CHAPTER IV

TELESCOPE SITES

1. Criteria for Site Selection

(a) A logical approach. There is a logical approach possible to the task of choosing the most suitable site for a radio telescope. This approach starts by defining criteria the site must meet. These criteria are often, for convenience, separated into two main classes--"primary" requirements which must be satisfied and "secondary" requirements, usually dealing more with practical matters of access, living conditions and so on, where adjustments can be made between the degrees to which the various requirements are met.

The various criteria can be assigned weights, expressed preferably in numbers. Then the site search locates those sites which rate highly according to the various criteria; number values are assigned to the degree of success various sites show in meeting the criteria and a final numerical mix of criteria weights and site scores gives the most desirable site.

The apparent certainty which such a process gives does, however, disguise its disadvantages. These are:

(i) Although it is easy to choose the primary and secondary criteria, to assign correct weights to them is often only a matter of judgment. In an expanding field of science it may be very difficult to make such a judgment with a high chance of its being correct.

(ii) Even when specific sites which look good are identified, the detailed information about them is often insufficient to allow of a reliable quantitative assessment being made of their relative goodness. And again, in a rapidly growing science, it may not be possible to devise site testing procedures which can make the site measurements which would be suitably definitive.

In the present site survey, therefore, although we shall use the framework of this approach, we shall not dignify it by the addition of a numerical system. We shall grade criteria in order, as far as we can, and give reasons for this ordering. We shall also attempt to put in some order the way in which sites meet the criteria.

(b) Primary site criteria. These criteria are all chosen because they affect the performance of the telescope as measured by its ability to make good observations, particularly at the short-wave end of the radio spectrum. We therefore adopt:

(i) Site latitude (A)*. There are no firm limits set for the latitude range in which the telescope should be placed, but the following reasons all argue strongly for a location as close to the equator as possible in view of other requirements.

- Many of the most interesting short-wave observations will be made on sources within our own galaxy; the galactic center is of particular importance. The further south the site is the better are such observations since the galaxy is seen higher in the sky and more of it is visible. (See paragraph 3(e) (ii) for a further note on the advantages of a site south of the equator.)
- Planetary observations also are better from sites near the equator, since planetary orbits lie near the plane of the ecliptic.
- A site fairly close to the equator has available to it a larger fraction of the total celestial sphere than can be observed from higher latitudes.

(ii) Freedom from clouds (A). Millimeter-wave observations can be seriously degraded by all kinds of cloud. This is a subject on which detailed quantitative experience is lacking, but experienced observers, using the NRAO 36-foot telescope on Kitt Peak, classify the absence of cloud as being of the highest importance in choosing a millimeter-wave telescope site.

In view of the fact that the telescope will work best at short wavelengths only at night, this criterion should be stated as:

- The site should have the maximum possible number of cloud-free (say less than 3/10 average cloud cover) nights per year. Its daytime cloud cover should also be reasonably low.

(iii) Low and stable atmospheric water vapor (B). Radio-wave absorption by water vapor has already been discussed in Chapter III, Section 6 so that the need for as dry an atmosphere as possible has been explained. We can state the criterion more sharply by agreeing (somewhat arbitrarily) that by "dry" we mean an atmosphere whose total precipitable water vapor (W_V) is 3 mm or less. Figure 27 of Chapter III shows that, at this level of dryness, the radio windows are very useful. We add the need for as much good observing time per year and arrive at:

- The atmosphere above the site should have $W_V \leq 3.0$ mm for a large fraction of nights throughout the year.

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* We are classifying the primary criteria with letters. A is a criterion to which the greatest weight must be given.

The criterion for a dry atmosphere is not too heavily stated, or weighted, since other factors, particularly the variability of the atmosphere, confuse the simple picture. A completely uniform dry (W_V = 3 mm) atmosphere at a uniform temperature of 10° C contributes an absorption factor of about 7 percent at 85 GHz and adds about 20° K to the radiometer noise. These are not harmful figures. But now let the total water vapor vary in amount with time (as will occur, for example, in the presence of atmospheric turbulence). A variability of 0.1 mm with W_V even as low as 3 mm gives 0.17 degree change in the radiometer temperature; this change usually has a noise-like variability with time, and thus can quickly become the limitation to the telescope performance. For special observations, this "sky-noise" can be reduced by techniques such as beam-switching or frequency-switching, and the 65-meter telescope is designed so that such techniques can be used. Nevertheless, since there are some observations where sky-noise cannot be removed or reduced, its existence must be recognized and minimized by good site selection.

Even now, the whole story of atmospheric irregularity has not been told. The variability of the atmosphere makes changes in the optical path length for a radio wave reaching the telescope. If the path differences are themselves different across the telescope aperture, the pointing of the telescope may be changed or its apparent gain reduced. These effects are very important in interferometry and have been studied experimentally and theoretically (see Hinder and Ryle 1971 for a recent survey). To show the importance of low variability in water content, we will quote two results only. If W_V differs by 0.05 mm for ray paths from a point source entering the atmosphere 65 meters apart, then the apparent direction of that source varies by 1 arc second at 86 GHz. If W_V varies over small distances of a few meters by more than 0.02 mm, the gain of the telescope will begin to suffer.

This subject of measuring atmospheric variability with time and across rather small distances in space is difficult. Observations of phase stability with interferometers suggest that the sort of W_V differences being discussed here are not exceeded with a dry and fairly stable atmosphere. But it appears not to be possible to state a measurable requirement on atmospheric stability, and so we make the reasonable assumption that a low value of W_V will be associated with low variability of W_V, and accept a low W_V as the main criterion.

(iv) <u>The radio environment (C)</u>. The chosen site should be as free as possible from harmful radio interference. This may come from a variety of man-made sources; these in turn are of two kinds: (1) Radio transmitters on the ground, in the air, or in space. All such sources in the USA operate in frequency bands assigned and controlled by official organizations (the Federal Communications Commission or the Office of Telecommunications Policy). Internationally frequencies are allocated by agreements made in the framework of the International Telecommunications Union. (2) Unlicensed and unregulated sources of radio noise, such as electrical machinery, automobile ignition systems, some kinds of lighting systems and so on.

