A 25-METER TELESCOPE for MILLIMETER WAVELENGTHS

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VOLUME II

NATIONAL RADIO ASTRONOMY OBSERVATORY

A 25-METER TELESCOPE FOR MILLIMETER WAVELENGTHS:

VOLUME II

by

The 25-Meter Telescope Working Group

of the

National Radio Astronomy Observatory*

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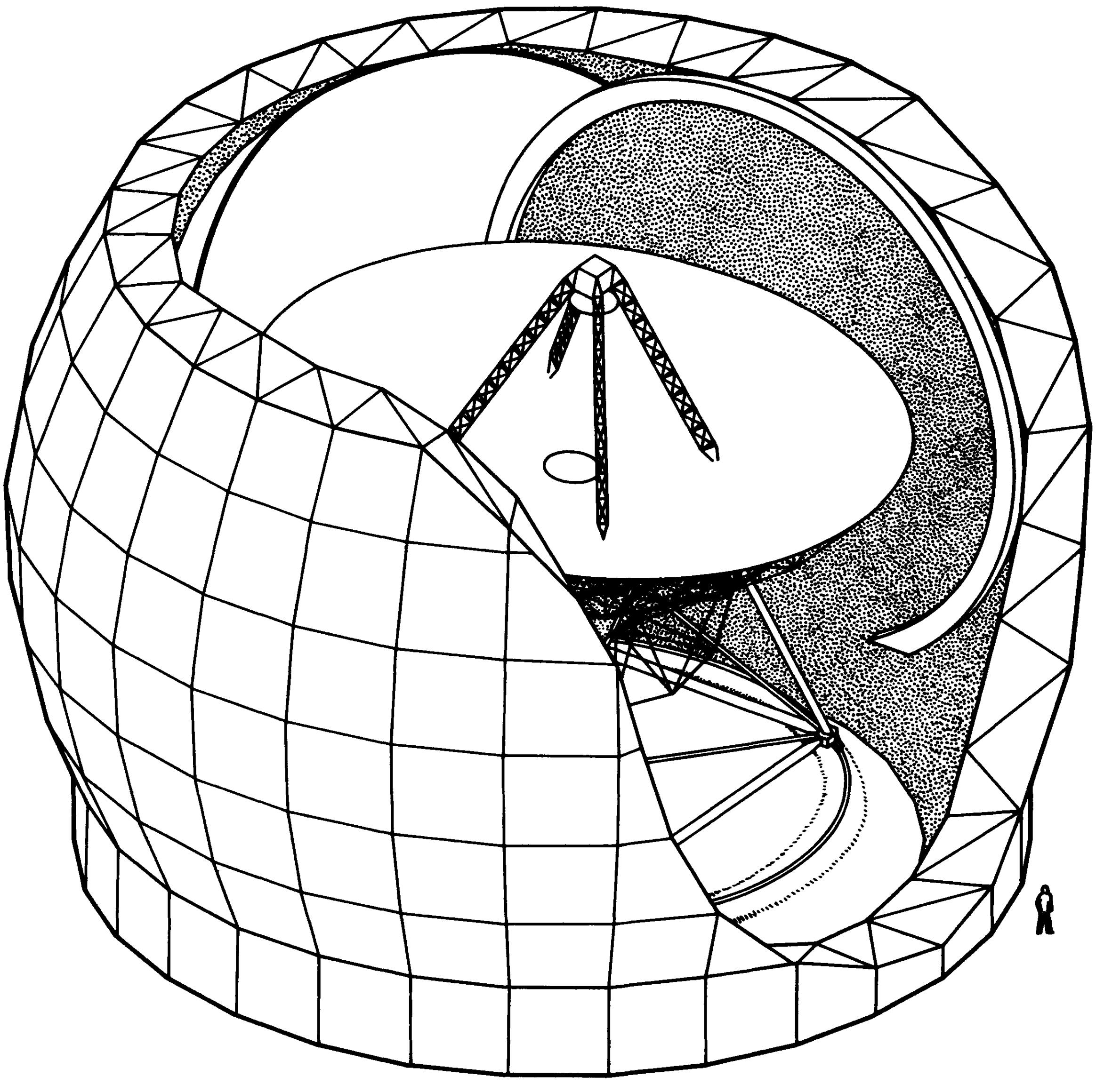

The 25-m telescope within the opened astrodome

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PREFACE

The work described in this volume involved a number of scientists and engineers at the National Radio Astronomy Observatory and elsewhere. The ad hoc Committee consisted of

A. Barrett	Massachusetts Institute of Technology
D. Buhl	National Aeronautics and Space Administration
B. Burke	Massachusetts Institute of Technology
E. Conklin	National Astronomy and Ionosphere Center
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In addition to this committee, we had the advice of an NRAO Internal Committee:

J. Findlay	H. Hvatum	G. Peery
M. Gordon	K. Kellermann	L. Rickard
D. Heeschen	H. Liszt	B. Turner
S. von Hoerner	F. Owen	C. Wade
D. Hogg		

The project was carried out on a day-to-day basis by a Working Group, consisting of:

J. Findlay	Surface Measurements and Panel Setting
M. Gordon	Chairman and Project Manager
S. von Hoerner	Panel Construction
H. Hvatum	Project Planning and PERT Scheduling
G. Peery	Engineering
B. Ulich	Electrical Performance
C. Wade	Site Evaluation
D. Webb	Cost Estimates

This group was augmented by two structural engineers of the NRAO;

L. King

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We also acknowledge the help of the Aeronutronics Division of Philco-Ford, the Electronics Space Systems Corporation, the French-German SAGMA cooperative effort, and the United Kingdom Millimeter Wave Astronomy Committee.

We are particularly indebted to B. Turner, who supervised the work described in Volume I of this proposal.

CHAPTER I

INTRODUCTION

The National Radio Astronomy Observatory proposes to build a radio telescope of diameter 25 m, having a surface accuracy of 75 μm to permit operation to a wavelength of 1.2 mm and shorter. The pointing accuracy will be 0.6 arc seconds. The telescope will be housed in a steel astrodome, the slit of which is closed by two movable segments of a radome. The instrument will be located on the summit of Mauna Kea, Hawaii, at an altitude of 4300 m and a latitude of 20° N. The cost of this instrument will be $12.5M, in 1976 dollars.

As a national center for research in radio astronomy, the NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation. It now operates radio telescopes in Green Bank in West Virginia, on the Plains of San Augustin in New Mexico, and on Kitt Peak in Arizona. These telescopes are open to any qualified astronomer or student, on the basis of the scientific excellence of their proposal. The 25-m telescope will be operated on the same basis. More than 60% of the observing time will be utilized by scientists from institutions other than the NRAO.

In recent years, scientific discoveries and electronic developments have enhanced the importance of the millimeter wavelength range, particularly at wavelengths shorter than 3 mm. For the NRAO 36-ft telescope at Kitt Peak, the number of proposals received each year, and the number of institutions using this telescope each year, have doubled over the last five years. A number of countries have begun projects to acquire their own millimeter-wave instruments. Within the United States, a few universities and research institutions have built telescopes operating in this wavelength range, both because of the intrinsic importance of millimeter-wave astronomy and because the 36-ft telescope is oversubscribed.

Although the 36-ft telescope continues to be in heavy demand, an increasing fraction of the important research proposals are being limited by the restrictions of angular resolution, sensitivity, and wavelength range which are characteristic of this telescope. It has a smaller collecting area than is needed and cannot operate well at wavelengths shorter than 2.4 mm. While recent advances in radiometer technology offer an improvement in sensitivity, the limitations on resolution and wavelength range can only be removed by the construction of a larger telescope with a more precise surface. Certain of the research areas, involving sources with high surface brightness and small-scale angular structure, will require a millimeter-wave interferometer. However, the wide range of astronomical problems discussed in the next chapter needs not only the higher angular resolution but also the sensitivity and frequency flexibility provided by a large filled aperture.

To meet this need, the National Radio Astronomy Observatory has designed a fully steerable, parabolic reflector having a diameter of 25 m and an ability to operate well to wavelengths of 1 mm and shorter. This telescope will provide not only greater collecting area in the wavelength range now accessible to the 36-ft but also good performance at much shorter wavelengths. We propose to build this instrument on a high-altitude, low-latitude site, Mauna Kea, so as to maximize its performance at the short wavelengths subject to atmospheric absorption, and to extend its coverage of the inner regions of our own galaxy.

This telescope will help develop the new subject of astrochemistry, investigate star formation on galactic and extragalactic scales in regions otherwise inaccessible because of optical extinction, and attack the fundamental problem of the structure and evolution of galaxies by measuring the amount and composition of their gas content. It will be a powerful instrument for investigating activity in the nuclei of galaxies and quasars by permitting continuum observations in the wavelength region between the traditional optical and radio domains. And, it can explore the atmospheres and surfaces of planets, satellites, and asteroids within our own solar system.

The telescope was first described in a formal proposal submitted to the National Science Foundation in September 1975. That proposal described the scientific need for, and the design and structural detail of, the 25-m telescope. Since then, further work has been done on the surface plates, on the enclosure, and on the site for the telescope. Volume II, this report, reviews material contained in the original proposal (Chapters II and III) and specifically describes the new work on the measurement and setting of the reflector surface (Chapter IV), on the choice of the protective enclosure (Chapter V), on the selection of the site (Chapter VI), and on the cost estimates based upon experience with the 36-ft telescope and with construction contracts for the summit of Mauna Kea in Hawaii (Chapter VII).

Every design goal has now been met by a specific concept, proven either by actual experiment or by computer analysis. The major steps in this project, from the site choice to the telescope design, have now been taken. The procurement and construction plans have been broken down and ordered by the management program PERT (Project Evaluation and Review Technique). The NRAO is now ready to proceed with construction of this telescope.

CHAPTER II

SCIENTIFIC USES OF THE 25-M TELESCOPE

A. OVERALL OBJECTIVES

There are two basic reasons underlying our choice of a 25-m millimeter-wave telescope. First, it is important to extend the wavelength range to shorter wavelengths, particularly to the atmospheric windows at 1.2 and 0.8 mm (see Table 1 and Figure 4), where the performance of existing telescopes is inadequate. Second, there is a need to improve the resolution and sensitivity in the spectral regions around 3 and 2 mm, in order to follow up the many exciting discoveries of the last decade. As will be shown in Chapter III, engineering considerations of these scientific objectives lead to a 25-m diameter having an rms surface accuracy of 75 μm.

Table 1. Atmospheric Windows in the Millimeter-Wave Domain

Center Wavelength (mm)	Center Frequency (GHz)	Width ($\Delta f/f$)
3.1	98	0.46
2.0	150	0.38
1.2	260	0.52
0.87	345	0.10
0.81	370	0.01
0.74	405	0.07
0.70	430	0.02
0.65	460	0.03
0.63	480	0.03
0.60	500	0.05

Millimeter line emission from molecules has provided astronomers with a new tool for the study of regions of gas and dust in the Milky Way and in external galaxies. Prior to 1963, when the first radio detection of an astronomical molecule occurred, only CN, CH, and CH^+ had been detected in the interstellar medium. Today, principally because of millimeter-wave astronomy, approximately 46 molecules have been reported, not including isotopically-substituted species. Table 3 shows a list compiled in May 1977 by L. E. Snyder.

Most molecules in the interstellar medium must form within dense clouds, although a few can be found in the atmospheres of cool stars. Within dark clouds gas densities are sufficiently great to permit efficient production by gas-phase reactions, to contain adequate numbers of interstellar grains for catalytic reactions on their surfaces, and to shield the newly formed molecules from dissociation by the ultraviolet light of the stellar radiation fields.

Because of the high densities intrinsic to dark clouds, cooling via molecular lines is effective and leads to typical kinetic temperatures of 100 K or less. These temperatures concentrate the molecules in ground vibrational and ground electronic states. Because of the physical dimensions of the molecules, the fundamental rotation transitions occur in the millimeter range of the electromagnetic spectrum. For heavy molecules, these transitions can occur in the 3.1-mm window. For lighter molecules such as hydrides, these transitions can lie in the shorter-wavelength windows.

The exploitation of molecular line radiation as a probe of the interstellar medium is only just beginning. The study of line profiles, particularly along with isotopic and additional transitions, provides a new way to investigate the astronomical environment in regions inaccessible to optical methods because of extinction. Unfortunately such progress is now slowing because of the limited surface accuracies and collecting areas of existing telescopes, and because of the limited atmospheric transmission over existing sites of millimeter-wave telescopes.

Table 2. Molecules Reported in the Interstellar Medium as of May 1977

Complexity	Inorganic	Organic
Diatomic	H_2-hydrogen (UV) OH-hydroxyl radical SiO-silicon monoxide NS-nitrogen sulfide SO-sulfur monoxide SiS-silicon monosulfide	CH-methyladyne radical CH^+-methyladyne ion (optical) CN-cyanogen radical CO-carbon monoxide CS-carbon monosulfide
Triatomic	H_2O-water N_2H^+-protonated nitrogen H_2S-hydrogen sulfide SO_2-sulfur dioxide	CCH-ethynyl radical HCN-hydrogen cyanide HNC-hydrogen isocyanide HCO^+-formyl ion HCO-formyl radical OCS-carbonyl sulfide
Quadratomic	NH_3-ammonia	H_2CO-formaldehyde HNCO-isocyanic acid H_2CS-thioformaldehyde HC_2H-acetylene (IR) C_3N-cyanoethynyl radical
Quintatomic		H_2CNH-methanimine H_2NCN-cyanamide HCOOH-formic acid HC_3N-cyanoacetylene H_2C_2O-ketene
Sexatomic		CH_3OH-methyl alcohol CH_3CN-methyl cyanide $HCONH_2$-formamide
Septatomic		CH_3NH_2-methylamine CH_3C_2H-methylacetylene $HCOCH_3$-acetaldehyde H_2CCHCN-vinyl cyanide HC_5N-cyanodiacetylene
Octatomic		$HCOOCH_3$-methyl formate
Nonatomic		$(CH_3)_2O$-dimethyl ether CH_3CH_2OH-ethyl alcohol HC_7N-cyanotriacetylene CH_3CH_2CN-ethyl cyanide

An important aspect of millimeter-wave astronomy is its ability to investigate the structure of our Galaxy and of its nucleus. Line emission from molecules allows us to probe not only the cold gas but also the dust regions which produce the well-known optical extinction. The low-latitude site of Mauna Kea will permit observations of the entire galactic plane. In addition, the region of the galactic center will transit at an elevation of 41°, enabling a longer observing period each day in comparison with higher latitude sites. Thus the combination of the low latitude and the small atmospheric extinction characteristic of a high-altitude site will make the 25-m telescope better suited to the investigation of the Galaxy than any other instrument either proposed or in operation.

Finally, the 25-m telescope as a continuum instrument will enable observations in the wavelength range between traditional radio and infrared astronomy, effectively doubling the frequency range that is now available to radio astronomy. Measurements at 1 mm of such diverse objects as radio stars, ionized hydrogen regions, and compact extragalactic sources will be possible.

B. SPECIFIC TOPICS

The 25-m telescope will be able to address a wide range of major scientific problems. While the majority of these topics involve galactic and extragalactic research, some topics are associated with our solar system. We list below a number of specific areas, working outward from the sun.

1. The Sun. At millimeter wavelengths, solar photons come from the chromosphere, the transition region between the $2x10^6$ K corona and the 5000 K photosphere that is not well understood and is difficult to observe optically. By using different wavelengths in the millimeter regime, astronomers will be able to investigate the vertical structure of the chromosphere by means of limb-darkening (or limb-brightening)

observations. Because of transient phenomena, these measurements must be repeated many times to deduce the behavior of the quiet sun--a measurement technique not possible with solar eclipses.

Active regions such as sunspots, flares, and plages also are part of this transition region. Not only can the structure of these regions be mapped in different wavelengths and correspondingly at different densities, but observations in opposite circular polarizations will give magnetic field strengths and, perhaps, the theoretically predicted spatial displacement between the polarized emissions.

2. Moon. At the distance of the moon, the telescope beam will subtend linear distances of 180 km at 9.5 mm and 15 km at 0.8 mm. Measurements of thermal emission through a lunation will place further constraints on models of lunar soil. The combination of millimeter-wave data and infrared and radar data can be used to refine surface models.

3. Planets and Satellites. Although most of the planets and their satellites will not be resolvable with the 25-m telescope, it will be possible to measure their fluxes at millimeter wavelengths with signal-to-noise ratios greatly improved over existing measurements. All of the major planets will be observable (including Pluto at the shorter wavelengths), as will the Galilean satellites of Jupiter, four of Saturn's satellites, and the two dozen largest asteroids. Observations of Mercury, Venus, and Mars over a wide range of phase angles will be important for atmospheric and surface models. Data on the variations of disk temperatures with phase are at present sparse for Mercury, unreliable for Venus, and non-existent for Mars at useful sensitivity. For Venus and to a lesser extent for Mercury, the 25-m telescope will resolve the planet.

At the shorter wavelengths, the rings of Saturn can be resolved from the main body of the planet, and they should produce a measurable signal which will help in solving the problem of the size and nature of the particles which compose them. It will be possible to observe the variation of the thermal radiation of the Galilean satellites as they center and leave eclipse; in fact, it will be possible to follow Ganymede and Callisto from ingress to egress with a good signal-to-noise ratio and without serious contamination by the radiation of Jupiter itself. This will provide an excellent delineation of the thermal properties of their surfaces. Some useful data on temperature differences between polar and equatorial regions of Jupiter will be obtainable, for depths into the atmosphere not achieved by other types of observation.

At this time rotational lines of CO have been detected at millimeter wavelengths in the atmosphere of Earth, Venus, and Mars. Observations of line shapes of atmospheric molecular emission provide a new means of exploring pressure, temperature, and kinematic characteristics of planetary atmospheres. With the great sensitivity of the 25-m telescope, it should be possible to observe such molecules as OCS, HCN, OH, CS, and SO.

4. Comets. Millimeter-wave studies should teach us much about comets as well. The line shapes and center frequencies will contribute additional information regarding the comet velocity and internal kinematic conditions. Continuum emission should be observable from the cometary core which contains a high density of electrons, and from at least the inner parts of dust clouds now known to surround comets. Physical differences between "dusty" and "icy" comets may be elucidated.

Cometary material is presolar. Unlike that contained in meteorites, it has not been subjected to the intense heat generated in passing through the earth's atmosphere. Study of the constituents by radio techniques may help in refining theories of the formation of the solar system.

5. Stars. Recent millimeter-wave observations have shown the association of molecules with cool and variable stars. For example, Mira variables are often found to be sources of molecular masers, the line profiles of which vary in shape and intensity with the phase of the light

curve. Not only should the extended wavelength range of the 25-m telescope permit many other rotational transitions which are masering to be observed, but the smaller beam will produce stronger signals than those now seen with the 36-ft telescope because of the angular beam-filling factor. The line profiles should be useful in understanding the velocity fields in the atmospheres as the gas periodically expands away from and falls into the stellar photosphere. Objects such as red giants and the somewhat more evolved "Transition Objects", described below, are important participants in the interchange of material between stars and interstellar medium. The chemical evolution of our galaxy may be determined by such mass transfers.

Electron densities and temperatures of many of these stars should produce turnover frequencies in the millimeter portion of the spectrum. Together with centimeter-wave observations made with the VLA, the characteristics of the ionized component of the atmospheres can be observed, not only in variable stars but in nonvariables with extended envelopes.

6. Transition Objects. Infrared observations have detected many cool stellar-like objects in the interstellar medium. Some, such as the Kleinmann-Low nebula, may be examples of protostars. Others, such as IRC 10216, and the "Egg Nebula" in Cygnus may be objects midway between a red giant star and a planetary nebula. Studies of these objects promise to help us understand the chemical composition of planetary nebulae and the physical mechanisms responsible for their gas ejection. Both phases of stellar evolution are poorly understood, principally because of the difficulties of observing these transition objects with optical telescopes. To understand the complete evolution of stars, it is essential to make actual observations of birth and death. At the moment this is best done in the infrared and, particularly, in the millimeter-wave regime, where both spectroscopic and continuum measurements can be made.

As an example of the interplay between chemistry and kinematics, we cite the molecular emission of the extended envelopes of the carbon stars IRC 10216 and CIT-6. Here the millimeter-wave line profiles have provided detailed information on the mechanisms of gas and dust ejection from the stellar surfaces into the surrounding interstellar medium. The molecular observations seem to confirm many ideas of the chemistry in a carbon-rich environment which were first explored nearly forty years ago. The 25-m telescope will resolve the extended envelopes, permitting better interpretation of several shells detected at near-infrared wavelengths. Thus, the combination of molecular line observations of older envelopes and continuum observations of the younger (a few hundred years) envelopes may enable us to reconstruct the thermal history of these stars over a span of some tens of thousands of years.

Also included in this category are novae. Models predict the physical characteristics of the blown-off atmosphere. Observations of the flux emitted in the millimeter range, combined with those of the radio and optical range, are necessary to refine these models.

