Technical Report 445

1 of 1

H. G. Weiss

Design Studies for 440-Foot-Diameter Radio and Radar Telescope

20 February 1968

Prepared under Electronic Systems Division Contract AF 19(628)-5167 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

This report is based on studies supported by staff and funds from the Cambridge Radio Observatory Committee, the National Science Foundation (Grant GP-5832), and the U.S. Air Force under Contract AF 19(628)-5167.

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DESIGN STUDIES FOR 440-FOOT-DIAMETER RADIO AND RADAR TELESCOPE

H. G. WEISS

Division 4

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ABSTRACT

Studies conducted by the Cambridge Radio Observatory Committee during the past two years show that a large steerable telescope can be constructed at lower cost and with higher precision if the antenna is protected from the environment by a radome. These studies also indicate that the extremely high pointing precision (10 arc-sec) needed to make effective use of a large aperture at wavelengths as short as 5 cm can be obtained with a radome-protected antenna. The proposed 440-foot antenna employs a deflection-compensated vertical truss reflector support structure to maintain a 0.09-inch rms tolerance in the primary reflector under all operating conditions. The low cost of the antenna results from the ability to use lightweight reflector panels, an efficient computer-optimized reflector support structure, a small-diameter azimuth bearing, and a low-power control system. The estimated cost of this novel antenna design and the radome is substantially lower than the cost of alternative exposed antennas. The equivalent aperture and gain of the proposed antenna-radome system are made equal to that of a 400-foot antenna by increasing the antenna diameter by 10 percent. This report also describes the 520-foot-diameter space-frame radome and the planned electronic instrumentation and control facilities for a proposed radio and radar observatory.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

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DESIGN STUDIES FOR 440-FOOT-DIAMETER RADIO AND RADAR TELESCOPE*

The Cambridge Radio Observatory Committee (CAMROC) was established in 1965 by Harvard University, Massachusetts Institute of Technology, and the Smithsonian Astrophysical Observatory to develop plans for an advanced regional radio and radar astronomy research facility. The formation of CAMROC was in response to the very evident need for a large telescope within a few hours' drive of the greater Boston area which would enable both the staff and students of the many New England universities to participate more actively in radio and radar astronomy. As the plans for this facility evolved, representatives of fourteen universities in New England formed the Northeast Radio Observatory Corporation (NEROC) to cooperatively seek support for the construction and operation of this proposed research installation.

I. PERFORMANCE REQUIREMENTS

Detailed studies were initiated at the beginning of the program to define the principal research objectives[1] in radio and radar astronomy of direct interest to the scientists in New England. These objectives, which included spectral-line and continuum analysis of galactic and extra-galactic sources, investigations of the interstellar medium, radiometric and radar studies of the solar system, high-resolution studies of low-brightness sources, and multiple-site interferometric research, were then used to establish the performance requirements[2] for a proposed telescope.

A variety of filled-aperture and array antennas were studied, and it was concluded that the diverse needs of the New England scientific community could be fulfilled most effectively by a large, very precise, steerable, filled-aperture telescope, provided that it could function efficiently over a wide spectral range. The principal characteristics desired in the proposed instrument are:

- Broad spectral range
- Simultaneous spectral coverage
- High resolution
- Low sidelobes
- Large absolute aperture
- Polarization measurement capability
- Long integration times
- Effective use of low-noise radiometers
- Maximum sky coverage
- Compatible for radar use
- Versatile tracking capability
- Observation of short-time-period phenomena
- Ease of experimental changeover

While it was obvious that the largest and most precise steerable aperture would have the greatest scientific potential, it was also recognized that considerations of engineering feasibility and

* This report is based on a paper presented at the International Symposium on Structures Technology for Large Radio and Radar Telescope Systems, Massachusetts Institute of Technology, Cambridge, Massachusetts, 18-20 October 1967.

cost would have a major influence on the attainment of the necessary financial support for the project. Because several steerable antennas in the 200- to 300-foot-size class are now in operation and because National Radio Astronomy Observatory (NRAO) is currently investigating telescopes 600 feet and larger in size, the NEROC group decided to focus its attention on very high precision antennas in the 300- to 500-foot-size range.

TABLE 1

EFFECTS OF LINEARLY SCALING ALL DIMENSIONS OF EXPOSED ANTENNA

Deflections		
Gravity	$\sim D^2$	
Wind	$\sim D$	
Thermal	$\sim D$	
Structural Natural Frequency		$\sim \frac{1}{D}$
Drive Torque		
Inertia	$\sim D^4$	
Wind	$\sim D^3$	
Cost	$\sim D^3$	

After studying the performance capabilities and limitations of all existing and planned telescopes, it was concluded that significant new opportunities for scientific exploration would become available if a 300- to 500-foot-diameter telescope could be made with the very high precision needed for efficient operation at wavelengths as short as 5 cm. However, it was recognized that it would be extremely difficult and costly to construct a large steerable precision antenna by just linearly scaling an existing design (Table 1). Studies initially based on a 400-foot-diameter antenna were eventually changed to a diameter of 440 feet to compensate for radome effects. If feasible at a reasonable cost, it was desired that the telescope be usable at high efficiency at all wavelengths between 5 and 300 cm, and some performance degradation at shorter and longer wavelengths would be acceptable.

This requirement for 5-cm operation dictated that the contour errors of the reflector system should not exceed 0.1 inch (rms) [Ref. 3]. The ratio of the diameter to tolerance required to meet this performance criteria with a 440-foot telescope would have to be approximately 48,000 (Table 2). The only known steerable telescope with this high a diameter-to-tolerance ratio is the 120-foot-diameter Haystack system.[4]

II. SELECTION OF CONFIGURATION

After the nominal size and tolerance of the telescope were established (see Table 3), many different concepts for filled-aperture antennas were examined to determine the most economical configuration. A variety of conventional and nonconventional antennas (folded horns, tilting plates, floating spheres, off-axis paraboloids, etc.) were investigated[5,6] to ascertain which general configuration would be most suitable. These studies indicated that the cost of a telescope is determined not only by the area and precision of the reflecting surface, but also by (a) the total weight of the structure, (b) the environmental operating and survival requirements, and

TABLE 2

CHARACTERISTICS OF TYPICAL RADIO TELESCOPES

Present	Diameter (D) (feet)	Tolerance* (ϵ) rms (inches)	λ_m† (cm)	Precision $D/\epsilon \times 10^{-3}$ (000)	Beamwidth‡ (minutes)	Remarks
Lincoln Laboratory	28	0.008	0.26	42	1.3	
Lebedev	72	0.022	0.70	39	1.3	
Michigan	85	0.030	1.0	34	1.5	
Haystack	120	0.027	0.9	53	1.0	In radome
Greenbank	140	0.040	1.3	42	1.3	
Algonquin	150	0.045	1.4	36	1.5	
Parkes	210	0.14	4.5	18	2.8	Elevation min = +30°
Jodrell Bank	250	0.40	13	7.5	7.1	
Greenbank	300	0.47	15	7.6	7.0	Transit instrument
Arecibo	1000	1.2	40	10	5.3	Spherical reflector (±20° scan)
Proposed						
Bonn	328	0.15	5	26	2.0	
University of Manchester	400	0.50	16	9.6	5.5	
NEROC	440	0.10	3.2	53	1.0	In radome

* Data from various sources; sometimes inconsistent (nighttime, no-wind conditions).

