contribution. Here, all wind deformations have $n = 2$, thermal deformations $n = 1$, while only $n = 1/2$ was assumed for the manufacturing accuracy of the surface plates. After scaling each single contribution in this way, the total surface deviation then is calculated (as the root of the sum of the squares); as in the original design, the shortest wavelength finally is defined as 16 times the total surface error, $\lambda = 16$ rms (Δz).

The same procedure is applied to the pointing errors, $\Delta\phi$. Here, we have $n = 2$ for the wind deformations, $n = 1$ for atmospheric contributions, and $n = 0$ for thermal deformations and all intrinsic errors of the pointing system. Both results, shortest wavelength and pointing error, are plotted in Figure 5 as functions of the telescope diameter D.

Also shown in Figure 5 is the half-power beamwidth of the telescope, calculated as $\beta = 1.2\ \lambda/D$. Since the shortest wavelength λ is mostly defined by the thermal deformations, which vary in proportion to D, the beamwidth is almost independent of the diameter, between 12 and 14 arcseconds.

IV. EXPOSED TELESCOPE OR RADOME?

Three arguments are mostly mentioned for enclosing a high-precision telescope in a radome: (a) shielding against wind-induced deformations during observation, (b) decrease of thermal deformations by giving shadow, air circulation and cooling, and (c) shielding against highest winds in survival conditions. Estimates show, however, that a radome is not to be recommended, at least not for the design suggested here.

First, wind deformations go in proportion to the telescope surface, multiplied by the length of its supporting members, thus $\Delta z \sim D^3$. Wind deformations can be diminished by increasing the cross-section of all supporting members, but this was not necessary for the 65-m design, which was basically defined by survival stability and which then fulfilled the deformation requirements automatically (after some optimization of the geometry of the structure). The 65-m design can observe at the shortest wavelength for winds up to 18 mph, which is 3/4 of all time. Since higher winds are mostly correlated with clouds making millimeter observations impossible anyway, while observations at longer wavelengths can still go on in higher winds, the remaining loss of observing time was considered very small.

For decreased telescope diameter, the wind deformations go as D^3, while the dominating thermal deformations go with D; for $D < 65$ m the wind deformations soom become negligible as compared to the other deformations and surface errors.

Second, thermal deformations have two causes: (a) long-lasting temperature differences ΔT, because of partial shadowing during sunshine, and because during nights some parts of the structure look more at the cold sky and others more at the warm ground; (b) a different time-lag between thick and thin members, if the ambient air temperature changes (minimized in the 65-m design by keeping the wall thickness of all members within narrow limits). Effect (a) dominates (b) considerably in our design.

Temperature differences have been measured in many experiments at NRAO (see Findlay and von Hoerner 1972). The values used in the performance calculations are $\Delta T = 2^{\circ}F$ during calm clear nights, and $12^{\circ}F$ in full sunshine without wind at noon, for the surface plates and their ribs; and $1.5^{\circ}F$ in sunshine and $9.0^{\circ}F$ at noon for both the panel structure and the back-up reflector structure (tower deformations being omitted by our optical pointing system). All values mentioned represent the 95% level of their distribution, meaning that conditions are worse for only 5% of all days.

The experiments have also shown a strong temperature-equalizing effect of already very low winds on an exposed telescope (1/2 of ΔT for 3.8 mph). Since the values given above refer to absolute calm, the actual temperature differences will be much smaller for most of all time.

Emclosure of the telescope in a radome needs a highly effective ventilation and cooling system. It seems very difficult to beat the thermal performance of an exposed telescope during nights; the only advantage will then be during sunshine, with about a factor two for the wavelength, see Table 2 for details.

On the other hand, no telescope operates always at its shortest wavelength; the existing telescopes do so only for less than 1/3 of all time, because different astronomical programs ask for different wavelengths. It seems not too inconvenient to schedule all short-wavelength programs for the nights only (while optical telescopes observe during nights only, anyway). The total thermal advantage, for day and night, seems rather low.

Furthermore, a radome structure gives shadow and reduces the effective telescope area by about 5%-10% for short wavelengths and considerably more for longer ones; and the radome skin gives a further reduction by its absorption.

