CHAPTER I

A SURVEY AND SUMMARY

1. Introduction

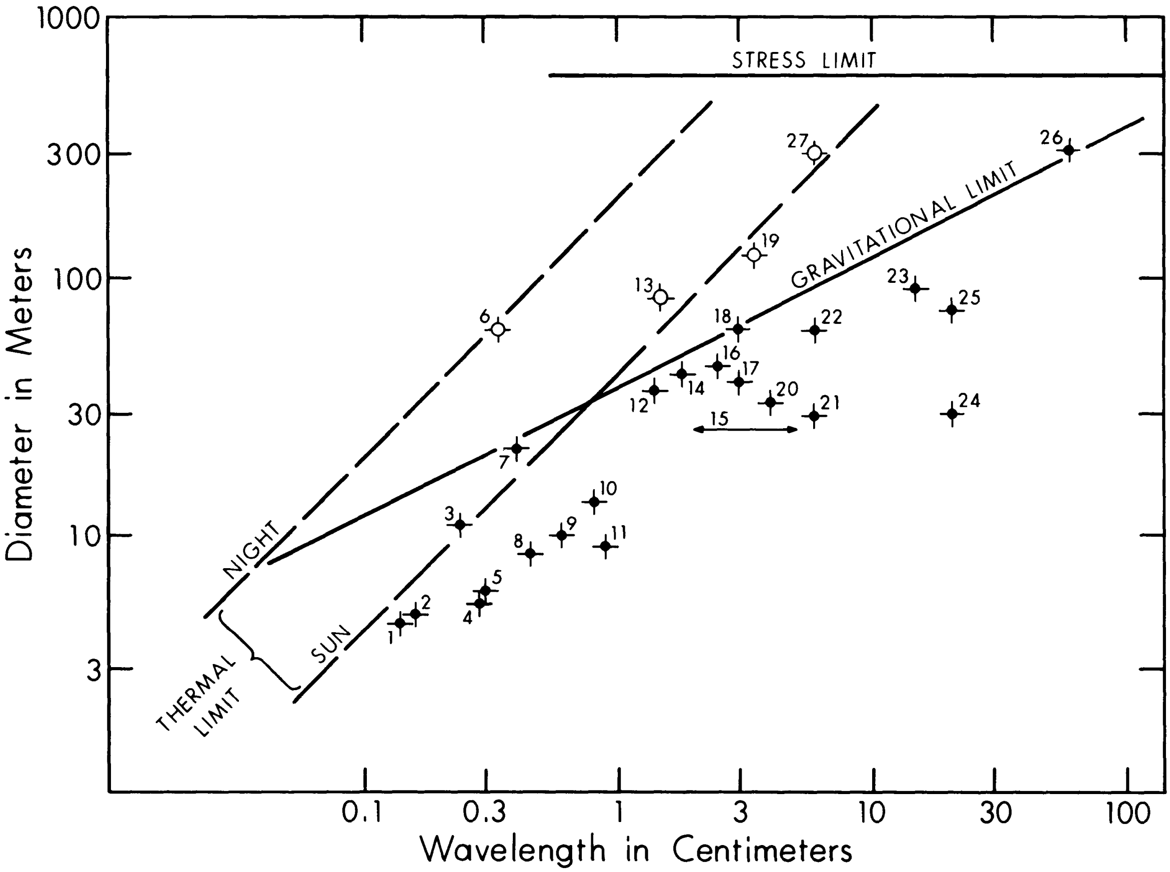
This report gives the results of a design effort which establishes the feasibility of building a 65-meter diameter, fully-steerable radio telescope and provides an estimate of the cost of such an instrument, including the development of a suitable, typical site which, at 1972 prices, is 9.42 million dollars.

The present design is the outcome of work of many years; it incorporates the homology principle as stated and worked out in 1965 by S. von Hoerner. When this principle is correctly applied, a 65-meter telescope used under good observing conditions can be expected to work to wavelengths as short as 3.5 mm (86 GHz). The design was planned to meet the specifications given in Table 1.