† λ_m where gain in maximum ($\lambda = 4\pi\epsilon$); reduction in gain due to tolerance errors at λ_m = 4.3 db.

‡ Half-power beamwidth at λ_m.

TABLE 3 PROPOSED CHARACTERISTICS	
Reflector	440 feet (178 m)
Surface accuracy	0.1 inch (0.25 cm) rms
Operating range	
(high efficiency)	5 cm (6 GHz) to 100 cm (300 MHz)
(reduced gain)	3.2 cm (9.6 GHz) to 300 cm (100 MHz)
Equivalent area	$\sim 1.3 \times 10^5$ ft^2
Beamwidth at 3.2 cm	50 arc-sec (0.02°)
Pointing accuracy	10 arc-sec (0.003°)
Sky coverage	Azimuth 360°; elevation 0 to +85°

(c) the required pointing precision. Configurations that required multiple surfaces (tilting plates and horns) and systems in which the reflector surface constituted only a small percentage of the over-all moving weight had greater over-all cost. A series of five parallel studies[7] carried out over a nine-month time span by five design teams (Ammann & Whitney; Simpson Gumpertz & Heger; the Rohr Corporation; P. Weidlinger, and Lincoln Laboratory) provided useful comparative data on a variety of antenna configurations. From these studies it was concluded that the conventional parabolic configuration offered the most promise for fulfilling the performance goals at the lowest over-all cost.

III. POINTING CONSIDERATIONS

The desire to operate at the shorter wavelengths requires that the reflecting surface be solid or have a very fine mesh. Preliminary design studies clearly indicated that it would not be realistic to expect any 400-foot-diameter exposed antenna with a comparatively solid reflecting surface to fulfill this very rigorous pointing requirement due to the enormous stiffness required in the reflector mount, control, and alidade structure. It also became apparent from these studies that the requirement to point the antenna with very high precision would be the most difficult design requirement to fulfill.

At the shortest operating wavelength of 3.2 cm, a 440-foot-diameter aperture will have a half-power antenna beamwidth (3-db response points) of only 1 minute of arc (0.017 degree). Efficient operation necessitated the control of the beam position with an uncertainty of less than about one-sixth of a beamwidth, or approximately 0.003 degree. This pointing precision has not been achieved to date on any large exposed steerable reflector except during very low wind conditions and at nighttime when the thermal gradients are low. The radome-enclosed Haystack telescope is, again, a unique example of a large steerable antenna capable of fulfilling this pointing requirement.

IV. ENVIRONMENTAL CONSIDERATIONS

The environment in which the telescope must survive and function has, of course, a very important influence on the design.[8] Two factors are of principal concern – the winds and the thermal environment. Figure 1 indicates the peak wind velocities averaged over a 5-minute interval which have a 1-percent likelihood of occurrence in a 25-year time span at a height 50 feet

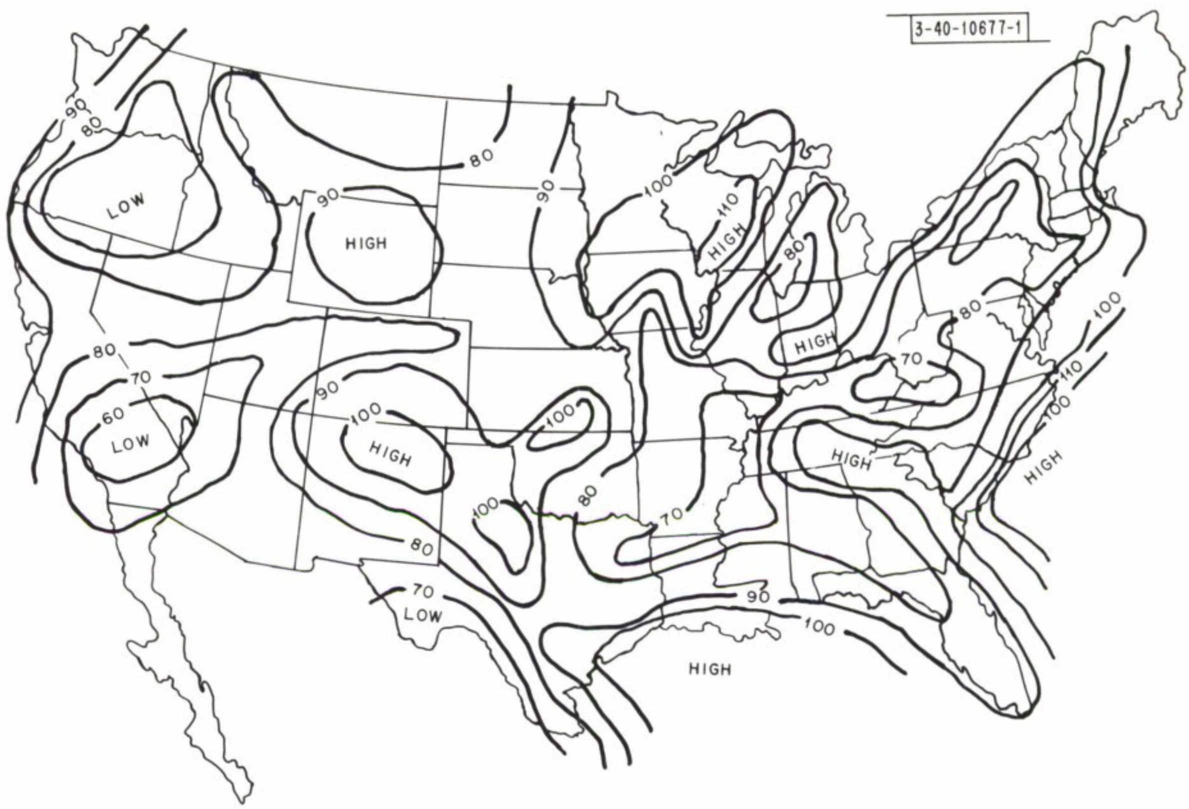

Fig. 1. Five-minute peak winds in the United States.

above the ground.[9,10] It will be noted that in New England, at locations at least 75 miles from the sea coast, the peak wind velocities are substantially lower than throughout a large fraction of the United States. While the actual winds in any area will be dependent on the local terrain features, the selection of telescope sites and the establishment of survival and performance criteria are very strongly affected by winds.

Figure 2 is a representative wind escalation curve relating the frequency of occurrence winds as a function of height above the ground.[11] These curves indicate that, as the antenna size increases, the design wind speed must also be increased significantly if operation is to be maintained for a large fraction of the total time. For example, an antenna 50 feet above the ground designed to function in a 30-mph wind could be operable except for about 3 percent of the time, whereas winds at a height of 400 feet will exceed 30 mph about 30 percent of the time.