7. Radio Stars. Continuum radio emission from a number of galactic stars has recently been found at centimeter wavelengths. In most cases, the radio emission is strongly and rapidly variable, and the signal strength is highest at the shortest wavelengths. This behavior has been observed in a number of X-ray sources (e.g., Sco X-1 and Cyg X-3) and in seemingly normal binary stars (e.g., Algol). Data at millimeter wavelengths are needed in order to find the frequencies where the radio bursts are strongest, and to follow the spectral and intensity evolution of the bursts in sufficient detail to guide theoretical interpretation.

8. HII Regions. The available radio and infrared data clearly show HII regions to be mixtures of both hot and cold components. The hot component is usually detected by the existence of emission lines of ionized atoms in the optical regime and by the spectrum of the bremsstrahlung of the ionized gas. The cold component manifests itself in the extreme infrared, where detected flux levels are characteristic of those expected of dust grains of approximately 100 K. Because no instrument is now

available to measure the long wavelength side of their Planck emission, it is difficult to measure grain densities, and to determine how the emissivity varies with wavelength. The 25-m telescope will be able to make these observations, thereby permitting new investigations of the heat and radiation transfer between grains and gas of the interstellar medium in the vicinities of early-type stars. This information should substantially help explore the long-standing problems of grain sizes and composition, and, by extension, to the problem of molecule formation, since it is likely that certain molecules are formed in catalytic reactions on the surface of grains.

Observations of hydrogen recombination lines at the very short wavelengths accessible to the 25-m telescope will help in the discovery of relatively cooler and denser condensations in HII regions. The cooler or denser the ionized gas, the higher the frequency where the recombination line-to-continuum intensity ratio reaches its maximum. Observations at wavelengths longer than 2 cm are sensitive to temperatures around 10,000 K and densities of the order of 3000 cm^{-3}. Recent observations at 3 mm have detected small knots which are cooler ($\sim$7000 K) and denser ($\sim$30,000 cm^{-3}). At 1 mm, knots as small as 0.001 parsec, with temperatures of 5000 K and densities of 10^6 cm^{-3}, will become observable. These may in fact be stars in the very earliest self-luminous stages, or possibly early-type stars still imbedded in a dense molecular cloud. These observations might reveal the effects of still-infalling material on the ionized region around a newly born star.

9. <u>Dark Clouds</u>. The formation of stars in the galactic disk is associated with dark clouds. Only there do the large densities exist within the interstellar gas over the scale lengths required for self-gravitation to begin (Jeans Length). Because of the great opacity of these clouds, optical photons cannot escape nor can ultraviolet photons produced by embedded stars contribute enough ionization to be easily detected in the traditional radio regime. While infrared technology has begun to permit the detection of lines, it is primarily in the millimeter-

wave region that spectral lines from dark clouds can be detected easily; only with these spectral profiles can astronomers deduce temperatures, densities, and velocity fields in these star-forming regions.

10. Astrochemistry. With the detection of a large variety of molecules (see Table 2), it is possible to investigate chemical reactions within the interstellar medium. Several molecules not yet found in the terrestrial environment have already been detected, including C_2H and C_3N. Several others, including N_2H^+, HCO^+, HNC, and HC_5N, have only recently been isolated terrestrially. A number of chemists have already been attracted to this new branch of astronomy; their contribution together with the observational results should greatly help in our understanding of the interstellar medium as well as of the chemistry itself.

The improved resolution of the 25-m telescope will almost certainly lead to the detection of new molecules in small dense regions of interstellar clouds. If these regions are at high temperatures (as in the vicinity of protostellar objects such as the Kleinmann-Low nebula), then we may expect to detect many refractory species as they are volatized from the surface of dust grains. Such species as PN, MgO, FeO, HCP, and SiC all require high temperatures to exist in the gas phase; their laboratory spectra are only approximately known, and the detection in interstellar space will provide accurate and useful spectroscopic data. The hot, small core may also be a detectable source of emission from excited vibrational states in a variety of molecules. If, on the other hand, the dense regions are at low temperatures, very complex species may appear if catalytic reactions on grain surfaces are important. Examples of such molecules are propynal ($HCOC_2H$), heavy alcohols (propyl and higher), alkanes, and aromatic rings.

To understand the chemistry of interstellar clouds, spatial distributions of such molecules as CN, N_2H^+, HCO^+, HCN, and HNC must be observed with high angular resolution to obtain better estimates of their relative abundances as a function of depth in the cloud. The 25-m telescope can provide that angular resolution. It has already been deduced theoretically, for example, that C^+, which is important in current theories of molecular formation, shows a sharp decrease in abundance with increasing depth in the clouds. High resolution observations are also necessary to find if a correlation exists between molecular abundances and sources of ultraviolet radiation, since such radiation may prevent molecules from freezing out on cold dust grains. A correlation in position should also be sought for molecular abundance and infrared sources. In summary, ion-molecule and grain catalytic reactions will be much better understood when the distributions of molecules are more clearly delineated.

Other sites where molecule formation might occur include the edges of expanding supernova remnants and the bright rims and "elephant-trunk" structures near ionized hydrogen regions. Here again high angular resolution, as provided by the 25-m telescope, is required to isolate and identify the shock regions.

The chemical considerations discussed so far depend more on the higher angular resolution of the 25-m telescope than on its higher limiting frequency. This telescope will operate well at wavelengths shorter than its specification design of 1.2 mm. For example, its maximum gain occurs at 0.9 mm. The ability to observe at wavelengths of 1 mm and less will bring a whole new class of molecules into radio astronomy, those with only one heavy atom. It will then be possible to observe many of the less dense components of the interstellar medium. Until now, molecules with only one heavy atom generally have been accessible only to optical and ultraviolet observations, which in turn are limited to the local region and to highly rarefied clouds, and can be made only in the direction of hot stars. But, because of the small moments of inertia, many of the rotational transitions of these molecules can be observed through atmospheric windows shortward of 1 mm. Table 3 lists some of the transitions corresponding to wavelengths where the atmosphere attenuation at zenith, at a good 4300-m site such as Mauna Kea, is acceptable.

Table 3. Some Molecules with Fundamental Transitions between 0.6 and 1.3 mm

Molecule	Ground State	Wavelength Number (cm^{-3})	Wavelength (mm)
SiH^+	$^1\Sigma^+$	15.111	0.662
LiH	$^1\Sigma^+$	14.8166	0.675
$A\ell H^+$	$^2\Sigma$	13.128	0.762
NH^+	$^2\pi_r$	13.02	0.768
MgH^+	$^1\Sigma^+$	12.6192	0.792
$A\ell H$	$^1\Sigma^+$	12.5956	0.794
PH_2	$^2B_1$	12.312	0.812
H_2D^+	?	11.488	0.870
MgH	$^2\Sigma^+$	11.4692	0.872
NaH	$^1\Sigma^+$	9.667	1.034
CH_3	$^2A_2''$	(9.57)	(1.045)
CaH	$^2\Sigma$	8.4593	1.182
PH_3	$^1A_1$	8.382	1.193
CH_2	$^2\Sigma_g^-$	(7.8)	(1.282)

Many of these molecules are believed to occur in observable quantities in clouds of only moderate density (100-300 H atoms cm^{-3}). Because line strength increases strongly with increasing frequency, the light highly-reactive species listed in the table will be detectable if the column density is no more than 10^{12} molecules per cm^2. This is comparable with the optically determined abundances of CH and CH^+. The importance of the study of molecules in such rarefied clouds lies in the fact that only a limited number of reactions can occur at low densities. If we can understand this precursor phase of interstellar chemical evolution, we will be better able to follow the more complex reactions that occur as clouds contract and become denser.

Because of the high spectral resolution of radio measurements, observations of light species will provide a reliable standard for comparison with optical data. In particular, accurate radio measurements of doppler line widths will aid the interpretation of many highly saturated ions (e.g., C^+) observed in the ultraviolet. The strengths of MgH and AℓH relative to those of their ions will be sensitive indicators of the ultraviolet and optical fluxes reaching the interiors of medium or dense clouds.

11. Isotopic Studies. Information about the relative abundance of atomic isotopes historically came from direct measurements on the earth and from optical spectroscopy of the Sun and nearby stars. Yet, the isotopic abundances are determined primarily by the processing of nuclear material in stars, the isotope formation rate of which should therefore vary substantially over the Galaxy. To understand the evolution of our galaxy (and of others), we should investigate the variation of isotopic ratios over the whole of the Galaxy. Only with radio observations can one observe the entire Galaxy. Because of the relatively small opacity of the rotational transitions, molecules can be investigated in regions well beyond the optical limit of a couple of kiloparsecs in the Galactic plane. Because the isotopes can only be observed--on a galactic scale--in molecular compounds, it is necessary to observe a large number of molecules in order to determine actual abundances in the presence of complicated formation and excitation mechanisms. The great sensitivity of the 25-m telescope, together with the higher rotational transitions which can be observed at short wavelengths, should be of great help in this area of research.

12. Excitation Mechanisms. Detailed study of the processes responsible for the formation of a molecular line requires that at least two transitions be observed. Current efforts in this direction are

hampered seriously by low angular resolution. To minimize assumptions about the brightness temperature distributions, one must compare all lines of a given species at equal resolution, which necessarily is the resolution at the longest wavelength in the set. For CS, with lines at 50, 100 and 150 GHz, excitation studies are now based on a resolution of about 3 arc minutes, which is about half the total angular resolution applied to the higher-lying transitions. Increased resolving power will keep our understanding of physical conditions and excitation mechanisms in molecular clouds, as well as greatly improve estimates of molecular abundances.

13. Galactic Structure and Evolution. Photographs of spiral galaxies show the structure to be most visible in the distribution of the extreme Population I material (occasionally called Population 0). This material contains a large number of dark clouds from which the young stars and HII regions form, and from which molecular lines are emitted in the millimeter portion of the spectrum. The investigation of the large scale dynamics of our Galaxy may best be done through certain molecular lines, because of the limitations of the optical extinction and of the overly broad and confused distribution of the 21-cm line of atomic hydrogen. The 25-meter telescope at Mauna Kea will be the premier instrument for this work, because it alone will be able to view the entire Milky Way.

To date investigations made with the CO molecule show that most of the interstellar gas within 8 kpc of the nucleus is in molecular form. The picture of our Galaxy derived from older observations of atomic hydrogen, which is much less confined to the inner Galaxy, has been substantially revised. Additional studies with higher angular resolution may also show us the detailed structure of our spiral arms, and aid in the understanding of the dynamics of the Galaxy.

The central regions of many galaxies, including our own, show signs of eruptive activity. The energies involved are large, as are the fluxes of disrupted material. Although the mechanisms resulting in this activity are unknown, it is clear that an understanding of the activity in the nucleus is crucial to an understanding of the evolution of the entire Galaxy. The high angular resolution of the 25-m telescope, combined with the low latitude of the Mauna Kea site, will provide a unique instrument for detailed studies of the kinematic structure and composition of the nucleus of our own Galaxy.

14. The Gas Content of Galaxies. One particularly promising field for the 25-m telescope is the study of molecular line emission from other galaxies. The presently studied objects show extended sources ($\gtrsim 3'$) that represent the integrated emission of many clouds, each individually unresolved ($\lesssim 3''$). The 25-m telescope would thus provide both finer resolution for nearby galaxies (for CO $J=1\rightarrow 0$, it would be comparable to the Westerbork 21-cm synthesis maps) and increased sensitivity to the individual clouds (thus increasing the distance range over which galaxies can be detected). In addition to revealing the structure and kinematics of the total gas content (molecular plus atomic) of nearby galaxies, it would also enable studies relevant to Galactic work; e.g., tests of the degree of confinement of CO to narrow spiral patterns.

Attendant upon such extragalactic molecular work is the very exciting prospect of using observations of isotopically-substituted species to determine isotope abundances within galaxies. For example, from the variation of $[^{13}C]/[^{12}C]$ across a galaxy, one can infer relative values of the astration rate (the rate at which material is processed through stars). The determination of these astration rates within individual galaxies, and of their variations from galaxy to galaxy, is a powerful tool for investigation of the formation and evolution of galaxies.

15. Active Regions of Galaxies. Explosions occurring in several types of extragalactic objects evidently produce rapidly expanding clouds of relativistic particles. The radio properties of these sources at wavelengths of a few centimeters and more are now quite well known,

although theoretical understanding remains rudimentary at best. To date, accurate millimeter-wave observations have been obtained only for the strongest sources, and only at one or two wavelengths, owing to the sensitivity limitations of existing instruments. With infrared data now becoming available at wavelengths as long as 350 μm, the filling of the millimeter wave gap by the 25-m telescope will complete the coverage of the spectrum from X-rays and the far ultraviolet down to meter wavelengths, a range of about nine decades in frequency. The millimeter-wave data will be of particular value in the understanding of the radio emission of galaxies in general, since it is in this wavelength range and the far infrared that accurate data will most severely test the theoretical models.

The radiation at millimeter wavelengths comes mainly from dense, compact (angular diameters $\lesssim$ 1 arc second) regions. They are associated with QSO's and the nuclei of radio galaxies, as well as with normal spiral and elliptical galaxies. Their radio spectra at centimeter wavelengths are often complex, and they often are dramatically variable on a time scale as short as weeks. The variations are sharpest at the shortest wavelengths. Enhanced infrared radiation from these objects is fairly common. It is clear that processes are acting in which there is a rapid release of very large amounts of energy, although their nature is little understood. The variations frequently do not fit current theoretical models, and the sources which also vary at optical wavelengths generally show no correlation between the radio and optical fluctuations. Progress in understanding these energetic objects requires the constraints which will be imposed by accurate millimeter-wave data for a large number of them.

The sources which show excess emission at millimeter wavelengths are so small that they are self-absorbed at centimeter and longer wavelengths. The 25-m antenna, when used for VLBI, together with other millimeter wavelength radio telescopes throughout the world will have a resolution $\sim$ 50 micro arc seconds, sufficient to resolve the small millimeter wavelength components. The large collecting area and sensitive radiometers will be important in millimeter wavelength VLBI since the coherence time is necessarily limited by atmospheric instabilities.

For continuum observations, the 25-m telescope should be useful at wavelengths considerably shorter than the design limit. The maximum gain of the telescope occurs at 0.9 mm, where the telescope is diffraction-limited. Unlike many existing telescopes, the pointing and back structure integrity can support useful operation in the incoherent mode, as Chapter IV will show. Incoherent detectors will be well-suited to this wavelength range, and effective continuum observations should be quantitatively reliable at sub-millimeter wavelengths.

CHAPTER III

THE DESIGN AND PERFORMANCE OF THE TELESCOPE

The specifications of the telescope contained in the formal proposal--a diameter of 25-m, and an rms surface accuracy of 75 μm--have not been changed. This chapter will review the considerations which led to these specifications. In addition, the chapter summarizes the extensive description of the mechanical design of the telescope which was presented in the earlier report.

A. NATURAL LIMITATIONS

Figure 1 shows qualitatively the atmospheric transparency over 12 decades of wavelength for a ground-based observatory. Millimeter-astronomy covers the nominal range of 10 mm to 0.8 mm, principally by using the atmospheric "windows" through the absorption by telluric molecules. Together with infrared astronomy, it provides a bridge between optical and radio astronomy.

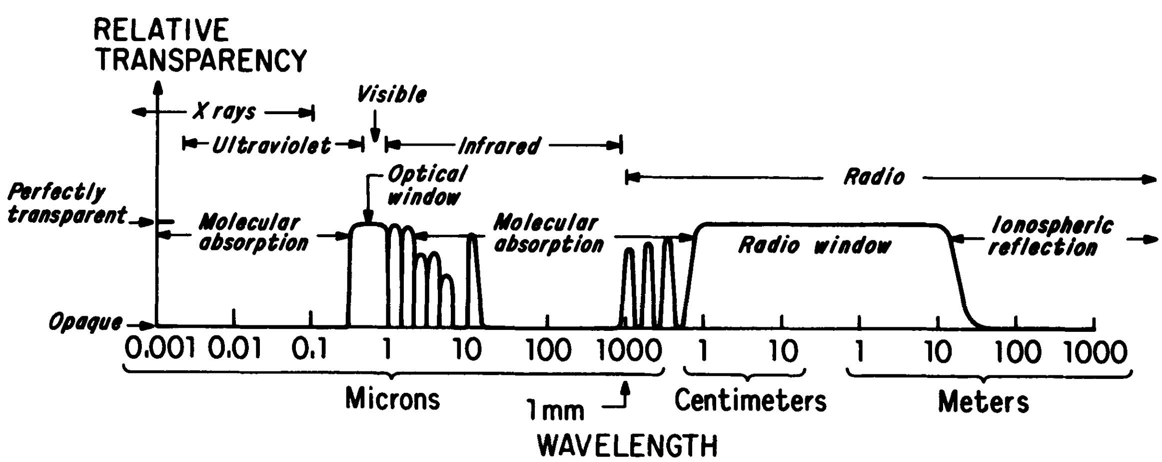

Figure 1. The qualitative transmission of the earth's atmosphere (after Kraus, 1966).

Apart from the noise contributions of the receiving systems, the radio astronomer must contend with noise contributed by the environment. If an antenna can be built with sufficient directivity to avoid the background radiation from the earth, then all of the background brightness at wavelengths shorter than 10 m is contributed by our galaxy, the microwave background, and the terrestrial atmosphere. Figure 2 gives their relative contributions and shows how the atmospheric effects become substantial in the millimeter-wavelength range, because of telluric oxygen and water vapor.

While the background radiation in the millimeter range can be minimized somewhat by a careful choice of the telescope site, the earth-based astronomer has to concentrate his observations in a number of specific atmospheric "windows", located between the oxygen and water absorption features. (See also Figure 4.)

The transmission and, to some extent, the width of these windows depends upon the site altitude and the amount of water vapor above that site. For the astronomer, these windows become increasingly important as he observes sources well away from the zenith; for example, radiation from a source at elevation 20° must traverse approximately 3 times as much atmosphere as for a source at the zenith. And, of course, the signal actually received at the telescope decreases exponentially as atmospheric absorption increases. We shall minimize these effects by locating the 25-m telescope at a high-altitude, low-latitude site.

B. ELECTRONICS DEVELOPMENTS

The early development of radio as an astronomical tool concentrated on long wavelengths, for technical reasons. The physical dimensions of electronic devices are comparatively large in this wavelength range and were easy to fabricate. The physics of semiconductors was unknown. Not until World War II did radio technology move toward shorter wavelengths.

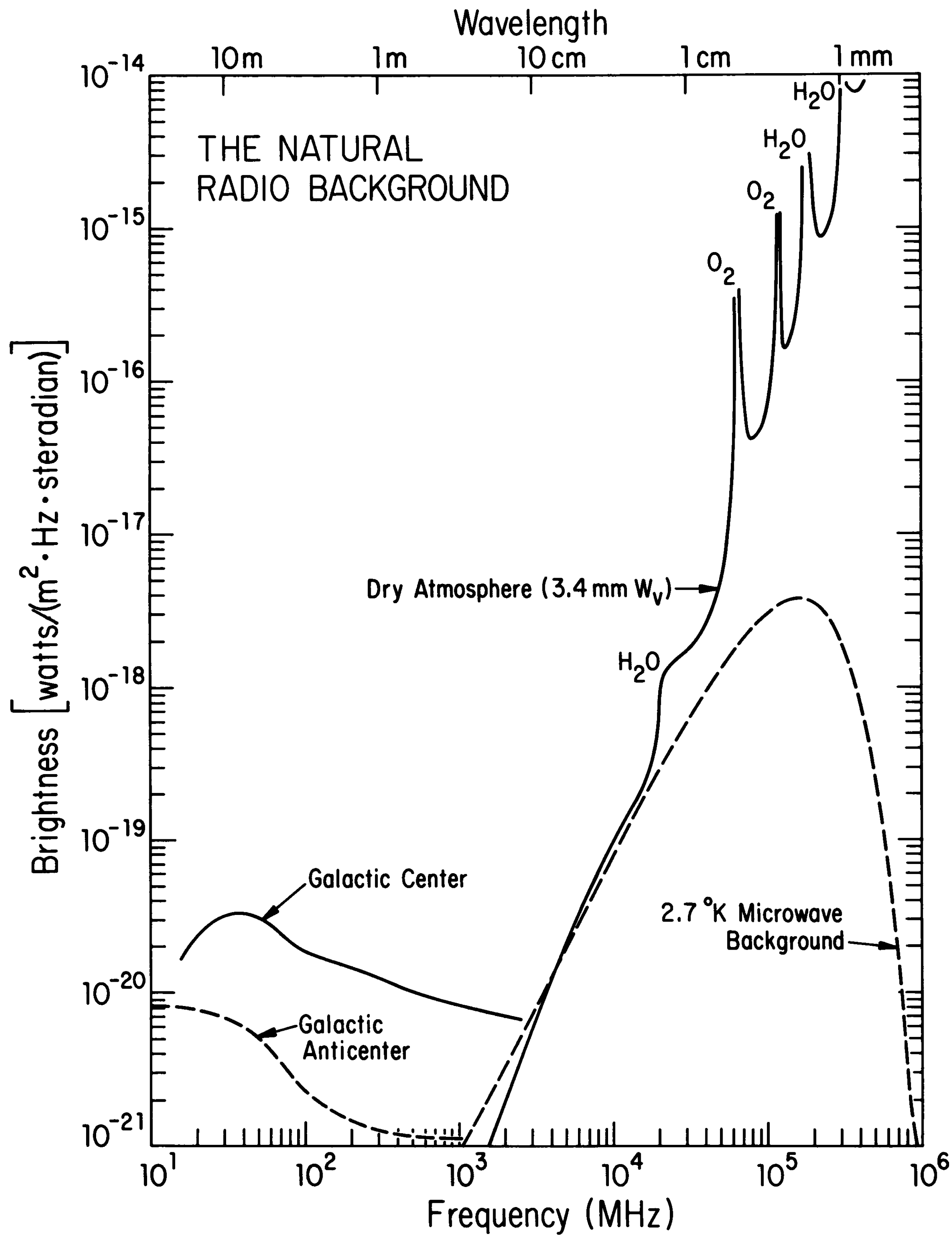

Figure 2. The background radiation in the radio domain, assuming an antenna directivity large enough to avoid the 300 K radiation from the ground.