Third, the survival stability against highest winds (or heaviest snow) must be provided by something, and it does not matter much whether the needed steel is put into the structure of the radome or that of the telescope. The radome has a better shape aerodynamically, but has a larger size, and both effects cancel each each other. Furthermore, the telescope needs a certain minimum amount of steel anyway, for stable self-support and for high dynamical rigidity. As an example, the radome-enclosed Haystack telescope would already survive in winds up to 85 mph if its radome were removed. The weight of the 65-m design, as defined by survival, is not so much higher than its stable minimum weight, at most a factor of two as some estimates have shown. But the cost of steel is small compared to the labor of fabrication, and the cost decreases much less than the weight if the size is kept constant. A weight decrease of 50% (factor two) may give a cost decrease at most 20% but not more. The subtotal of all heavier parts of Table 3 is 3.44 million dollars for 1972, or about 4.00 M$ for 1974. If the cost of all these parts is reduced by the radome by 20%, this reduction then is 800,000$, which now must be compared with the cost of a radome of, say, 75 m height and 100 m diameter, with its foundation and ventilating system.

V. RESULTS AND CONCLUSIONS

For the design of any new short-wavelength radio telescope, the shortest wavelength λ should be selected from Table 1, in one of the "atmospheric windows" of good transparency. With this wavelength we then enter Figure 5 and find the largest telescope diameter D, and the resulting pointing error $\Delta\Phi$ and the beamwidth β, as well as the total cost C. The results for all four windows are given in Table 4.

Most recommended is the second line of Table 4, with 40 m diameter and for 2 mm wavelength, at a total cost of 6.3M$ (including all items of Table 3). This recommendation is also entered in Figure 1 (as No. 28) for comparison with the existing telescopes. The suggested telescope would clearly be the best of its kind, being considerably larger than any other millimeter-wavelength telescope; and it still could be used for shorter wavelengths, below 2 mm, as a rather good "light bucket." At the same time, it is comparable in diameter to many existing telescopes for general-purpose work at all longer wavelengths, and it is still large enough for a millimeter sky survey.

Finally, the enclosure of the telescope in a radome is not to be recommended. It would increase the total cost and give some additional problems, yielding only very little advantage for the performance.

Table 4

Four Possibilities for a Short-Wavelength Telescope

Diameter, D		Shortest wavelength, λ	Total cost, C	Beamwidth, β	Pointing error, $\Delta\theta$
meter	feet	millimeter	million dollars (1974)	arcsec	arcsec
65	213	3.5	10.7	13.3	4.04
40	131	2.0	6.3	12.4	2.50
22	72	1.2	4.0	13.5	2.16
14	46	.8	3.2	14.1	2.12

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FIGURE CAPTIONS

Figure 1 - Natural limits for steerable radio telescopes. Telescopes plotted with open circles are either not yet completed or have not yet demonstrated the performance indicated.

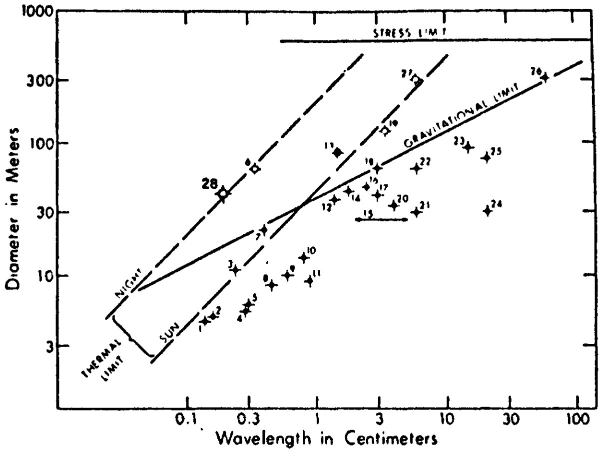
Figure 2 - One-way zenith absorption of radio waves in the atmosphere. The four deep minima, at 3.5, 2.1, 1.2 and 0.8 mm wavelength, are the "atmospheric windows" for observation.

Figure 3 - The 65-meter telescope for millimeter wavelengths. The alt-azimuth mount consists of two tetrahedral tower structures, holding the elevation axis, and moving on trucks on the azimuth ring on the ground. The back-up structure of the reflector is designed in such a way that, if tilted, the surface deforms under its weight from one parabola to another one, giving an exact mirror for any angle of tilt (homologous deformations). Focal length and direction change slightly during tilt, to be automatically corrected for by elevation-dependent movements of the secondary mirror close to the focus.

Figure 4 - The principle of the stable reference platform for pointing. At the crossing point 0 of azimuth

and elevation axes, a servo-controlled tiltable and rotatable platform is mounted, with seven mirrors M. Seven optical autocollimation beacons C are fixed on the ground, and deviations of the mirror from being perpendicular are read in two coordinates at each beacon. Readings go to an on-line computer, which finds a least-squares fit for correcting the platform directions with its servo-motors. The platform thus is tied optically to the ground and kept stable within 1.5 arcsec. Azimuth α and elevation Φ then are measured by encoders with reference to this platform, and all deformations occurring between point O and the ground are omitted. Seven beacons give enough redundancy to allow for blocking of some light paths by structural members in all telescope positions.