V. NEED FOR RADOME

Many of the smaller and less precise telescopes now in use are not capable of operating at full efficiency when in direct sunlight or when the winds exceed 20 to 30 mph. It was recognized that the severity of the wind and the thermal problem would increase as a function of the antenna area and precision and would be further aggravated by the requirement for a fine mesh or solid reflector surface. These considerations, as well as the very consistent performance of the Haystack antenna and the clear indication that there will continue to be a copious supply of scientific problems and investigations to keep the proposed telescope in use essentially 100 percent of the time, motivated a study to ascertain the influence of a radome upon telescope performance and cost.

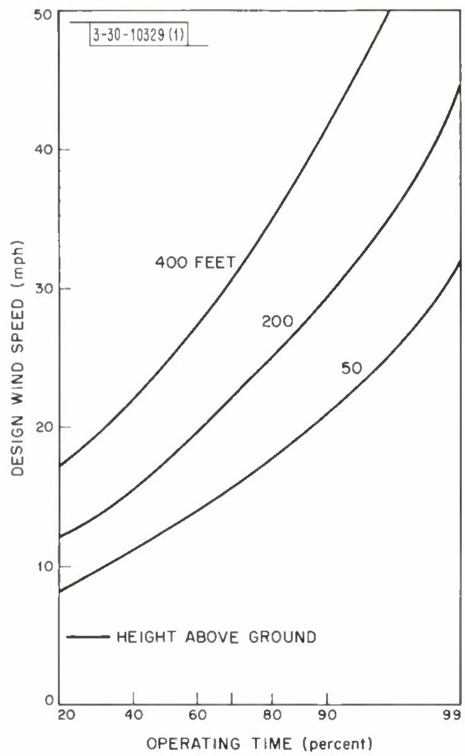

Fig. 2. Wind escalation vs height.

Because of extensive experience on the JPL 210-foot Goldstone antenna and other radio telescopes, the Rohr Corporation was asked to study the comparative cost and feasibility of exposed and radome-protected telescopes 210, 328, and 400 feet in diameter. The studies[12] indicated that it would not be feasible at any reasonable cost to fulfill the ±0.003-degree angular pointing requirement in an exposed, large, steerable microwave antenna. Within the radome, however, the desired performance objectives seemed completely feasible.

The attractiveness of the radome concept stems from the ability to deal independently with those design considerations which influence the precision of the telescope and those which influence its survival and performance. The price for this design freedom is not just the need to increase the diameter of the aperture by about 10 percent to overcome the blockage and noise contributed by the radome, but also the cost of the radome must now be included in the over-all cost of the telescope.

VI. HOW RADOME SIMPLIFIES DESIGN AND REDUCES ANTENNA COST

The underlying philosophy for the design of a radome-protected antenna differs substantially from that for an antenna which must operate in an exposed environment. Some of the ways in which a radome can simplify and reduce the cost of the antenna system are listed below.

(a) The reflecting surface and its supporting structure can be light in weight.

(b) Simple techniques can be used to compensate for the only variable loads on the structure (gravity).

(c) The antenna can have a low natural frequency (~0.2 Hz) (low mass, low stiffness).

(d) Small-diameter bearings can be used, since the overturning moments and weight are reduced.

(e) The power required to drive and control the antenna system will be low (~20 hp).

In contrast to an outdoor antenna, the reflecting surface and many of the other components can be made exceedingly light in weight, limited primarily by fabrication, shipping, and erection requirements. For example, detailed studies show that the over-all weight for a reflector surface and the structure needed to attach it to the main backup support members can be as low as 0.25 pound per foot, only about 15 percent of the weight of the equivalent structural elements in a typical exposed antenna. This low panel weight simplifies the supporting structure and control system.

With the advent of advanced computer techniques, which make it possible to calculate precisely the elastic deformations that will occur as the antenna is rotated about its elevation axis, it becomes possible in the controlled environment of a radome to introduce inexpensive preprogrammed compensation techniques. A variety of methods for correcting the gravity-induced elastic deformations have been studied,[13] including the following:

- The adjustment of the reflector panels, each about 400 square feet in area, by controlled jacks at the corners of each panel,
- The use of a small number of active motor-driven jacks or cam mechanisms in the reflector backup structure (displacement compensation),
- The introduction of a variable pre-stress by means of control cables (force compensation),
- The use of homology,[14] i.e., the maintenance of a parabolic contour by appropriately selecting the geometry and the size and stiffness of the structural members,
- The use of appropriately coupled counterweights and linkages in the backup structure.

In the radome environment, because there are no rapidly changing wind loads and because of the light weight of the structure, the compensation mechanisms can be small and inexpensive. It was further found that the option was available to achieve the desired precision while maintaining an "invariant" parabolic contour, a capability not normally achieved in existing antennas. This eliminates the need to move the focal position as a function of the elevation angle.

One of the studies to investigate the improvement possible in the contour of a simple cantilevered truss as a function of the number of compensation elements is summarized in Table 4. The deflections of a 200-foot-long cantilevered truss of the type that might be used in a radial rib of a 400-foot-diameter telescope were computed with the truss horizontal and vertical. The deflection at the tip was about 10 inches, but a new parabolic contour with an rms error of about 2.2 inches could be "best fitted" to the changed contour. It was shown that, by placing a single controllable actuator in the appropriate location in the truss, the residual rms contour error could be reduced to about 0.08 inch, an improvement of about 25 to 1. The use of additional compensators resulted in the further improvements as listed.

The absence of wind forces and the comparatively slow acceleration and tracking requirements for observing distant stars permit the design of a telescope with a comparatively low stiffness and structural natural frequency. In contrast to exposed antennas, which must be very stiff and have a lowest resonant frequency of at least one cycle if they are to point accurately in the presence of winds, the radome-enclosed antenna can have a natural frequency as low as

TABLE 4

DEFLECTION IMPROVEMENT
VS NUMBER OF COMPENSATION POINTS
(Weidlinger Study)

Number of Compensation Points per Truss	Rms Deflection (inches)	Rms Gain
0	2.17	1
1	0.077	28
2	0.033	66
3	0.013	167
4	0.0087	250
.	.	.
.	.	.
.	.	.
9	0.0011	1970

0.2 Hz. This allows a major reduction in the material required in the structure and is a significant factor in permitting a low-cost design.

Equally important cost savings result because the lack of wind forces permits the telescope to be supported on a relatively small bearing and alidade structure. This, in turn, lowers the total weight and inertia of the telescope, and reduces the bearing "stiction" problem and the cost. All these factors, plus the absence of wind loads, make it feasible to control the antenna with a low-power drive motor. In contrast, one of the alternative designs for use with an exposed 400-foot antenna required in excess of 2,000 hp on each axis of the telescope.

