THE 65-METER TELESCOPE FOR MILLIMETER WAVELENGTHS

A Progress Report

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INTRODUCTION

This report gives the progress of the design effort which is intended to establish the feasibility of building a 65-meter diameter fully-steerable radio telescope and to give an estimate of the cost of such an instrument.

The present design is the outcome of work of many years; it incorporates the homology principle as stated and worked out by S. von Hoerner. The reflector support structure is designed in such a way that, as the dish moves in elevation, the reflector itself remains parabolic in shape, changing only in focal length and axial direction. Thus, considering gravity deformations only, a 65-meter telescope using homology in its design can be expected to work to wavelengths as short as 3.5 mm (86 GHz). To ensure that this can be achieved under reasonable observing conditions, it is necessary to consider carefully the effects of wind and temperature differences on the telescope structure; these disturbances affect both the figure of the reflector surface and the precision with which the telescope can be pointed. The design which is described here can achieve good performance at 3.5 mm so long as the average wind at the center of the telescope reflector is below 17 miles/hour and when no temperature differences of more than 2° F exist across elements of the telescope structure. Climatic conditions on various sites and measurements on telescope structures show that this good short wavelength performance of the telescope will be available to the observer for a very useful part of the total time. At other times, it is expected that the telescope performance will deteriorate and at some times only measurements at wavelengths longer than 10 mm (30 GHz) will be possible. The climatic conditions at a well-chosen site will be, to some extent, predictable and so the choice of wavelengths can be made in scheduling the telescope to avoid too serious a loss of observing time.

SCIENTIFIC OBJECTIVES OF THE TELESCOPE

The broad scientific objectives 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 2 or 3 cm (15 GHz to 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 35-200 times the sensitivity of instruments at present in use and will permit of this deeper exploration and give accurate measurements for a very wide variety of astronomical problems. The following Table I is an attempt to list the kinds of observations which would be made and the specific scientific objectives to which the observations are directed. It is probably an oversimplification--it is almost certainly incomplete--but it may be of value in showing the range of problems known to await the telescope.

Table I

Specific Scientific Objectives of the 65-meter Telescope

Type of Observation	Wavelengths known to be of interest	Specific Scientific Objectives
Detect, locate and measure the spectra of molecules in interstellar space. Discover new molecules.	NH_3 1.3 cm H_2O 1.3 cm CO 2.6 mm* CN 2.6 mm* HNC 3.4 mm* ? 3.4 mm HC_3N 3.3 mm CH_3CN 2.7 mm* OCS 2.7 mm* CS 2.0 mm*	Study distribution of molecules in sources. Understand formation and excitation of molecules. Relate to other properties of interstellar medium and the known energy sources. Study relative abundances of molecules. Are more complex exobiologically interesting molecules formed in space?
Study the properties of extragalactic radio sources in the short wavelength part of the radio spectrum.	10 cm† to 3.5 mm	New outbursts of quasars occur first and most strongly at the shorter wavelengths. Study intensity and polarization variability to help explain mechanisms of radio energy production in such sources. Extend knowledge of source spectra to find more about magnetic fields and high energy particles. Use as one end of a radio-link or tape-recording interferometer to provide resolutions of better than 10^{-4} seconds of arc from earth-based observations. Survey sky at short wavelengths.
Observations of objects within our own galaxy.	10 cm† to 3.5 mm	Map fine structure in regions of ionized hydrogen--may lead to better knowledge of star formation. Study specific stars and novae (recently discovered to be observable at short radio wavelengths) to understand nova explosion processes and stellar envelopes.

* These lines are at shorter wavelengths than the 3.5 mm design limit of the telescope. It will, however, be of value for spectral work at wavelengths below its design limit.

† The long-wavelength limit has been arbitrarily chosen. The phenomena are of interest at longer wavelengths but telescopes other than the 65-meter can work well at such wavelengths.

Table I, continued

Type of Observation	Wavelengths known to be of interest	Specific Scientific Objectives
Solar, lunar and planetary observations	10 cm† to 3.5 mm	Observe active regions on sun to improve understanding of solar disturbances. Measure millimeter-wave spectra of planets to study constituents of planetary atmospheres and meteorological phenomena. Study temperature differences on planetary and lunar surfaces to help understand surface and subsurface properties.