The worst effects of the licensed transmissions are avoided by observing in those bands of the spectrum protected for radio astronomy. Such bands exist (with more or less actual protection) throughout the spectrum but the following should be noted as being of interest in the frequency range where the telescope will be most used, i.e., frequencies above 1400 MHz.

Table 19. Frequency Bands Above 1.4 GHz Allocated (to some extent) to the Radio Astronomy Service

Frequency Band	Degree of Protection Provided
1400-1427 MHz	Worldwide allocation
1611.5-1612.5 MHz	Protection requested by footnote
1660-1670 MHz	Primary allocation but shared
1720-1721 MHz	Protection requested by footnote
2670-2690 MHz	Protection requested by footnote
2690-2700 MHz	Worldwide allocation
4825-4835 MHz	Protection requested by footnote
4990-5000 MHz	Primary allocation, some sharing
5750-5770 MHz	Protection requested by footnote
10.60-10.68 GHz	Mainly primary, shared allocation
10.68-10.70 GHz	Mainly worldwide allocation
14.485-14.515 GHz	Protection requested by footnote
15.35-15.40 GHz	Worldwide allocation, some sharing
22.21-22.26 GHz	Protection requested by footnote
23.6-24.0 GHz	Worldwide allocation, some sharing
31.3-31.5 GHz	Worldwide allocation, some sharing
36.458-36.488 GHz	Protection requested by footnote
86-92 GHz	Worldwide allocation
115.16-115.38 GHz	Protection requested by footnote

Table 19, continued

Frequency Band	Degree of Protection Provided
130-140 GHz	Worldwide allocation
230-240 GHz	Worldwide allocation

This table shows, in simplified form, the allocations most important to the USA made at the 1971 World Administrative Conference for Space Telecommunications. Experience has shown that good protection can be obtained in a country such as the USA within many of the bands allocated to radio astronomy. Nevertheless, a new telescope capable of being used over a wide frequency range should also be sited where the present (and if possible the future) density of licensed radio transmitters is low.

The unregulated radio noise is very directly dependent on the concentration of people living and working near the site. Fortunately, automobile interference power density falls off quite rapidly at the higher frequencies (above a few GHz). Shielding by ranges of mountains is also advantageous in reducing interference from ground-based sources.

Thus we can state a radio-environment criterion:

• The site should be as free as possible from interference generated either by licensed and controlled transmissions or by other radio noise sources. Some shielding by mountains may be desirable.

(v) Meteorological factors (C). We have discussed atmospheric effects on the radio performance; the other meteorological effects of importance are the effects of wind and temperature on the performance of the telescope and the possible high loading of the structure in strong winds, large snow or hail storms or by ice loading. We therefore state two meteorological criteria, one dealing with operating conditions and one with survival:

Operating Criteria

• To make the telescope work at full accuracy the wind at the 100-foot level on the site should be below 18 miles per hour (29 km per hour) for as much time per year as possible.

• The rate of change of ambient air temperature on clear nights should be below 1.5° F per hour for a large part of the night.

Survival Criteria

• The extreme climatic conditions must not exceed the following more than once in 100 years:

Winds at the 100-foot level--90 miles per hour (145 km per hour)

Snow load deposited in 3 hours on a horizontal surface--20 lbs. per sq. foot (97.7 kg per sq. meter).

Ice load deposited in a single ice storm on a horizontal surface--20 lbs. per sq. foot (97.7 kg per sq. meter).

(c) Secondary site criteria. The secondary criteria are the obvious ones which, if followed, lead to a site which is reasonably easy of access, not expensive to develop and which provides satisfactory living conditions near the telescope for staff and visitors. We will not discuss the criteria in detail but merely list them. (No priority order is stated or implied in the listing.)

(i) A good construction and working site. Level or gently rolling ground, good subsurface conditions for azimuth track foundation, no serious surface or subsurface water problems. Easy water supply and sewage disposal.

(ii) Good access and utility supply. Not too far from a good highway (but not within 10 miles of a heavily travelled highway). Good power line (500-1000 KVA) available within a few miles. A major jet airport should be within 100 or so miles.

(iii) Reasonable living conditions. Within about 30-40 miles (or 45 minutes by car) of adequate schools, shops, hospital and medical facilities, some recreation.

(iv) Freedom from natural hazards. Avoid major earthquake zones, areas where there is a high probability of tornados or hurricanes. Avoid natural gas or oil producing areas (actual or potential).

(v) Land acquisition and local government. If possible, locate in area with surrounding land already controlled (national or state forest). Land acquisition costs should be low. Local government should be helpful; willing to control adjacent land use by zoning, for example.

2. Sources of Information on the Primary Criteria

Having established the criteria, we will discuss briefly the information which is available and which can be used to judge various sites according to the criteria. The requirement for a low latitude is obvious. The second, for low cloud cover, is not so easy to determine in detail.

(a) Information on cloud cover.

(i) General information. General information on cloud cover over the United States can be derived from several sources, but detailed knowledge of cloud climatology is not good. An excellent survey (McDonald 1958) with the title "Cloudiness Over the Southwestern United States and Its Relation to Astronomical Observing", makes this point and gives references to several general studies.