VII. DESCRIPTION OF SPECIFIC TELESCOPE CONFIGURATION

Figure 3 shows the type of vertical-truss telescope now under study. Before selecting this concept, a variety of structural configurations for large parabolic reflectors were studied. The basic types may be classified broadly into three groups: those with radial symmetry (radial ribs and circumferential trusses), those which are symmetrical about a single axis of rotation (vertical trusses), and those based upon shell configurations. While each of these configurations has specific advantages and limitations, when a radome is used and the structure only rotates about a single axis, there appears to be an advantage in employing a support structure based upon a series of deep vertical trusses. The rationale for this approach lies in the realization that an efficient use of the material in the backup structure involves the selection of a geometry with a high bending moment perpendicular to the axis of rotation; i.e., a deep truss oriented perpendicular to the elevation axis. In addition, the vertical-truss geometry is compatible with a variety of deflection compensation techniques and can be analyzed with only moderate complexity. It also provides a geometry that permits a small azimuth bearing to be used and allows a large instrumentation laboratory to be located directly behind the apex of the reflector. Its disadvantages are that it is a novel configuration and, therefore, must be very intensively studied; and, being symmetric about only one axis, it may be more susceptible to temperature effects.

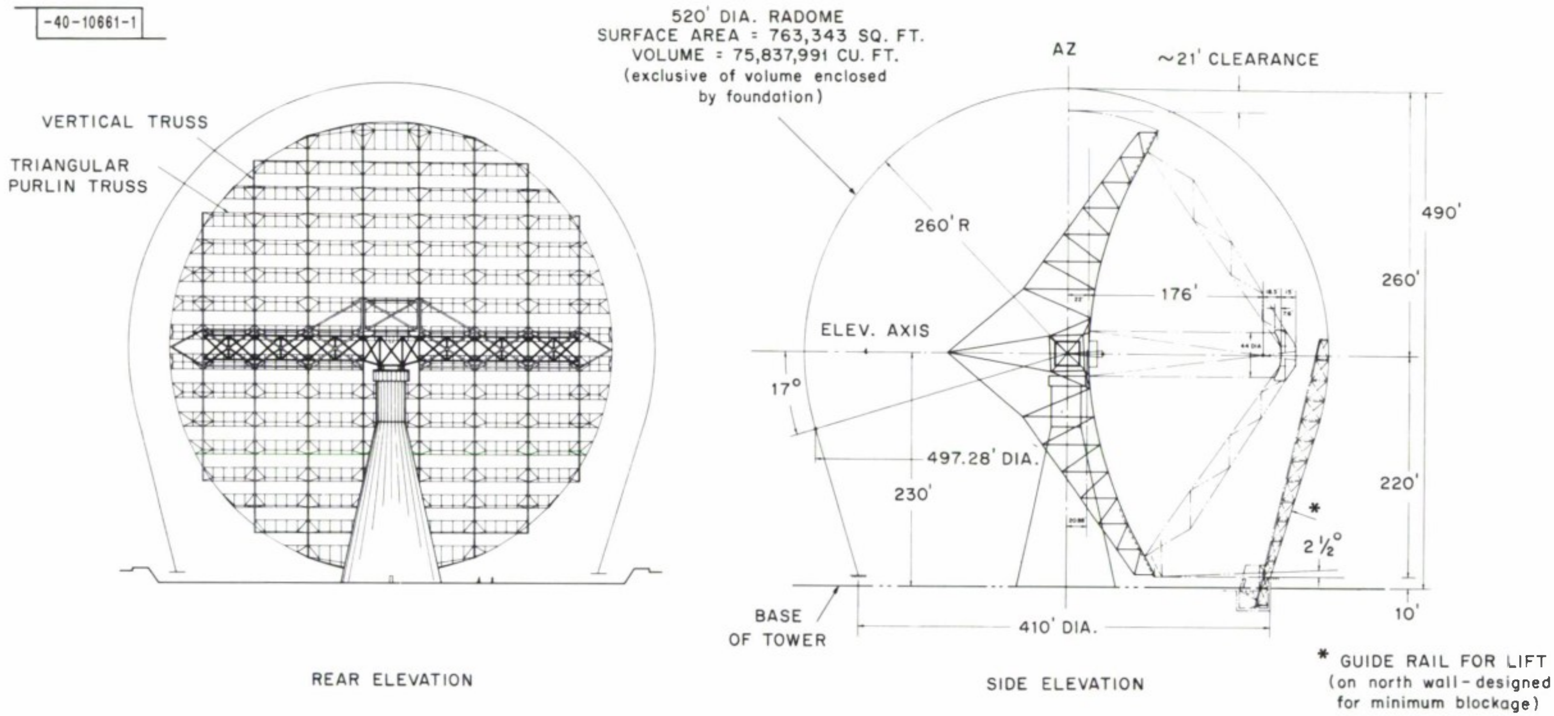

Fig. 3. NEROC vertical truss telescope.

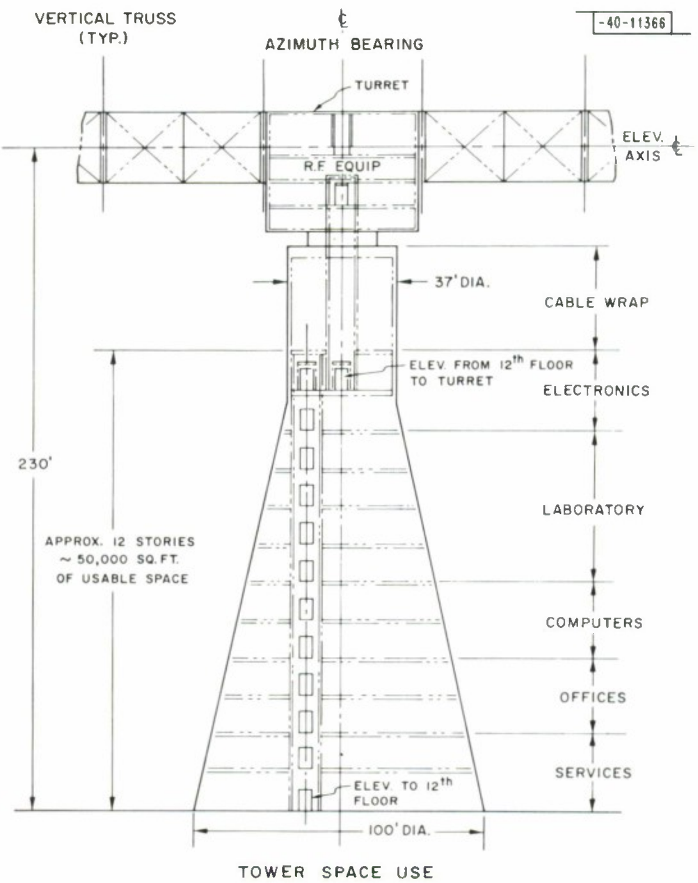

Fig. 4. Tentative tower configuration.

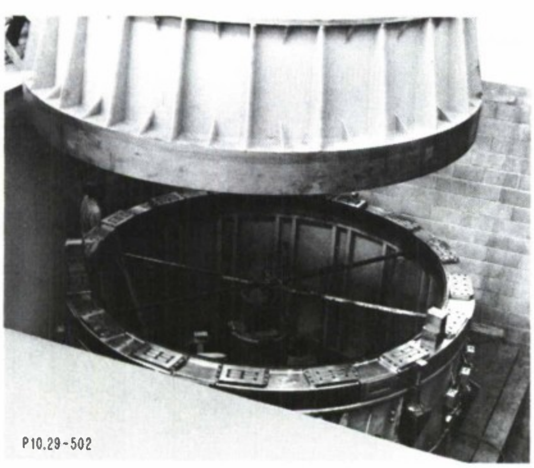

Fig. 5. Haystack hydrostatic bearing.