†The long-wavelength limit has been arbitrarily chosen. The phenomena are of interest at longer wavelengths, but telescopes other than the 65-meter can work well at such wavelengths.

THE TELESCOPE DESIGN

The performance specification is given in Table II. The telescope is, except for the special features which give its good short-wave performance, of a quite conventional simple type (Figs. 1 and 2). The reflector is mounted on elevation bearings which allow it to move from the horizon to 25° beyond the zenith. The towers which support these bearings themselves rotate about the central pintle bearing; the vertical loads are carried by the azimuth trucks on the circular rail track; horizontal loads are carried by the pintle bearing. Drive in elevation is by DC electric servo motors and a bull gear and in azimuth by DC electric servo motors driving the wheels of the azimuth trucks through gear reducers. The drives are fully servo-controlled and the

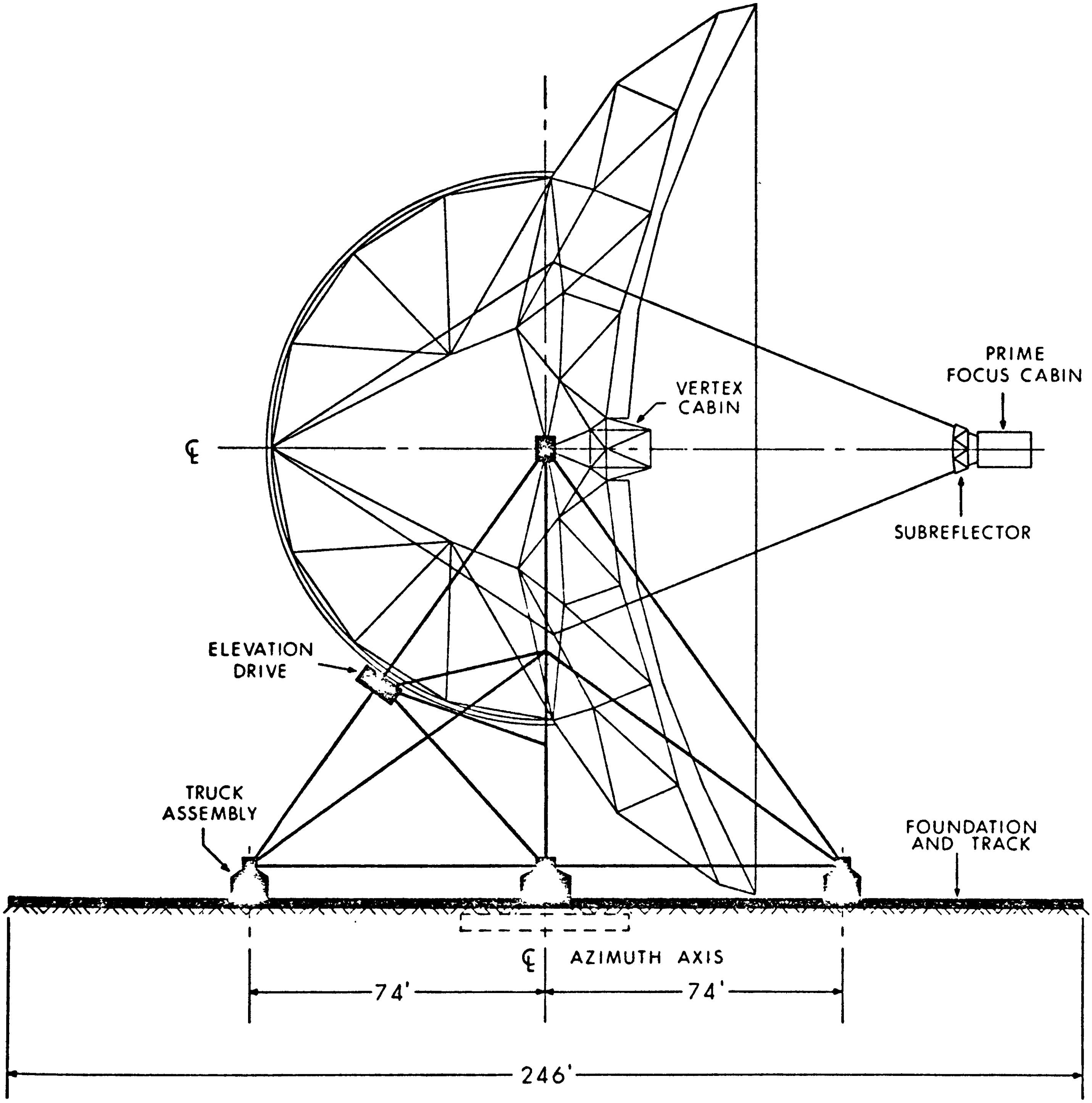
PRIME FOCUS CABIN
VERTEX CABIN
℄
SUBREFLECTOR
ELEVATION DRIVE
TRUCK ASSEMBLY
FOUNDATION AND TRACK
℄ AZIMUTH AXIS
74'
74'
246'