The use of short wavelengths led to important technical developments of great potential value to astronomers. A direct result of this research was apparatus useful in the decimeter wavelength range, which led to the detection of hydrogen emission from our galaxy in 1951 and subsequently from other galaxies as well.

The movement of radio technology toward shorter wavelengths continues, resulting in increasingly sensitive receivers in the millimeter-wavelength range. In the ten years since the 36-ft telescope was placed into service, superheterodyne radiometers have increased their sensitivities by more than 1 order of magnitude, or 2 orders of magnitude in observing time. Figure 3 shows how the sensitivity (in terms of the equivalent noise temperature radiated by the receiver itself) has improved since 1967, and the prospects for further improvement are excellent.

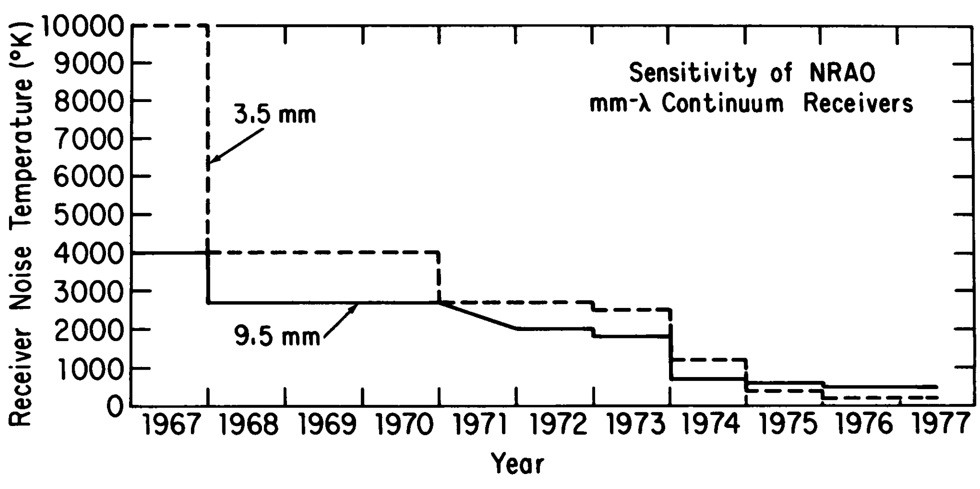

Figure 3. The decrease of the equivalent noise temperatures of receiving systems from 1967 to 1977.

Although the most sensitive, phase-coherent receivers currently in use at millimeter wavelengths are cooled mixers, other devices under development in the laboratory may offer even better performance. At wavelengths greater than 2.5 mm, the University of Massachusetts has been developing traveling-wave masers with possible system temperatures less than 100 K. Kerr, of the Goddard Institute for Space Studies, has built a receiver of 3 mm which uses a Josephson junction and has a system temperature of less than 100 K. A varactor down-converter, developed by Weinreb of the NRAO, now gives a system temperature of 160 ± 40 K at 2.6 mm. This device can be used at wavelengths as short as 0.87 mm, theoretically with a system temperature of 200 K or less. Weinreb expects the system temperature of the 2.6-mm down-converter to be less than 100 K, eventually.

Incoherent receivers are also improving in performance. For several years, Phillips of Bell Telephone Laboratory has made observations at 1.3 mm with a narrow-band, hot-electron bolometer. This device, useful for both line and continuum work, has recently been adapted to operation at 0.87 mm.

As we shall see, the 25-m telescope may be effective at wavelengths well beyond the diffraction limit, where incoherent receivers are particularly useful. Unlike many existing radio telescopes, the pointing and structural figure of the 25-m telescope will be reliable at wavelengths where the surface no longer permits diffraction-limited operation.

In conclusion, we may be certain that receiver performance at millimeter wavelengths, and even shorter, will continue to improve in future years. Good receivers will be available over the full wavelength range of the 25-m telescope.

C. THE SENSITIVITY AS A FUNCTION OF WAVELENGTH

To predict the quantitative sensitivity of a radio telescope as a function of wavelength, we need to know the roughness and size of the surface.

At the shortest wavelengths, the sensitivity is defined by the surface errors which themselves depend on the size of the telescope. If the errors are randomly distributed over the surface, Ruze (1952) shows that the efficiency is degraded by a factor

$$k = e^{-(4\pi\sigma/\lambda)^2} , \qquad (1)$$

where σ is the rms error, and λ the wavelength. It has become a convention to define the shortest wavelength of observation as

$$\lambda_{limit} = 16\sigma \qquad (2)$$

where the efficiency has dropped by almost a factor of two, or

$$k = e^{-(\pi/4)^2} = 0.540.$$

Actually, the telescope is still useful at shorter wavelengths, although with decreasing efficiency. In fact, the maximum gain occurs at $\lambda = 4\pi\sigma$.

Because the telescope will be shielded from wind, precipitation, and sunshine, and because gravitational distortions can be controlled by a design having homologous deformations, the principal remaining deterioration of the surface accuracy (after erection and adjustment) is given by thermal deformations, resulting from any thermal gradient within the enclosure and from fast changes of the ambient temperature.

For purposes of comparison, Figure 4 gives the effective collecting area as a function of wavelength for a number of telescopes useful at millimeter wavelengths. The effective collecting area of a telescope is the product of its geometrical area, its aperture efficiency, and the degradation factor (k) given by Equation (1). The plots assume an efficiency of 60 percent. Also shown is the zenith transmission for dry atmospheres as given by the SRC report. The solid curve would describe a high-altitude site.

The Ruze formula (Equation 1) is usually valid only where $\lambda > 4\pi\sigma$; $\lambda = 4\pi\sigma$ is the wavelength at which the telescope has maximum gain. At shorter wavelengths, marked by dashed regions of the curves, the formula describes the performance of the telescope under the assumption that the surface errors are distributed randomly and uniformly over the reflector surface. Should there be correlated sections of surface roughness, leading to only small deviations from a uniform distribution, then the performance of the antenna could exceed that predicted by random roughness theory in the region $\lambda < 4\pi\sigma$ (cf. Zarghamee, 1967). Because the surface of our telescope is made of separate plates, we would expect some correlated roughness and hence perhaps appreciably more gain than predicted by the Ruze theory in the dashed region. It is however extremely difficult to predict performance in this region; one must await empirical tests after assembly and adjustment of the telescope.

The preceding discussion applies only to the <u>diffraction-limited</u> situation; that is, where the main beam of the telescope is formed by interference of wavefronts coherently reflected from the entire telescope surface. This phenomenon is functionally identical to the Airy pattern formed by plane waves passing through a small circular aperture. The diffraction-limited mode, while principal at $\lambda > 4\pi\sigma$, is probably not the only useful mode of operation for this telescope.

The second mode, the <u>incoherent mode</u>, obtains at wavelengths substantially less than $4\pi\sigma$. P. Richards (1976) of the University of

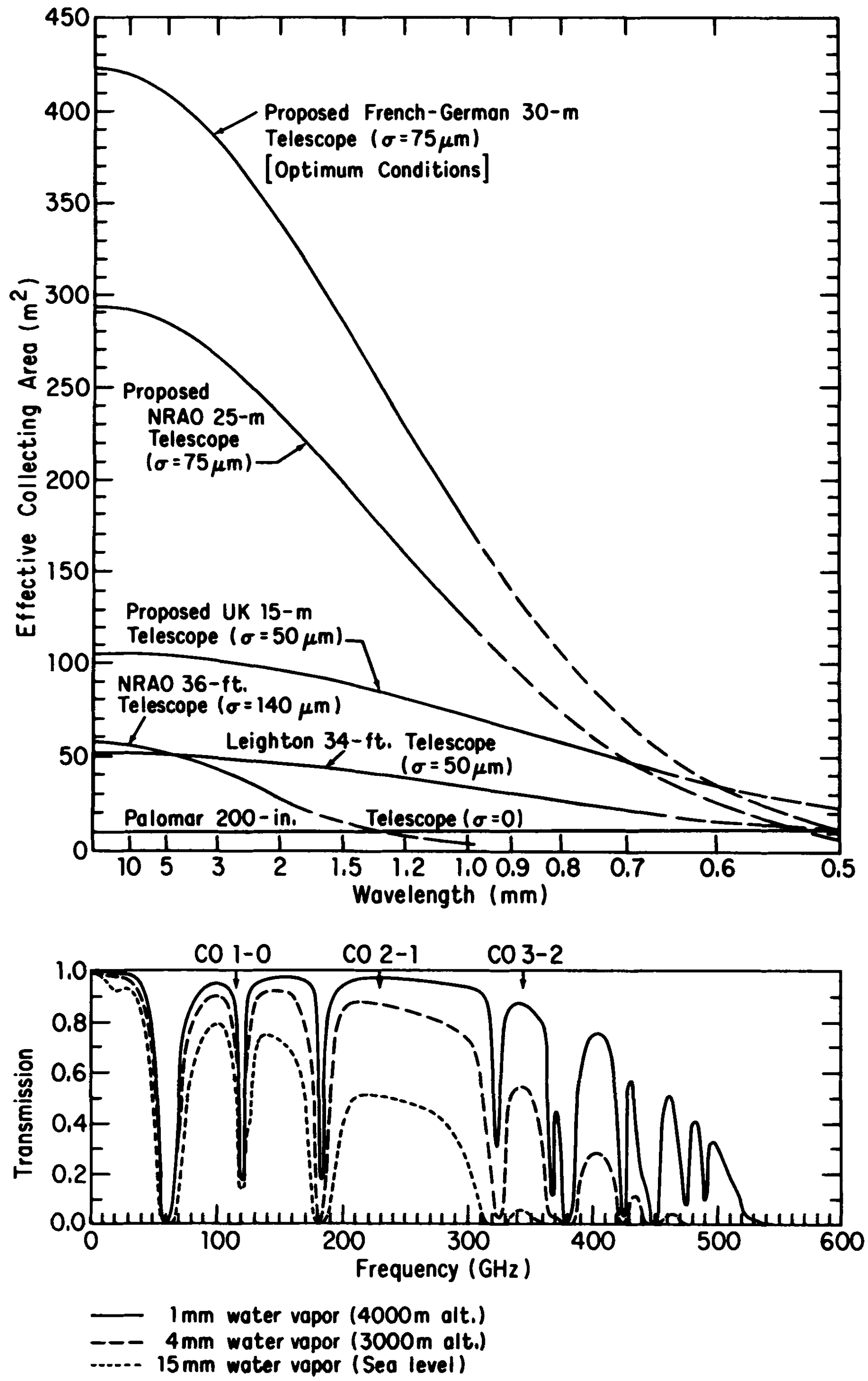

Figure 4. Top: The variation of collecting area as a function of wavelength for a few telescopes useful at millimeter waves. Bottom: The transmission of the atmosphere at 3 levels of precipitable water vapor (from the SRC proposal).

California, Berkeley, has described the possible use of the 25-m telescope in this regime. Under these conditions, often called the "light bucket" mode, the energy density in the image region is determined by reflection from regions of the surface rather than by a coherent reflection from the overall surface. The dimensions of the beams, called the error beam by radio astronomers and the circle of confusion by optical astronomers, is set jointly by the surface roughness and by the correlation length ℓ of this roughness. Because the beam is formed by interference of wavefronts reflected from regions of the surface, the beamwidth is independent of the overall dimensions of the reflector in units of wavelength. In fact, the half-power beamwidth θ_E is given by

$$\theta_E \text{ (arc seconds)} = 1.4 \times 10^6 \, \sigma/\ell \ . \qquad (3)$$

Because the proposed 25-m telescope has its surface composed of individual plates, we should expect correlation lengths on the order of the plate sizes, 1.5 m. With a surface roughness of 75 μm rms, the error beam could then be expected to have a beamwidth θ_E of 70". At the prime focus, this circle of confusion would have a diameter of 3.4 mm, small enough to fall on the sensitive surfaces of incoherent infrared detectors of the type now available.

The incoherent mode is the usual one for ground-based optical telescopes; seldom are the surfaces of optical telescopes adequate for diffraction-limited operation. In fact the refraction effects of the atmosphere (seeing) do not generally permit diffraction-limited operation by ground-based optical telescopes. Perhaps only the CTIO 4-m telescope, with its surface roughness of $\lambda/14$ at 5000 Å, is capable of diffraction-limited operation in the optical domain.

We conclude that the 25-m telescope will give diffraction-limited performance certainly to wavelengths as short as 940 μm ($\lambda = 4\pi\sigma$) and quite possibly to much shorter wavelengths. Incoherent operation is also a possibility at even shorter wavelengths, depending upon the correlation lengths appearing in the surface. For example, the 36-ft telescope at Kitt Peak has a σ of 140 μm, which corresponds to a diffraction-limited wavelength of 1.8 mm. Yet it is routinely used at 1.3 mm for narrow-band observations, fully 30% beyond its diffraction limit. It has a well-defined diffraction beam even at this wavelength, albeit superimposed upon an error beam. Should the 25-m telescope have similar characteristics, the corresponding wavelength would be 660 μm, very nearly the edge of the atmospheric windows shown in Figure 4. Correlation lengths of the solid surface of the 36-ft are known to be small; we would expect better performance from the segmental surface of the 25-m design. The pointing ability of this telescope should permit useful operation at these short wavelengths.

D. THE CHOICE OF APERTURE SIZE

Von Hoerner (1967) shows that the thermal deformation ε of a parabolic steel reflector is a function of its diameter D and of the temperature difference ΔT between structural members,

$$\varepsilon \approx 3.4\mathrm{x}10^{-3}\, D \cdot \Delta T, \tag{4}$$

where ε is in mm, D is in m, and ΔT is in °K.

Measurements show ΔT to be 0.8 K for good telescopes in protective enclosures. Setting $\varepsilon = \sigma$ and combining Equations (2) and (4), we find that the largest antenna diameter is related to λ_{limit}, the design limit, by

$$D \approx 23\ \lambda_{limit} \tag{5}$$

where λ is in mm. The application of this equation to the wavelengths listed in Table 1 gives a "maximum" aperture for each atmospheric window.

Table 4. "Maximum" Aperture as a Function of Atmospheric Window

Center Wavelength of Window (mm)	Aperture (m)
3.1	62
2.0	42
1.2	25
0.87	18
0.81	17
0.74	16
0.70	16
0.65	15
0.63	14
0.60	14

The choice of the telescope diameter was based upon many considerations, in addition to those of temperature difference described above. The decision involved a balance of scientific possibilities, construction costs, and engineering difficulties. Extensive discussions among the members of the ad hoc Committee, the NRAO Internal Committee, and the Working Group resulted in the choice of a "limiting" wavelength of 1.2 mm and the associated aperture of 25 m. This difficult choice seemed the best compromise between the demand for a large collecting area, and that for short wavelengths.

E. THE HOMOLOGY CONCEPT

The two main mechanical factors which establish the short-wavelength limit of a radio telescope are surface accuracy and pointing accuracy. Von Hoerner (1967) has theoretically investigated limitations upon surface accuracy as a function of gravitational stiffness and thermal gradients, most recently described in a review article (von Hoerner, 1977).

Apart from pointing accuracy, one way to describe antenna performance is in terms of its rms surface accuracy σ, measured radiometrically by means of the Ruze formula (Equation 1). Table 5 lists these values, along with a figure of merit D/σ, for 22 telescopes. Figure 5 is a plot of these figures-of-merit, D/σ, versus antenna diameter D.

Table 5. Radiometric Antenna Tolerances

Number	Antenna	D(m)	σ(mm)	D/σ
1	Aerospace	4.6	0.079	58,000
2	MWO	4.9	0.093	52,000
3	JPL	5.5	0.18	31,000
4	Mitaka, Japan	6.0	0.20	30,000
5	MIT	8.5	0.20	42,000
6	DRTE	9.1	0.53	17,000
7	NRAO-Tucson	11.0	0.15	73,000
8	Helsinki	13.7	0.31	44,000
9	MacKenzie	13.7	0.35	39,000
10	Lebedev-Crimea	22.0	0.35	63,000
11	NRAO-VLA	25.0	0.54	46,000
12	NRAO (Homology Design)	25.0	0.075	333,000
13	NRAO-Green Bank	25.9	1.75	15,000
14	NEROC	36.6	0.82	45,000
15	OVRO	39.6	1.9	21,000
16	NRAO-Green Bank	42.7	0.92	46,000
17	ARO	45.7	1.0	46,000
18	JPL	64.0	1.9	34,000
19	CSIRO	64.0	3.6	18,000
20	NRAO-Green Bank (Transit)	91.4	2.6	35,000
21	MPIR (Quasi-Homologous	100.0	0.9	111,000
22	NAIC (Static Reflector)	305.0	5.0	61,000

The performance constraints theoretically predicted by von Hoerner are also plotted in Figure 5. The dominant limit is _gravitational_, shown by the solid line decreasing from left to right. This limit comes from an analysis of conventional telescope structures. It says that, in the absence of wind or thermal forces, there is a natural precision limit to a telescope set by its size. Any attempt to increase stiffness by increasing the bar area of the truss structure correspondingly causes an increase in weight, thereby causing about the same

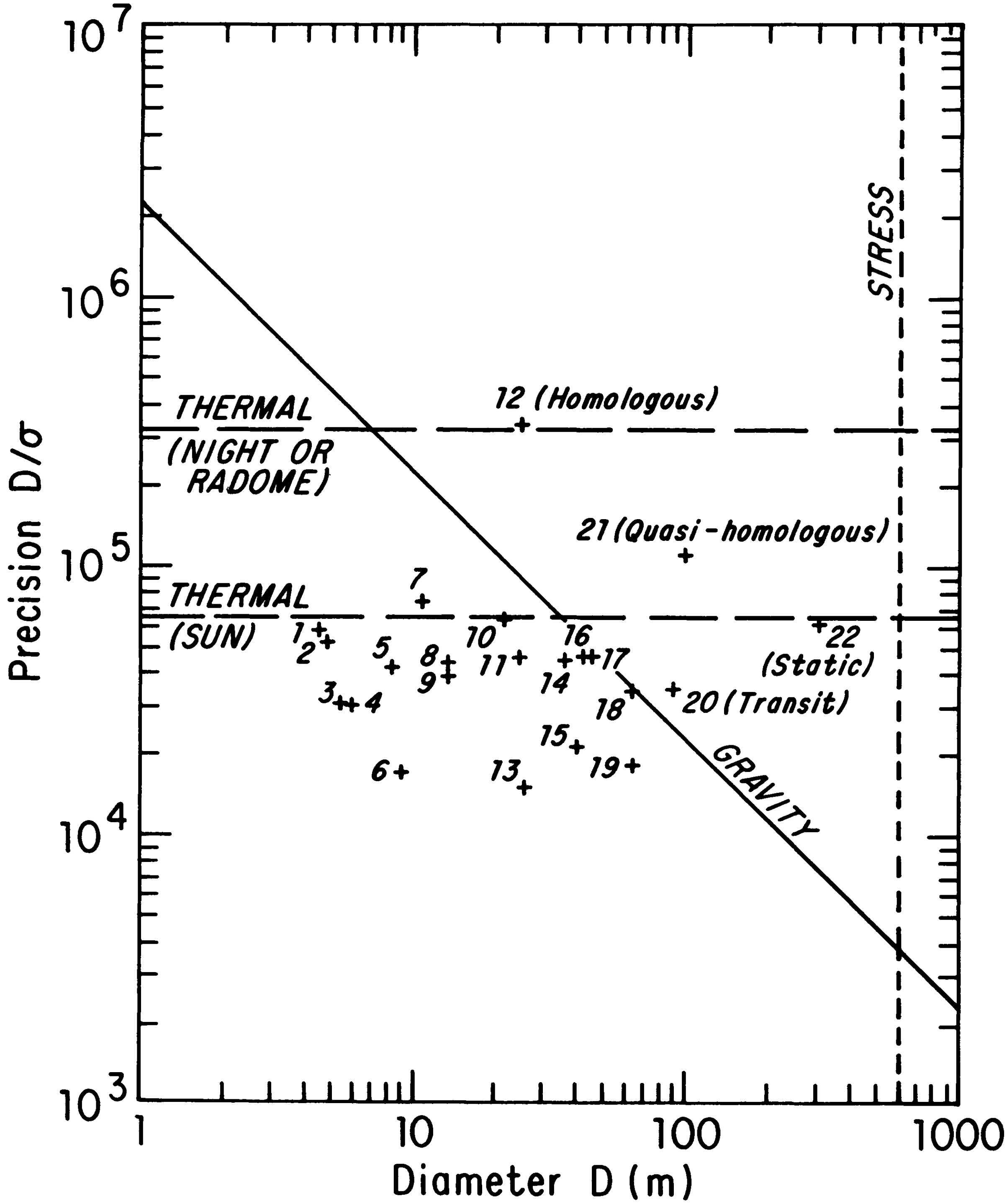

Figure 5. Measured figures-of-merit plotted against antenna diameter.

deflection. Because both aluminum and steel have about the same stiffness/mass characteristics, this limit applies to any conventionally built telescope. The vertical line at 600 m marks the stress limit, the largest possible telescope size using conventional materials. Note that with four exceptions, all telescopes fall below the gravity limit.

