Ats 16,600

FINAL REPORT

STUDY OF THE ATMOSPHERIC CONDITIONS AFFECTING INFRARED ASTRONOMICAL MEASUREMENTS AT WHITE MOUNTAIN, CALIFORNIA

FUNDED BY
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NGR 05-003-459 and supplement number 1
Duration: 1971 April 23 to 1972 June 30

Principal investigator: George B. Field

Project Director: David D. Cudaback

1974 January 24

University of California
Department of Astronomy
Berkeley, California

John G. Phillips, Chairman
Astronomy Department
(for George B. Field, Principal Investigator)

I. SUMMARY

Measurements are described here of atmospheric conditions affecting astronomical observations at White Mountain, California. Measurements were made at more than 1400 times spaced over more than 170 days at the Summit Laboratory and a small number of days at the Barcroft Laboratory. The recorded quantities were ten micron sky noise and precipitable water vapor, as requested in the original communications from NASA, plus wet and dry bulb temperatures, wind speed and direction, brightness of the sky near the sun, fisheye lens photographs of the sky, description of cloud cover and other observable parameters, color photographs of air pollution, astronomical seeing, and occasional determinations of the visible light brightness of the night sky. Not all those quantities could be measured simultaneously, of course. Measurements of some of these parameters have been made for over twenty years at the Barcroft and Crooked Creek Laboratories, and statistical analyses were made of them. These results and interpretations are given here in identical form to the prospectus entitled, "An infrared observatory for White Mountain, California", submitted to NASA in 1973 July.

On the basis of careful statistical analyses of significance, we compare the White Mountain data with some available from other sites. In most of the parameters analyzed, we find White Mountain better than or not significantly different than the best of other sites.

The bulk of the collected data are statistically analyzed in this report, and disposition of the detailed data is described. Most of the data are available in machine readable form.

A detailed discussion of the techniques proposed for operation at White Mountain is given, showing how to cope with the mountain and climatic problems. However, the measurements reported were made without those techniques being available. Therefore it was a major effort to make the measurements, and operational problems prevented some from being made.

II. THE WHITE MOUNTAIN SITE

A. Atmospheric and Meteorological Conditions

1. General weather conditions

An early summary of the general meteorological conditions was organized in 1948 by Commander E. Bollay of the Office of Naval Research. Presumably he had no commitment to White Mountain, and he concluded that it "is probably the only location in the United States enjoying so many meteorological advantages and desirable geological characteristics for a high altitude observatory and laboratory."

Commander Bollay reported that Dr. I. S. Bowen and Dr. Fritz Zwicky had brought White Mountain to his attention, and Dr. Zwicky wrote, "As far as a site for observation of celestial objects and of the optical phenomena in the upper atmosphere is concerned, I consider White Mountain Peak the best on the North American continent."

The general climate at White Mountain is mild and clear, as compared to experience at similar altitude in the Sierra Nevada, Cascades, and Rockies. The distribution of weather with time usually is at worst an alternation of several days of excellent weather with several days of bad weather. At best there can be periods of several months of good weather except for afternoon thunderstorms.

The dominant air masses are maritime polar and continental polar, but on occasion in summer the maritime tropical air masses from the Gulf of Mexico slop over White Mountain. The maritime air masses become drier as they move over land, so the inland location of White Mountain is a considerable advantage. For example, the maritime tropical air is much drier and less troublesome than when it passes over the Arizona observatories.

There is some pollution at White Mountain, which seems to originate both in the San Francisco and Los Angeles areas. The accompanying photographs, taken on an unusually hazy day, clearly show a colored band above the horizon, but it should be remembered that it is obvious because the air is generally so clear. The horizontal visibility in the photographs is over 125 km, and is limited by a combination of man made and natural materials.

The cloud cover increases in going from south to north in the Inyo Mountains, partly because of increasing elevation and partly because of normal latitude effects. There are sites with fewer clouds 200 km to the south, but the greater water vapor due to lower altitude takes away the advantage.

The White Mountain Research Station has collected weather data for essentially every day, except for long periods when recording anemometers were out of operation, since the high altitude laboratories were started. The Crooked Creek data at 3090 m altitude started in 1949 and the Barcroft data at 3800 m altitude started in 1950. The Barcroft data in table II A-1 are copied from a summary going through 1970, and published in great detail by the Station (Pace et al., 1971). The individual measurements are available in machine readable form going to the present. In addition to the data shown in the table there are recorded wet bulb temperatures, cloud cover, and approximate cloud height. Further statistics can very easily be derived from this data upon request.

The weather at the Summit Station is of course worse than at the lower stations, but the precipitable water vapor decreases with a scale height of 1.6 km. This more than compensates for the times of bad weather. Lightning is a serious problem at the Summit during summer afternoon thunderstorms, and suitable protection must be provided for all structures.