Preliminary studies showed that, because of the lightweight design, the weight on the azimuth axis would not exceed about 1000 tons, about 40 percent of the moving weight of the 210-foot Goldstone antenna and of the 140-foot Green Bank antenna. The weight could easily be carried on an azimuth bearing only about 30 feet in diameter. In addition, a small azimuth support system would allow the bearing to be located between the center set of vertical trusses. With this geometry, the inertia and cost of the azimuth support system would be very low compared to alternative configurations that used large-diameter bearing systems. The use of a tall, central tower to support the antenna provided a suitable enclosure for housing the control computer radar and other instrumentation. The general nature of this central tower is shown in Fig. 4.

The pointing precision requirement indicated that it would be advantageous to "float" the antenna on an oil-film hydrostatic bearing. The 14-foot-diameter Haystack hydrostatic bearing (Fig. 5) which supports a 120-foot radome-enclosed antenna has been very satisfactory and has contributed to the attainment of a very high pointing precision. The geometry of the antenna led to the use of only four hydrostatic pads, each with an area of about 20 square feet. A sketch of the bearing system now under study for NEROC by the Franklin Research Institute of Philadelphia is shown in Fig. 6.

Supported by the azimuth bearing system is a large, framed steel truss analogous in many ways to that used on the "Hammerhead" crane. This truss contains eight elevation bearings,

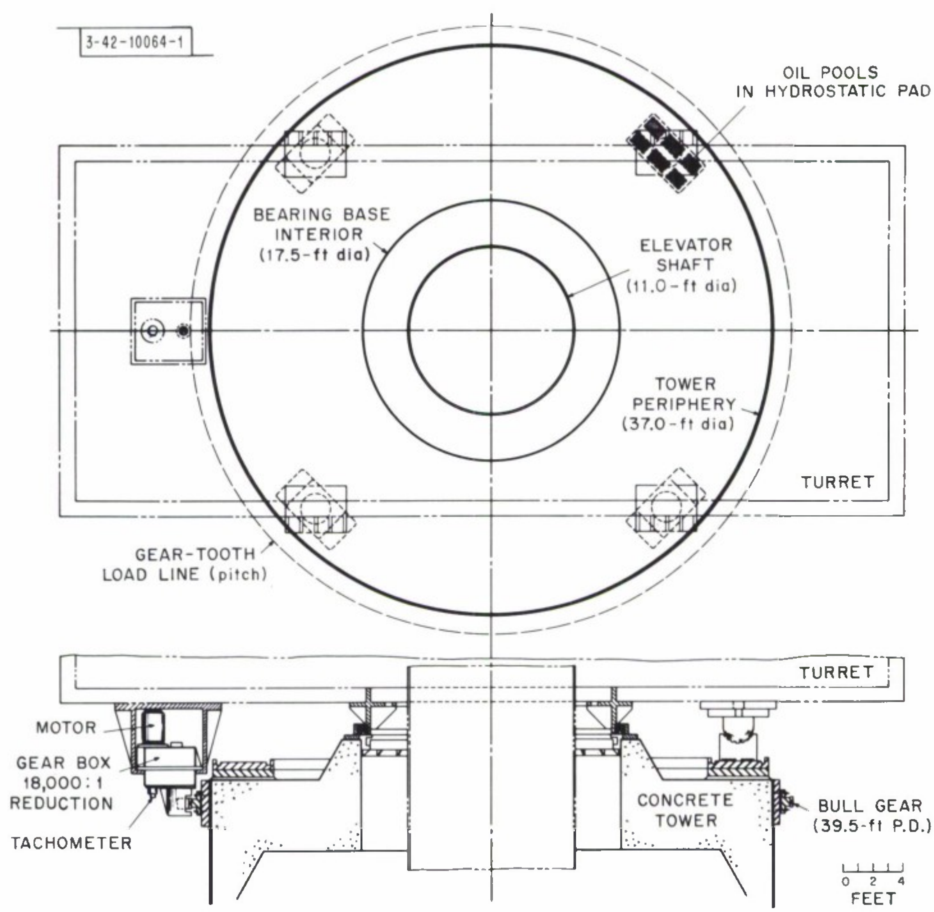

Fig. 6. Four-pad bearing system.

TABLE 5

TOLERANCE BUDGET (inches)

Primary Reflectar	Peak	Rms	Rms^2
Gravity			
Panels and purlin trusses	0.10	0.033	0.001089
Vertical truss	0.12	0.04	0.0016
Thermal			
Panels and purlin trusses	0.07	0.023	0.000529
Vertical trusses	0.08	0.027	0.00073
Geametry and Manufacture Panels	0.117	0.039	0.001525
Measurement and Rigging Panels	0.085	0.028	0.0008
Dynamic			
Vertical truss	0.03		
Tarque tube wrap-up	0.06		
Subtotal	0.09	0.03	0.0009
Jacks	0.09	0.03	0.0009
Hammerhead	0.072	0.024	0.000569
Total Primary Reflectar			0.008642

Rms errar af primary reflectar $\sqrt{0.008642} = 0.093$ inch.

Tatal rms errar af secandary reflectar $\sqrt{0.00094} = 0.031$ inch.

Tatal primary and secandary rms errar $\sqrt{0.008642 + 0.00094} = 0.0971$ inch.

one for each vertical truss. Surrounding the horizontal truss is a rotating torque tube which interconnects the eight vertical trusses.

The loads as seen by the Hammerhead truss are the same for different elevation angles of the antenna. This allows the elevation bearing axis to be adjusted only once during the final assembly stage. It has been possible to obtain 85° of elevation rotation without resorting to any design complications, and 90° of elevation travel could be achieved if it were essential.

The vertical trusses are spaced approximately 56 feet apart and are spanned by a series of lightweight purlin trusses, which in turn support the reflector panels. The base members of the purlin trusses are 14 feet apart and the trusses are also 14 feet apart.

The reflector surface consists of a thin (about 0.011 inch) perforated aluminum sheet, about 62 percent open, attached to a 14- × 14-foot lightweight but stiff doubly contoured frame. A grid of smaller framing members subdivides the large spans. To minimize construction fabrication and alignment problems, each of the 14- × 14-foot reflector panels, when viewed from the face of the aperture, will have the same projected rectangular shape. The reflector surface will deform if stepped on, but will support the weight of a person. By the careful selection of materials, it has been possible to keep the weight of a 14- × 14-foot section of the panel and its supporting framework to approximately 0.25 pound per square foot.

The vertical trusses have been extensively analyzed and optimized in a computer. By proper selection of geometry and member areas (homology) and with a single compensator in each of the eight upper and eight lower trusses, it has been possible to maintain an "invariant" parabolic contour to within the tolerance budget shown in Table 5. The compensation will probably be achieved by appropriate coupling of the counterweight to the truss structure.