Thermal constraints, defined by Equation 4, are also shown in Figure 5. The lower limit assumes a temperature difference of 4.0 K; the upper limit; 0.8 K. These figures result from actual measurements of various telescopes. We assume that wind loading is of no consequence for this figure, and that thermal lags are short.

To overcome the gravitational limit, von Hoerner developed a design process called homology. Conventionally designed telescopes usually involve a truss structure supporting surface panels and feed, movable in both elevation and azimuth. Gravitational deformation of these structures occurs by a sagging of the surface panels between the hard support points, and by an overall deterioration of the entire surface from a paraboloid. Von Hoerner reasoned that while this deformation could never be avoided, careful design could render it harmless in terms of radiometric performance. First, the surface should be supported by many points close together, resulting in equal softness of the truss structure. Second, the truss structure can be designed so that it always deforms to a paraboloidal surface, albeit of differing focal length. By using a design with homologous deformations, it is possible to construct radio telescopes which exceed the gravitational limit of Figure 5. Of the three telescopes which substantially exceed this limit, Arecibo (22) does not move and is thus not subjected to varying gravitational forces. The Effelsberg telescope (21) is a quasi-homologous design, and the proposed 25-m telescope (12) is a fully optimized design.

While a special computer program may be required to design and to optimize homology telescopes, the analysis of a completed design is performed by standardized structural programs such as NASTRAN or STRUDL. The NRAO design program has been developed and used for many years to produce homology designs for 100-m, 65-m, and 25-m telescopes. It incorporates a manufacturer's catalog of available tubing within it, so as to use commonly available components. Analysis of these designs by conventional structural programs predicts excellent performance. To investigate further the effects of manufacturing irregularities, a variational analysis has been developed. The performance figure of the backstructure incorporated into our tables uses this "worst case" estimate.

Finally, the only homologous telescope which has actually been built is the 100-m Effelsberg telescope. Its performance is as predicted by the designers, thereby proving the effectiveness of a homology design.

F. THE 25-M TELESCOPE DESIGN

Volume I of this proposal describes the telescope design in detail. the only substantial change since 1975 is to increase the size of the vertex room to a diameter of 4.5 m. Other characteristics remain unchanged.

The telescope is an optimized homologous design having a diameter of 25 m and a focal ratio of 0.4 as shown in Figure 6. The azimuth support is wheel and track. It will operate from the horizon to zenith, at all azimuth angles.

The surface is composed of 528 panels, each having four adjustment jack screws. These jacks are accessible from the front, making adjustments as easy as possible. Each panel is 1.515 m long, measured along the curved surface.

The drive system is conventional, consisting of electric motors and gearboxes. The servo system receives angle input from inductosyns mounted on the ends of the elevation shaft and of the torque tube associated with the central pintle bearing. Angular resolution is 0.31 arc seconds.

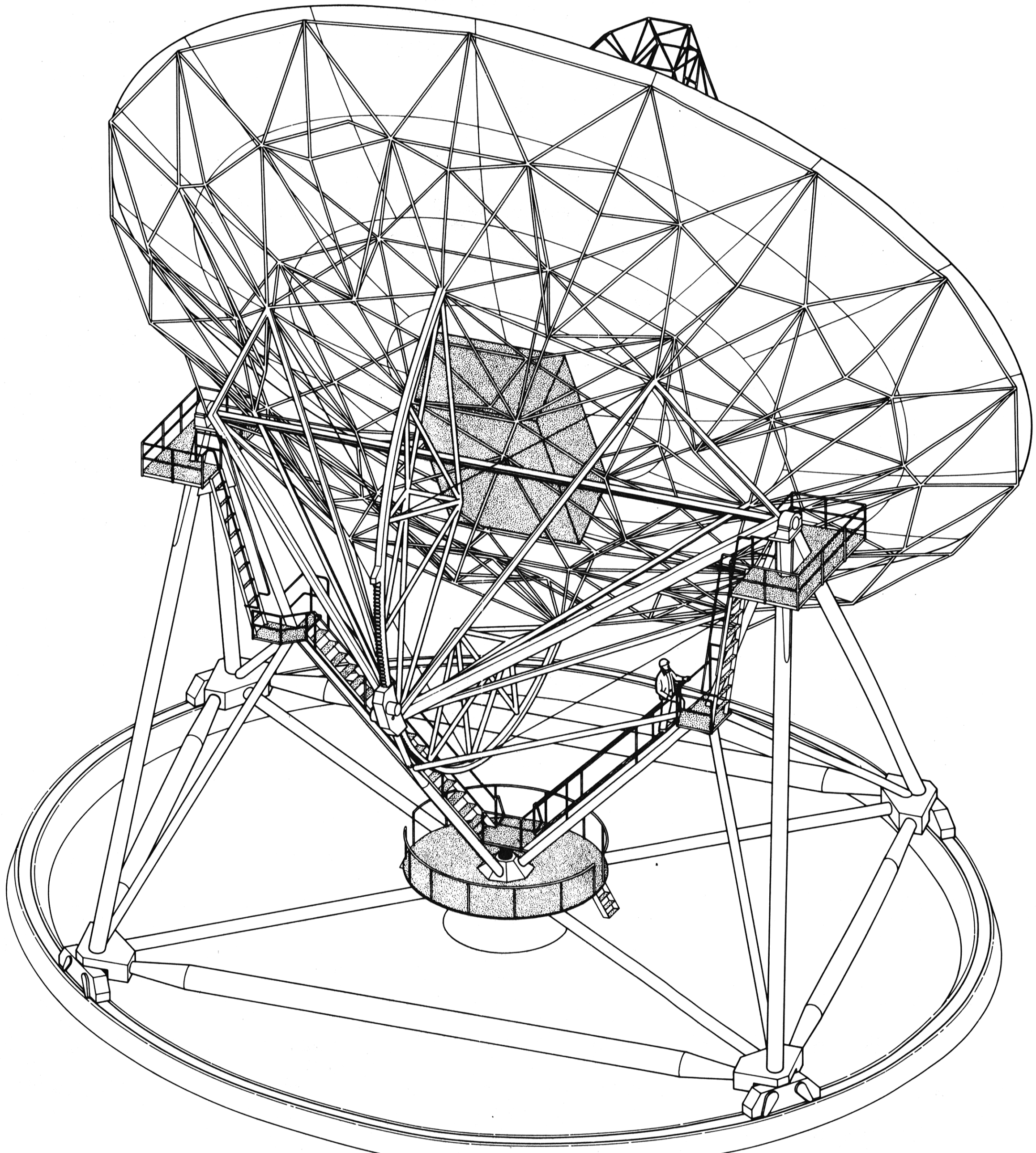

Figure 6. Rear perspective of the 25-m telescope, showing truss structure.

The control computer performs the telescope and receiver control functions, in a way similar to that now used at the 140-ft. A second computer, identical to the control computer, will be provided for data processing and analysis in the control room. Should the control computer malfunction, the processing computer will take control.

All design goals have been met as of this writing. Table 6 shows the error analysis for calm conditions, with the telescope exposed to the ambient air but shielded from winds and direct sunlight. The calculated total error is 70 μm, slightly less than the design goal of 75 μm. Additional calculations show that this performance should hold during most of the day, except for short periods near sunrise and sunset when the air temperature is expected to change rapidly. In these calculations the effect of illumination taper has not been considered. We expect the actual performance to give a radiometric σ somewhat less than the conservative number of 70 μm listed in Table 6.

The principal contributions to the error of Table 6 are the manufacturing and measuring errors of the surface panels. Should we improve these, a considerably improved RF performance should be possible during much of the observing time.

G. POINTING

For a telescope to be an effective instrument, it must also point well. A consequence of the homology design is a variation in focal length and in the symmetry axis of the paraboloid as the telescope moves from horizon to zenith. The focal length changes by 2.8 mm, and the lateral translation of the focal point is approximately the same amount. These variations do not involve hysteresis in any way; they can be calculated or measured and treated as a pointing correction by the on-line computer controlling the telescope.

The width of the diffraction beam of a parabolic radio telescope depends upon the illumination of the reflector. A usual illumination is

Table 6. Mechanical Performance of the 25-m Telescope

Source	Amount	
Surface Errors	μm	
Surface Plates	61	
Manufacture		40
Gravity		12
Setting		15
Measurements		40
Thermal		12
Wind		1
Panel Structure	7	
Manufacture and Gravity		7
Thermal		2
Wind		1
Backup Structure	21	
Assembly and Gravity		16
Thermal		13
Wind		1
Subreflector	25	
Manufacture and Gravity		25
Total Errors (RSS)		70
Pointing Errors		arc seconds
Angle Encoder		0.2
Servo and Drive		0.5
Thermal		0.2
Wind		0.1
Total Errors (RSS)		0.6

(Footnote: The RSS error is the quadratic sum of the individual, uncorrelated, rms errors.)

to taper the electric field in the central region by 12 dB at the reflector edge. The width of the beam between half-power points is then approximately 70°/diameter in wavelengths. For the 25-m telescope, we can expect the beamwidth, in arc seconds, to be 10 times the wavelength in mm. At the design wavelength of 1.2 mm, the beamwidth of this telescope would then be 12 arc seconds.

We do not expect the performance of this telescope to be limited by pointing. Table 6 shows the calculated pointing error to be 0.6 arc seconds, which should permit acceptable operation even at wavelengths much shorter than the design goal.

H. OTHER MILLIMETER-WAVE TELESCOPES

It is useful to compare the 25-m telescope with the characteristics of other millimeter-wave telescopes throughout the world. Table 7, based upon one in the proposal by the Science Research Council of the United Kingdom, lists many of the world's millimeter-wave instruments (established, under construction, and proposed). Only one larger diameter, short wavelength instrument has been proposed. This telescope, the Franco-German (SAGMA) 30-m paraboloid, almost certainly will not be enclosed in a true radome or astrodome. Its minimum wavelength goal of 1.2 mm, corresponding to a surface rms of 75 μm, may be attainable only during good weather conditions. Figure 4 shows the comparison of effective collecting area versus wavelength for a number of these instruments. Because of its low-latitude, high-altitude location, the 25-m telescope will be an especially powerful instrument for astronomical research at the short millimeter wavelengths, compared to other telescopes now in existence or proposed.

TABLE 7 SOME TELESCOPES USED AT MILLIMETER WAVELENGTHS

Telescope		Altitude (m)	Latitude (°)	Diameter (m)	λ_{MIN}†† (mm)
Established					
Aerospace Corporation ..	El Segundo (USA)	0	34 N	4.6	1.3
Caltech	Mt. Palomar (USA)	1700	34 N	5	Optical
CAO	Crimea (Ukrainian SSR)	500	46 N	22	5.6
CSIRO	Parkes (Australia)	400	33 S	18*	5.1
MPI	Effelsberg (W. Germany)	300	51 N	50*	8
NRAO	Kitt Peak (USA)	1900	32 N	11	2.4
NRL	Maryland Point (USA)	0	38 N	25	9
Tokyo Observatory	Mitaka (Japan)	100	36 N	6	3.1
UBC	Vancouver (Canada)	0	49 N	4.5	2
U. California	Hat Creek (USA)	1100	41 N	2x6†	2
U. Texas	Fort Davis (USA)	2100	31 N	4.9	1.5
Recently Completed or Under Construction					
BTL	Holmdel (USA)	0	40 N	7	1.6
Caltech	Big Pine (USA)	1200	37 N	10	0.8
Chalmers U.	Onsala (Sweden)	0	58 N	20	2.6
CSIRO	Epping (Australia)	0	34 S	4	1.5
Geographic Institute ...	Madrid (Spain)	2000	41 N	14	2.2
Mackenzie	Atibaia (Brazil)	600	23 S	14	4
NASA	New York (USA)	100	41 N	1.2	1
U. Helsinki	Helsinki (Finland)	0	60 N	13.7	5
U. Massachusetts	Amherst (USA)	500	42 N	14	2
UKIRT	Mauna Kea (USA)	4300	20 N	3.8	Near IR
USSR Academy Sciences ..	Zelenchukskaya (Ukrainian SSR)	1000	45 N	600 (ring)	8
Proposed					
Caltech	Big Pine (USA)	1200	37 N	4x10†	2
Caltech	White Mt. (USA)	4300	38 N	10	0.5
NRAO	Mauna Kea (USA)	4300	20 N	25	1.2
SAGMA	Plateau de Burre (France)	2500	45 N	4x10†	2
	Pico Valeta (Spain)	3300	37 N	30	1.2

* Center section only.

† Synthesis telescope.

†† $\lambda = 16\ \sigma$, measured radiometrically for established instruments and estimated for others from specifications given in the contract or in descriptive articles.

Table 7. Some Telescopes Used at Millimeter Wavelengths

CHAPTER IV

SURFACE PLATES AND MEASUREMENTS

A. PLATE FABRICATION

As described in Volume I, the surface plates proposed for the 25-m telescope are based upon a design developed for the 65-m telescope. The concept is to machine aluminum castings by using numerically-controlled milling machines.

Since 1975 the NRAO has purchased two cast-aluminum plates manufactured especially to meet the tolerances of the 25-m telescope. These plates, produced by Aeronutronics-Ford, were cast from A356 aluminum and from Precident 71 alloy. These were milled to rms accuracies of approximately 40 μm. Twenty-seven similar panels have been purchased by Bell Telephone Laboratory, and 21 of them have been machined to 35 μm rms by the same firm. There is no doubt that, with careful quality control, this fabrication technique can meet or exceed the specification of 40 μm measured normal to the telescope surface.

The search for better and less expensive surface plates is an active concern of the Working Group. The choice of cast aluminum plates for the 25-m telescope might not be the optimum choice in the years to come. Fiberglass-epoxy and aluminum honeycomb construction is slowly becoming an attractive approach, as material properties and construction techniques improve. The California Institute of Technology is now using these materials for their 10-m telescope, and the SRC group of the United Kingdom is experimenting with them for their proposed 15-m telescope. Alternatively, the Electronics Space Systems Corporation (ESSCO) has developed an imaginative and inexpensive method of producing surface plates, using sheet aluminum pressed onto a precision mold and epoxied to an aluminum support frame. Their approach has been used for the new millimeter-wave telescopes of the University of Massachusetts and of Chalmers University of Sweden.

Although the cast-aluminum panels now in hand meet the design specifications, we shall continue to evaluate new construction techniques. One possible disadvantage to light-weight panels compared to the cast-aluminum panels may be their susceptibility to damage from walking upon them. While this activity has been occasionally required for telescope and receiver maintenance, we would certainly adopt other operational procedures should they be necessary to accommodate superior surface panels.

B. PLATE ADJUSTMENTS

Each of the 528 surface plates is supported by 4 jack screws, for a total of 2112 adjustment jacks over the surface. Because of the time which would be required to set each jack manually, and because of the possibility of human errors, the NRAO is developing a computer-controlled wrench. The wrench consists of a stepping motor connected to a hexagonal socket. The angular size of the step is $1^{\circ}\!.8$ which, combined with the pitch of the jack threads, permits an axial adjustment of a jack to an accuracy below our design goal of 15 μm, including hysteresis effects.

The individual bolts will be coded, so that the computer can automatically compute and command each jack adjustment with minimal human interaction. To make adjustments physically easy, the adjustments will be accessible from the front surface of the telescope.

C. SURFACE MEASUREMENTS

1. Introduction. Since the start of design work on millimeter-wave telescopes (about 1970), it has been clear that one of the critical areas was that of measuring the reflector surface to the necessary accuracy. The first step in this measurement, to measure the shape of individual reflector panels, does not raise fundamental difficulties. The panels can be measured in a controlled environment by one of several

methods. As an extreme case, optical telescope reflectors are measured and figured to precisions of a fraction of a micrometer. Commercial 3-dimensional measuring machines can measure shapes of solids of 2 meters or so in size to about 10-15 μm. Specially designed, automated panel-measuring machines can be designed and built to give comparable accuracies.

In building the 25-m telescope surface we shall start with individual panels which have been measured and marked by the manufacturer to a precision of about 15 μm. The task then will be to set these panels on the telescope so that the surface is parabolic to the required accuracy. Basically this will require good measurements of the positions of the panel adjustment points (or points on the panels near these points). The shapes of the panels will already be known.

These measurements need only be made with the telescope in the zenith. The deflection pattern of the instrument at different zenith positions is accurately known from the design. The measurements must also be made when the telescope is in a known, stable, temperature environment. The fact that it is to be built in an astrodome with good control of the ambient air will be of considerable value.

The questions to be answered are these:

(a) Do any methods of measurement exist which can achieve the desirable 40-μm measurement accuracy for our telescope?

(b) If so, which are the most suitable methods to adopt?

(c) If not, can any novel methods be devised?

To answer these questions we have worked for about seven years to survey and evaluate known measurement techniques. We conclude that there are four methods known which are capable of making the measurements.

2. A Survey of Measuring Methods. The methods by which a large curved surface may be measured can be simply subdivided as follows;

(a) Range-angle measuring.

(b) Angle measuring alone.

(c) Range measuring alone.

(d) Holographic methods.

(e) Other.

In summarizing methods under these titles, let us accept two general points, without giving detailed supporting facts. First, in free air, it is quite difficult to measure the direction of a light ray to better than about 2 arc seconds (10^{-5} radians). Conventional distance measures, with good tapes, work well to accuracies of about 1 in 10^5 of the distance with a zero-point error of 50 to 100 μm. Neither of these limitations is absolute or exact. They show, however, that the task is somewhat beyond normal good surveying metrology.

(a) Range-angle measuring:

(i) Tape and theodolite methods.

(ii) Tape, rod and optical level methods.

(iii) Laser beam, tape and quadrature-split detectors.

(iv) Tape and pentaprism methods.

(v) Tape and kine-theodolite photography of targets.

We should really include here the UK method and our stepping method, but we prefer to defer these. All these (a) methods rely on an angle measure in free air. This measure is of an elevation angle, measured over the expanse of the reflector surface, where vertical refractive gradients are likely.

However, because of their simplicity, we propose that the first setting of the 25-m surface be made, by the telescope builder, using one of these methods. Of them, we prefer (iv) and estimate that it could achieve a setting accuracy of about 150 μm at the telescope edge, and comparably higher accuracy for the inner rings of panels.

(b) Angle-only methods:

(i) Optical range-finder methods.

(ii) Photogrammetry.

Both techniques have been used on antennas; neither can provide the required accuracy.

(c) Range-only methods:

(i) Pulse modulated radar.

(ii) Phase-sensitive radar.

*(iii) Amplitude-modulated light beams.

*(iv) Phase-sensitive light beams.

Because these methods avoid the angular refractive effects of air, all except (i) can reach the range sensitivity needed. We set (ii) aside; it has been well-studied at NRAO and used to measure the deformations of the 140-ft telescope (Findlay and Payne, 1974). It cannot, however, be easily applied to mapping an antenna surface. Method (iii) has also been developed to a higher accuracy at NRAO (Payne, 1973) than by anyone else. A more complex system based on our work has been installed at Arecibo to measure the 305-m dish. It appears that, with a further development effort, (iii) could be brought to the accuracy needed to measure the 25-m telescope.

Method (iv) is highly accurate, available for use in the H-P laser interferometer, and could certainly be designed into a system suitable for our task. It is the basis of a well-designed system planned by the UK group in their 15-m telescope proposal.