TABLE II A-1

MONTH SUMMARY, BARCROFT LABORATORY, 1953-1970

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	18 Yr Mean or Extreme	Date of Extreme
AV MAX TEMP	°F	22.8	22.5	23.5	28.3	35.6	45.3	53.5	52.9	47.6	39.8	31.1	25.2	35.7	
HI MAX TEMP	°F	46	45	45	50	55	65	72	72	61	62	50	48	72	++
AV MIN TEMP	°F	8.2	7.3	6.8	11.2	19.3	28.8	36.4	35.9	30.4	23.7	16.0	10.2	19.5	
LO MIN TEMP	°F	-25	-21	-35	-30	-15	2	12	15	4	-20	-28	-26	-35	10 Mar 64
AV MEAN TEMP	°F	15.5	14.9	15.1	19.7	27.4	37.0	45.0	44.4	39.0	31.7	23.6	17.7	27.6	
AV DIURNAL DIFF	°F	14.6	15.2	16.7	17.2	16.4	16.5	17.1	16.9	17.2	16.1	15.2	15.0	16.2	
HI DIURNAL DIFF	°F	44	37	47	48	43	49	40	38	37	56	37	39	56	17 Oct 69
LO DIURNAL DIFF	°F	3	2	4	7	4	6	2	7	3	2	2	2	2	++
TOT DEGREE DAYS	°F	1512	1410	1533	1344	1157	831	612	623	773	1022	1233	1454	13504	
TOT DAYS 33°F OR +		3	4	4	10	21	28	31	31	29	25	15	7	208	
AV 8AM REL HUM	%	63.7	66.5	64.7	61.6	56.8	50.2	46.9	47.8	47.2	47.4	56.4	58.2	55.6	
AV 8AM BAROM	mmHg	477.1	476.8	475.9	476.9	479.1	481.7	485.4	484.8	483.1	481.5	479.5	478.0	480.0	
HI 8AM BAROM	mmHg	489.0	488.6	487.6	489.6	487.2	490.5	492.5	491.3	490.7	490.0	490.2	491.9	492.5	15 Jul 70
LO 8AM BAROM	mmHg	462.0	464.9	461.3	461.7	466.6	468.6	478.9	474.0	472.7	461.9	465.6	461.7	461.3	23 Mar 64
AV SNOWFALL	in.	20.6	19.4	18.0	20.7	22.6	8.8	1.8	0.8	4.9	10.4	14.4	18.1	160.5	
HI SNOWFALL	in.	30.0	17.0	15.0	38.0	26.0	15.0	12.0	3.0	12.0	19.0	12.0	44.0	44.0	6 Dec 66
AV SNOW DEPTH	in.	13.6	21.4	25.4	24.0	17.6	5.1	0.4	0	0.2	1.1	4.3	9.3	10.2	
HI SNOW DEPTH	in.	81	94	123	106	91	46	15	3	6	28	33	93	123	22 Mar 69
AV SNOW H_2O	in.	2.26	1.72	1.82	1.84	2.05	0.96	0.16	0.08	0.62	0.96	1.29	2.49	16.25	
AV RAINFALL	in.	0	0	0	0	0	0	1.41	0.99	0.19	0	0	0	2.59	
HI RAINFALL	in.	0	0	0	0	0	0.02	2.00	1.30	1.15	0	0	0	2.00	9 Jul 70
AV H_2O PRECIP	in.	2.26	1.72	1.82	1.84	2.05	0.96	1.57	1.07	0.81	0.96	1.29	2.49	18.84	
AV DAYS PRECIP		9.7	9.2	10.3	9.6	9.2	5.9	4.8	4.2	3.4	4.2	7.2	7.8	85.5	
AV MAX WIND	knots	28.0	28.9	26.4	23.8	21.8	18.4	16.0	16.3	18.0	20.3	23.9	25.8	22.3	
HI MAX WIND	knots	N 82	++ 70	NW 65	W 72	W 56	W 44	S 46	SW 46	NE 44	W 70	N 58	W 68	N 82	20 Jan 59
LO MAX WIND	knots	E 5	S 4	S 5	NW 7	NE 4	NE 4	NW 4	S 4	++ 5	NW 4	E 5	++ 6	++ 4	++
MAX WIND DIR															
NORTH	%	17	21	18	10	11	7	4	2	7	14	15	17	12	
NORTHEAST	%	4	4	5	5	9	5	6	4	6	7	7	8	6	
EAST	%	2	1	3	2	6	4	12	8	7	8	3	1	4	
SOUTHEAST	%	0	1	1	3	4	12	15	10	7	4	3	1	5	
SOUTH	%	3	5	4	4	9	13	23	24	14	6	6	3	9	
SOUTHWEST	%	11	11	16	17	18	20	19	23	21	11	19	14	17	
WEST	%	48	46	37	48	36	33	19	26	33	41	33	42	37	
NORTHWEST	%	15	12	16	11	7	6	3	2	5	10	15	14	10	