Table 1. 65-meter Telescope Design Specification

Dish diameter	:	65 meters (213 feet)
Mounting	:	Altitude-Azimuth
Elevation range	:	From horizon to 35° beyond the zenith
Sky cover	:	Complete--but no tracking inside a small zone near zenith of about 1 degree in radius
*RMS surface accuracy	:	0.222 mm (0.009 inches)
*Short wavelength limit	:	3.5 mm (86 GHz)
*Tracking accuracy	:	3 arc seconds RMS
Slew rates (both axes)	:	20° per minute
Optics	:	Prime focus f/D = 0.42. Cassegrain--subreflector diameter 3.7 m (12 feet)
Instrument cabins	:	Behind prime focus; behind Cassegrain focus
Equipment room	:	Rotates in azimuth

* This performance is only possible under benign environmental conditions.



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

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.

It is realized that such specifications surpass those of other large radio telescopes so far built. As von Hoerner (1967a) has shown in general terms, there are natural limits set by the effects of gravity, temperature, wind and material strength to the size of any reflector telescope. The size limit is related to the telescope's precision, measured in turn by its short wavelength limit. Figure 1 is a later version of Figure 2 in von Hoerner's paper. A wide variety of telescopes, one of which is only in the design stage, and the present design, are shown. None pass the gravitational limit except those which have taken care to do so (Bonn 100 meter, NEROC design, and the present design) and Arecibo, where the reflector surface is fixed to the ground.

The design work has shown that the performance stated in Table 1 can be achieved under good climatic conditions. The actual conditions are discussed in detail in Chapter III; in general they require a situation typical of a clear night where the wind is below 18 miles per hour. When such conditions do not exist, during a calm, sunny day, for example, the telescope performance will deteriorate and accurate measurements only at wavelengths longer than 10 mm (30 GHz) will be possible. Thus, the best use of the instrument will be achieved by careful planning of the experimental work to be performed. It is large enough to be an important instrument when used at centimeter wavelengths; its design allows for rapid change-over from one wavelength to another and good scheduling of the programs can thus make the best use of the telescope at all times.

2. The Scientific Objectives of the Telescope

(a) General objectives. The broad scientific objective of the new telescope is to extend a wide variety of radio astronomical observations of many phenomena in the universe to wavelengths shorter than a few centimeters. The best large reflecting telescopes of today work well to wavelengths of about 3 cm (10 GHz). Although the radio universe has not been deeply explored at wavelengths between 3 cm and 3.5 mm (10 GHz - 86 GHz), existing smaller radio telescopes have already made many exciting new discoveries in this wavelength range; the new telescope will have 35 times the collecting area of the NRAO 36-foot instrument, which is at present the largest in the world capable of good work at 3.5 mm. The 65-meter telescope will thus give both the ability for deeper exploration and also will allow of much more accurate measurements for a wide variety of astronomical problems.

(b) Molecular spectral lines. The array of problems currently of most interest in molecular line work, but which are presently not soluble because of limited sensitivity and spatial resolution of existing equipment, is already large and is rapidly growing. These problems are largely soluble only at millimeter wavelengths and with telescopes larger than existing ones for several reasons.

(i) We now know that interstellar molecules of typical molecular weight (20 to 50) are populated up to quite high rotational energy levels; because the transition probabilities increase rapidly toward higher levels, the brightness temperatures of the lines arising from these higher levels are correspondingly large. These higher transitions occur at millimeter wavelengths for nearly all astrophysically interesting molecules. Because of these excitation conditions, far fewer molecules are needed to produce a detectable line at millimeter wavelengths than at longer (cm) wavelengths.

(ii) Significant structural detail in molecular clouds has been established at angular sizes as small as 1 arc minute, and physical arguments indicate that smaller structure yet is to be expected. In several of these cases (e.g., NH_3) the brightness in the lines is low, making these objects difficult to study even with a large array at the required resolutions. Observations of other transitions, or other molecules, at millimeter wavelengths, appear necessary to solve these problems.

It is believed that many additional interstellar molecules will be discovered with an improvement over current sensitivity of perhaps no more than a factor of five at millimeter wavelengths. Among these are several molecules containing hitherto undetected atoms such as Fe, Mg, $C\ell$, and P. Even if these are not detected with such an improvement in sensitivity, the corresponding upper limits that can be placed on their abundances will be low enough to be very significant in terms of understanding interstellar chemistry. More complicated molecules containing only H, N, C, and O may also be discovered, and the important question might be answered of how large interstellar molecules may be.