(d) Holographic methods.

The only practical experience has been that described by Scott and Ryle (1977), although there are other articles in the literature. The

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* Methods marked (*) are sufficiently accurate to be used.

Cambridge results are good, but it does require a second antenna, a good phase-stable millimeter-wave interferometer and a good strong signal from a distant point source. It also includes the atmospheric path effects in its results.

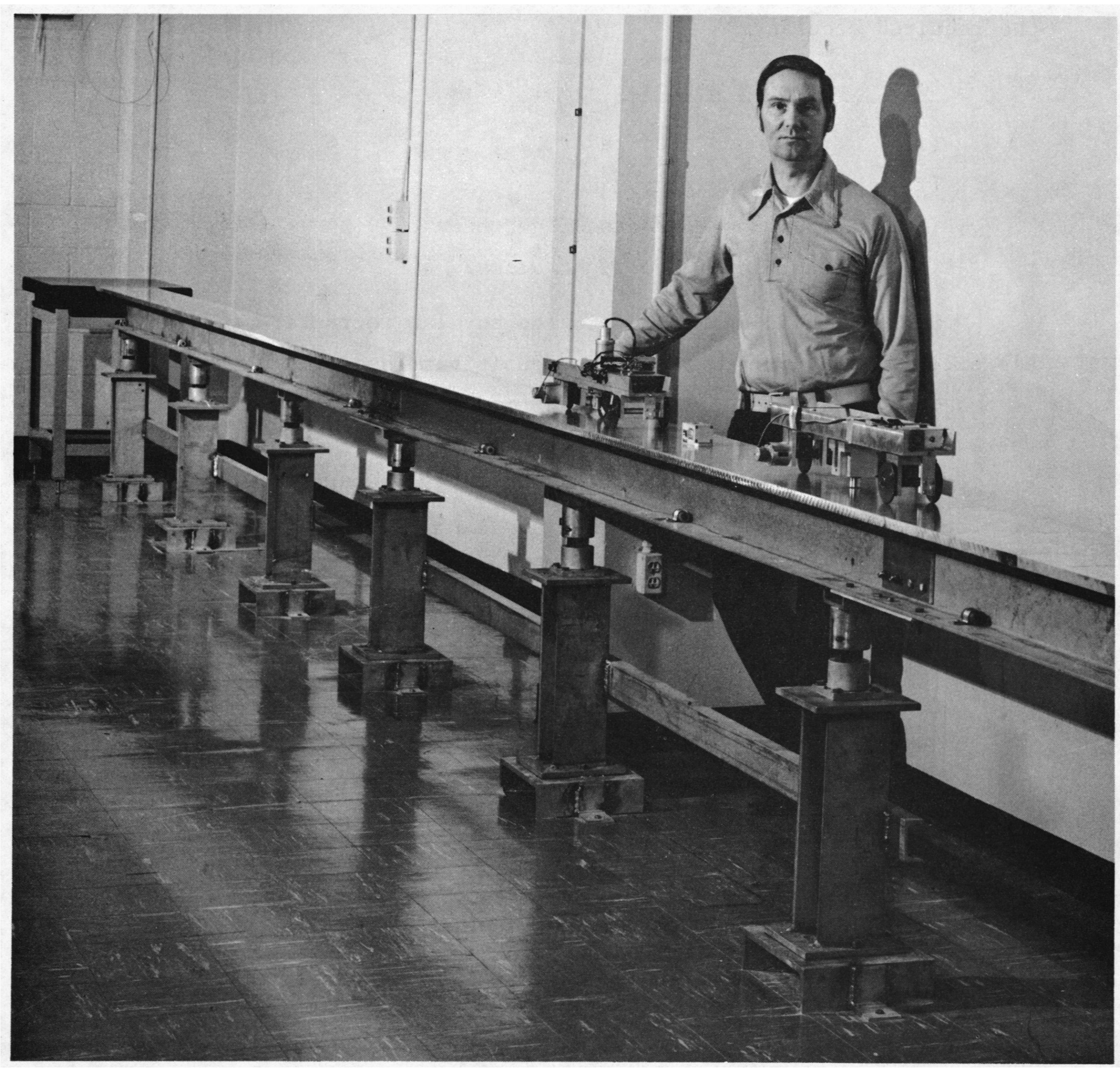

Figure 7. The 12.5-m test track, shown with John Ralston and the two spherometer carts which he designed.

(e) Other methods.

*(i) Measures of curvature (cart method).

*(ii) Range-angle by stepping (stepping method).

(iii) Use of a template.

We will not consider (iii) further. It is good for smaller telescopes but becomes very difficult to use for large surfaces.

Both (i) and (ii) of these are NRAO inventions. (i) has been described in Part I of this document and in the literature (Payne, Hollis and Findlay, 1976). It has been the study of exhaustive tests over the last two years at NRAO, where a special test track (Figure 7) has been built to evaluate its accuracy. As an example of the accuracy obtained in these tests, Figure 8 shows the profile of this track measured by the cart and by a precise optical level. It also shows the difference between the results of these methods, suggesting that this method meets our needs.

The stepping method (ii) is a simple range-angle process, but the angle is measured by a precise, wide-range inclinometer. The inclinometer tested at NRAO (Schaevitz LSOC) has an angular range of ± 14.5° and measures to an accuracy of 1 arc second. Its output can be encoded and fed to a small HP9825A computer. The inclinometer is mounted on a bar, whose length for the present was 650 millimeters, and this bar is stepped out along a radius of the telescope to be measured. At present the steps are defined by holes drilled in the surface. Thus the profile of the radial line is determined. The method has already been tested in two ways. First, it has been tested on the indoor track to determine its measurement errors. A comparison between the track profile measured by stepping and by optical means has been made. Second, the method has been used to measure one radial track on the 140-ft telescope at Green Bank.

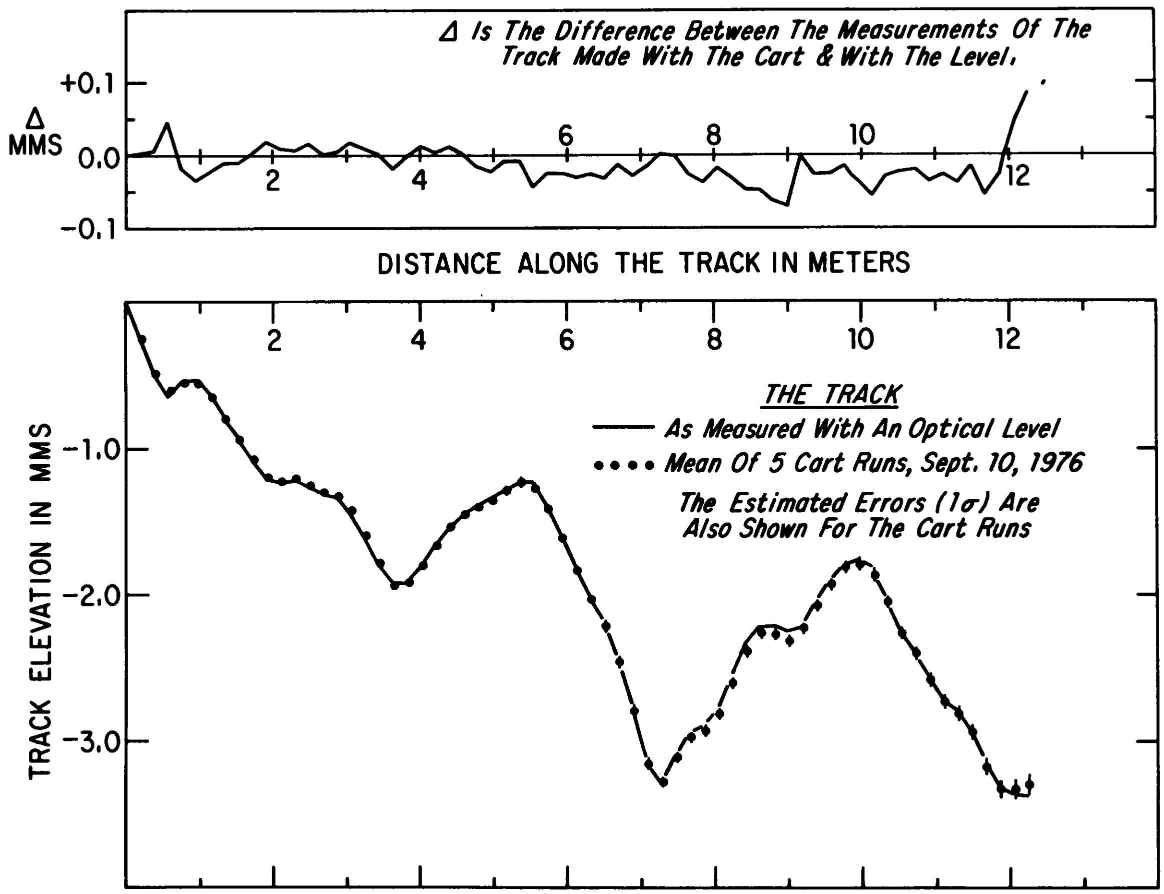

Figure 8. Bottom: Track figure measured by both optical and spherometric techniques. Top: Difference between these measurements.

The tests of reproducibility on the test track showed that the measurement error after traversing a 12.5-m distance had only grown from zero to 38 μm. A comparison of measurements by stepping with optical measures is shown in Figure 9. The upper curve in this shows the

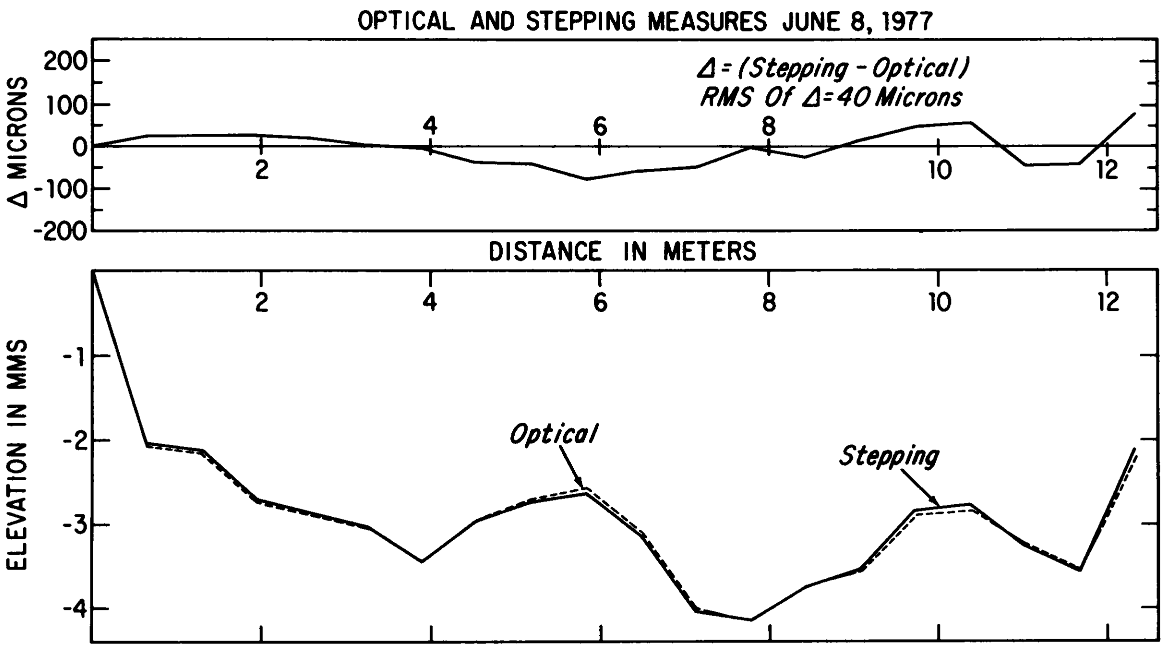

Figure 9. Bottom: Track figure measured by optical and stepping techniques. Top: Difference between these techniques.

differences between results of a single stepping run and optical measures. The optical measuring instrument used was somewhat imperfect and this may have added to the error. Nevertheless the rms value of the difference is only 40 μm. The 140-ft tests were done to show that the method would work on an exposed telescope. The climate conditions were not good; in spite of this, the method achieved an average measuring accuracy of 66 μm over the 21.3-m radius

3. The Choice of the Final Method. We believe that the telescope will be measured and set first as described in 2(a), and so its final design must allow of the installation of the pentaprism system. This should result in a telescope of about 40% aperture efficiency at $\lambda = 2$ mm. We suggest that the telescope be accepted by NRAO on the basis of:

(a) Certified measurements of individual panels.

(b) Contractor setting to give the above performance.

Our choice of a final measurement technique is between the cart (2(e)i) or the stepping (2(e)ii) methods. Either or both systems may be used. If the cart were used alone, our present view is that it should be used in a "transfer" mode. That is, a single precise radius of the telescope should be built, in a good environment (the astrodome floor) and used to run the cart and determine its constants. The cart is then used to "transfer" this profile to the telescope by running it on the various radii. This is rather like using a template except that the cart is used to carry the template to the telescope for the comparison.

The stepping method, however, seems to meet our needs best of all. It would be designed and used to give measurements at surface points close to the panel reference points. It requires that a well-defined reference plane with a nominally central starting point be built at the reflector vertex. This plane will be monitored during measurement by two orthogonal inclinometers. These details are easily provided for in the telescope design. The methods of data collection, analysis and display already developed will extend easily to providing computer data for adjustment control at each panel adjustment point.

We envision this final surface setting as a task for the NRAO. We believe we have examined and developed techniques by which the surface can be measured and set. The next steps of turning the techniques into a finally engineered system should start when the first serious commitments to fund the telescope are made. This will give sufficient time for final system design.

CHAPTER V

THE PROTECTIVE ENCLOSURE

A. THE WIND AND RADIATION PROBLEM

Quite apart from the homologous design, the ultimate performance of the telescope requires that the structure be maintained as close to isothermal as possible. Not only surface accuracy, but also pointing accuracy, requires excellent thermal control.

In Volume I we concluded that the telescope should be protected either by a radome or an astrodome. We therefore have studied possible materials for a radome in some detail, so that we could be more precise about the performance of the telescope enclosed in a radome. These studies have also helped in choosing a material for the window of an astrodome. We have studied costs of radome structures, which were easy to obtain because radomes are commercially available. And we have also carried out considerable design work on a suitable astrodome.

Our conclusion is that the best possibility is the astrodome, with a large transparent slit which can be opened for observations or closed to protect the telescope from sunlight or from storms. We now describe the work in more detail.

B. PROPERTIES OF MEMBRANE FABRICS

While, in a sense, the most desirable enclosure would be a radome, the problem with a radome is its relatively poor transmissivity at very short wavelengths. As discussed, the proposed telescope will be useful at wavelengths much shorter than its design goal of 1.2 mm. The maximum gain of the telescope will be at 0.9 mm. Figure 4 shows that its collecting area will be greater than the higher precision Leighton and UK telescopes to wavelengths at least as short as 800 μm, even by the pessimistic predictions of the Ruze formula. The atmospheric transmissivity from a high altitude site is acceptable at short wavelengths. It is highly desirable that the radome transmission not limit the RF performance at these wavelengths. Unfortunately, we have not been able to find an appropriate fabric which meets this requirement.

The transmission of radio waves through a radome has been understood for many years (cf. Volume 26 of the MIT Radiation Laboratory Series, edited by Cady, Karelitz, and Turner, 1948). Figure 10 shows what is expected for a modern spaceframe covered with an excellent fabric. Transmission is controlled by three components: the geometrical blockage of the space frame supporting the membrane, the resistive loss characterized by the loss tangent of the membrane material, and the reflective properties of the membrane itself.

The space frame blockage is usually 5%, geometrically, for a well-designed large radome. At the high frequencies considered here, this loss is due simply to shadowing of incoming radiation by the projected area of the frame itself. To reduce this blockage would probably mean relaxing the survival limits for the radome, which is unacceptable. Alternatively, one could use more esoteric materials than aluminum, such as carbon fiber tubes, which would enormously increase the cost of the radome.

The resistive loss of modern radome membranes is very low. However, it becomes increasingly important for the high frequency performance we wish to preserve. The resistive loss of a material can be characterized by tan δ, where δ is the ratio of the imaginary to real parts of the dielectric constant. Typically tan $\delta \leq 0.01$ for an excellent radome material. Indeed, the materials are designed expecially with this characteristic in mind. For normal incidence and small values of tan δ

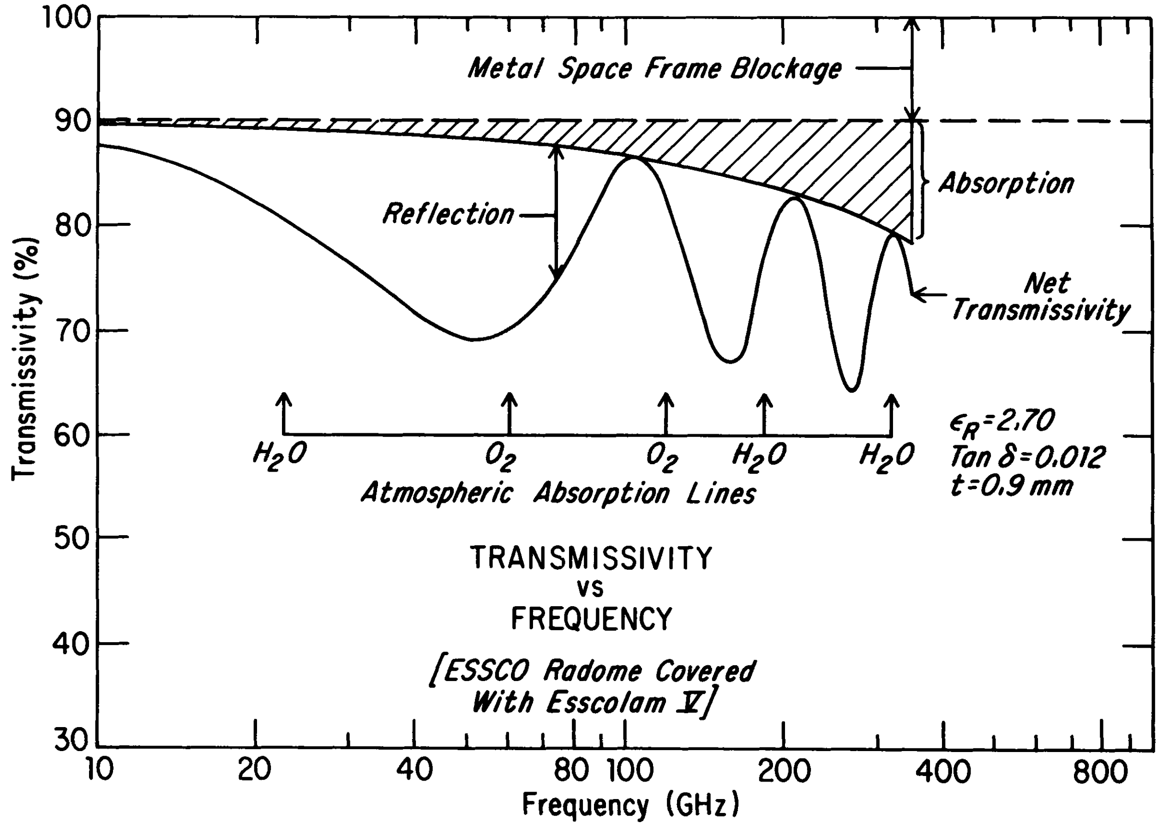

Figure 10. Hypothetical transmission of a modern spaceframe covered with an excellent fabric.

the attenuation factor A of a wave passing once through a membrane is given by

$$\ln A = - \frac{\pi t}{\lambda_o} \quad \frac{\varepsilon'}{\sqrt{\varepsilon' - 1}} \tan \delta \ , \qquad (6)$$

where t is the physical thickness of the membrane, ε' is the real part of the dielectric constant of the material relative to that of free space, and λ_o is the free-space wavelength. Under these conditions $\ln A$ scales inversely with wavelength, as can be seen in Figure 10.