2. Sampling and significance

A large part of the work reported here is an extensive set of measurements of atmospheric conditions affecting astronomical observations, which were made on selected days between 1971 July 1 and 1972 June 30 at the summit of White Mountain. We attach particular importance to measurements made at sunrise, which were made on 169 days out of that period. The NASA funded survey of several sites used only noontime observations of water vapor, however, which we made on 156 days out of the same period, having 149 days with both sunrise and noon measurements. This section discusses randomness of sampling of each of these sets of days out of the year.

A major cause of the difference between the sets of days with sunrise and noon measurements was a need for the observer to use shop facilities of the Barcroft Station. He always spent the night at the Summit Station and drove to and from the Barcroft Station during the middle of the day. At that time we did not know that some other sites were only making noon measurements, and we were focussing our effort on nighttime and sunrise measurements. Otherwise the difference between the sets of noon and sunrise measurements simply is due to arrival and departure times for runs at the Summit Stations.

We did not occupy the Summit Station continuously during the year for financial reasons only. We hired people solely to operate the survey at that Station, since the permanent staff only occupy the Crooked Creek and Barcroft Stations. The gaps in our observations are due entirely to accumulated time off by our staff and not to weather.

The tests discussed below show that we did occupy the Summit Station during a random sample of weather conditions, which is well attested to by the anecdotes of the observers who sat out storms. Even travel to the Summit Station was sometimes done on foot in bad weather.

The times of operation of the ten micron sky noise machine were selected in a still different manner, being affected by instrumental problems. We have not yet analyzed the significance of the sampling of the times those measurements were made.

We also discuss measurements of a smaller number of meteorological quantities, which have been made almost every morning at 8 AM at the Barcroft and Crooked Creek Stations since 1953 and 1950 respectively. So few days have not had those measurements, that we assume without further discussion that they are a random sample.

We determine randomness of sampling and significance of most of our conclusions by means of the χ^2 test, about which there are some important qualifications to be applied throughout this paper. Few of the quantities we measure have a normal distribution, except for air temperature and pressure at fixed times of day over a limited range of season. Therefore the powerful tests for significance of mean values and standard deviations are useless.

We do make many χ^2 tests for significance of frequency distributions and median values, although there are a variety of non-parametric tests for ordinal distributions which are more powerful than the χ^2 tests. All of the quantities we discuss here are at least on an ordinal level of measurement, and the Kolmogorov-Smirnov tests should be useful for them. However, in the cases where we have made both Kolmogorov-Smirnov and χ^2 tests, the results are the same, so we have reported only the χ^2 results because of their familiarity to many readers. In addition that test is widely used in the climatological literature, so our conclusions will have the same basis.

The major limitation to the power of the χ^2 test is the small deviation from strict independence of observations discussed here. We commonly analyze runs of measurements made once a day, and there is some correlation extending over two or three days. Our runs are always much longer than that correlation time and our numbers of observations are always much greater than the minimum necessary for a test. In comparing distribution functions we have always pooled the data into categories giving minimum expected frequencies of five, and usually giving much higher expected frequencies. Therefore we are reasonably confident that the small deviations from independence are not harmful to the tests, which is in agreement with the general usage in the meteorological literature.

The occasions on which a man made measurements at the summit were selected by many factors in the personal lives of the observers. One might expect that a man would be on the summit preferentially in good weather, but this section gives several arguments why that is not so.

Because of availability of a particular observer, we have more observations per month in summer than in other months. For this reason as well as the distribution of water vapor described below, I have analyzed the data in two periods of the year only, being summer and not-summer. I define summer as the calendar months of June, July, and August. These two periods then each contain sufficient numbers of measurements to enable use of significance tests.

Inspection of the distribution of precipitable water vapor as a function of date also shows that the year can be divided into two distinct sections. During June, July, and August the PWV is two to three times higher than in other months with a maximum in late July. All of the other months appear to be similar to each other.

Another reason for choosing the breakdown by summer and not-summer is given by the details of an analysis of expected water vapor by Kuiper (1970). He calculates this from radiosonde measurements, taking three month averages. The time I call summer is one of his periods, and the time I call not-summer is his period of the best nine months for low water vapor.