Figure 5 - Cost and performance, for telescopes of various diameters. The open circles represent the four atmospheric windows of Figure 2.



KEY

1. AEROSPACE CORPORATION
2. UNIVERSITY OF TEXAS
3. KITT PEAK, NRAO
4. JPL, GOLDSTONE
5. HAT CREEK
6. 65-M TELESCOPE DESIGN
7. RT-22, CRIMEA, RUSSIA
8. MIT, LINCOLN LABORATORY
9. BONN, GERMANY
10. ITAPETINGA, BRAZIL
11. NPC, CANADA
12. HAYSTACK, NEROC
13. BONN, GERMANY, 100 M
14. 140-FOOT, NRAO
15. VARIOUS 85-FOOT TELESCOPES
16. ALGONQUIN, CANADA
17. OWENS VALLEY
18. GOLDSTONE
19. NEROC DESIGN
20. WERTHOVEN, GERMANY
21. MARK II, JODRELL BANK
22. PARKES, AUSTRALIA
23. 300-FOOT, NRAO
24. MARK III, JODRELL BANK
25. MARK I, JODRELL BANK
26. ARECIBO
27. ARECIBO WHEN RESURFACED
28. PRESENT SUGGESTION

Figure 1 - Natural limits for steerable radio telescopes. Telescopes plotted with open circles are either not yet completed or have not yet demonstrated the performance indicated.

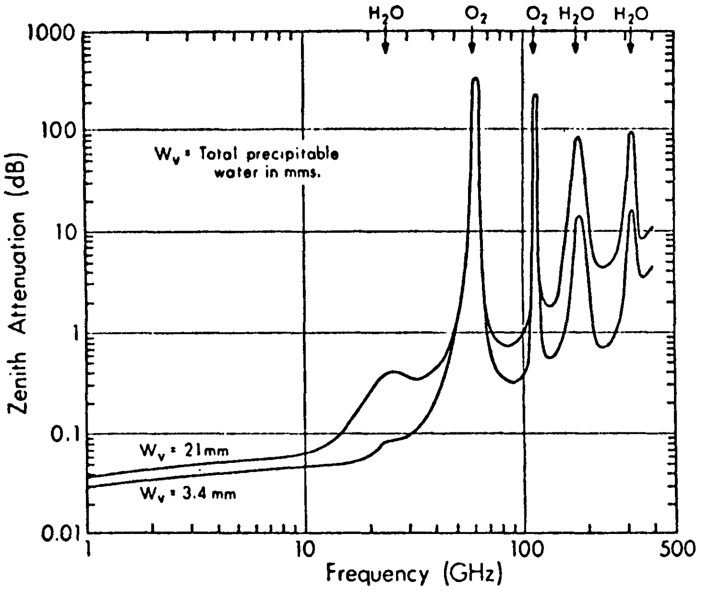


Figure 2 - One-way zenith absorption of radio waves in the atmosphere. The four deep minima, at 3.5, 2.1, 1.2 and 0.8 mm wavelength, are the "atmospheric windows" for observation.