Figure 1

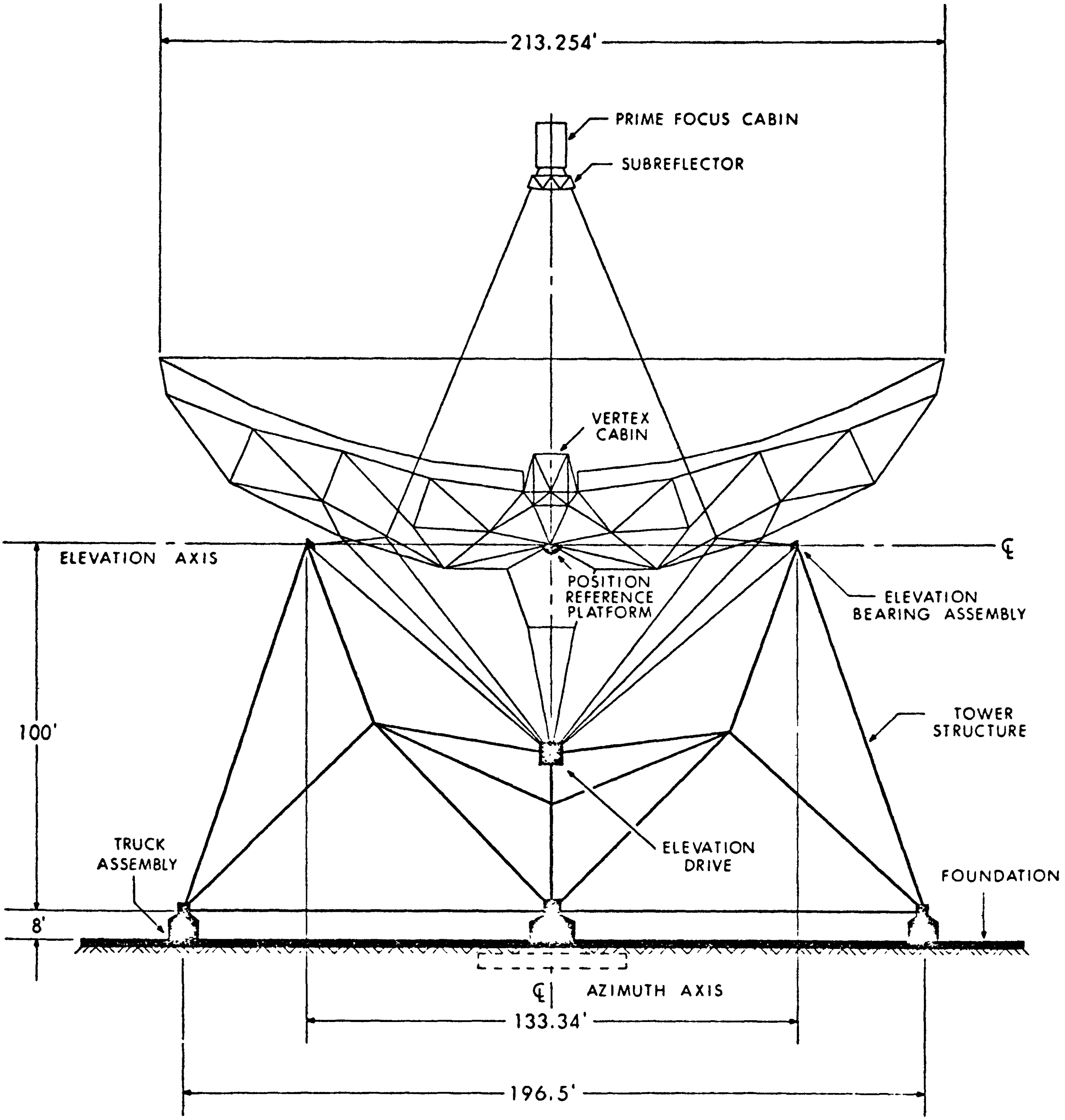
213.254'
PRIME FOCUS CABIN
SUBREFLECTOR
VERTEX CABIN
ELEVATION AXIS
℄
POSITION REFERENCE PLATFORM
ELEVATION BEARING ASSEMBLY
100'
TOWER STRUCTURE
ELEVATION DRIVE
TRUCK ASSEMBLY
FOUNDATION
8'
℄ AZIMUTH AXIS
133.34'
196.5'