We are especially interested in an analysis of conditions at night. The water vapor should be lowest at night, because of low air temperature, low evaporation of water from the ground, and minimum convection up from the valleys. The cloud cover is also minimum then, especially in summer when there is a major buildup of convective clouds during the day. Since we measure water vapor by its spectral line absorption of sunlight, our best estimate of night-time values is made shortly after sunrise. We have chosen to make our sunrise measurements when the sun is ten degrees above the horizon, and the analysis of all of our different kinds of data is emphasized for that time.

At 8 AM each day weather conditions are recorded at the Barcroft Laboratory which is 5.6 km away from the summit and 540 meters lower in elevation. That was done for each of the 366 days (including a leap year February) of the year that was analyzed. My statistical analysis of randomness of weather conditions when we made summit measures is based upon those Barcroft measurements. The 8 AM Barcroft measurements of cloud cover would be expected to be well correlated with summit conditions at sunrise, because of their closeness in both time and space.

This section demonstrates with high significance that the mornings and noons on which we made measurements at the summit are separately represented by random samples of cloud conditions at Barcroft. I expect this signifies a random sample of cloud conditions at the Summit.

During the nine months of not-summer we made measurements on 107 days at sunrise and 100 days at noon, being 39% and 37% of the days in that period. During the three months of summer we made measurements on 62 days at sunrise and 56 days at noon, being 67% and 61% of the days in that period. Those days when we made summit measurements we call summit days.

The Barcroft estimates of cloud cover are recorded in five categories: 1 = clear, 2 = scattered clouds, 3 = broken clouds, 4 = overcast, 5 = obscured horizontal vision. Frequencies of occurrence of those categories are analyzed here.

Table II A-2 and Figure II A-1 contain the relative frequencies of cloud categories for several selections of days, with part A for not-summer and part B for summer. The first line in the table shows the relative frequencies of cloud categories for all the days in the period. The next two lines refer to the summit days, and the next twelve lines represent a set of ten random samples of all days with replacement after sampling. These samples were taken to approximate the fraction of all days that were summit days. The third and fourth lines of the table show the means and standard deviations of the sets of ten samples.

The first columns of each table give the number of days in the periods analyzed, in which the random samples give some dispersion in the number of days selected. The remaining five columns give the relative frequencies of occurrence of the five cloud categories.

Inspection of the first three lines shows that there is no very large difference between all days and summit days during not-summer, but there may be a difference in summer in categories 1 and 3. However the random days show standard deviations in cloud cover such that the summit days are within one standard deviation of the mean of the random days in fourteen out of twenty cases. The largest difference is 2.8 standard deviations, so there is probably no significant difference even in summer.

Inspection of the sets of ten random samples shows that, regardless of any questions about the normality of the distribution of the samples, there is not much difference between all days, summit days, and random days.

Finally we have taken the χ^2 of the distribution of relative frequencies on the summit days for each of the two periods and for sunrise and noon separately. The expected frequencies are taken to be the observed frequencies for all days, and where necessary the cloud categories are further pooled than in table II A-2. In all cases the χ^2 tests satisfy the hypothesis that the summit days represent a random sample of cloud conditions at the usual 0.05 level of significance, and they even satisfy that hypothesis at the 0.30 level of significance and higher.

In this organization of data the cloud distributions in summer and not-summer are quite similar. This is because the best weather is in the fall and the worst in the winter. When those periods are taken together in the sampling, they average out to become similar to spring and summer. Nevertheless, the variation of cloud cover between seasons is only two sigma of the variation within one season.