The relative properties of a radome membrane are much more complicated to describe, because modern membranes are usually a sandwich of different fabrics. The general properties can be qualitatively explored by considering the reflection of waves passing through a single layer. A wavefront entering a membrane (or leaving it) will experience partial reflection at the place where the dielectric constant changes. The voltage reflection coefficient r for a transition from medium a to medium b is given for normal incidence as

$$r = \left(\sqrt{\varepsilon_a} - \sqrt{\varepsilon_b}\right) \Big/ \left(\sqrt{\varepsilon_a} + \sqrt{\varepsilon_b}\right) \tag{7}$$

$$= (n-1)/(n+1) \quad , \tag{8}$$

where ε is the dielectric constant relative to that of free space, and $n \equiv \sqrt{\varepsilon_a/\varepsilon_b}$ is the index of refraction between the two media. At each interface, partial reflection will occur such that wavefronts will echo back and forth across the membrane. (For sandwiched membranes involving three layers and four interfaces, the situation is correspondingly more complicated.) The wavefronts can mutually interfere, such that the power transmission T through the single membrane is for normal incidence,

$$T = \frac{(1-r^2)^2}{(1-r^2)^2 + 4r^2 \sin^2\rho} \tag{9}$$

where ρ the phase thickness of the membrane at that λ_o,

$$\rho = 2\pi tn/\lambda_o \ . \tag{10}$$

Referring again to the "reflection" component shown in Figure 10, we see that the membrane designer can in principle try to minimize the change in dielectric constant at the interface so as to reduce the reflection coefficient r and hence the amplitude of the "channel spectrum", Also, he can vary the electrical thickness n•t of the membrane so as to match the resonances of the channel spectrum to the frequencies of telluric absorption of the atmosphere. In practice, the optimization of radome membranes requires sandwiches of different kinds of materials, as was done for the ESSCOLAM V (ESSCO-laminate) used for illustration in Figure 10. Because of the increased number of internal reflections for these membranes, the equations describing their transmission are considerably more complicated than Equation 9. These equations show that there are fundamental limits to membrane transmission which cannot be overcome easily.

In principle, the designer could move the first resonance of the channel spectrum to higher frequency by decreasing the membrane thickness. Figure 11 gives an example of this effect; it shows the RF transmission of dacron sailcloth. Here the thickness is 1/6 that of ESSCOLAM V, and the frequency of the first reflection has been correspondingly increased as described by Equations 9 and 10. Furthermore, the loss tangent is negligibly small.

Practical considerations provide the ultimate limitations to the membrane design, however. The material must withstand long exposure to the elements, which sailcloth cannot do. The surface must shed water quickly, to preserve transmission properties through the radome in all directions. The material must be opaque to solar radiation, which sailcloth is not. And, the material must be mechanically strong enough to survive large wind forces.

Both the National Physical Laboratory in England and the NRAO have investigated the transmission of a large number of radome membranes.

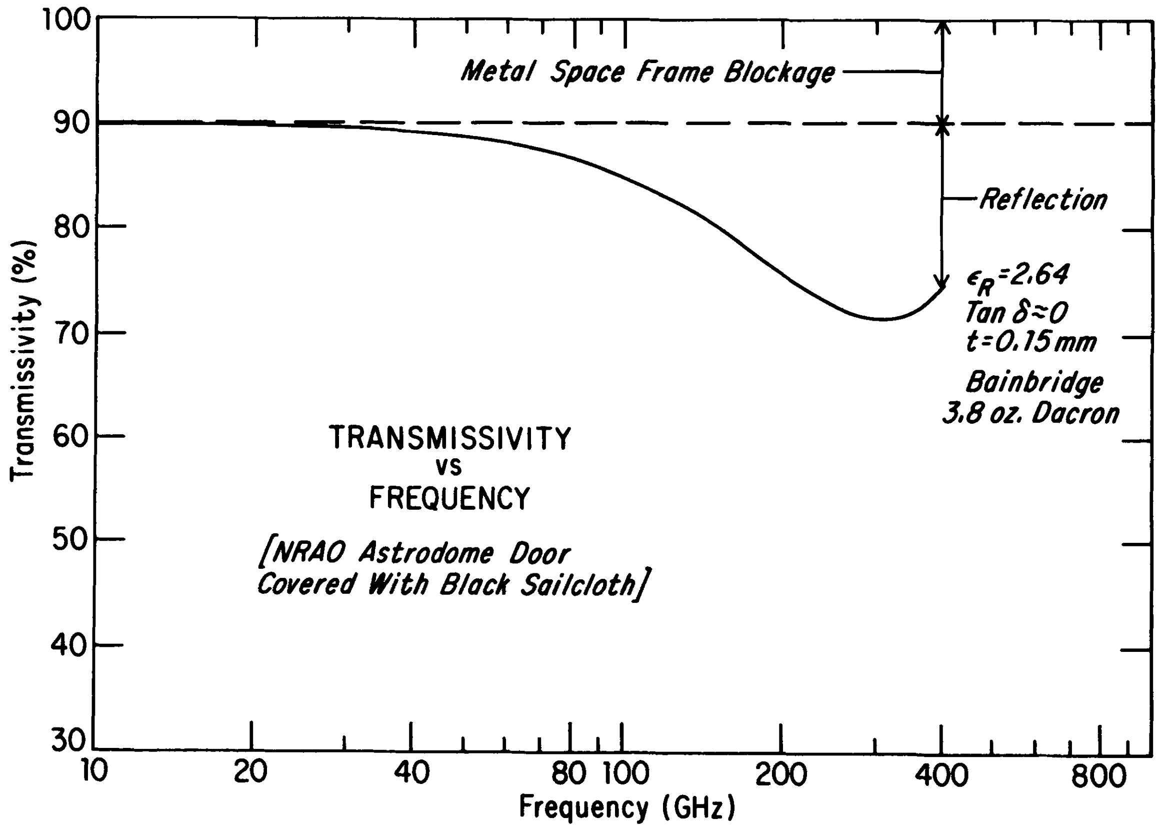

Figure 11. Hypothetical transmission of a radome covered with dacron sailcloth.

Many of these are excellent at frequencies below 300 GHz. But, we have found no material which does not compromise the frequency response of the 25-m telescope to some extent. For example, the telluric absorption features due to water vapor and oxygen are not harmonically related; therefore we cannot find a membrane with reflection resonances at these exact frequencies (see Equation 10). The telescope will be a useful instrument, under certain thermal conditions, to 640 μm and shorter. Yet, the best available radome membranes, such as shown in Figure 10, do not transmit well in that region.

There is another possible disadvantage of a radome; it can act as a lens at very short wavelengths. Although not having an optimum space frame, the 36-ft transparent astrodome is a valuable test facility. We can compare observations taken through its open slit with those taken through its transparent wall. These observations, shown in Figure 12, give the ratio of astrodome transmission for observations of a point source to transmission for observations of an extended source. The point source emits plane wavefronts from a spot of angular extent much less

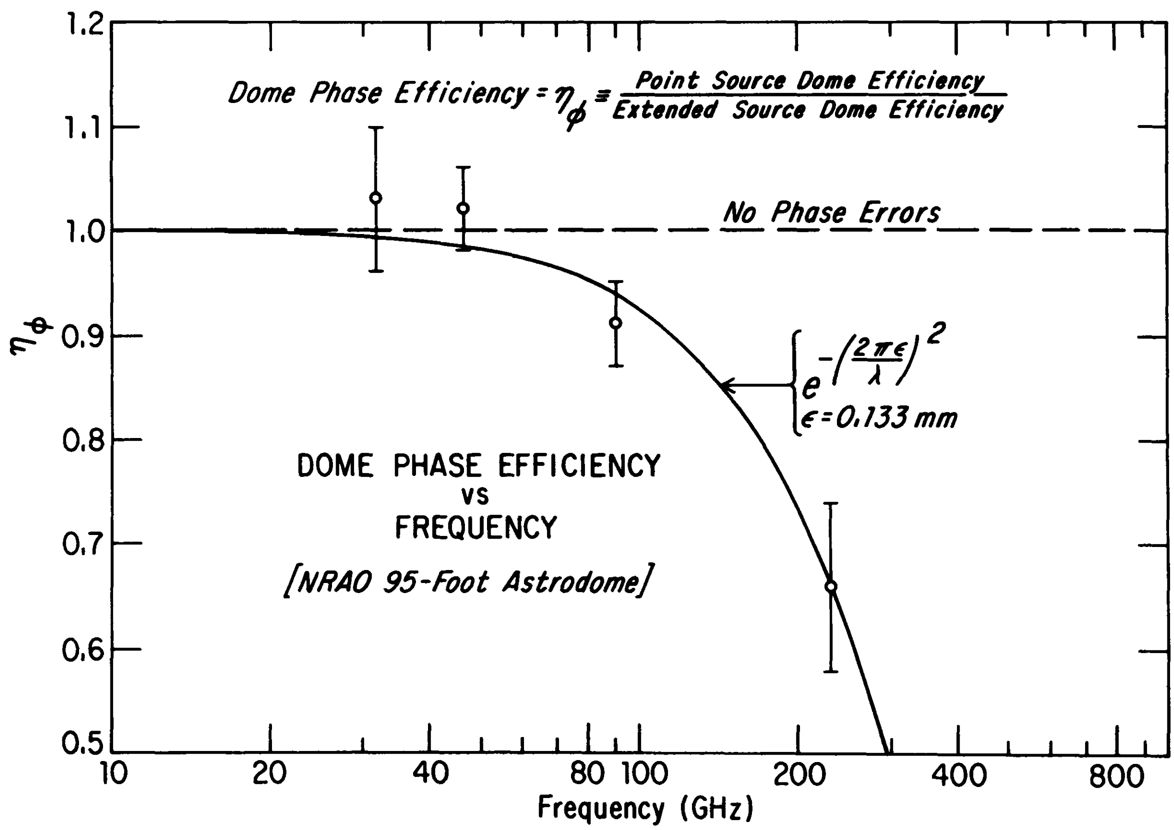

Figure 12. Phase efficiency of the NRAO astrodome at Kitt Peak.

than the beam. The extended source can be modeled as a continuum of point sources, collectively having an angular extent much larger than the beam. A logical explanation for the decrease of the "point source efficiency" relative to the "extended source efficiency" toward high frequencies is that the radome is acting as an imperfect lens. Had it acted as a normal lens, its effect could have been largely overcome by refocussing the telescope. In fact, the model of the imperfect lens fits the data well and is drawn as a solid curve in Figure 12. Whatever the explanation, the importance of these measurements is that the transparent walls of the Kitt Peak astrodome cause appreciable phase errors in incoming waves.

While it is certainly true that the space frame of the NRAO astrodome on Kitt Peak is not the quasi-random structure used for modern radomes, it is also true that very little research has been done on radome transmissivity at extremely high frequencies such as these. This lens-like characteristic of the NRAO astrodome on Kitt Peak could also apply to modern radomes.

C. THE ASTRODOME

Because we do not wish to restrict the short wavelength performance of the 25-m telescope in any way, we propose construction of a radome which can be opened: a steel astrodome with radome sections as shutters. While expensive, this approach gives us the full benefit of a radome at frequencies appropriate for it, without its potential liabilities at other frequencies.

An additional benefit of an astrodome is ease of thermal control. Unlike a radome, an astrodome permits the installation of large fans near the top and on the walls of the structure, as well as near the base. Fans distributed in this manner can minimize thermal gradients in the air surrounding the telescope surface.

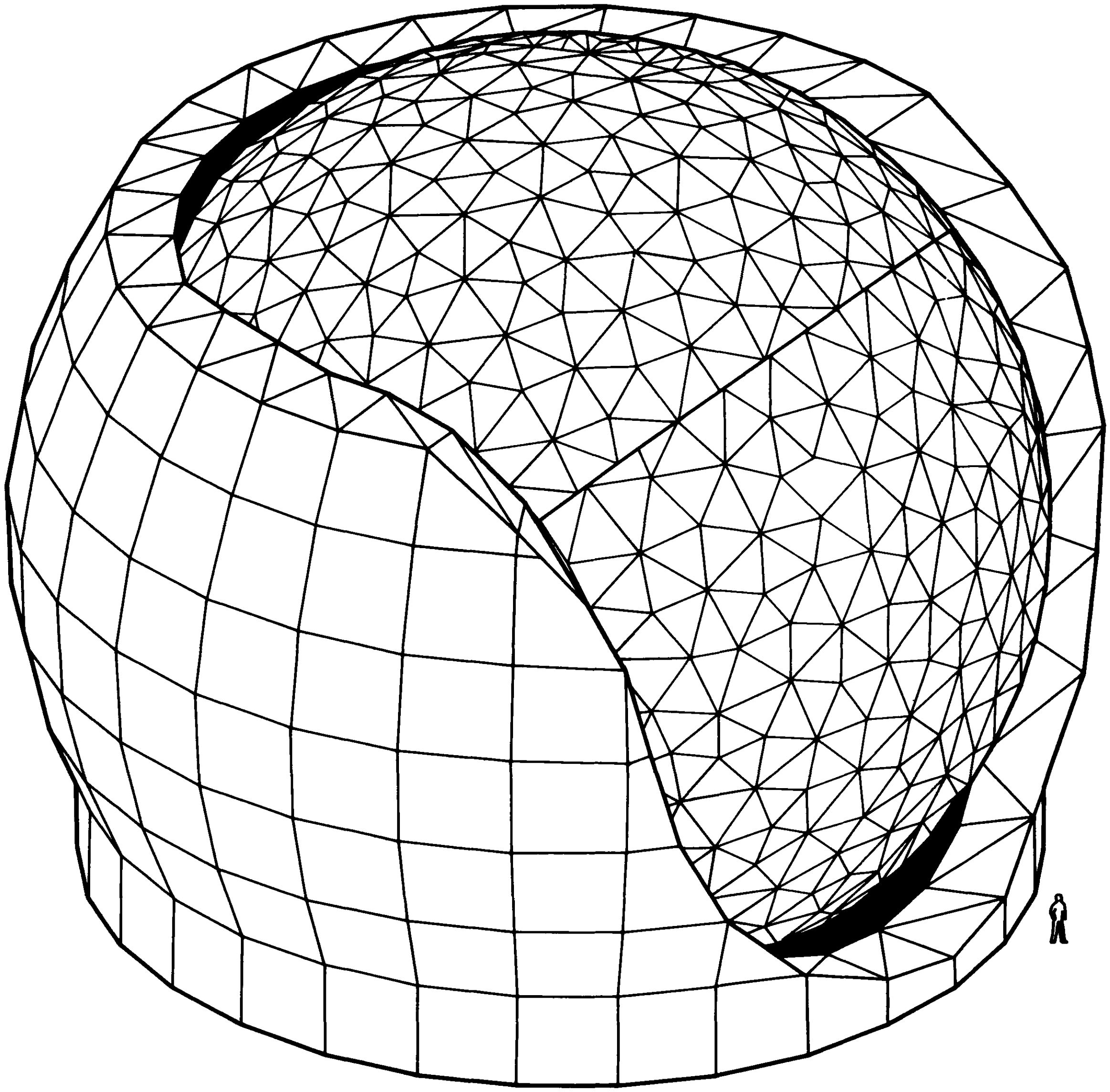

Figure 13. The astrodome with its radome segments closed.

Figure 13 shows the proposed astrodome with its radome segments closed. The frontispiece shows the astrodome with the segments open. Figure 14 use cross-sectional views to illustrate how the two segments store.

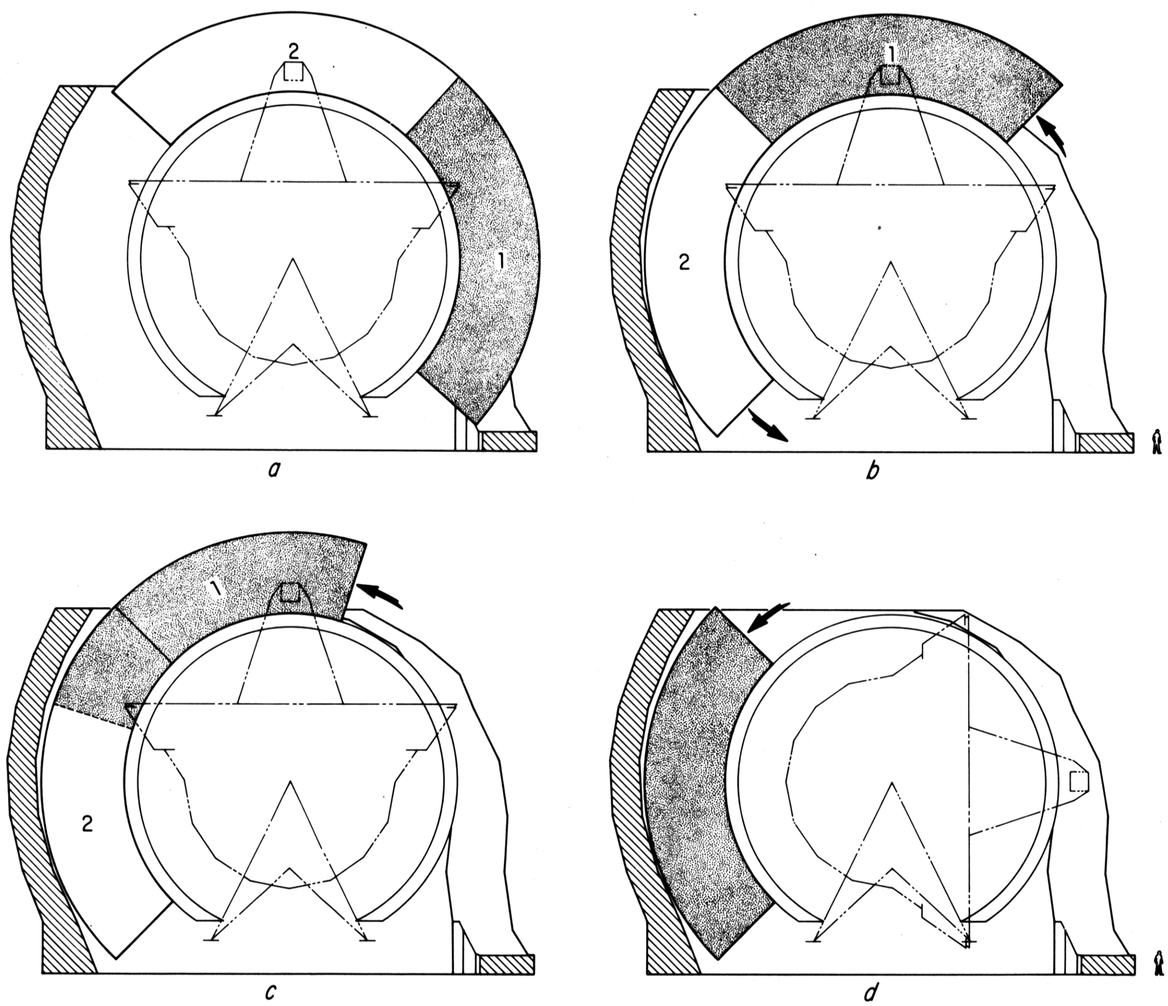

Figure 14. Astrodome operation. a. Both semgments closed. b,c,d, segments telescoping to the rear of the astrodome.

The design shown in Figure 13 is the result of extensive engineering design and structural analysis. The wall sections are sufficiently stiff to prevent jamming of the shutter sections during moderate to high winds. The astrodome walls are fabricated from approximately 636 metric tons of sheet steel. It will rotate on steel rails mounted upon a concrete pad. The over-all height is 33 m, the maximum diameter is 44 m, the diameter of the base is 36.5 m, and the door width is 27.3 m. The shutter segments will consist of a quasi-random space frame covered with the best available membrane available at the time of construction. The slew rate can be large enough so as to not restrict the access time of the telescope, as it moves from source to source.

The effect of a thermal gradient and varying air temperature upon the 25-m telescope in the astrodome has been analyzed.* Except for the two short periods near sunrise and sunset, the telescope should perform according to the calculations shown in Table 6. At the comparatively long wavelengths of 2 mm, observations can be made 100% of the time. At the design limit of 1.2 mm, observations can be made 80% of the time, the 20% accounting for fast temperature changes at sunrise and sunset. At shorter wavelengths, the situation is only slightly worse. During all of this time, the pointing will be adequate.

These calculations assume good mixing of air provided only by fans attached to the astrodome walls. In principle, we may be able to improve the performance of the telescope by actually ducting air to specific regions of the back structure. This approach should probably not be considered in detail, however, until we have actual experience with the operating telescope.

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* In the normal mode of operation, the door will be open during the night; during the day, depending on the observing wavelength and the ambient thermal conditions, the door may be closed.

In summary, we believe that the proper solution to the protective enclosure is the astrodome. We know of no inherent disadvantage to this design. Rather, the unrestricted transmission offered at short wavelengths is an important benefit, and justifies the greater cost.

CHAPTER VI

THE TELESCOPE SITE

A. INTRODUCTION

Three primary criteria were considered in the selection of the site for the 25-m telescope:

1. Low Atmospheric Water Vapor. As has been discussed in the preceding chapters, the absorption in the atmosphere and the associated contribution to the system temperature is the dominant effect during cloudy weather for observations at the relatively long wavelength of 3 mm. The magnitude of this effect increases at the shorter wavelengths where the 25-m will be expected to operate, as is shown in Figure 4. It is crucial therefore to locate the telescope at a site which has low water vapor and which is free from cloud cover a large part of the time. The water vapor criteria implies a high altitude site.

2. Low Geographic Latitude. Since a large part of the observing time will be spent on galactic problems--the Galactic center, galactic structure, molecular clouds--it is advantageous to locate the telescope at a low latitude, since the Galactic nucleus and the inner part of the Galaxy both lie below the celestial equator.