We rely first on these studies, choosing one which McDonald regards as good (U. S. Department of Agriculture 1941 Yearbook of Agriculture, Climate and Man). Figure 28 is taken from that publication

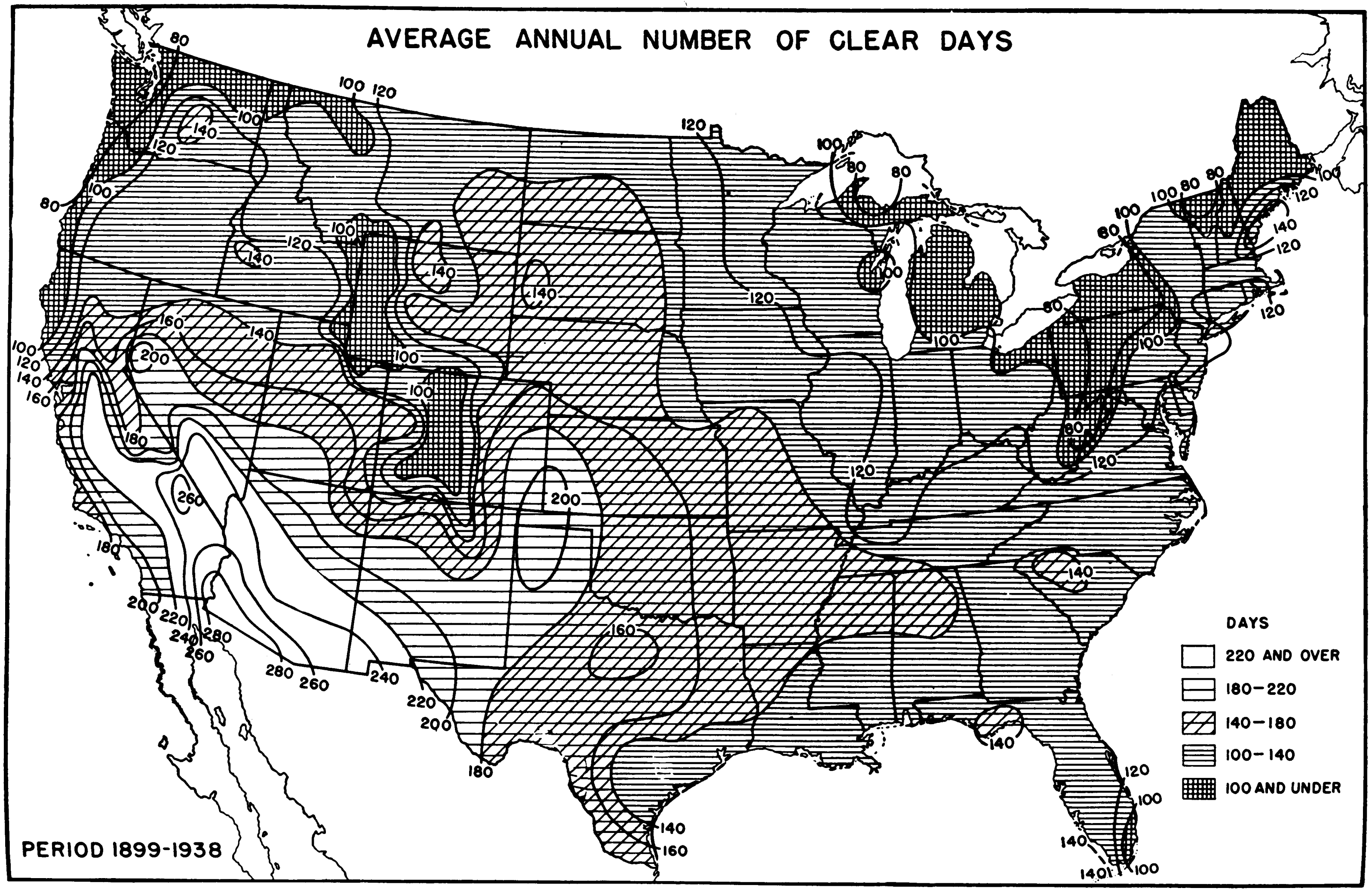

Figure 28. Nationwide pattern of clear days.

and shows the average annual number of "clear" days for the United States over the period 1899-1939. By "clear" is meant days when the average cloud cover was less than 3/10, and we must also remember that Figure 28 refers to days and not to nights. We will return later to the problem of obtaining good cloud information at night over large areas of the country. McDonald was able to compare the cloud cover as shown in Figure 28 with careful studies made over Arizona, and although there are detailed differences, Figure 28 seems to be broadly correct. A similar conclusion seems possible from the cloud-cover information used by Kuiper (1970).

(ii) Cloud cover in more detail. Observations of the earth from meteorological satellites have been made since Tiros 1 was launched in April 1960, so there should be a wealth of data available on world-wide cloud cover (at least for daylight hours). However, a good published summary of satellite information has appeared only as this report was in its final stages of preparation. This is the "Global Atlas of Relative Cloud Cover 1967-70", a joint production of the U. S. Department of Commerce and the Air Force (Washington, D. C., September 1971). This atlas shows the average statistics of clouds over very large areas of the earth; the unit area is a square of 40 km on the side. It thus will be invaluable for comparisons of average cloudiness on about the right scale of detail for estimating the value of sites for a radio telescope, and the information in it will be used before a final site selection is made.

Estimates of night-time cloud are usually only available from astronomical observatories in the sort of detail which is of value for site cloudiness comparisons. When such estimates can be found, they are of considerable qualitative value and should be used.

One project is at present being carried out which will produce some very valuable night cloud comparisons. This is a survey of possible sites for a large infrared telescope, being undertaken under the leadership of Prof. J. A. Westphal of the California Institute of Technology*. We shall refer to this survey again, since its results are relevant to the search for low precipitable water and to the measurement of atmospheric stability. The survey uses fully automatic infrared telescopes (in the 8-14 micron range) to observe fluctuations of apparent sky brightness. This is done by switching the telescope beam rapidly between two small areas of sky about 10 minutes of arc apart and measuring the difference of sky brightness between them. This is a good measure of sky noise for the infrared astronomer. It is not certain that this observation is directly related to the millimeter-wave sky noise, but it seems likely that low infrared sky variability will go

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* The site survey is being supported by the Planetary Astronomy Section of NASA's Office of Space Science and Applications.

along with a stable millimeter-wave atmosphere. The infrared observations are very sensitive to clouds, and so the Westphal site survey will, when complete, give a year's comparison of night-cloud between the sites under study. Nine identical installations are being used, at the following locations:

White Mountain, California
Kitt Peak, Arizona
Mount Lemmon, Arizona (2 installations)
McDonald Observatory, Texas
Mauna Kea, Hawaii
Palomar Mountain, California
Cerro Diablo, Baja California
Cerro Tololo, Chile

In addition to the telescopic observations, daily measurements are being made (when the sun is visible) of the total precipitable water in the atmosphere. This is done by measuring the absorption of the solar infrared radiation by water vapor in the 1.87 micron absorption line.