TABLE II A-2

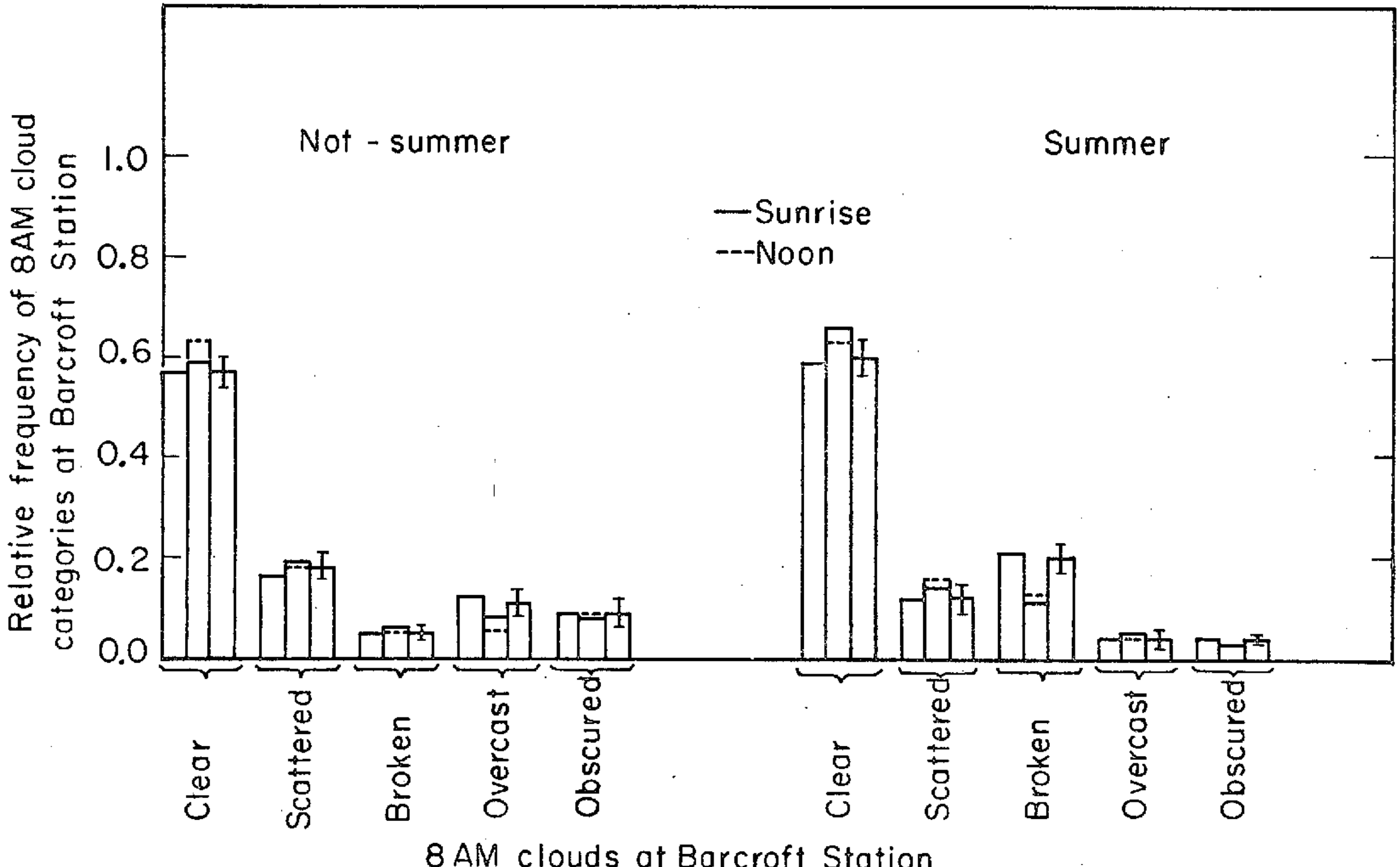
A. NOT-SUMMER

			Cloud Category				
		N	1 %	2 %	3 %	4 %	5 %
All days		274	57.3	16.4	4.7	12.0	9.5
Summit Days:	Sunrise	107	58.9	18.7	5.6	8.4	8.4
	Noon	100	63.0	18.0	5.0	5.0	9.0
Mean of Random Days		107.4	56.8	18.0	4.8	11.2	9.2
Standard Deviation of Random Days		6.5	3.0	2.9	1.5	3.2	2.8
		111	54.1	18.0	4.5	16.2	7.2
		101	58.4	16.8	5.0	12.9	6.9
		105	57.1	23.8	4.8	10.5	3.8
		95	55.8	18.9	7.4	5.3	12.6
Random Days		104	58.7	19.2	3.8	6.7	11.5
		111	50.5	18.0	7.2	11.7	12.6
		110	55.5	20.9	3.6	10.9	9.1
		106	60.4	15.1	3.8	12.3	8.5
		115	57.4	15.7	5.2	11.3	10.4
		116	60.3	13.8	2.6	13.8	9.5

TABLE II A-2

B. SUMMER

		N	Cloud Category 1 %	2 %	3 %	4 %	5 %
All Days		92	58.7	12.0	20.7	4.3	4.3
Summit Days:	Sunrise	62	66.1	14.5	11.3	4.8	3.2
	Noon	56	62.5	16.1	12.5	5.4	3.6
Mean of Random Days		61.6	59.9	12.2	20.4	3.9	3.7
Standard Deviation of Random Days		5.0	4.0	2.6	3.3	1.9	1.2
		59	59.3	11.9	20.3	5.1	3.4
		67	55.2	14.9	20.9	3.0	6.0
		54	68.5	7.4	16.7	5.6	1.9
		59	54.2	13.6	27.1	0	5.1
Random Days		58	60.3	13.8	19.0	3.4	3.4
		67	58.2	9.0	23.9	6.0	3.0
		59	61.0	15.3	15.3	5.1	3.4
		59	62.7	11.9	20.3	1.7	3.4
		69	60.9	10.1	20.3	4.3	4.3
		65	58.5	13.8	20.0	4.6	3.1



XBL 737-3558

Figure II A-1. Distribution of cloud cover at the Barcroft Station. All days in summit year on left, days when summit was occupied in middle, mean of ten random samples of days on right. Error bars are standard deviations of the sets of random samples. Slightly different sets of days for sunrise and noon occupation shown by solid and dashed lines.