Figure 2

entire motion of the telescope, whether it is slewing, scanning or tracking, is controlled by a central computer. The required motions of the instrument will normally be entered into this computer, although manual control will also be possible.

Table II

65-meter Telescope Performance Specification

Dish diameter	65 meters (213 feet)
Mounting	Altitude-Azimuth
Sky cover	Complete--but no tracking inside a small zone near zenith
*RMS surface accuracy	0.22 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

* The highest precision performance is only possible when the wind velocity is below 17 miles per hour and when no temperature differences greater than 2° F exist across parts of the structure.

The instrument may be used as a prime-focus telescope, when the radiometers in the prime focus cabin are used, or as a Cassegrain. In this mode, which is preferable at the shorter wavelengths, a subreflector sends the radio energy to the feed horns and radiometers in the vertex cabin. The change of optics from one mode to the other is made by removing or replacing the subreflector. All the general concepts involved are well understood and well tested on existing instruments, so that in the descriptions which follow we will concentrate on those parts of the design where the stringent accuracy requirements are of the greatest importance.

The main reflector support structure has been designed using the homology program. The influences of manufacturing and selection tolerances in the lengths and sizes of the structural members on the homology solution have been studied. So have the effects of joint flexibility and the results confirm that the deflection errors will be within the required limits. The structure is simple--it is made mainly of steel pipes (Corten steel has been selected) and the pipes are connected using spherical joints. This design is good in that all forces at a joint intersect at a point; the spherical joints themselves are made from half-sphere castings welded together. All members are welded to the spheres, in some cases the geometry requires a tapered end to the tubular member; this tapered end is also a casting.

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 deflections 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 reflector surface has to be fabricated, set and measured in the shop, mounted on the telescope and set and measured in place; all these operations must result in a surface of RMS accuracy of 0.22 mm (0.009 inches). One method of fabricating and setting surface plates has already been developed and tested. 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, one which withstands a man's weight without suffering a permanent set and which deflects well within the limits in 20 miles per hour winds or under its own weight.

Despite the apparent success of this type of reflector plate, an alternative design is also being studied. This would accurately machine the surface plate support structure and then fix pre-formed metal sheets to conform in shape to the supports.

The surface plates will be mounted on specially designed adjustable supports (one at each corner) and finally surveyed in place on the telescope using the Zeiss pentaprism and tape technique. This method has been well tested on telescopes built in West Germany. The distances to rings of targets are measured by a surveyors tape and the angles are determined by accurately made pentaprisms.

It is necessary to know to within 3 seconds of arc where the radio beam of the telescope is pointed and to be sure that the telescope will track a source in the sky to within such an RMS error. Although homology essentially 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--will 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 at Goldstone and in the Canadian N.R.C. 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 is being used in the design of the 65-meter telescope. The reflector axis will be referenced to a platform which is held at the position where the elevation and azimuth axes of the telescope intersect. This reference platform will itself be locked to remain fixed in azimuth and elevation as the telescope moves, and highly accurate encoders will measure the reflector position relative to this stable reference platform. Instead of mounting this reference platform on a central shielded tower, it will be held locked to the ground by a servo-control system which gets its error indications from beams of light transmitted in fixed directions from seven stations on the ground around the telescope and reflected from mirrors on the reference platform back to the ground.