(b) Atmospheric water vapor

(i) General distribution of W_v. Total precipitable water vapor (W_v) in the atmosphere can be measured by sampling the atmosphere throughout the elevation range from the ground to the level where the water vapor has become negligible. This is at about 40 to 50 thousand feet (12 to 15 km) and so meteorological radiosonde observations can be used with reasonable accuracy, even though they often do not extend above the 25,000 foot level. The general distribution of W_v across the country and throughout the year can thus be found; the fine detail of W_v is however not determinable because radiosonde observations are only made at fairly widely spaced intervals and are averages over the horizontal track of the instrument. The report by G. P. Kuiper already referred to shows some W_v values calculated in this way from the basic data contained in the "Atmospheric Humidity Atlas--Northern Hemisphere" (Gringarten et al. 1966). The following Table 20, extracted from Kuiper's Table I, gives values of W_v for various sites, expressed in millimeters of water. Values corresponding to the 5 and 50 percent levels in the W_v distribution are given; these may be read as the "average best" and the "median" values. As Kuiper is careful to explain, such general information cannot lead to a reliable choice of the driest and best site, but it indicates the general trend in any area.

The following general conclusions can be drawn about the values of W_v. W_v will be low in those areas where the ground-level relative humidity is low. W_v falls as the ground elevation rises (the effective tropospheric scale height for water vapor is about 2 km).

Table 20. Precipitable Water (mm) in a Vertical Column Over a Number of Sites

Site	Elevation (meters)	January		April		July		October	
		5%	50%	5%	50%	5%	50%	5%	50%
Mt. Palomar (Calif.)	1706	1.8	3.4	1.9	4.4	3.5	9.5	2.6	6.1
White Mt. (Calif.)	4340	0.44	1.1	0.49	1.2	1.1	1.9	0.7	1.3
Kitt Peak (Ariz.)	2064	1.7	4.4	1.8	3.7	5.5	10.9	2.3	7.1
Mt. Lemmon (Ariz.)	2800	1.0	2.7	1.3	2.8	5.0	9.1	1.8	5.0
Pikes Peak (Colo.)	4300	0.40	1.0	0.7	1.3	1.6	4.2	0.81	1.9
Baja California (Mexico)	2830	1.2	2.6	1.35	2.8	3.5	8.2	1.9	4.7
Mauna Kea (Hawaii)	4215	1.2	1.5	1.0	1.8	1.3	2.0	1.2	2.3
Green Bank (W.Va.)	823	1.2	4.3	2.6	8.0	12	20	3.4	10

(ii) Specific information of W_V. To be more specific about values of W_V to be expected requires measurements to be made at the sites of interest. Such measurements can be made, on clear days, by using the infrared absorption meters already described. They could, in principle, be made by measuring the radio emission from the atmosphere in one of the water-vapor absorption lines. (Equipment for this purpose has been built and used at Green Bank in the attempt to correlate atmospheric water vapor with interferometer performance.) Vertical profiles of absolute humidity up to 2000 m have been measured by observing Raman scattering of a powerful laser beam (Cooney 1971). As has been noted, the Westphal survey is making W_V measurements at a number of sites. In the site survey for the Very Large Array (VLA Report Volume III, Chapter 4) measurements of W_V were made at three sites over a 30-month period. Thus there is some detailed information on W_V for sites of particular interest to be used in comparisons.

(c) The radio environment. Good general information on the radio environment insofar as licensed or controlled radio transmitters are concerned can be obtained. In recent years, for example, the Electromagnetic Compatibility Analysis Center of the Department of Defense has been collecting data on the location and operating characteristics of a variety of communications and electronic equipments. This data is stored and referenced in a Univac 1108 computer and thus may be retrieved and used in a variety of ways. As an example of the information which can be extracted, topographic data is stored so that path-loss calculations over transmission paths from one place to another can be made (Fuhrmann and Scott 1970).

The environment for man-made noise can be estimated broadly from a survey of nearby operations likely to generate noise and from information about automobile traffic near the site. Fortunately, no very detailed information is needed here for radio observations above a few GHz in frequency, but care is needed to avoid the possibility of later damaging developments.

Before a final selection of a site, it is wise to make radio noise measurements on the site, although it can be very difficult to make such measurements to the very low power levels that sensitive radiometers will reach.

(d) Meteorological factors. Records of wind, temperature, relative humidity and precipitation are available from many weather stations. They are adequate to answer the broader meteorological questions that the site criteria pose. In detail, however, it is often difficult to compare sites with precision. For example, the average distribution of wind velocity is not always known, and thus a judgment has to be made on the basis of an average value of the wind rather than on a knowledge of the percentage of time that the wind is below a given speed.

3. Specific Sites

(a) General. One consideration which has not been included in the site criteria obviously has to be given careful attention when discussing sites for a telescope such as the 65-meter dish. It will be part of the National Radio Astronomy Observatory, and will be operated for the benefit of visiting and staff scientists following the policies and practices already well-established by national observatories. This operation would be much easier if the telescope were sited to be near, or even a part of, an existing or planned national observatory site. This is not an over-riding consideration, but if, in judging a list of sites, several can be found which are about equal in other respects, it would then become the decisive factor in choosing the site. With this in mind, therefore, we shall include the Green Bank site in our list of sites and discuss it first.

(b) Green Bank, West Virginia.