3. Ease of Access. Judging by the experience in operating the 36-ft telescope at Kitt Peak, reliable operation of the 25-m telescope will require the presence of a technical support staff (in addition to the telescope operator) on a day-to-day basis. To make this practical, the site should be no further away, in travel time, than one and one-half hours from the town in which the staff could live and in which a support laboratory might be located.

We have reviewed the sites discussed in the earlier report, and have considered an additional number of sites in the southwest

United States. We conclude that the site on Mauna Kea, Hawaii is the best site, and recommend that the telescope be placed there.

B. SELECTION OF THE SITE

Atmospheric water vapor is a major factor in the choice of a site for the 25-m telescope. At the writing of Volume I, the search had been restricted mainly to sites having in situ measurements of water vapor, preferably those made as parts of surveys which utilized infrared hygrometers. Because of calibration difficulties with these hygrometers, because the measurements were not made by the same individual, and because the periods sampled did not always overlap from one survey to the other, it is difficult to generate consistent quantitative estimates of the precipitable water vapor for the different sites.

To insure that no acceptable site would be overlooked, the search was extended to sites not included in the infrared or other water vapor surveys. Emile Blum of the Paris Observatory pointed out that, over a long time-base, the infrared measurements made in situ correlated well with predictions of water vapor made from the national grid of radiosonde probes routinely carried out by the National Oceanic and Atmospheric Administration. By making use of radiosonde data, therefore, sites could be considered even though detailed infrared observations are not available for them.

The global distribution of water vapor is fairly well known, at least for the northern hemisphere (Gringorten et al. 1966). Atmospheric water vapor decreases with increasing altitude and with increasing latitude. Typically, the scale height of atmospheric water vapor is 1.6 km. But, regional terrain and circulation can impose appreciable perturbations upon the general global patterns.

During most of the year, the winds of the southwestern United States are predominantly westerly and dry, leaving much of their moisture on the western slopes of the coastal and Sierra Nevada mountain ranges. As it flows over those ranges, the damp oceanic air cools below the dew point as it is lifted in altitude. Consequently, arid regions, such as the Owens Valley, the Mohave and Sonoran Deserts, and southwestern Nevada, lie downwind of the mountains. The cloud-cover data presented in Figure 15 shows this effect clearly. The absence of clouds is by itself advantageous, because cumulus and stratiform clouds are generally opaque to millimeter-wave radiation.

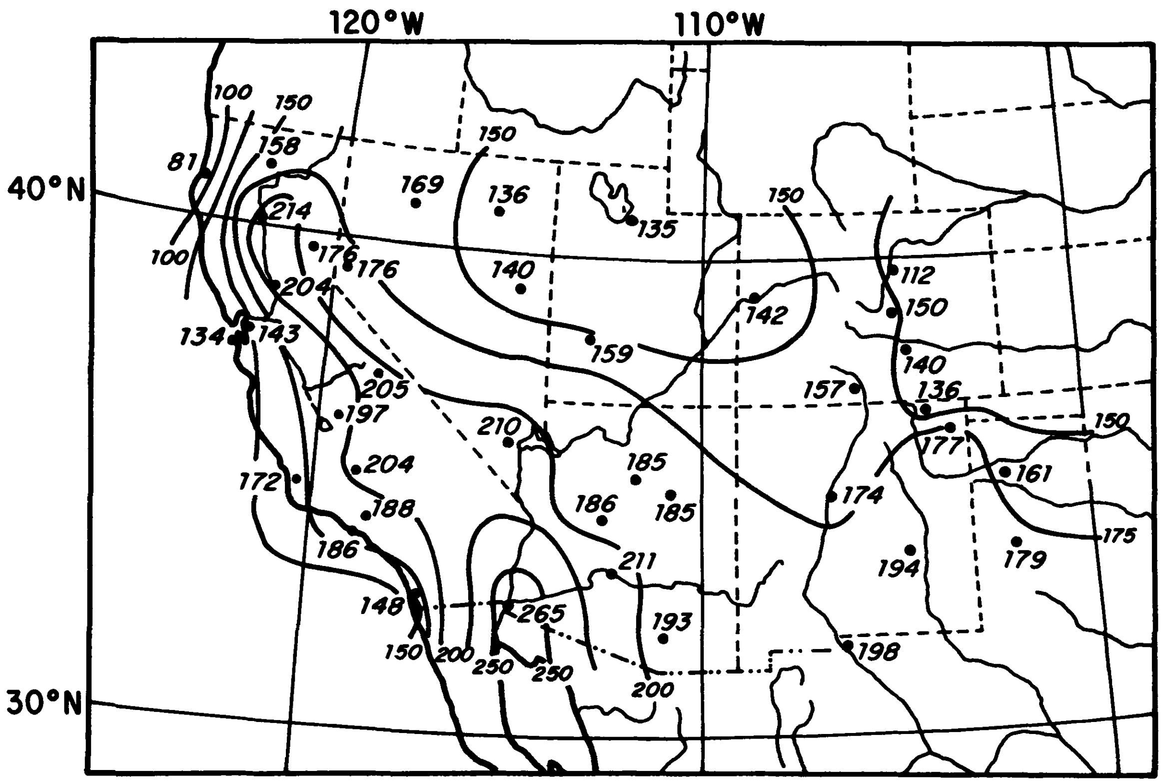


Figure 15. Mean annual number of clear days for 39 southwestern Weather Bureau stations. Here a "clear" day is one with 0-3 tenths mean sky cover (McDonald, 1958).

In summer, the situation is different. Southeasterly winds bring moist air from the Gulf of Mexico into the dry corridor, a situation occurring generally during July and August.

The expanded site search made use of these regional characteristics. Topographic maps of the American Southwest were examined systematically for locations meeting the following criteria:

(a) Latitude <37° N. More northerly sites tend to be cloudier (see Figure 15), and would unduly restrict observing at southerly declinations.

(b) Longitude >110° W. There are frequent incursions of wet air from the Gulf of Mexico to the east of this limit. Such incursions rarely penetrate west of the Colorado River.

(c) Elevation >2750 m (9000 ft) above sea level. Lower elevations are unlikely to be greatly superior to Kitt Peak from the standpoint of water vapor.

(d) Within 80 air kilometers (50 miles) of an established community which could serve as a base for the observing station. Ground travel time would necessarily be excessive for more remote sites.

The map search turned up several sites which had not been considered previously, owing to the lack of direct water vapor measurements. The more promising of these sites were visited by members of the Working Group. Consideration was also given to sites which were suggested by individual scientists.

There are a number of sites in the continental United States which meet the criteria of water vapor and cloud cover. Most are of high elevation, and are remote; many would be expensive to develop. None of these sites lies below latitude 30°. In contrast, Mauna Kea offers a site having significantly lower latitude, while remaining comparable with the best continental sites in terms of water vapor, cloud cover, and ease of access. We conclude therefore that the 25-m telescope should be built on Mauna Kea.

It is perhaps useful to describe in more detail the advantages that the southerly latitude provide. First, the most southerly declination of the Galactic plane is -62°; the Mauna Kea site thus enables the entire plane to be observed, albeit at low elevation for the southernmost portions. Second, the Galactic center and the inner regions of the Galaxy transit at higher elevations for the Mauna Kea site, which means lower atmospheric extinction at transit and an increase in the length of time during which the source may be observed. The Galactic center, as an example, is above elevation 10° for an hour and a half longer each day than it is for the 36-ft at Kitt Peak. Finally, 91% of the astronomical sky may be observed from Mauna Kea, in contrast with the 84% available from Kitt Peak.

An additional advantage of Mauna Kea over sites in the Southwest stems from the weather pattern. In the Southwest, the wettest period of the year occurs during the summer, when the galactic center transits at night. At Mauna Kea, the best weather occurs during spring and summer, the optimum season for galactic astronomy.

We recognize that construction of the 25-m telescope on Mauna Kea will be more expensive than on a well-developed mainland site, such as Kitt Peak. However, much of the differential construction costs will obtain for suitable high-altitude mainland sites as well. For a remote mainland site such as White Mountain, where extensive site development would probably be required, the construction cost is likely to be comparable with that of Mauna Kea.

There are some additional burdens in operating at Mauna Kea. Observers will have a significantly longer journey, the salaries of the resident staff will be higher, and certain materials, goods, and services will be expensive. Thus the annual cost at Mauna Kea will be approximately 40% greater than that at Kitt Peak; the cost of a high altitude site such as White Mountain will be somewhere between these two extremes. However, we conclude that the excellence of the Mauna Kea site warrants the additional operating expense.

C. MAUNA KEA

The excellence of the night sky above Mauna Kea and its remoteness from city lights and industrial pollution make it a superb site for an optical observatory. The Institute for Astronomy of the University of Hawaii has operated a 2.2-m telescope on Mauna Kea since 1970. There are also two 61-cm telescopes. The 3.6-m Canada-France-Hawaii telescope is nearing completion. Construction has started on two large infrared telescopes: the NASA 3-m and the United Kingdom 3.8-m. Clearly, Mauna Kea is becoming a major center for astronomy.

Mauna Kea is the highest of the five large volcanoes which have coalesced to form the island of Hawaii. It is dormant, and perhaps extinct; the geological evidence indicates that the last eruption took place between 2000 and 4000 years ago (Macdonald and Abbott, 1970). As for the other volcanoes, Kohala has long been extinct, Hualalai last erupted in 1801, while Mauna Loa and Kilauea have erupted frequently since 1800.

Some of the relevant features of the island of Hawaii are shown in Figure 16. The positions and elevations of the volcanoes are indicated. The locations of major towns and the principal roads are shown also. To the northwest are part of the island of Maui and the uninhabited island of Kahoolawe.

Figure 17 shows the south slope of Mauna Kea from the Humuula Saddle (where it meets the north slope of Mauna Loa) to the summit. The Saddle Road connects Hilo and Waimea. The road distances from the Mauna Kea turnoff are 28 miles to Hilo and 32 miles to Waimea. The distances from the turnoff to Hale Pohaku and to the proposed site for the 25-m telescope are respectively 6 and 14 miles. Hale Pohaku, originally

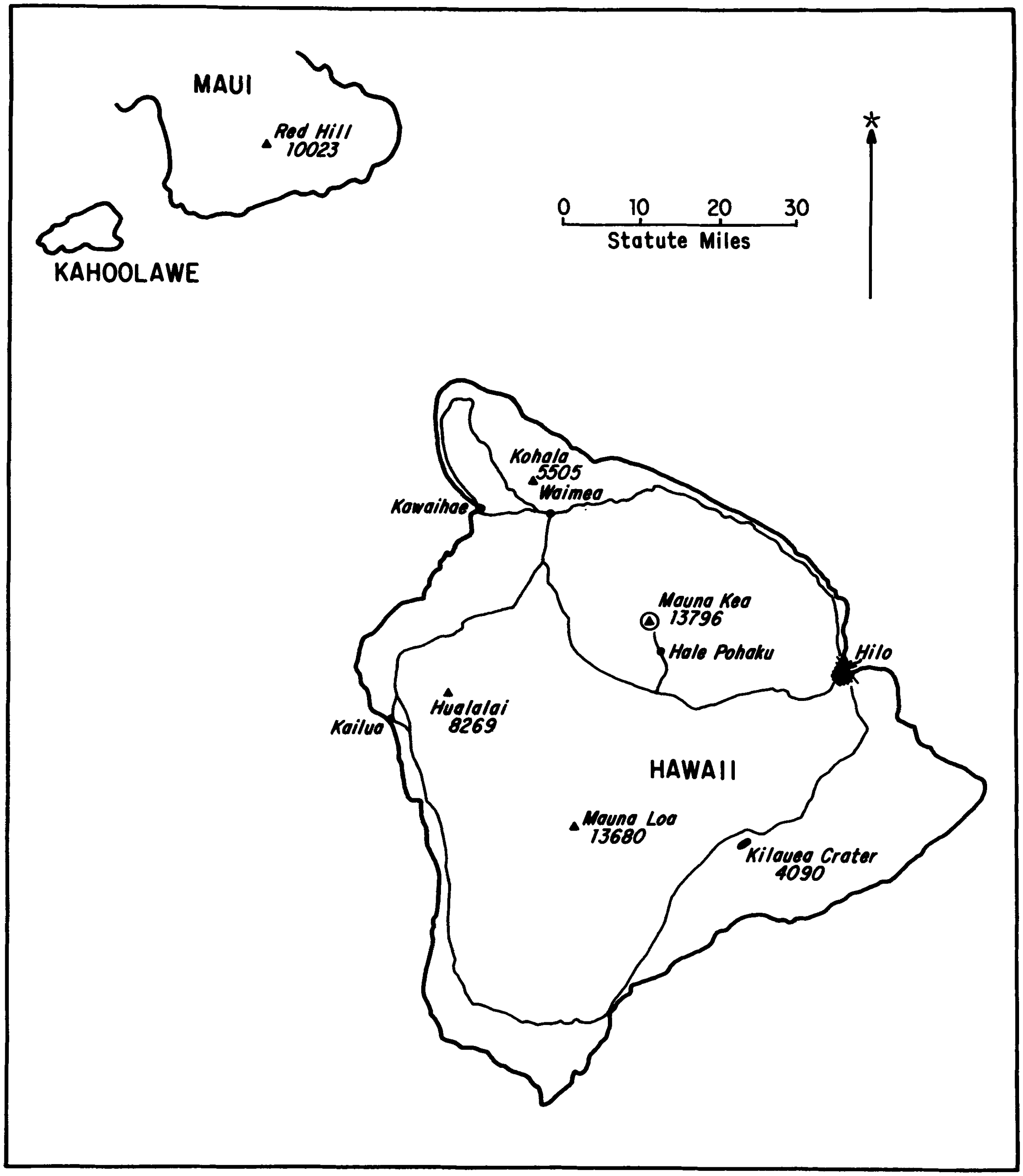


Figure 16. The Island of Hawaii. The indicated altitudes are in units of feet above sea level.

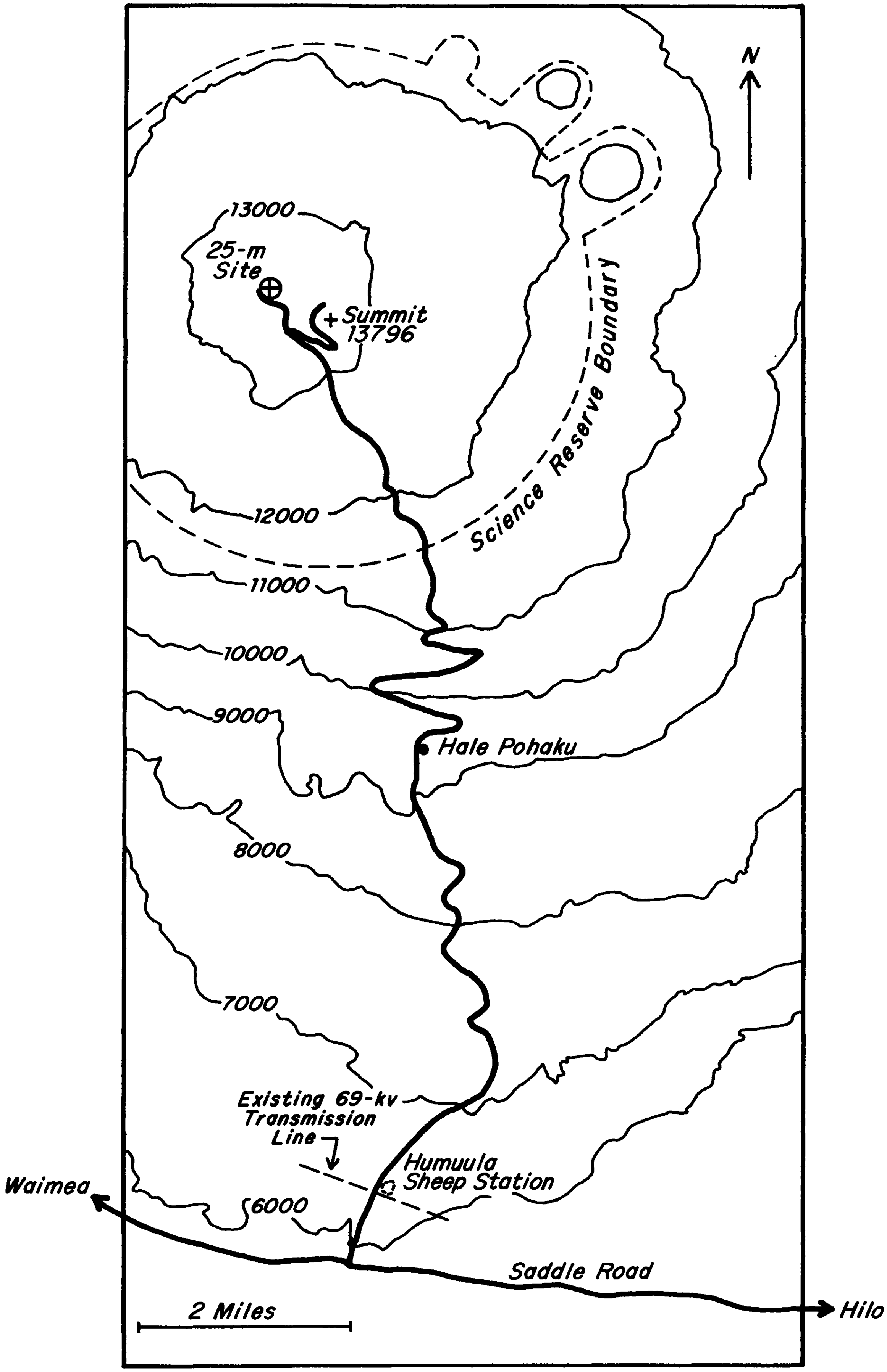


Figure 17. The south slope of Mauna Kea. Altitudes are in units of feet.

a ranger station, is a modest collection of mostly temporary buildings which serve as a mid-level base for the observatories and for the contractors working at the summit. The present facilities are minimal. The summit area, including all of the ground above 12000 feet, is in a dedicated "Science Reserve" administered by the University of Hawaii under a long-term lease from the State. The road up the mountain is quite good. It is paved as far as Hale Pohaku. It is in effect graded cinder from there to the top, since the light paving put down early last year soon broke up under the heavy truck traffic.

The summit is shown in Figure 18, which includes an area of about 4 square miles. A circled cross marks what we believe to be the best location for the 25-m telescope. The optical telescopes are all on the cresent-shaped summit ridge, which consists of several coalasced cinder cones. To the left is Puu Poliahu, which was earlier thought to be a good place for the telescope. The road to its top was made for Kuiper's original site tests in 1963. The beautifully symmetrical cone at the bottom of the map is Puu Kau Kea (also called Goodrich Cone), which is off limits for development.

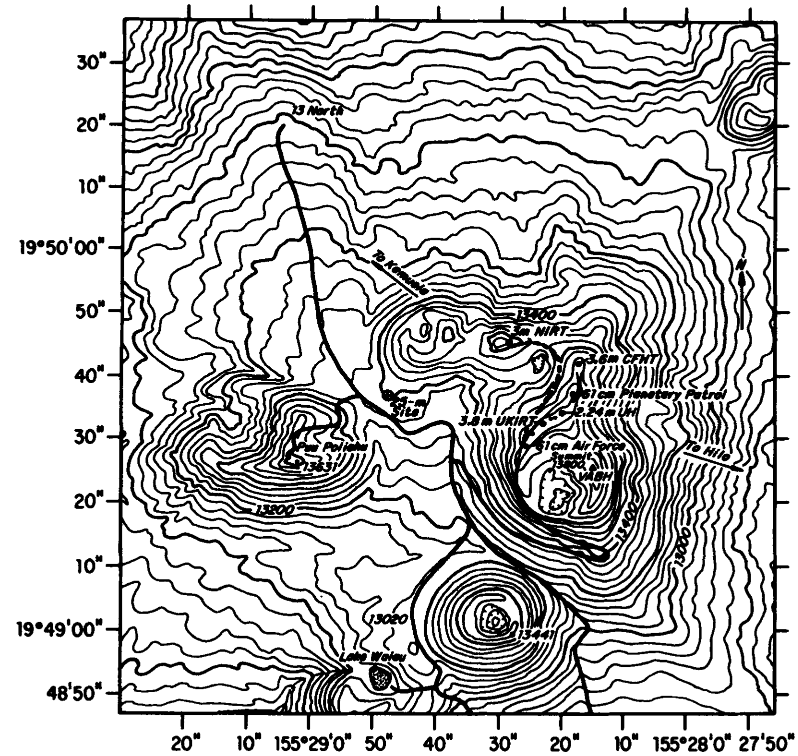
The site chosen for the 25-m telescope lies on the 13400-ft contour. Its geographic coordinates are:

latitude: 19° 49' 37" N
longitude: 155° 28' 48" W

The primary reason for this location is that the summit ridge gives it considerable protection from the prevailing tradewinds, which come from northeast to east. This should allow more observing time with the dome open. The location has important subsidiary advantages as well:

(1) The dome should be invisible from every inhabited part of the island. The importance of this is discussed later.