3. Precipitable water vapor measurements

We started making water vapor measurements at White Mountain in 1971 January, using a meter designed, built, and calibrated by Dr. Frank Low. When the NASA funded water meter supplied by Dr. James Westphal arrived, our personnel preferred to continue using the Low meter because of familiarity. In addition the Low meter appeared to give greater reproducibility in a series of observations. Accordingly most measurements were made with that meter until 1972 June, when almost all measurements were made with both meters. The Westphal meter was used for most measurements made at lower stations than the Summit.

These two meters were extensively intercompared to relate their scale readings in 1971 June and in 1972 May and June. These comparisons were done at the Summit Station under a variety of cloud conditions and zenith distances. A numerical fit was made to the comparison of the scale readings, using the 1972 data and 132 points. That fit was then used to calculate equivalent readings for the Westphal meter, using actual readings with the Low meter. In the fitting process the standard error of the residual of one Westphal meter reading from the derived curve was 14 units on the Westphal meter scale, although the fit was much better than that value at the low water end of the scale. That standard error of a single meter reading calculation leads to about a fifteen percent error in the derived value of water vapor. The statistical parameters of the distribution of water vapor will of course be much smaller.

After the equivalent Westphal readings were submitted to the NASA survey, we went back to the 1971 comparison to look for any change over the year, and found no change.

For the sake of uniformity of comparison with other sites we are stating the statistical parameters of the water vapor at noontime by measurement from the plots distributed by Westphal in 1973 July, based on his best calibration. However, in the discussion of variation of water vapor during the day and between different stations at White Mountain we calculate the water vapor by first calculating the equivalent Westphal meter reading and then calculating the water vapor from an empirical formula provided by Westphal. That formula does indeed reproduce the value given in his plots, starting with the quantities which we sent to him and our direct measurement of zenith distance of the sun.

The quantities of water vapor reported by Westphal are the equivalent amounts of vapor which would give the observed amount of band absorption at sea level pressure. The effect of the vapor upon an astronomical observation depends upon whether the observer is interested in wide band photometry or in high resolution spectroscopy. In the former case the effect is determined by the sea level equivalent amount of vapor. In the latter case the effect is determined by the actual amount of vapor, so it is necessary to correct the observations for pressure effects.

The absorption by a single, strong spectral line is proportional to the square root of the pressure, but the measured absorption of many water bands is proportional to roughly the fourth root of the pressure (Holter et al., 1962). Since the absorption is proportional to the square root of the amount of water, the pressure correction for amount of water goes as the square root of the pressure.

After choosing an altitude above observing sites which has a representative pressure, we derive the following table of pressure corrections. The apparent water vapor is multiplied by these factors to derive the actual water vapor.

Station	Elevation (km)	Correction factor
White Mountain Summit	4.34	1.405
Mauna Kea	4.20	1.393
White Mountain Barcroft	3.78	1.357
Mt. Lemmon	2.80	1.276
Kitt Peak	2.06	1.218

In order to evaluate the effect of observing from different stations at different altitudes on White Mountain, we use the scale height of the density of water vapor. This can be derived from the Gringorten (1966) Atlas of Atmospheric Humidity, giving 1.85 km at the altitude and geographic location of White Mountain, using the 50 percentile dew point in April and probably in midday. Kuiper (1970) suggests a representative value of 1.6 km. Simultaneous noontime measures of water vapor at the Summit and Barcroft Stations during 1971 June and July and during 1972 March and April give 2.3 km and 0.6 km respectively, using the 1973 Westphal calibration and the pressure correction described above.

An attempt to determine scale height from 8 AM wet and dry temperature readings at the Crooked Creek and Barcroft Stations over twenty years gave very high values. This is probably due to a surface layer of water vapor which lies over the mountain.

Plass and Yates (1965) show the result of calculations of absorption in a complex model atmosphere, reduced to equivalent amount of water at sea level pressure. This is exactly the quantity measured directly with the water meters, and the calculations give a scale height of 1.3 km between 3 and 8 km altitude. Our direct measurements, uncorrected for pressure, give 2.0 km in summer and 0.6 km in spring.

The greater scale height in summer is probably due to convection bringing up water vapor from lower altitudes. During one afternoon in July a series of measurements were made at both the Barcroft and Summit Stations. The water vapor at each station was a maximum at 1530 PST, and the ratio between the stations was a minimum at the same time, giving a maximum scale height. Since that time coincides with the well known time of maximum thunderstorm activity, there is strong support for convection reducing the scale height.