VIII. ELECTROMAGNETIC CONSIDERATIONS

Because of the desire to operate the antenna over a wide spectral range (5 to 100 cm) with high efficiency, it has been decided to employ both prime-focus and Gregorian feed systems. The prime-focus feed system would operate at wavelengths between 100 and 21 cm, and the Gregorian system would be used between 21 and 3.2 cm. At the prime-focus position, an equipment room approximately 20 × 20 × 20 feet with a 4000-pound instrumentation capacity will be provided directly behind the Gregorian subreflector. The prime-focus feed will be withdrawn within the instrumentation room when it is not in use. Access to this equipment room will be achieved when the antenna is pointed toward the horizon by means of an elevated platform support from the radome.

For Gregorian operation, feeds will be mounted on the face of an equipment room which will extend approximately 10 feet forward of the vertex of the prime reflector. Figure 7 is one view of a typical feed configuration at the vertex of the antenna. A number of feeds could be located in this area and could be operated either concurrently or in sequence with appropriate corrections to the beam-pointing instructions. Figure 8 is a photograph of a model of the telescope which shows the feed elements.

The achievement of an over-all 0.1-inch rms tolerance in an antenna with over 150,000 square feet of surface area is, indeed, a rigorous requirement. The care that must be utilized in the design, manufacture, and erection of this large precision antenna will become very evident by a brief study of the allowable error budget in Table 5. Nevertheless, based upon the experience of the Haystack system, these goals appear achievable at low risk by utilizing a very

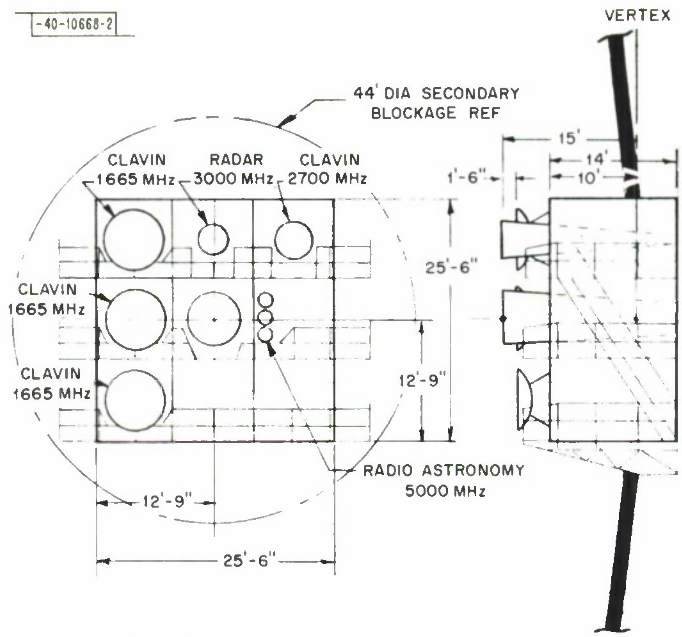

Fig. 7. Typicol vertex feed configurotion.

Fig. 8. Model of telescope showing feed elements.

simple but carefully evaluated design concept and by paying great attention to the quality control, the assembly of the system, and the environment within the radome.

Since contour errors due to tilting a reflector can now be made negligibly small, it is becoming increasingly evident that the precision in a large reflector will, in the limit, be determined by thermal environment. This is particularly true for an exposed antenna, but careful control of temperature changes and temperature gradients will also be needed if a radome is used. It is not feasible to build very-high-precision large antennas at low cost unless materials such as steel, aluminum, or fiberglass are used; and since these materials have thermal coefficient of expansion of about 1 part in 100,000/°F, precisions higher than about 1 part in 30,000 are difficult to maintain unless the structure is in a very stable thermal environment. Antennas with closed-loop feedback systems or which use the circulation of liquids throughout the structure to minimize the thermal effects become complex and costly.

IX. SELECTION OF 440-FOOT ANTENNA SIZE

After completion of a series of studies to evaluate the feasibility and cost of fully steerable reflectors in the 300- to 500-foot size range, there appeared to be sound, scientific arguments for choosing a size with an equivalent effective aperture of not less than 400 feet. Studies of the electromagnetic performance which might be achieved in large radomes (Table 6) indicated that the aperture blockage could be in the vicinity of 0.7 db and the noise temperature contribution of the radome would be about 5°K. To overcome these system losses, it appeared appropriate to increase the antenna diameter by approximately 10 percent to achieve a gain/temperature ratio equal to that of an ideal 400-foot telescope (Fig. 9).

X. RADOME STUDIES[4,5,7]

The over-all geometry of the radome to protect the 440-foot antenna is shown in Table 7. Although the exact design details are still under investigation, the tentative characteristics of the space frame and the membrane of the radome are shown in Fig. 10. The challenge in the design of a very large radome is to provide a structure that will survive under the environmental loads and at the same time have a minimum influence on the electromagnetic properties of the antenna. This requires a detailed understanding of the environment and the structural properties of these reticulated shells.

A number of three-dimensional linear and nonlinear mathematical studies have been undertaken to establish buckling criteria for large space-frame radomes. To check the validity of the calculations, a structural model of a 14-foot-diameter space-frame radome has been constructed (Fig. 11), and its performance has been measured under controlled load conditions. In addition, wind tunnel tests have been conducted to obtain pressure profile distributions around the radome under a variety of conditions.

One concept under investigation is to provide a pressurization system within the radome to minimize the likelihood of buckling under severe wind conditions. A pressure of approximately 0.25 pound per square inch can be achieved within the radome with only about 50-hp hours of energy. Studies are also under way to determine the most appropriate means for maintaining the proper thermal gradients within the radome as well as for preventing snow from forming on the top of the structure. While the exact design for this air circulation and heating system is still under study, it is expected that the eventual system will, in many respects, resemble that in use at Haystack.

TABLE 6 DESIGN GOALS FOR RADOME	
Aperture Blockage	0.7 db
Noise Temperature Contribution	5°K
Resolution	No change in beamwidth
Sidelobes	Not significant to −30-db level
Polarization Effects	Negligible
Pointing Errors	Less than 1/100 of a beamwidth

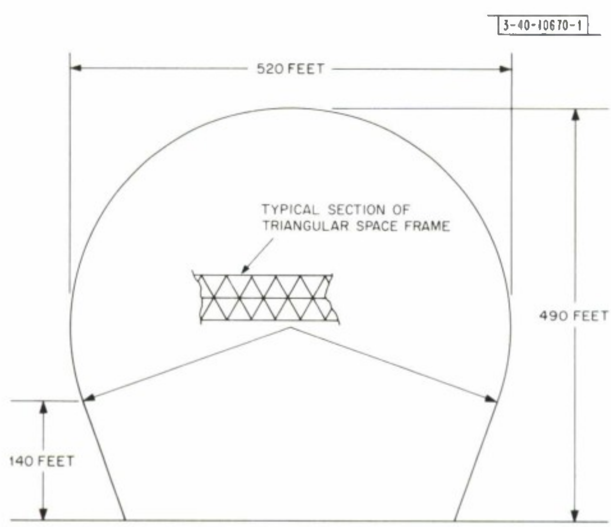

Fig. 9. Ratio of actual diameter to effective diameter of radome-enclosed antenna.