Several problems involving presently known molecules will be soluble with better spatial resolution. Better positions for several point-like molecular clouds are needed to establish how well they coincide with small infrared sources that are being discovered frequently in the molecular regions. The physical relation between different molecular species on the small-scale level is important in determining if chemical abundances or formation processes vary rapidly with location in molecular clouds. This type of detail is essential even to derive meaningful relative abundances of the various molecular species, which in turn is necessary even to begin a study of interstellar chemistry.

Perhaps the best indication of the essential advantages of the millimeter range for molecular work is shown by the number of new molecules found, and their frequencies, over the past three years. In 1968-1969, before millimeter facilities were available, three new interstellar molecules were found at centimeter wavelengths. In 1970, the first year of good millimeter line observations, seven molecules were found of which four were at millimeter wavelengths. In 1971-72, eleven molecules were found, eight of them at millimeter wavelengths. To understand the excitation of molecules, several transitions need to be observed. In 1971-72, some 26 new transitions of previously known interstellar molecules were detected, and all but four of these lay in frequencies above 25 GHz. Only through the study of these additional lines has it been possible to deduce such fundamental parameters as the density and temperature within the interstellar clouds, quantities which have not in fact been deducible in any other direct way.

The following Table 2 lists lines already detected in the frequency range from 20 GHz - 115 GHz (1.5 cm to 2.6 mm wavelength). The frequency

Table 2. Known Molecular Lines in the Frequency Range 20-115 GHz

Molecule	Transition	Frequency GHz
H_2O water	$6_{16}\rightarrow 5_{23}$	22.24
NH_3 ammonia	Inversion doublets	22.83
" "	" "	23.10
" "	" "	23.69
" "	" "	23.72
" "	" "	23.87
" "	" "	24.13
" "	" "	25.06
CN cyanogen	$N = 1\rightarrow 0$	113.49
CO carbon monoxide	$J = 1\rightarrow 0$	115.27
$C^{13}O^{16}$ carbon monoxide	$J = 1\rightarrow 0$	110.20
$C^{12}O^{18}$ " "	$J = 1\rightarrow 0$	109.78
HCN hydrogen cyanide	$J = 1\rightarrow 0$	88.63
$HC^{13}N$ hydrogen cyanide	$J = 1\rightarrow 0$	86.34
Unknown U.89.2	?	89.19
Unknown U.90.6	?	90.67
CS carbon monosulfide	$J = 2\rightarrow 1$	97.98
OCS carbonyl sulfide	$J = 9\rightarrow 8$	109.46
H_2CO formaldehyde	$3_{12}\rightarrow 3_{13}$	28.97
H_2CO "	$1_{01}\rightarrow 0_{00}$	72.84
HNCO isocyanic acid	$4_{04}\rightarrow 3_{03}$	87.02
HNCO " "	$1_{01}\rightarrow 0_{00}$	21.98
HC_3N cyanoacetylene	$J = 8\rightarrow 7$	72.78
HC_3N "	$J = 9\rightarrow 8$	81.88
HC_3N "	$J = 10\rightarrow 9$	90.98
HC_3N "	$J = 11\rightarrow 10$	100.08
CH_3OH methyl alcohol	$4_2\rightarrow 4_1$	24.93
CH_3OH " "	$5_2\rightarrow 5_1$	24.93

Table 2, continued

Molecule	Transition	Frequency GHz
CH_3OH methyl alcohol	$6_2 \rightarrow 6_1$	25.02
CH_3OH " "	$7_2 \rightarrow 7_1$	25.12
CH_3OH " "	$8_2 \rightarrow 8_1$	25.29
CH_3OH " "	$4_1 \rightarrow 3_0$	36.20
CH_3OH " "	$5_1 \rightarrow 4_0$	85.52
CH_3CN methyl cyanide	$6_5 \rightarrow 5_5$	110.33
CH_3CN " "	$6_4 \rightarrow 5_4$	110.35
CH_3CN " "	$6_3 \rightarrow 5_3$	110.36
CH_3CN " "	$6_1 \rightarrow 5_1$	110.38
CH_3CN " "	$6_0 \rightarrow 5_0$	110.38
H_2CCO	$4_{04} \rightarrow 3_{03}$	80.83
CH_3C_2H methylacetylene	$4_{04} \rightarrow 3_0$	85.46
	$4_1 \rightarrow 3_1$	85.46

range from 25 GHz - 50 GHz has not yet been explored to any large extent, and many other lines can be expected in that region. The table has not been extended below 20 GHz since some existing large telescopes can work in that frequency range. The table has also been extended somewhat above the telescope's 86 GHz design limit, since it can be expected to be very useful for line work in that range.