This 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 operating 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 0.3 arc seconds resolution) have been issued and offers to supply have been received and evaluated.

The main drive and control system is of fairly straightforward design. Estimates of the main telescope resonance frequencies (which are now being calculated to a greater accuracy) show that the azimuth and elevation servo bandwidths can be about 0.7 Hz wide. The performance of the first servo design in the presence of sticking and rolling friction and wind-induced torques on the structure has been estimated and appears to be satisfactory; more detailed work in this area is proceeding.

THE PRECISION OF THE TELESCOPE

Two further factors which can affect the performance of a very precise radio telescope are the effects of the variability of the wind forces on the instrument and the structural deformations resulting from changes in temperature of the whole or of parts of the structure.

The telescope is planned to be exposed to the atmosphere. Although the protection of a radome would simplify some design problems, there appears to be no way in which such a radome could be built and yet preserve the performance of the instrument over its wide range of millimeter wavelengths.

The main effects of variable wind forces on the structure are the disturbances to the pointing precision due to the inability of the servo drive to correct for the more rapidly varying wind torques and the deformations of the reflector surface due to its support structure bending in the wind. Both these effects can be calculated when the parameters of the telescope and the probable nature of the wind forces are known. Preliminary results of such calculations suggest that in winds with mean velocities below 17 miles per hour the effects will not limit the shortest wavelength performance. This in turn says that, when higher winds occur, observations must be restricted to the longer wavelengths which require less precision. Such statements can, when sites for the telescope are considered, be transformed into more quantitative estimates of the amounts of time at which the instrument can work at various wavelength ranges. For example, were the telescope now to be at Green Bank (which is, in fact, not a probable site but is one where good wind statistics are known), winds would permit it to work at its shortest wavelength for 75 percent of the total time in any one year.

Thus, the wind forces limit the telescope performance, but in a fairly reasonable way. A similar result seems to be true for the effects of temperature and temperature differences.

The telescope only has its correct shape when all members are at the same temperature. Sunlight and shadow, radiation to a cold ground or from a hot ground, differences in the rate at which various parts of the telescope heat and cool, all these effects produce temperature differences across the structure. Such differences, by altering lengths of structural members, deform the dish. This shows as a loss of surface accuracy, and, in some conditions, as a degradation in the pointing precision of the telescope.

Thus the basic questions are: What temperature differences are likely to occur and how would they distort the structure? Measurements have been made and are continuing on the telescopes at Green Bank and Kitt Peak which, together with calculations, answer the first of these questions. The second can be answered by computing the changes in shape of the telescope structure when various possible regimes of temperature differences exist. Such calculations are being made using the computer programs which are used in the telescope design.

At present, results suggest that the telescope will, at its shortest wavelength, be close to a temperature difference limitation, in that no more than 2° F can be permitted to exist as a temperature difference between members before the shape of the reflector departs enough to spoil its performance at the shortest wavelength. A clear day with bright hot sunshine followed by a clear, fairly calm night has been used as an example to show how the telescope would behave. Figure 3 shows how the shortest usable wavelength would vary over such a 24-hour period. In such an instance, 10 of the 24 hours are good for 3.5 mm observing, at the worst time of day the telescope still is good at 9.3 mm.

PROGRESS AND THE FIRST COST ESTIMATE

By early April sufficient progress had been made in all design areas to allow of the first estimate of cost to be made. Twenty-nine design drawings were complete (Appendix A). The main structural design was complete and member sizes and weights and the spherical joints were known. Three surface plates had been fabricated, and the design sent to an experienced fabricating firm to comment on and to price. Engineering estimates were made of the components of the telescope. A site development plan for a possible site* (the VLA site Y-15 on the Plains of San Augustin) had been made. So had an annual operations budget for such a site. The results of this estimating are given in Tables III, IV, and V. These require some comment. All figures are preliminary and are in 1971 dollars. The additional cost to

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* No site for the 65-meter telescope has been selected. This site was chosen to work as an example of a site development cost. The example was worked on the assumption that no VLA development had taken place.