TABLE 7

CAMROC 520-FOOT-DIAMETER RADOME
(Tentotive Chorocteristics – Bosed Upon 150-mph Design Criterio)

Space Frame	
Beam Length (overoge)	30 feet
Beam Cross Section	3 X 14 inches
Material	Steel (60,000 psi, yield)
Tatol Length af Beoms	9 X 10^4 feet
Tatol Weight of Steel	2400 tons
Membrane	
Material	Fiberglass
Thickness	0.040 inch

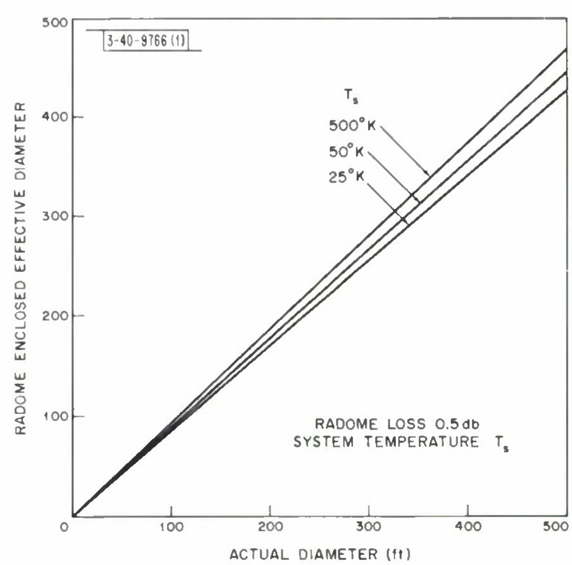

Fig. 10. Space-frome ond membrone chorocteristics.

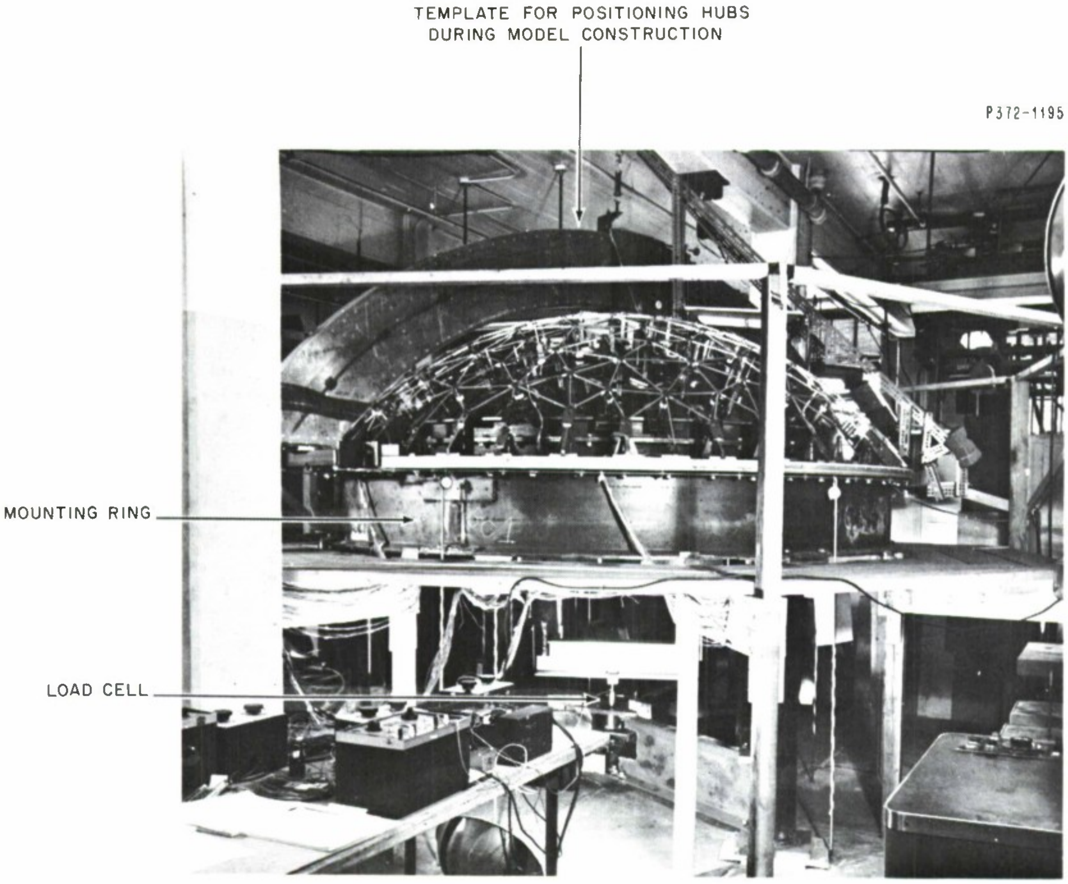

Fig. 11. Space-frame radome model. (Courtesy of Aeroelastic and Structures Research Laboratory, M.I.T.)

Based upon tests on a variety of possible dielectric panel materials, it is planned to employ pre-pregnated fiberglass panels approximately 0.040 inch thiek. These panels, which will be probably shipped to the site in rolls, will have metal edging strips bonded to the panels, and these edging strips in turn will be fastened into recessed grooves in the metal space frame. To obtain a strueture with the greatest eleetromagnetie transparency, the fiberglass panels will be used to stabilize in-plane buckling of the metal beams. Accelerated life tests on a variety of plastic materials have been started and, to date, the structural properties seem suitable for at least a 30-year life. Many other tests to evaluate the dieleetric properties, the absorption of moisture, and optieal eharaeteristies of radome materials have been completed.

A number of teehniques are under investigation for ereeting this large radome. It is evident that between 25 and 30 pereent of the total cost of the structure will result from the on-site erection eosts. In addition to the more obvious ereetion methods, one possible technique under investigation involves the assembly of the radome from the top down with sueeessive tiers being raised as the assembly proeeeds. This teehnique is attraetive because all the assembly work is aeeomplished within 30 feet of the ground, sinee the dielectrie panels would also be installed to stiffen the space frame as the assembly proceeds.

XI. COST STUDIES

The attainment of a realistic cost estimate for the CAMROC antenna and radome has been a pivotal part of the design studies. To obtain meaningful data, several analyses were conducted on a preliminary design by independent groups within both industry and Lincoln Laboratory.[7,15] These cost studies show that because of a large number of factors, all resulting more or less because a radome is used, the cost of the antenna alone is substantially below that which would be anticipated for a large, exposed antenna. Tables 8 and 9 indicate that the actual construction

TABLE 8

ANTENNA COST SUMMARY

	Dollars (millions)
Antenna (440 ft, 0.1-in. rms)	
Primary reflector	$2.35
Secondary dish	0.13
Reflector support structures	0.17
Laboratory space behind reflector	0.09
Tower foundation	0.43
Azimuth bearing	0.28
Azimuth drive	0.10
Elevation bearing	0.48
Elevation drive	0.14
Miscellaneous items	1.26
Construction total	5.43
Engineering	1.40
Engineering supervision	0.85
Contingency 25%	1.92
Total Antenna Cost	$9.60

TABLE 9

RADOME COST SUMMARY

	Dollars (millions)
Radome (520-ft dia.)	
Steel space frame	$2.20
Fiberglass	1.46
Foundation	0.30
Miscellaneous	0.50
Structure total	4.46
Air circulation and heating	1.00
Construction total	5.46
Engineering design	0.70
Engineering supervision	0.30
Contingency 25%	1.64
Total Radome Cost	$8.10

cost for the antenna should be about $5.5 million and that the total assignable cost including engineering and contingencies are estimated to total $9.6 million. The radome structure and the air heating and circulation system are also estimated to cost about $5.5 million with the total over-all radome cost of $8.1 million.