(2) There is no serious sky blockage by the terrain. The highest horizon, at elevation 9°, is to the northeast. Puu Poliahu to the



LEGEND

19°49'37" N 155°28'18" W	61 cm Planetary Patrol
19°49'34" N 155°28'20" W	2.24 m Telescope
19°49'29" N 155°28'26" W	61 cm Air Force

1" LATITUDE = 100 FT.
1" LONGITUDE = 95 FT.
Rev. 5/12/74
Redrawn By NRAO 5/17/77

0 500 1000
FEET
Contour Interval 40'

TOPOGRAPHIC MAP OF MAUNA KEA SUMMIT
COURTESY OF UNIVERSITY OF HAWAII
INSTITUTE FOR ASTRONOMY
MAUNA KEA OBSERVATORY

Table 18. Topographic map--Mauna Kea summit. Altitudes are marked in feet.

southwest rises less than 8°. The southern horizon is perfectly clear (the site is about level with the top of Puu Hau Kea).

(3) An existing road, which would need little improvement, passes within 300 feet.

(4) Although the ground is covered by loose cinder, it probably is underlain at shallow depth by the massive flows which outcrop nearby. Test boring will show whether this is the case, and if so whether the lava has sufficient thickness and strength to carry the foundations. The foundations otherwise must be designed to "float" in the cinder, like those for the optical telescopes.

(5) The site is well removed from other activity on the mountain, existing or proposed.

(6) There is no need for a steep stretch in the access road, as there would be were the telescope put on Puu Poliahu or on the summit ridge. Thus the access is less subject to interference from snow. The summit ridge is unreachable for several days each winter because of heavy snow on the steep final section of the road.

The cloud cover on Mauna Kea has a dominant diurnal component and a much weaker seasonal component. Of primary concern are water clouds, not cirrus. This is helpful, since over half of the time lost to clouds by optical and infrared observers on Mauna Kea is due to cirrus. The most serious cloud problem for us is the regular afternoon buildup. The mountain rises well above the normal inversion layer, which usually lies at approximately 8000 ft. By noon this inversion layer breaks up, thereby permitting clouds to rise toward the mountain summit. Approximately two-thirds of the afternoons between 2 to 6 P.M. are cloudy at the summit, according to Morrison et al. (1973). By sunset, strong downslope winds, generated by rapid cooling, push these clouds down the slope. Thus the major portion of the days are free from wet clouds, other days are completely clear.

Clouds occur at night relatively infrequently. Through the courtesy of John Jefferies, we have been given copies of the monthly time-lost reports for 31 consecutive months (March 1974 through September 1976). These show that nighttime observers lost an average of 41 hours per month (out of an average of 360 scheduled) to cirrus, and 30 hours per month to other clouds or fog. The latter component shows an appreciable seasonal variation--an average of 16 hours per month during May to October, and an average of 46 hours per month during November to April.

It appears therefore that while the latter part of many afternoons may be cloudy, clear weather could be expected for about 90% of the remaining time since night sky conditions tend to persist until late morning.

The precipitable water vapor above Mauna Kea certainly is low, as one would expect for such a high site. Just how low, unfortunately, is rather uncertain. On the basis of mean radiosonde data, Kuiper (1970) estimated values of the 5 and 50 percentile levels of W_v for a large number of places, including Mauna Kea. For Mauna Kea, the median value through the year (there is little seasonal difference) is 1.9 mm*. Daytime measurements with Westphal's infrared hygrometer during the year ending 1 July 1972 gave a median of 1.2 mm and a 25th percentile of 0.7 mm (corrected to ambient pressure).** Nighttime 8-25 micron

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* Kuiper's figures are based on data from Gringorten et al. (1966), which in turn rests on radiosonde measurements during 1962-1966 inclusive. We have analyzed monthly mean radiosonde data from Hilo for the 1966-1971 period. We find a 12-month mean value of 2.2 mm for W_v at the level of Mauna Kea. This is perfectly consistent with Kuiper's median of 1.9 mm. We also agree with Kuiper that there is little seasonal variation of W_v.

** These numbers are taken from Morrison et al. (1973), who give a detailed histogram of the value of W_v measured by Westphal (1974). Using the data from the same Westphal report, we get a much broader histogram and a corrected median W_v of 2.6 mm. We have no explanation for the discrepancy.

spectral measurements of the moon and Mars, during July to September 1971, are best matched by synthetic spectra calculated for $W_V = 0.5$ mm (see Morrison et al. 1973). Dyck and Simon (1975) measured an average W_V of 0.5 mm at 33 microns, and they state that a lower value would be expected on about 25% of the photometrically clear nights. There is of course a tendency for all of these values except Kuiper's to be biased toward better than average conditions because they follow from measurements which necessarily were made in good weather.

There are two communities where we might reasonably put the Observatory offices and laboratory. The most obvious is Hilo, the largest city on the island (population 26353 in the 1970 census). Hilo has direct air service several times daily from the mainland as well as from Honolulu and other places in the islands. It has most of the "urban amenities" to be found on the island. It is one of the two places with port facilities (the other is Kawaihae, on the west side of the island). It probably could absorb 35 new families without great strain. However, it has a very wet climate, with an average annual rainfall of 137 inches.

The other possibility is Waimea (also called Kamuela), in the saddle between Mauna Kea and Kohala. It is a small community of a few hundred people. The headquarters of the Parker Ranch, which owns much of the northern part of the island, are located here. Waimea is 2700 feet above sea level and has a much less rainy climate than Hilo. The surrounding country is rolling grassland with plenty of big trees, reminiscent of parts of northern Arizona. It is about 15 miles by road to the Kona coast, where the island's best beaches are. Inter-island air service is available at Kamuela airport, about 2 miles south of town. Waimea is 60 miles by road from Hilo, where the main shopping and medical facilities on the island are located. It is nearly 40 miles to Kailua, which probably will rival Hilo in a few years. Not many houses are available, although plenty of homesites are to be had.

The travel time to the Mauna Kea summit is about one and one-half hours from either Waimea or Hilo in good weather, if no acclimatization stop is made at Hale Pohaku.

Residents of the island have expressed considerable concern about further development on Mauna Kea. For example, the local chapter of the Audubon Society and the sheep hunters are both interested in the preservation of the existing environment. They have had some support from a larger body of people who are uneasy about future development for more diffuse reasons. Many, for example, are understandably disturbed by the high visibility of the domes on Mauna Kea. An important advantage of the proposed site is that the dome will not be visible from the communities below.

In an attempt to provide for a controlled and orderly development of the summit of Mauna Kea, a Master Plan for the mountain has recently been approved by the State. This plan does permit the possibility of putting a new telescope on Mauna Kea, by making application to the State of Hawaii. Each application will be reviewed on a case-by-case basis, and the need for access to Mauna Kea will have to be clearly demonstrated.

D. COMPENSATION FOR ALTITUDE

At the 4300-m altitude of Mauna Kea, the air is thin. Many observers accustomed to living and working at lower altitudes find it difficult to work efficiently at the summit at first. While acclimatization is not a problem for most people in good health, the process may require several days.

The system now in use by the University of Hawaii involves time. New observers arrive at the midway station of Hale Pohaku a few days before beginning observing. The sojourn at this 9000-ft station is adequate to acclimate most observers. Although the 2.2-m telescope was designed with provision for increasing the partial pressure of oxygen within the building, it was never put into service. The maintenance crew, as well as the construction crews for the telescopes now under construction, do not use supplementary oxygen. Nor do the skiers, who also use the summit area during the winter. But, the situation is most critical for sleeping.

Because the 25-m telescope will be operated in a manner similar to that of Kitt Peak, it will be advantageous to enrich the oxygen supply in the control room and in the sleeping quarters. At Kitt Peak, observers usually begin observing on the day they arrive. This system would allow no time for acclimatization. Our present plan is to pressurize a modest room containing the controls for the telescope and receivers, and also containing several pipe beds of the kind often used on ships. While ingress and egress to the room will be made via airlocks, the degree of pressurization will be modest, probably only to an equivalent altitude of 10,000 ft.

E. ADMINISTRATIVE ARRANGEMENTS

Discussions with representatives of the University of Hawaii have included our relationship to other institutions with telescopes on Mauna Kea. On the mountain it may be possible to share responsibility for road maintenance, for water, for electricity, and for heavy equipment such as cranes, etc. For reasons of economy and technical stimulation, the NRAO is interested in participating with other observatories in Hawaii in a common "sea-level" location. This might comprise a cluster of small buildings on the outskirts of the same town, each building housing the offices and the support crew for a given astronomical organization. Common facilities, such as the library, machine shop, and transportation system to and from Mauna Kea, could be shared.

CHAPTER VII

COSTS

A. METHOD OF CALCULATION

The two sets of cost figures relevant to this project might be classified as construction (non-recurring) and operation (recurring). Although Volume I discussed these in some detail, the evolution of the 25-m project over the two intervening years has required further analysis.

The cost estimates presented in the following tables have been prepared based on experience gained in operating the 36-ft and on recent construction costs on Mauna Kea. The costs are made with respect to the reference year of 1976, and must be adjusted for inflation to be applicable to future years.

B. NON-RECURRING COSTS

Table 8 is a summary of design and construction costs based upon our engineering studies and actual contracts experienced by NASA in construction of their infrared telescope upon Mauna Kea. Further refinement of these numbers must await completion of the detailed design. Note that no provision is made for receivers, which historically are funded from the annual operating budget of the NRAO.

Table 8. Summary of Non-Recurring Costs
(thousands of dollars)

Item	Cost
1. Design	$ 1138
2. Telescope (Installed)	4130
3. Astrodome (Installed)	4051
4. Site Facilities	1752
5. Computer Control and Data Systems	331
Subtotal	$11402
10% Contingency	1140
Total	$12542

Each of the number items in Table 8 is itemized in detail in the following tables. The design costs are assumed to be 12% of the capital costs. The building costs include an allowance for "sea-level" facilities.

Table 9. Design Costs
(thousands of 1976 dollars)

Item	Cost
A. Telescope	$ 477
B. Astrodome	467
C. Site Buildings	159
D. Survey and Soil Tests	35
Total	$1138

Table 10. Telescope Installed
(thousands of dollars)

Item	Cost
A. Surface Plates	$ 1371
B. Intermediate Panels	304
C. Feed Support	78
D. Subreflector	46
E. Backup Structure	503
F. Counterweights	43
G. Bearings and Drive	461
H. Servo	257
I. Tower Structure	242
J. Foundation and Track	288
K. Ladder and Walkway	33
L. Control Cabling	55
M. Painting	72
N. Final Setting System	85
O. Freight	35
P. Cabling and Electronic Interface	170
Q. Voice-Keyed Intercom	10
R. Boresight Telescope	1
S. Visitor Area	5
T. Construction Worker Subsistence	165
U. Construction Worker Overtime	262
V. High Altitude Labor Efficiency Cost	121
Subtotal	$4607
Less Design Cost	(477)
Total	$4130

The construction worker subsistence, overtime, and labor efficiency have been based upon actual experience at the Mauna Kea summit.

Table 11. Astrodome Installed
(thousands of dollars)

Item	Cost
A. Astrodome Structure and Drive System...........	$2310
B. Door Structure and Drive System................	382
C. Door Covering..................................	550
D. Foundation and Floor...........................	413
E. Crane..	30
F. Air Handling System............................	350
G. Freight..	94
H. Construction Worker Subsistence................	117
I. Construction Worker Overtime...................	186
J. High Altitude Labor Efficiency Cost............	86
Subtotal..................	$4518
Less Design Cost..........	(467)
Total.....................	$4051

The crane is an internal one needed to mount receiver boxes. The air handling system consists of large fans which maintain an isothermal environment within the astrodome.

Table 12. Site Facilities
(thousands of 1976 dollars)

Item	Cost
A. Water System..................................	$ 66
B., Grading, Waste Disposal.....................	38
C. Electrical System } D. Standby Generators }......................	250
E. Access Roads.................................	40
F. Telephone Link...............................	15
G. Dormitory, Laboratory Offices, Control Room..	1287
H. Temporary Construction Offices...............	15
I. Office and Lab Equipment, Tools, Furniture, and Library (Including Freight)...........	110
J. Halon Fire System............................	12
K. Receiver Weigh Station.......................	3
L. Uninterruptable Power Supply (UPS)...........	75
Subtotal..............	$1911
Less Building Design..	(159)
Total.................	$1752

Table 13. Computer Control and Data System
(thousands of dollars)

Item	Cost
A. Card Reader	$ 6
B. Line Printer	9
C. 3 9-Track Tape Drives	39
D. 2 7-Track Tape Drives	29
E. 3 DDP 11/45 Main Frames	152
F. 3 Tektronix Graphic Materials	17
G. 3 Tektronix Hard Copy Units	13
H. 3 Tektronix Interfaces	10
I. 6 Disk Units	54
J. 1 Video Terminal and Interface	2
Total	$331

This computer system differs from the one described in Volume I. It consists of three identical computers. One controls the telescope and acquires the data, the second permits the astronomer to evaluate the observations and serve as a backup to the control computer, and the third is located at the sea-level facility for program development and electronic testing. Because of the rapid evolution of computer systems, it is likely that the configuration will change again by the time of construction.

C. RECURRING COSTS

The operation on Mauna Kea will be similar to the one on Kitt Peak. The recurring costs result from application of this model. For comparison the actual costs and personnel levels at our 36-ft telescope are included.

Table 14. Employees Planned for Telescope Operation

Position	Present 36-ft Telescope Staff	25-m Telescope Mauna Kea, HI
Director....................	1	1
Electronics Head...........	1	1
Telescope Operations Head..	1	1
Business Manager...........	1	1
Programmer.................	1	1
Electronic Engineer........	5	5
Mechanical Engineer........	1	1
Buyer-Accountant...........	0	1
Chief Telescope Operator...	1	1
Telescope Operators........	5	5
Technicians................	4	4
Maintenance Technician.....	1	2
Janitor....................	0.5	1
Shipping and Receiving.....	1	1
Secretary..................	1	1
Total..........	24.5	27

For the staff listed in Table 14, and assuming the 12.5% salary bonus now allotted Civil Service employees stationed in Hawaii and a continuation of the present mode of operating, the operating costs are shown in Table 15.

Table 15. Annual Recurring Expenses
(thousands of dollars)

Category	1976 Kitt Peak Actuals	25-m Telescope Mauna Kea, HI
1. Salaries and Fringe Benfits...	$463	$521
2. Employee Travel...............	32	51
3. Observer Travel...............	11	78
4. Freight.......................	6	38
5. Vehicle Expense...............	19	21
6. Electricity...................	11	94
7. Telephone.....................	13	106
8. Library.......................	3	5
9. Road Maintenance..............	0	18
10. Oxygen and Pressurization.....	0	3
11. Rent..........................	25	5
12. Water.........................	2	4
13. Electronic Supplies...........	218	261
14. Operating Supplies and Services..................	144	144
Total..	$947	$1349

The telephone costs will rise substantially because most sources of electronic supplies are located within the continental United States. At present, the Federal Telephone System (FTS) charges $1/minute for a call from Hawaii to California. Also, this plan assumes that generators will produce electricity at the summit location. Should commercial power be extended to the summit, the cost of electricity should decrease sharply.

CHAPTER VIII

CONSTRUCTION SCHEDULE

To better evaluate the time scales and detailed steps involved in construction of the telescope, the management program, Project Evaluation and Review Technique (PERT), has been used. As the detailed design work proceeds, the framework of this program will become increasingly fleshed out and, of course, revised. The following chart gives the general time scale for design and procurement, based upon a large condensation of the PERT analysis.

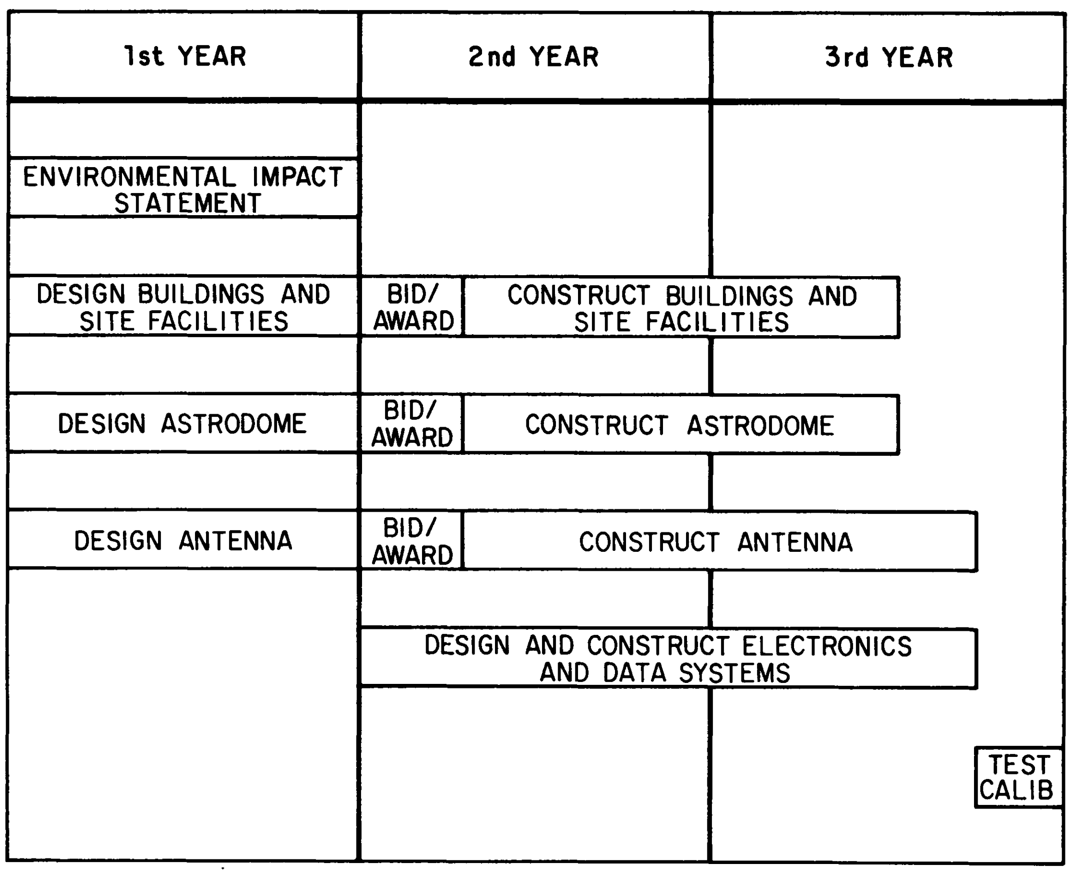

Figure 19. Activity estimated time required for design and construction.

REFERENCES

Cady, W. M., Karletiz, M. B., and Turner, L. A. (Editors) 1948, "Radar Scanners and Radomes", MIT Rad. Lab. Ser., 26 (New York: McGraw-Hill).

Dyck, M., and Simon, M. 1975, Ap. J., 195, 689.

Findlay, J. W., and Payne, J. M. 1974, IEEE Trans. Instrumentation & Measurement, IM-23, 221-226.

Gringorten, I. I., Salmela, H. A., Solomon, I., and Sharp, J. 1966, "Atmospheric Humidity Atlas--Northern Hemisphere", AFCRL Report 66-621.

Kraus, J. D. 1966, Radio Astronomy (New York: McGraw-Hill), p. 2.

Kuiper, G. P. 1970, Comm. Lunar and Planetary Lab., No. 142.

Mcdonald, G. A., and Abbott, A. T. 1970, Volcanoes in the Sea, University Press of Hawaii.

McDonald, J. E. 1958, "Cloudiness over the Southwestern United States and Its Relation to Astronomical Observing", University of Arizona Institute of Atmospheric Physics, Scientific Report No. 7.

Morrison, D., Murphy, R. E., Cruikshank, D. P., Sinton, W. M., and Martin, T. Z. 1973, P.A.S.P., 85, 255.

Payne, J. M. 1973, Rev. Sci. Inst., 44, 304-306.

Payne, J. M., Hollis, J. M., Findlay, J. W. 1976, Rev. Sci. Inst., 47, 50-55.

Richards, P. L. 1975, "Far Infrared Applications of a Large Millimeter-Wave Telescope", Lawrence Berkeley Laboratory, Report 3983.

Ruze, J. 1952, MIT Research Laboratory of Electronics, Tech. Report 248.

Scott, P. F., and Ryle, M. 1977, Mon. Not. R. Astron. Soc., 178, 538-545.

von Hoerner, S. 1967, Astron. J., 72, 35.

______________. 1977, Vistas in Astronomy, in press.

Westphal, J. A. 1974, "Final Report on the 10-Micron Sky Noise Survey", California Inst. of Tech., Pasadena.

Zarghamee, M. S. 1967, IEEE Trans. Antennas and Prop., AP-15, 777.