The molecular species already identified by their microwave lines can be expected to show many other lines arising from other transitions. A reasonable listing of these suggest that 30 or so more lines may be found with good instruments. Even this does not exhaust the future possibilities. As has already been suggested, molecules or radicals such as PN, HCP, FeO, $CH_3C\ell$, HC_2CHO, NH_2CN and NgO may exist and in their turn could be a rich source of lines in this part of the microwave spectrum.

(c) Observations in the radio continuum. We will again emphasize those tasks where the short wavelength performance of the telescope makes it unique, and thus refer mainly to observations made above about 20 GHz (1.5 cm). We will however note in passing that the telescope will be a major instrument in its own right and will do much more valuable work in the centimetric and decimetric wavelength range.

In the field of extragalactic studies, quasars and radio-bright galaxies will be studied. New radio outbursts in quasars and in the nuclei of galaxies often show effects first and most strongly at the short wavelength end of the spectrum. Their changes in intensity and polarization with time can be of help in explaining the mechanism of radio energy production. The radio spectra and polarization of galaxies and quasars should be extended to shorter wavelengths to add knowledge of magnetic fields and particle energies.

In our own galaxy the telescope will be used to map the fine structure in regions of ionized hydrogen and to study gas and dust concentrations where stars may be forming. Some (usually unusual) stars have already been found to be radio emitters, and some novae have also been found to show short-wavelength radio enhancements. These are fields for further study. The telescope can also have a wide field of view and thus can make surveys of the sky with good angular resolution and high sensitivity.

A large millimeter-wave telescope will have many uses in solar-system astronomy. It will observe active regions on the sun to improve our understanding of the origins of solar disturbances. Measurements of the millimeter-wave spectra of the planets will help discover the constituents of planetary atmospheres. Studies of temperature and polarization measurements of the moon and planets will tell more of the surface and subsurface properties of these bodies.

(d) Interferometric observations. It is not too early to speak of millimeter-wave interferometry; experimental work is already being undertaken by various radio astronomical groups. The 65-meter telescope will be a powerful instrument either for use with one or more smaller nearby telescopes in the phase-coherent mode or as one end of a very long baseline interferometer. Such VLBI experiments have already been made at 22 GHz, and the extension of the method to higher frequencies requires, at present, mainly improvements in technology and the availability of at least one large radio telescope.

(e) Conclusion. Any look forward in a rapidly advancing subject such as radio astronomy is always colored by the most recent discoveries. At present, these are very largely in the field of molecular spectroscopy, and the future of this field looks very bright. Only a very few years ago studies of the highly energetic quasars were more in the forefront of interest. These problems are still with us; so also are the problems of cosmology and the origins of the intense non-thermal emission of energy in the whole spectral region from radio to X-ray wavelengths.

The 65-meter telescope has the accuracy to make great advances possible at millimeter waves, yet it is large enough to continue and extend radio astronomical research at longer wavelengths. It will therefore be versatile enough to meet the future challenges which will arise as astronomy grows and changes.

3. Special Features of the Design

(a) Homologous deformation. The telescope design uses the principle of homologous deformation, or more shortly of "homology". Any massive structure must deflect under its own weight, and if, as is true of the reflector of a radio telescope, it must be moved with respect to the gravitational force, it will deform by different amounts as it moves. Suppose, however, that the entire reflector supported at its elevation bearings could be so designed that the reflector surface is a true paraboloid of revolution when the reflector points to the zenith and also when it points to any position between zenith and the horizon. It would then (in the absence of distortions due to wind or temperature) be a perfect radio telescope. It is known that this condition can be satisfied provided we are willing to let the focal length of the reflector surface change. We also have to allow the direction of the telescope's radio beam to move in a slightly different way from the way the elevation axis rotates. When we achieve this result that the reflector surface keeps the same geometrical shape but only changes by a scale factor, we say that the deformation has been homologous.

This principle has been the basic technique by which the whole of the present reflector structure has been designed. The method uses the well-established techniques by which stress and deflection analyses of complex structures made up of elastic material can be computed with a high accuracy. The programs developed to make these computations are novel, and include many checks to ensure that the structural design which results is both practical and accurate.