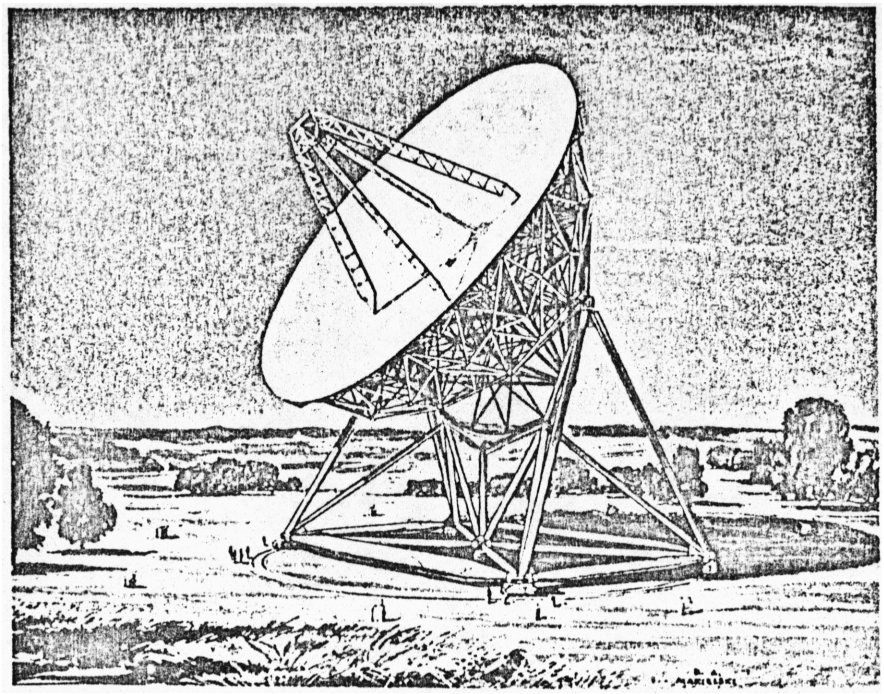


Figure 3 - The 65-meter telescope for millimeter wavelengths. The alt-azimuth mount consists of two tetrahedral tower structures, holding the elevation axis, and moving on trucks on the azimuth ring on the ground. The back-up structure of the reflector is designed in such a way that, if tilted, the surface deforms under its weight from one parabola to another one, giving an exact mirror for any angle of tilt (homologous deformations). Focal length and direction change slightly during tilt, to be automatically corrected for by elevation-dependent movements of the secondary mirror close to the focus.

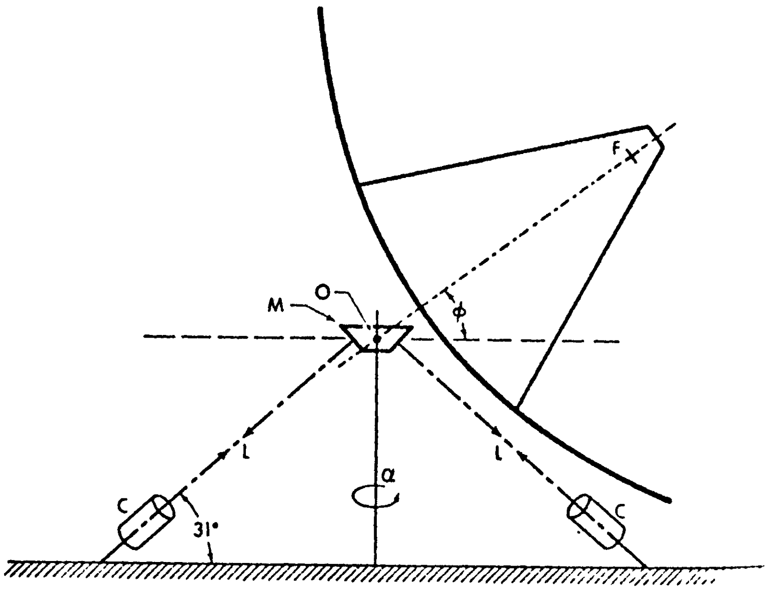


Figure 4 -- The principle of the stable reference platform for pointing.

At the crossing point O of azimuth and elevation axes, a servo-controlled tiltable and rotatable platform is mounted, with seven mirrors M. Seven optical autocollimation beacons C are fixed on the ground, and deviations of the mirror from being perpendicular are read in two coordinates at each beacon. Readings go to an on-line computer, which finds a least-squares fit for correcting the platform directions with its servo-motors. The platform thus is tied optically to the ground and kept stable within 1.5 arcsec. Azimuth α and elevation ϕ then are measured by encoders with reference to this platform, and all deformations occuring between point O and the ground are omitted.

Seven beacons give enough redundancy to allow for blocking of some light paths by structural members in all telescope positions.

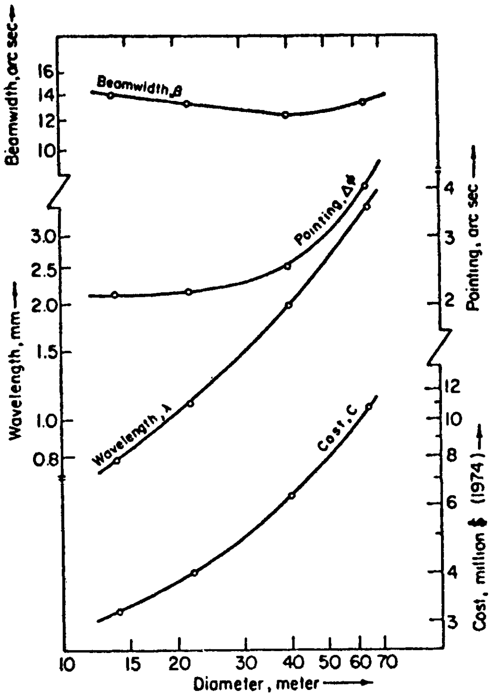


Figure 5 - Cost and performance, for telescopes of various diameters. The open circles represent the four atmospheric windows of Figure 2.