Latitude +38°26'   Longitude 79°50' W
Altitude 2700 feet - 823 meters
Clear days per year - 80

The atmosphere above Green Bank is definitely cloudy. This causes difficulties with single-dish observations at frequencies as low as 2 GHz (15-cm wavelength) and cloud effects can be very troublesome for observations at 10 GHz (3-cm wavelength). There are times, on some winter nights, when W_V at Green Bank falls to values as low as about 1 mm. However, summer days and nights can be quite humid (W_V = 20 mm) and the Green Bank interferometer does not show good phase stability at 3.7-cm wavelength (8.1 GHz) during the summer.

The radio environment is controlled around Green Bank by the radio quiet zone and by a West Virginia Zoning Act. The mean wind velocity throughout the year is 11.7 miles per hour; the extreme day to night temperature range and the clear night rate of change of temperature are within the limits required by the telescope design; so also are the extreme winds and snow and ice conditions.

Green Bank is a site where the wind speed statistics have been measured (S. von Hoerner Reports Nos. 16 and 23), and it is known that wind at the 100-foot level is above 18 miles per hour for 25 percent of the total time in an average year.

Green Bank meets the secondary criteria very well (though not completely).

The conclusion of the suitability of Green Bank rests heavily on the cloud cover and water vapor effects. As we shall see, other sites in the southwest have up to 260 cloud-free days per year and better W_V characteristics. The ratio of cloud-free time of 260/80 is so large that the usage of the telescope at millimeter waves at Green Bank would be very low, compared to a southwestern site.

(c) Arizona sites. Four possible sites in Arizona have been considered. This area of the country is obviously good from the point of cloud cover and atmospheric humidity. Tucson is already a major center of astronomical research, so that sites within reach of Tucson deserve study.

(i) Kitt Peak. A possible site on the mountain not far from the NRAO 36-foot telescope, but below the general level of the KPNO optical telescopes, has been considered.

Latitude +31° 57' Longitude 111° 37' W
Altitude 6300 feet - 1920 meters
Clear days per year - 260

Precipitable water above this site is low ($W_V \leq 2$ mm) on many nights during eight months of the year, but the wet season (July, August, September and October) has values of W_V rising to 20 mm. This season also has the cloudy months. The millimetric observing quality of the site has been well tested, since it lies only 150 meters from the location of the NRAO 36-foot telescope.

The radio environment on Kitt Peak is not controlled. However, the mountain lies within a Papago Indian Reservation, which extends about 15 km from the site towards Tucson, and this to some extent should provide a block to restrict industrial growth. It is also relevant that the site lies to the west of the mountain top, and hence is rather well shielded from the Tucson area. Mountains far to the north also block the line of sight to Phoenix, about 100 miles north. Automobile traffic up the mountain passes close to the site; this is not a problem for the 36-foot telescope but might as radiometer sensitivity improves become troublesome. The present KPNO policy is to let visitors drive their own cars to the mountain top, and on some weekends this traffic is considerable. The normal KPNO traffic would not be a problem, and even if it proved so in the future, the Observatory vehicles could be fitted with ignition suppressors.

Precipitation would be within the telescope limits, but the general winds could limit observations. The mean wind speed on the mountain is 12.5 miles per hour. Statistics of wind speed (and many other meteorological factors) were studied in the "Final Report on the Site Selection Survey for the National Astronomical Observatory" (Meinel 1963). From that publication the following Table 21 of values for the percentage of time the wind was $\geq$ 18 miles per hour at the 60-foot level above ground was derived. It will be seen from that table that wind will restrict millimeter-wave observations quite significantly, particularly during the months November through June when the atmosphere is clearest and driest.

The survival conditions would be met for a Kitt Peak site. The secondary criteria are all very well met by the proximity to Tucson.

Table 21. Winds Above 18 Miles Per Hour on Kitt Peak

Month and Year	Wind ≥ 18 m/h	Month and Year	Wind ≥ 18 m/h
Nov. 1956	28.5%	June 1957	30.5%
Dec. 1956	32	July 1957	8.5
Jan. 1957	20	Aug. 1957	8
Feb. 1957	30	Sept. 1957	14
Mar. 1957	26	Oct. 1957	14
Apr. 1957	29	Nov. 1957	20
May 1957	29	Dec. 1957	21

(ii) A site considered for the VLA (Y-23). The site survey for the Very Large Array antenna has dealt in detail with a possible site (indexed as Y-23 in Volume IV of the VLA Report*) which lies in the Aguirre Valley just north of Kitt Peak. Although this is at a lower elevation than Kitt Peak, it should be included in any list of sites to be considered.

Latitude +32° 05' Longitude 111° 35' W
Altitude 2800 feet - 850 meters
Clear days per year - 260

Total precipitable water above this site has been measured over a 30-month period, from July 1966 to November 1968, for the VLA site study (VLA Report Volume III, Chapter 4). The average results for 1968 are shown in Figure 29; they again show the seasonal wet period July through October, but the rest of the year shows reasonably low values. The lower elevation (compared to the mountain top) results in somewhat higher values of W_V, and these in turn make the site somewhat less attractive from that aspect.

The radio environment is perhaps rather better than that on the mountain top. It is less exposed to interference from noise sources in Tucson, since there is better terrain shielding, and it lies at about the same distance from Route 86.

Precipitation and survival winds would be within the limits of the telescope design. No statistics of wind are available for the site, but the average wind velocity should be about the same as at Tucson (8.1 miles per hour). On the assumption that the distribution of wind

* "A Proposal for a Very Large Array Radio Telescope", NRAO, Charlottesville, Virginia, 1967-71.