It should be emphasized that, although the homology program for designing the reflector structure is novel, the results of the design have also been checked by well-established methods of structural analysis. The initial structural geometry and the use of relatively few members were chosen to make the behavior of the actual structure conform closely to the predictions. Individual members are tubular steel pipes; these come together at joints which are specially designed, half-spherical castings welded together. The tubes in turn are welded to the spheres; sometimes where the geometry requires it, a cast tapered end is used to connect the steel tubular member to the sphere.

Simplicity in geometry and good joints are very valuable in ensuring that the structure does in fact behave under its gravity loads as the computations predict. That this will be so has been well demonstrated; for example, the agreement between calculated and measured distortions was excellent for the 300-foot telescope at NRAO, the 210-foot telescope at Goldstone and the 120-foot Haystack antenna. The Bonn 100-meter dish also relies on accurate computer predictions of deflections, but the final test of measurement has not yet been made on that telescope.

The homology program results in a structure with the required deflection pattern, and the program has been extended to obtain other practical results. It ensures that the structure can be built using for many of its members the regularly available sizes of tubes or pipes, although some members must be specially fabricated. The departures from homological perfection brought about by these choices, as well as by the manufacturing and erection tolerances of the members, have been calculated and shown to be acceptable. The survival strength of the structure in wind, snow and ice is adequately met by the design program.

(b) The pointing system. It is necessary to know very precisely (to within a few seconds of arc) where the radio beam of the telescope is pointed. Although homology neutralizes the effects of gravity on the reflector performance, the whole telescope will deform under gravity and the more conventional means of measuring its beam position--by using accurate angle measuring encoders on the azimuth and elevation axes--would show considerable differences between these axial position measures and the actual beam position. Other factors, such as wind forces, temperature differences, small movements of the telescope foundations or lack of exact leveling of the azimuth track, all result in position errors.

These gravitational, steady-wind and other position errors can be much reduced if the position of the structural axis of the parabolic reflector can be referred directly to a fixed reference system on the ground. This method has proved most useful in the Australian National Radio Astronomy Observatory's 210-foot telescope at Parkes, N.S.W., and it is also used in the NASA/JPL 210-foot telescope at Goldstone and in the Canadian NRC Algonquin Park 150-foot telescope. All these instruments have a central, independently founded tower, shielded from the sun and wind, which carries at its top the system which references the direction in which the reflector is pointing.

The same principle, but in a novel form, is used in the design of the 65-meter telescope. The reflector axis is referenced to a platform which is held in the position where the elevation and azimuth axes of the telescope intersect. This reference platform is locked to remain fixed in its azimuth and elevation angular position as the telescope moves (the platform may make small linear movements in absolute position) and highly accurate encoders measure the reflector angular position relative to this stable reference platform. Instead of mounting this reference platform on a central shielded tower, it is held locked to the ground by a servo-control system which gets its error indications from beams of light transmitted in fixed directions from several stations on the ground around the telescope and reflected from mirrors on the reference platform back to the ground.

The position reference system is intended to reduce the pointing errors of the whole telescope to the very low values required. The repeatable pointing errors due to gravity will be measured in the calibration procedure and then allowed for by the pointing computer. The reference platform has already been the subject of considerable design and test. A test stand of one element of the optical system has been built and has been operated at Green Bank for several months. This has demonstrated that the method will not fail because of irregularities in the atmosphere causing instability in the direction of the light beam. The design of the reference platform has been carried to a fairly advanced stage, since its performance is critical to that of the whole telescope. A suitable type of autocollimator has been chosen and the servo system which will lock the platform to the light beams has been designed. Specifications for such critical components as the 22-bit angle encoders (corresponding to 0.31 arc seconds resolution) have been issued and offers to supply have been received and evaluated.

(c) The reflector surface. The requirements of a reflector surface which will work well at millimeter wavelengths are stringent. The surface plates must be fabricated and measured, then mounted on the telescope, measured and set in position; all these operations must result in a surface which maintains in reasonable regimes of wind and temperature an accuracy (RMS) of 0.22 mm (0.009 inches). Higher accuracies than this have already been achieved on other telescopes with diameters up to 72 feet but the methods of fabrication have been too expensive for adoption in the present design.