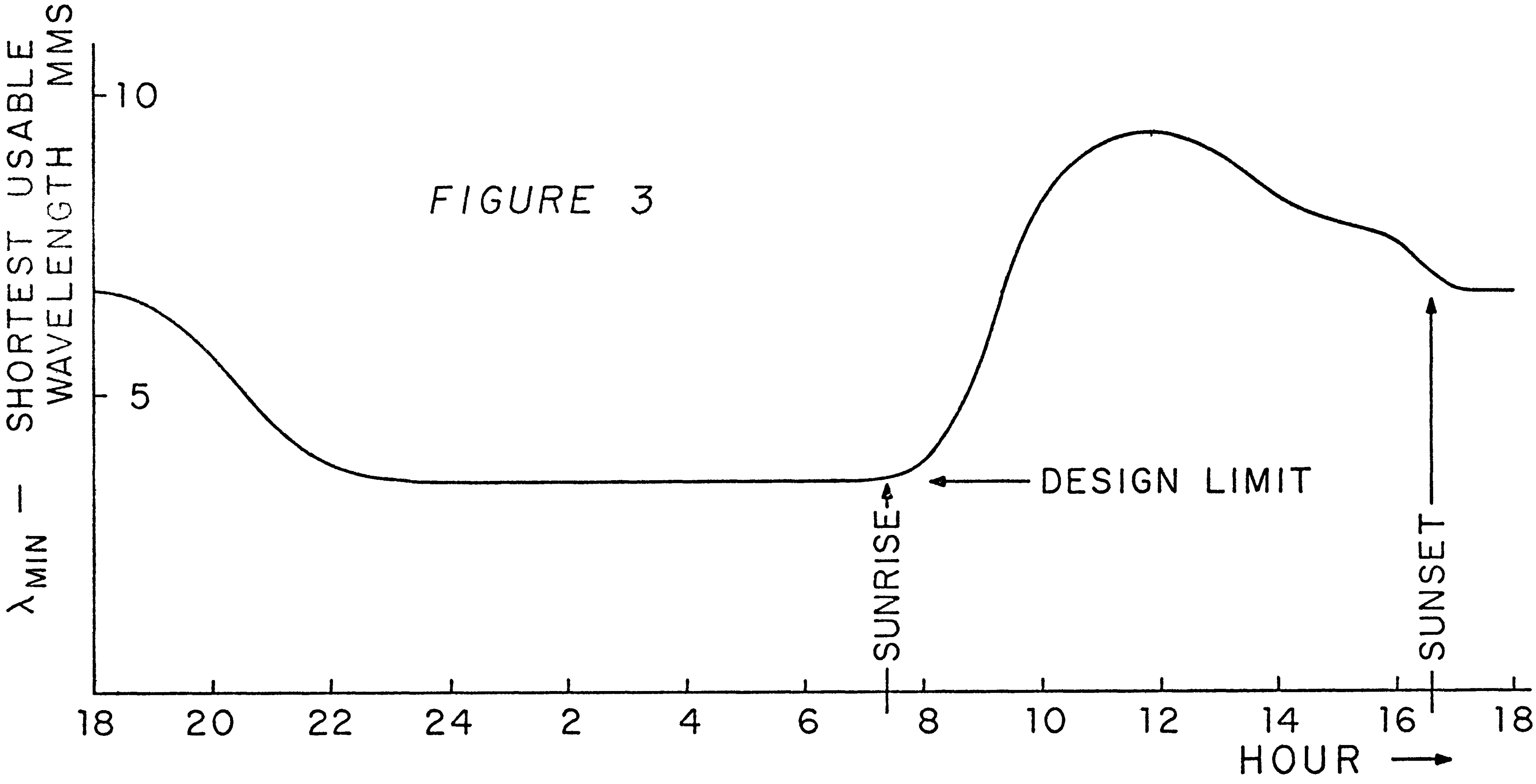
λ_MIN — SHORTEST USABLE WAVELENGTH MMS
10
5
DESIGN LIMIT
SUNRISE
SUNSET
18
20
22
24
2
4
6
8
10
12
14
16
18
HOUR →

FIGURE 3

NRAO of project management and engineering during construction is shown in the $350 k in Table III. Some NRAO staff (about four) would be used also during this phase of the work, which would last about two years.