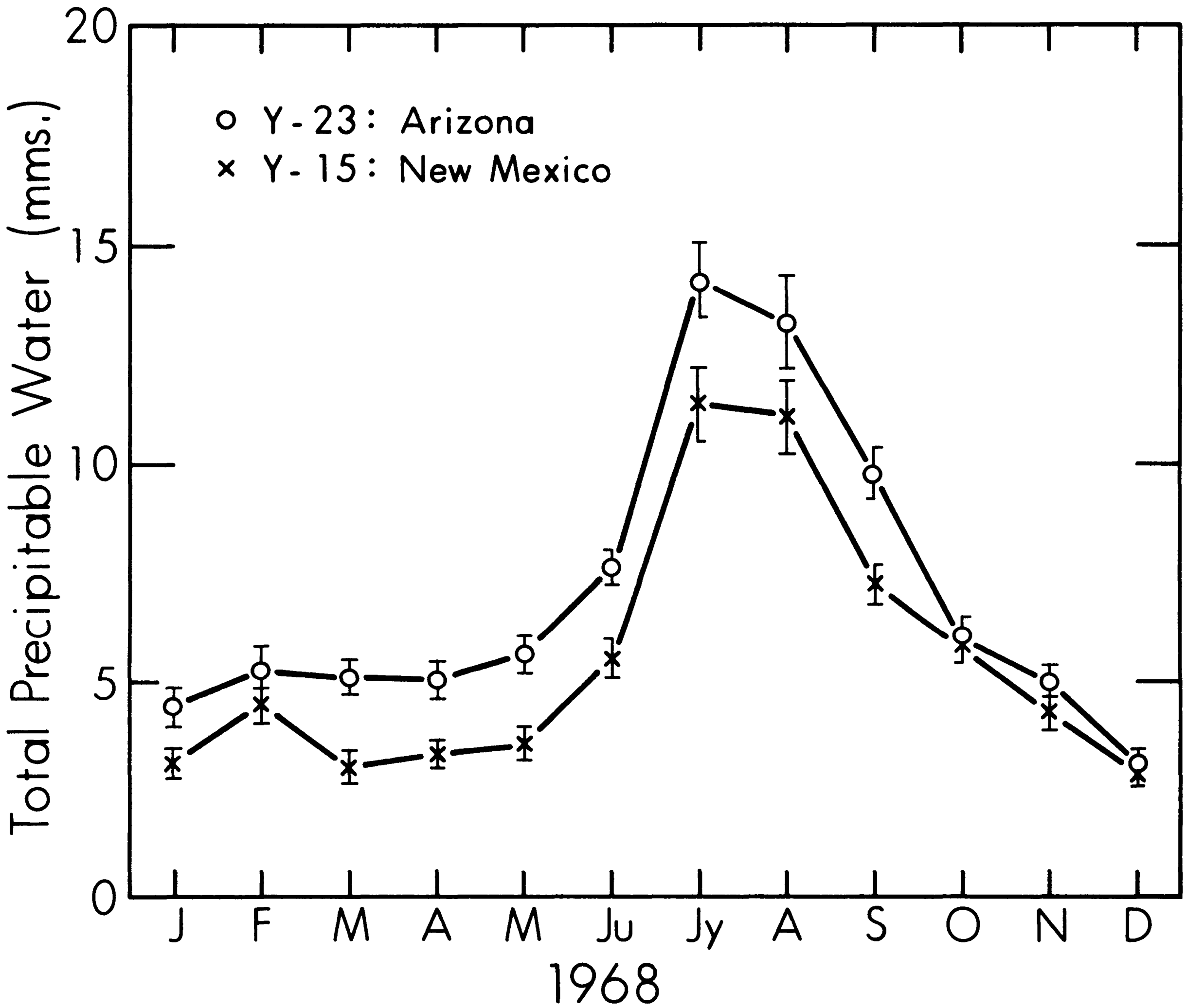

Figure 29. Precipitable water over VLA sites Y15 (New Mexico) and Y23 (Arizona).

of wind speed has a normal shape, this would give about 13 percent of the total time with winds above 18 miles per hour.

The secondary criteria are mainly well-satisfied by this site, but it does lie within the Papago Indian Reservation which could cause difficulty.

(ii) Two more Arizona sites. Two further sites within the low-cloud area of Arizona have been considered. One is near the summit of the Catalina Mountains, and one is near the summit of Mount Hopkins. The Catalina site is Mount Lemmon, well described in Kuiper's paper; the Mount Hopkins site is close to the Smithsonian Astrophysical Observatory. The meteorological conditions on Mount Hopkins are described in "A Metero-logical Report for the Mount Hopkins Observatory 1968-1969" (Pearlman *et al*. 1970).

Mount Lemmon		Mount Hopkins	
Latitude:	+32° 26'	Latitude:	+31° 41'
Longitude:	110° 47' W	Longitude:	110° 53' W
Altitude:	9190 feet - 2800 meters	Altitude:	8375 feet - 2554 meters

Clear days per year - 260

The precipitable water above Mount Lemmon is known to be low during the dry months of the year. The Lunar and Planetary Laboratory of the University of Arizona has made infrared observations from a site close to Mount Lemmon for several years, and so measures of W_v are available. Some typical values for 1964 are given below.

Table 22. W_v Measured on the Catalina Mountains*

Average During Months Of	No. of Days	W_v mm
February and March	6	1.44 ± 0.25
April	15	1.91 ± 0.15
May	7	2.70 ± 0.36
June	18	3.74 ± 0.19
July, August, September, October	16	7.71 ± 0.71
November	8	1.54 ± 0.21

* The measurements were reported by Dr. F. J. Low in an NRAO Millimeter Wave Internal Report No. 30, December 1964.

We have no comparable data on W_v for Mount Hopkins, but the absolute humidity values in the SAO Report suggest that the annual pattern will be very similar to that on Mount Lemmon or on Kitt Peak. The radio environment of Mount Hopkins is compromised by a Channel 11 television transmitter on the mountain. The site is 17 km in a direct line from Route 89 and 60 km in a direct line from Tucson. Mount Lemmon has a definitely poor radio environment. The main television antennas serving Tucson are on the mountain, with other radio installations also. Even though the radio frequencies being transmitted are much below the millimeter wave end of the spectrum, the power levels are very high and the environment would be impossible for longer wavelength work. Tucson itself is within 30 km and the road up the mountain is heavily travelled in both summer and winter. (The mountain top is used for skiing in winter.)