One method of fabricating the plates has been developed and tested at NRAO. This method produces an aluminum surface plate, with the required surface curvature and accuracy, of about 6 feet by 2-1/2 feet in size. The actual surface is made from originally flat 1/8-inch aluminum sheet. This is set to the required shape by 36 adjusting screws which deform it, acting against an aluminum support frame. Tests have shown that this type of construction gives a surface within the accuracy limits and one which withstands the required loads without permanent deformation or structural hysteresis. The cost of manufacturing this surface is reasonable.

The surface is so important a part of the whole telescope that other methods by which the surface plates might be made have been explored. Studies have been carried out by two companies experienced in the design and fabrication of antennas. Several alternative methods of making the surface plates have been considered; one of these which would machine the surface of a previously fabricated surface plate on its support structure is an acceptable alternative to the NRAO surface plate already described.

The reflector plates must finally be mounted and set in position to a high accuracy on the reflector support structure. Two methods for doing this setting have been evaluated. The first uses a combination of a measure of the distance from a point at the dish center to a target on the dish surface with a measure of the elevation angle of the target, also taken from the dish center. The distance measure is made by a high-quality steel tape and the angle is measured by comparing it to the angle by which a quartz pentaprism deflects a ray of light. This is a well-tested system, and it can give the required measurement accuracy.

A second method for surveying the surface has been devised. This measures two distances from the dish center to a target on the surface. The first distance is direct to the target; the second is from the dish center to a point near the dish focus and then to the target. Both distances are measured accurately and rapidly using a modulated laser-light instrument. This method also can give the required measurement accuracy.

Accuracy and speed of measurement are both important in the task of surveying the surface, since the best time to measure will be on calm nights after the structure has reached a fairly uniform temperature. The final check of the success of the surface setting is, of course, the radio measurement of the gain or aperture efficiency of the telescope at short wavelengths.

4. The Estimated Cost

(a) General. We have developed in Chapter V a complete estimate of the cost of bringing the telescope to completion on a site in the southwestern United States. This estimate includes the cost of the final engineering of the design, fabrication and erection of all parts of the telescope, acquisition and preparation of a typical site, including buildings and final test and check-out of the instrument. It includes the cost of all items, such as the control computer, to make the instrument fully operational. It does not include the cost of radiometers with their feeds, back-ends, data processing, extraction and recording equipment, since these items are provided from the Observatory's annual budget. An estimate is given, however, of how the telescope would impact the NRAO budget, both in this respect and in the additional manpower and cost which the new telescope would add to the NRAO operating budget.

(b) The telescope cost estimate. Table 3 is a summarized version of the later Table 25 in Chapter V.

In arriving at the site figure, we have assumed that the telescope was being built on one of the possible VLA sites, but we have included all work required at the site to make the 65-meter telescope fully operational. If in fact this telescope and the VLA were to share a site, the costs of site development would be shared between them, and our figure of $634,000 is too high.

We have estimated (see Table 27) that the new telescope would require a staff at the site of 26 and that its annual operating budget would

Table 3. Summary of the Cost Estimate (in 1972 dollars)

	Thousands of $
Fabrication of main structure	1,916
Erection of complete telescope	1,080
Surface plates, including installation and adjustment	1,540
Azimuth and elevation machinery	675
Foundation and track	146
Position reference system, drive and control system	1,160
Feed legs, access system, cabling, painting, start-up and test	592
Site acquisition, preparation and buildings	634
Project management and engineering	450
	8,193
Add 15% contingency	9,422

be $512,000. With rather less certainty, we suggest that the new telescope would require an added $250,000 yearly, divided between the NRAO electronics budget items for other observing equipment and test and repair equipment. This funding should start when the construction of the telescope is approved.

Finally (see Table 30), we estimate that the time for completion from the availability of funding would be 36 months.

(c) Cost escalation. In the situation at the time of writing (February 1972), it seems still prudent to assume a steady escalation of costs of labor and materials over the years. We will arbitrarily adopt a rate of 6 percent per year, to apply to all figures (which have all been in 1972 dollars).

The earliest date by which funds could be available to NRAO for this telescope is January 1, 1974. By that date our total cost, including contingency, would have grown to $10.587 million. Projections of cost beyond that date can be left (at present) to others more skilled than ourselves.

References

von Hoerner, S. 1967(a). *Astron. J.*, 72, 35-47.