X

VLA TELESCOPE (LK 4-16-74)

1. POINTING ERROR (NON-REPEATABLE) (18 MPH 5°F ΔT)

	CASSEGRAIN α=120° φ=0°	PRIME FOCUS α=0° φ=0°
Σ	10.3"	12.0"
REFLECTOR	.34"	.20"
MOUNT	9.50"	11.37"
SERVO & DATA SYST.	4.25"	3.34"

2. POINTING ERROR (REPEATABLE) = 84.3"

3. SURFACE RMS (18 MPH 5°F ΔT)

PANEL = .024"
STR. = .014"
Σ .028"

4. FEED BLOCKAGE

6.3% w/ 8.2'φ VERTEX SHADOW
7.7% w/ 13.'φ " "

5. WEIGHT = 507,370#

ELEV. STR	140,050#
COUNTER WT	180,000#
YOKE	82,090#
PEDESTAL	105,230#

#14

10/15/74

For Oct. 25 NSF

RADIO TELESCOPES FOR MILLIMETER WAVELENGTH

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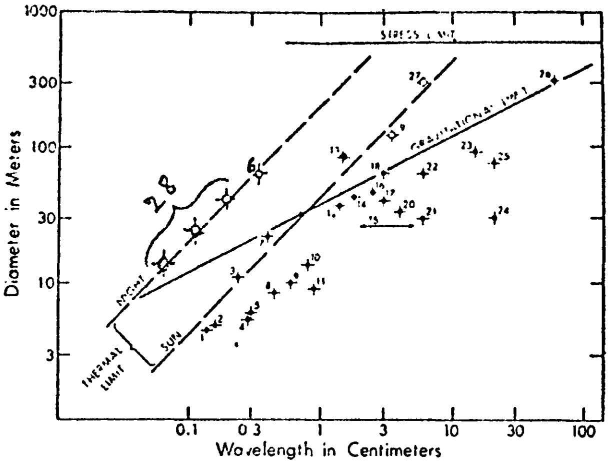
Summary

General rules are discussed for selecting the shortest observational wavelength, and for finding the largest technically possible diameter, for the design of steerable radio telescopes. The shortest wavelength should be selected in one of the four atmospheric "windows" of good transparency, and it depends also on the telescope site; the largest diameter then is defined for this wavelength by thermal deformations, if gravitational deformations are omitted by a homologously deforming design.

The NRAO design of 65-m telescope for 3.5 mm wavelength is briefly described. This design then is scaled down to smaller diameters, for cost reduction as well as for reaching still shorter wavelengths. Cost and performance (without radome) are calculated as functions of the diameter, and results are presented in the following table for all four atmospheric windows.

Enclosure in a radome is not essential for this type of design, as a detailed estimate shows. But the radome eases operation and scheduling considerably, by bringing shortest wavelength and pointing error during sunshine down to the same low value as at night.

Diameter		Shortest wavelength (millimeter)		Cost (million dollars,1974)	Beamwidth (arcsec)		Pointing error (arcsec)	
(meter)	(feet)	night	sunshine		night	sunshine	night	sunshine
65	213	3.5	8.5	10.7	13.3	32	4.0	8.0
40	131	2.0	4.9	6.3	12.4	30	2.5	4.5
25	82	1.2	3.0	4.0	13.5	34	2.2	3.8
14	46	.8	2.0	3.2	14.1	35	2.1	3.6



KEY

1. AEROSPACE CORPORATION
2. UNIVERSITY OF TEXAS
3. KITT PEAK, NRAO
4. JPL, GOLDSTONE
5. HAT CREEK
6. 65-M TELESCOPE DESIGN
7. RT-22, CRIMEA, RUSSIA
8. MIT, LINCOLN LABORATORY
9. BONN, GERMANY
10. ITAPETINGA, BRAZIL
11. NRC, CANADA
12. HAYSTACK, NEROC
13. BONN, GERMANY, 100 M
14. 140-FOOT, NRAO
15. VARIOUS 85-FOOT TELESCOPES
16. ALGONQUIN, CANADA
17. OWENS VALLEY
18. GOLDSTONE
19. NEROC DESIGN
20. WERTHOVEN, GERMANY
21. MARK II, JODRELL BANK
22. PARKES, AUSTRALIA
23. 300-FOOT, NRAO
24. MARK III, JODRELL BANK
25. MARK I, JODRELL BANK
26. ARECIBO
27. ARECIBO WHEN RESURFACED
28. PRESENT SUGGESTIONS

Natural limits for steerable radio telescopes. Telescopes plotted with open circles are either not yet completed or have not yet demonstrated the performance indicated.