When the summit was occupied we made at least five measurements each day of water vapor, weather permitting. The first and last measurements were at 80° zenith distance, measurements were at two or three hours each side of noon, and a measurement was at noon. The maximum amount of water vapor is usually in mid-afternoon, with more water remaining at sunset than there was at sunrise. The amount of change is greater in summer than in not-summer, and on a few not-summer days the water vapor is essentially constant over the day after zenith correction.

These facts about the variation with time give us confidence in applying the standard zenith distance correction, dividing the observed water vapor by secant z, which assumes that the water has a uniform horizontal distribution. If the water distribution was strongly asymmetrical in the east-west direction, and had alternate senses of asymmetry at different times, we would occasionaly expect to see maxima before noon. Since we never see that, strong asymmetry probably does not exist.

Mather, Werner, and Richards (1971) have reported on spectral measurements of the emission of water vapor over the range of 6 to 14 cm^{-1}. These measurements were made in late April and early May at the Barcroft Station, and were fitted to emission models containing amount of water vapor as a parameter. Because they superimpose observations made at different times, in order to get sufficient signal to noise ratio, it is difficult to determine an exact correspondence with measurements made with our water meter. They fit their observations with models containing between 1 and 1.5 mm of precipitable water vapor (actual and not equivalent), which is quite consistent with our measurements on the same days, at Barcroft, and with the Low meter and calibration.

They report privately that the water vapor along a path to the west with a 45° zenith distance is about 30 percent higher than along a similar path to the east. The land there has a slope of 17° down from west to east, so the angle of the atmospheric path above the ground is 28° to the west and 62° to the east. This may explain their asymmetry.

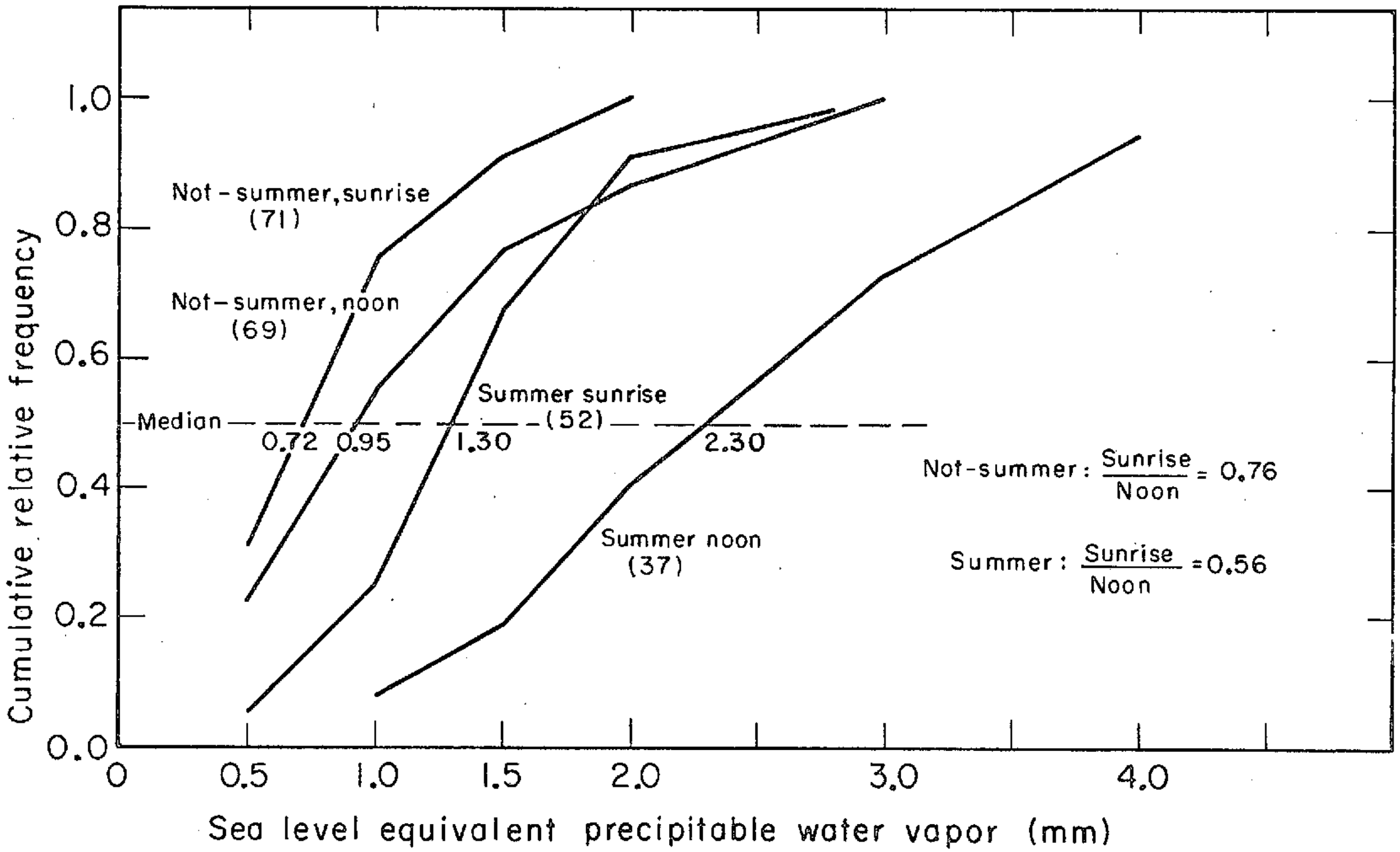
The zenith distance correction could give a false result if the majority of the water is in a blanket wrapped symmetrically around the mountain. O'Connor, et al (1969) report radiosonde measurements of water vapor above the Barcroft Station, which show a layer of water a few hundred meters thick. This could be a blanket which wraps around the mountain, but it appears to contain only ten or twenty percent of the total water. That small amount cannot account for the large difference in water vapor between sunrise and noon in summer, which we describe later.