Survival climatic conditions are within limits for both mountains. The average wind at the Observatory on Mount Hopkins is a rather surprisingly low 8.5 miles per hour, and during 1968-69 period the wind was above 18 miles per hour for only 6.5 percent of the total time.

The Mount Lemmon site meets the secondary criteria well. The Mount Hopkins site would require quite extensive work to build a suitable access road. It would be almost impossible to transport the telescope fabricated members over the present 18 mile long, rough mountain road from Amado to the present SAO site, and more road up to the selected site would be needed.

These latter two Arizona sites have been discussed, since both have possibilities, but both appear inferior to the first two described.

(d) <u>Sites in New Mexico</u>. The general distribution of cloud together with the existence of high elevation, fairly level land suggests that suitable sites should exist in the west and southwest areas of New Mexico. The site search for the VLA identified an area in the San Augustin Plains, about 140 km (88 miles) on a line southwest from Albuquerque, as a very desirable site. This and nearby areas have been examined in the present survey with the following results.

(i) <u>San Augustin Plains VLA site (Y-15)</u>

Latitude: +34° 01' Longitude: 107° 37' W
Altitude: 7200 feet - 2200 meters
Clear days per year - 220

This site is about four miles south of the suggested center of the VLA (VLA Report Volume 4, Chapter 5). The telescope in this position would not interfere with the VLA and yet would share many facilities. The significant drop in clear days per year from the Arizona area should be noted.

As with two other VLA sites, there has been a 30-month series of observations of precipitable water in the atmosphere above this site, and these are summarized in Figure 29. It can be seen that this site shows relatively high values for W_V in the July through October period, but that, in the dry months, the site is preferable to the Aguirre Valley site near Kitt Peak.

The radio environment appears to be good, although there is a microwave tower on the edge of the site. The land area around is mainly used for grazing cattle; the nearby towns are small and the large and growing city of Albuquerque is 140 km (direct line) away. Some useful terrain shielding exists between the site and Albuquerque and parts of the Rio Grande Valley.

Meteorological criteria for survival are met. The operating conditions for temperature changes also are within our limits. The mean wind on the site is 9.6 miles per hour. Wind statistics for the site itself are not known, but making simple assumptions as to the shape of the wind distribution function suggests that the wind speed is above 18 miles per hour for 18 percent of the total time. The quite high thunderstorm activity in the area should be noted--the Langmuir Laboratory for Atmospheric Physics was placed on a mountain east of the site to study thunderstorm activity. There have been, on the average, 45 summer and 33 winter thunderstorms per year in recent years (VLA Report Volume IV, Chapter 5).

The secondary site criteria are satisfactorily met. The site has been well studied as a VLA site and the VLA report gives further details.

(ii) South Baldy Peak. A possible site on a saddle 300 meters northwest of the Langmuir Laboratory has been studied.

Latitude: + 33° 58'   Longitude: 107° 11' W
Altitude: 10,400 feet - 3170 meters
Clear days per year - 210

Measurements of W_V are not available for this site. The average values for the mixing-ratio for water vapor show low values (below 4 gm/kgm) for all months except June, July, August, and September. The site could be expected to show the same sort of annual variation of W_V as the Y-15 site, with the probability that the dry month values would be lower on Baldy as a result of the 1000-meter altitude difference.

The radio environment would be reasonably satisfactory. The site has direct line distances of 30 km from Socorro (population 6000) and 125 km from Albuquerque. The Langmuir Laboratory operates active radar transmitters when thunderstorms are close. These transmissions would prevent observations, but so would the thunderstorms themselves. When no radar is operating, interference from the Langmuir Laboratory would not be troublesome.

The survival meteorological conditions are met. The mean wind over the period 1964-1967 was 8.6 miles per hour. Wind statistics are not available in a reduced form (the observations exist) but a reasonable estimate suggests that winds of 18 miles per hour would be exceeded 14 percent of the total time.

Secondary criteria are adequately met, except for access, which at present is by a 20-mile length of dirt mountain road from Route 60. This section of road would have to be rebuilt to allow the fabricated parts of the telescope to be carried to the site. If the VLA were to occupy Y-15, many administrative functions would be shared between the two telescopes.

(e) Sites outside the continental United States. Two sites have been considered; one near the summit Mauna Kea in Hawaii and one close to Cerro Tololo in Chile. These were included because both sites are highly regarded by infrared astronomers.

(i) Mauna Kea, Hawaii*

Latitude: +19° 50' Longitude: 155° 29.5' W
Altitude: 13,500 feet - 4120 meters
Clear days per year - 230

This site has been occupied for some years by an Observatory operated by the University of Hawaii; the major instrument is an 88 inch reflector telescope which was dedicated in June 1970. There are possible locations for the 65-meter telescope near the summit and near the optical observatory.

The "clear days per year" figure given above may not be strictly comparable with those quoted earlier for other sites, which are based mainly on Figure 28. The above quoted figure is estimated from the various reports*.

The total precipitable water above Mauna Kea is always low. A number of measurements and estimates have been made, in addition to the values given in Table 20. As an example, the following measurements of W_V (mm of precipitable water) were made on Mauna Kea using the 0.935μ absorption line instrument already described. Values of W_V during nine months in 1965 and 1966 ranged from 0.3 mm (low values such as this are hard to measure accurately with this instrument) up to one value of 5.1 mm. Table 23 shows the distribution of these measurements. There is no marked seasonal variability in W_V above Mauna Kea.

The radio environment at Mauna Kea could be good to very good. Hilo is 40 km away (direct line), the island is unlikely to suffer extensive commerical development and radio noise sources on the surrounding oceans will be in controlled frequency bands.