Table III

65-meter Telescope, Preliminary Cost Estimate
(1971 dollars)

	Thousands of $
Reflector and tower structure, including counterweight	2,100
Surface plates, including adjustment	1,456
Azimuth trucks and drive motors	340
Pintle bearing	55
Elevation bearings	100
Elevation gear and drive motors	230
Foundation and track	154
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, azimuth rotating equipment room	42
Telescope cabling	100
Painting, start-up and test	200
Site preparation	634
Project management and engineering	350
	7,171
Add 15% contingency -- Total	8,247

Table IV

65-meter Telescope

Site preparation estimates (in 1971 dollars) for placing the 65-meter telescope on the VLA site Y15 (Plains of San Augustin). These estimates assume that no site development for the VLA would have taken place.

	Thousands of $
Site acquisition	5
Grading and draining	40
Roads	10
Water System	52
Sewage system	12
Electric power distribution	35
Stand-by generator (500 kW)	80
Control building (3300 sq. ft.)	140
Dormitory building	115
Shop and garage	35
Telescope service tower (on control building)	110
Total	634

Table V

65-meter Telescope--Operating Cost Estimate

	Totals	$
On-Site Personnel		
Site manager, administrative assistant, clerk, secretary	4	49k
Electronic engineer (3) and electrical/mechanical	4	60k
Technicians, electronic (3) and computer (1)	4	40k
Telescope operators	6	60k
Telescope mechanics	2	20k
Programmer	1	15k
Laborers/handymen/driver	2	12k
Guards (night only)	2	12k
Housekeeper/cook	1	5k
Part-time, temporary, overtime -- 10%		27k
Totals	26	300k

Salaries of on-site personnel	300k
Benefits, 15%	45k
Travel	15k
Utilities--telephone 5k; power 15k	20k
Materials, services and supplies	100k
One-third cost of painting telescope (paint every three years)	32k
Total Annual Operating	512k

THE TELESCOPE SITE

In searching for possible sites for such a telescope it is desirable to have two classes of criteria by which the location is judged. The first of these we will call "general" or "administrative" and it need not be discussed in detail. This class includes such items as proximity to cities and towns, access, availability of utilities and services, land ownership, political and administrative problems, etc.

The second class of criteria, the "specific" criteria, are those which will determine the overall performance of the instrument on its chosen site. These need careful definition and study, particularly to determine how much weight to give to the various items in the list. For example, the following criteria are used for judgment:

(a) Atmospheric clarity -- i.e., radio-wave absorption, radio-sky noise and its fluctuations, cloud cover and precipitation as they affect radio observations, etc.

(b) Meteorological environment of the structure —i.e., wind and temperature effects on the telescope performance and the estimation of the fraction of the time that full precision performance is to be expected. Possible survival limits due to wind, snow or ice.

(c) Astronomical requirements — i.e., the ability to observe well over the most important areas of the sky, such as most of the galactic plane, the galactic center and certain important extragalactic objects.

(d) Radio interference — i.e., proximity to sources of radio noise which may now or in the future limit the telescope performance.

A site search is therefore a considerable task, since it involves not only the collection and analysis of existing data but the development of means by which some of the criteria can be evaluated. A start has been made on this task, with most of the interest being directed to the general area of the Southwest of the United States.

APPENDIX A

List of Drawings

111-D-001	6 sheets	Reflector structure
111-D-002	3 "	Tower structure
111-D-004	1 "	Azimuth cabling - pintle bearing
111-D-005	4 "	Elevation drive
111-D-006	1 "	Pintle bearing
111-D-007	1 "	Elevation bearing
111-D-003	3 "	Truck assembly
111-D-010	1 "	Azimuth turntable and foundation
111-D-001	2 "	Reference platform and autocollimator location
111-D-012	6 "	Reference platform
56-D-00086	Surface plate	

Total -- 29