It is difficult to place these costs in perspective because 400-foot-diameter antennas with the desired surface tolerance and pointing precision do not now exist. However, an attempt has been made to compare these costs with the known cost of two relatively large and precise antennas which have been placed in operation during the past two years (Fig. 12). One of these antennas is the 150-foot National Research Council antenna at Algonquin Park, Ontario, Canada. Its cost of $3.5 million (which could probably not be duplicated at a competitive cost in the United States because much of the design and engineering was completed in England and Germany),

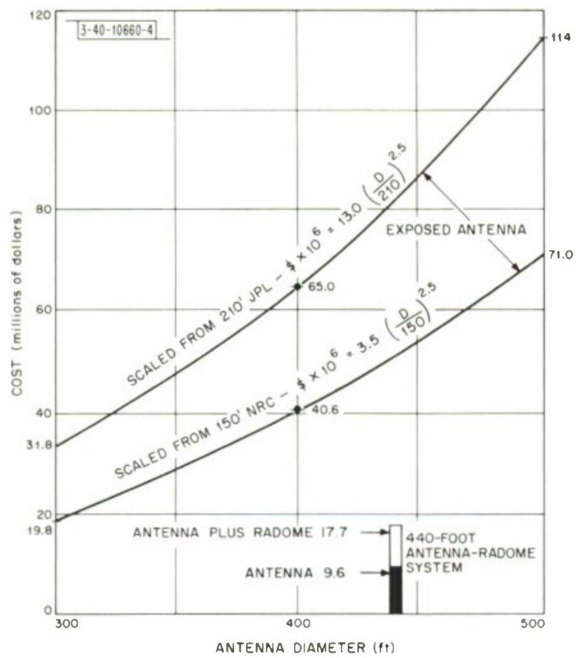

Fig. 12. Comparotive costs of lorge antennos.

TABLE 10 COST PER POUND OF RECENT ANTENNAS			
Antenno	Rototing Weight (tons)	Cost	Cost per Pound
150-ft NRC (1966)	900	$ 3,500,000	$ 1.95
210-ft JPL (1966)	2500	13,000,000	2.60
440-ft NEROC	1050	9,600,000	4.60 (in budget)

TABLE 11 COST PER SQUARE FOOT OF RECENT ANTENNAS			
Antenno	Aperture Areo (sq ft)	Cost	Cost per Squore Foot of Antenno Aperture
150-ft NRC (1966)	17,650	$ 3,500,000	$ 200
210-ft JPL (1966)	34,600	13,000,000	375
440-ft NEROC	152,000	17,700,000*	115 (in budget)

*Rodome cost of $ 8,100,000 included.

when scaled to 400 feet in accordance with a cost-vs-size relationship of $\$D^{2.5}$ is estimated to cost about $40 million. The other comparative example is scaled from the 210-foot JPL Goldstone antenna which probably provides a more appropriate basis for construction estimates in the United States. This same scaling law indicates that a 400-foot-diameter exposed telescope would cost about $65 million. While the validity of these cost-scaling relations is certainly open to considerable question, it is believed that there is still major significance in the approximate 3-to-1 cost spread between the radome-enclosed and the equivalent exposed telescopes. In addition, cost considerations notwithstanding, there appears little likelihood that it would be possible to achieve the desired surface tolerance and pointing precision with an antenna of any known design if it were exposed to typical environmental conditions.

An attempt has been made to compare the cost of the proposed design on the basis of cost per pound and cost per square foot using the NRC and JPL systems for comparison. This information is shown in Tables 10 and 11 and seems to indicate that the budgetary estimates generated by our studies are realistic in that we are allowing substantially more dollars for each pound of material in the structure. At the same time, the over-all cost per square foot of useful antenna aperture is significantly lower than has been achieved to date in large, steerable antenna systems.

XII. CONCLUSIONS

The studies that have been carried out during the past 18 months have outlined an attractive concept for a very-high-performance, steerable telescope. In addition, there now is a reasonable basis for predicting the performance and cost for this type of instrument. It is anticipated that one additional year of design and engineering effort will complete the planning and establish a firm design and more detailed cost information. The results to date also suggest that substantially larger steerable antennas can be constructed at a comparatively low cost per square foot, provided that radomes can be increased in size without degrading their electromagnetic performance.

ACKNOWLEDGMENTS

In this report, I am privileged to be the spokesman for a very large and competent team of scientists, engineers, industrial consultants, and design and manufacturing organizations who have participated and are continuing to participate in these studies. It is not possible to give proper credit to the approximately forty members of the Havard and M.I.T. family who are active in this program. It would be remiss, however, if specific mention were not made of the major contributions of Paul Stetson on the antenna configuration and of Richard D'Amato on the radome. Reference 7 includes a complete list of all the individuals and organizations who have participated in these design studies.

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DOCUMENT CONTROL DATA – R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M.I.T.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None

3. REPORT TITLE

Design Studies for 440-Foot-Diameter Radio and Radar Telescope

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Technical Report

5. AUTHOR(S) *(Last name, first name, initial)*

Weiss, Herbert G.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
20 February 1968	28	15

8a. CONTRACT OR GRANT NO. AF 19(628)-5167 b. PROJECT NO. 649L c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report 445 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TR-68-19

10. AVAILABILITY/LIMITATION NOTICES

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Air Force Systems Command, USAF

13. ABSTRACT

Studies conducted by the Cambridge Radio Observatory Committee during the past two years show that a large steerable telescope can be constructed at lower cost and with higher precision if the antenna is protected from the environment by a radome. These studies also indicate that the extremely high pointing precision (10 arc-sec) needed to make effective use of a large aperture at wavelengths as short as 5 cm can be obtained with a radome-protected antenna. The proposed 440-foot antenna employs a deflection-compensated vertical truss reflector support structure to maintain a 0.09-inch rms tolerance in the primary reflector under all operating conditions. The low cost of the antenna results from the ability to use lightweight reflector panels, an efficient computer-optimized reflector support structure, a small-diameter azimuth bearing, and a low-power control system. The estimated cost of this novel antenna design and the radome is substantially lower than the cost of alternative exposed antennas. The equivalent aperture and gain of the proposed antenna-radome system are made equal to that of a 400-foot antenna by increasing the antenna diameter by 10 percent. This report also describes the 520-foot-diameter space-frame radome and the planned electronic instrumentation and control facilities for a proposed radio and radar observatory.

14. KEY WORDS

radio telescope	radio astronomy	radomes	CAMROC
radar telescope	radar astronomy	Haystack	NEROC