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* Much of the information in this paragraph is derived from reports by Herring, A. K., Lunar and Planetary Laboratory, University of Arizona, November 30, 1965; Jefferies, J. T., and Sinton, W. M., Sky and Telescope, 36, 140-145, September 1968; Jefferies, J. T. and Zirker, J. B. "A Preliminary Report on a Site Survey for an 84" Telescope", U. of Hawaii, February 1966.

Table 23*. Distribution of Measured Values of W_v Above Mauna Kea

Range of W_v mm	Number of Observations
0 - 1	21
1 - 2	15
2 - 3	7
3 - 4	1
4 - 5	1
5 - 6	1
Above 6	0

The survival limits of the telescope would be adequate for the environment, although high winds occur more frequently than at other sites. The observational wind limit of 18 miles per hour needs careful study. Present evidence suggests (Jeffries and Zirker, Figure 6) that winds are above this level for about 35 percent of the total time. If this is true, it represents a serious disadvantage for the 65-meter telescope on this site.

The secondary criteria are not well met by a site on Hawaii. Immediate access to the mountaintop will soon be possible by a good road. There are, however, many disadvantages to placing a large radio telescope on such a site. Some support staff would have to live on the mountain, but at a level where hypoxia is not serious. Work on the telescope (changing radiometers, routine maintenance, etc.) would always be dangerous, since even if oxygen-breathing equipment were used, it hampers working efficiency. The isolation of Hawaii from the rest of the United States would make the travel for many visiting scientists arduous and expensive. The University of Hawaii is on Oahu, an airplane flight away.

(ii) <u>Cerro Tololo or Cerro Morado, Chile</u>. There is much interest on the part of some optical astronomers in sites in the Andes. The Cerro Tololo site has been occupied since 1965 by the Kitt Peak National Observatory and a 150-inch telescope is being built there. The general area has been well-surveyed for possible observatory sites, and we have, in what follows, relied on such reports ("Astronomical Observing Conditions in North-Central Chile", J. F. Stock, Chile Site Survey Technical Report No. 2, KPNO, May 1963; "Observatory Site in Chile", J. B. Irwin,

* Derived from Figure 12 of Jefferies and Zirker, already referenced.

CARSO Report No. 3, Carnegie Institute of Washington, June 30, 1966 are two examples). We will discuss a site near the Cerro Tololo Observatory on Cerro Morado, only a few miles south of Tololo.

Latitude: -30° 13'   Longitude: 70° 48' W
Altitude: 7100 feet - 2165 meters
Clear nights per year - 260

This is the only site in our list south of the equator, and it should be noted that many astronomers would value highly a site which sees the southern sky. There are at present no millimeter-wave radio telescopes working in the Southern Hemisphere, although one is just starting observations in Brazil. But the southern sky has interesting galactic objects of all kinds. The galactic center is high in the sky; the Southern Coalsack is potentially one of the richest sources of information on molecular lines. A southern radio telescope would find much of great interest in the Gum Nebula, the Carina Spiral Feature, the Magellanic Clouds and NGC 5128.

The estimate of clear nights (as opposed to days for many of our other sites) is derived from 1960-67 statistics given by Sanduleak (1967).

We are not aware of any existing series of measurements of precipitable water vapor in the atmosphere over Cerro Tololo, but the site is included in the Westphal infrared survey, and this information is being collected and soon will be forthcoming. There is much evidence in the reports, both written and verbal, of the high quality of optical seeing on Cerro Tololo, and we will accept this at present as indicating a good, stable and dry atmosphere.

The radio environment should be good. The site is isolated from population centers; the town used as CTIO headquarters, La Serena, is 33 air miles from Cerro Tololo; and there is little activity near the site likely to produce harmful radio interference.

The meteorological conditions at the site for survival are all satisfactory but there are high winds on occasions. Wind observations have been made on Cerro Morado on a 6-meter tower and at Cerro Tololo on a 12-meter and 28-meter tower. From the bi-monthly reports of CTIO we find the following cases between November 1965 (when observations at the 28-meter height started) and September 1971, of a recorded wind speed of greater than 70 miles per hour at the 28-meter height at CTIO.

There are no cases in Table 24 where our survival speed is materially exceeded, but the occurrence of winds of up to 88 miles per hour at the 28-meter (92 foot) level has to be taken into account.

The operating conditions are met by a site on Cerro Morado. The same bi-monthly reports give wind statistics (measured at 6 meters) for all months of 1965. These show that, in that year, winds would have been above our 18 miles per hour limit for approximately 21 percent of the time.

Table 24. Wind Speeds Greater than 70 Miles/Hour Recorded at CTIO (28 meters height above ground)

Month and Year	Wind Speed Recorded Miles/Hour	Month and Year	Wind Speed Recorded Miles/Hour
November 1965	76	October 1969	74
April 1966	78	May 1970	76
June 1966	74	July 1970	80
June 1968	76	October 1970	74
August 1968	77	July 1970	88
April 1969	72	August 1971	72
June 1969	71	September 1971	88

The secondary criteria would be adequately met by the site; the distance from the main centers of radio astronomy in the USA would cause as much (or more) difficulty and cost as for the site on Hawaii.

4. Summary and Conclusions

The requirements for a site for the 65-meter telescope are somewhat more strict than those for a longer wavelength instrument. Nevertheless, there are accessible and administratively practical sites where the telescope would perform well. Within the continental United States the locations near Tucson or the San Augustin Plains are preferred. It seems doubtful whether the possible sites in Hawaii or in Chile should be included. Hawaii has an excellent atmosphere, yet is both distant from most of those who would use and maintain the telescope and would present problems of wind and altitude which would limit the efficiency of the instrument. A southern site must at some time be occupied and used for millimeter-wave radio astronomy. It is, however, questionable whether the present instrument, taking account of all its features, should be the first to be located south of the equator.

It will be clear that this survey of possible sites has not been exhaustive; there are some sites which have not been included (Owens Valley and White Mountain in California and Cerro Diablo in Baja California are examples) but which deserve study before a final choice is made.

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