The above points of (1) some days having constant water vapor (2) maxima never being before noon and (3) radiosonde measurements showing only a small fraction of the water in a boundary layer lead us to conclude that there probably is a uniform horizontal distribution of water. Therefore we accept the standard zenith distance correction, but of course we apply that only with zenith distances less than 80°.

Figure II-A-2 shows the sunrise and noon water vapor data, broken down by summer and not-summer, after correction to the zenith and using the 1973 Westphal calibration. The median at sunrise for summer is 1.3 mm and for not-summer is 0.72 mm.

The χ^2 test shows that in not-summer there is no correlation between water vapor and cloud cover with a significance of .85. Therefore the random sampling of days insures a random sampling of water measurements, regardless of the impossibility of making measurements on heavily overcast days. We expect that this independence is due to the clouds being mostly ice in not-summer.

However, in summer there is a strong correlation between cloud cover and water vapor, so our water vapor distribution refers only to days when clouds were thin or scattered enough so that measurements could be made. This relationship between water vapor and cloud cover is very important at longer wavelengths, where the scattering by clouds is less important than at visible wavelengths. This is certainly the case at millimeter wavelengths and it may be relevant at twenty microns.



XBL737-3560

Figure II A-2. Cumulative distribution of precipitable water vapor at White Mountain summit. Summer is June, July, and August. Sunrise is when the sun is 10° above the horizon. Number of observations are in parentheses and median values are written below the median line. Sunrise to noon ratios are for median values.

Focussing our attention on the water vapor in the nine months of not-summer, we see that there is a modest difference between sunrise and noon as well as no difference between cloud conditions. As we show in other sections of this document on seeing and wind, wind is not importantly correlated with seeing nor with cloud cover. This is unfortunate since we would like all of the bad conditions to occur at the same time, but it does enable simple calculation of the probability of occurrence of a given set of limiting values of the atmospheric parameters. That probability is the product of the cumulative relative frequencies of each of the parameters at the chosen limits.

The situation is very different in summer, when most of the conditions disturbing astronomical observations are caused by convection. Then the nights are good and the days are bad.

The lowest measured precipitable water vapor at noon was 0.15 mm on 1972 January 29 at 1234 PST. There were 17 days with noon PWV less than or equal to 0.5 mm, and they were spread out over all of the not-summer months. The lowest PWV at sunrise was 0.11 mm on 1972 March 11 at 0750 PST and a somewhat late measurement at 74° zenith distance. There were 28 days with sunrise PWV less than or equal to 0.5 mm, and they were spread out over all months including summer.

Finally we emphasize that the values of precipitable water vapor given in this section are the amount which give equivalent absorption at sea level pressure and are calibrated by the 1973 Westphal technique.

4. Wind

Wind has been measured at the Crooked Creek and Barcroft Stations most of the time since 1950 and 1953 respectively, using chart recorders with the anemometers. For each day the maximum sustained windspeed for one hour was read off of the chart and ultimately recorded on punched cards. We have used some of the originally punched data and have made extensive use of the climatological data summary derived from them. (Pace, Kiepert, and Nissen, 1971). However, neither of those recorders were operating during the Summit Year.

The mean and standard deviation of the 16 year distribution of the annual mean maximum wind speeds at the Barcroft Station are 22±1.3 knots. The same quantities for the mean January maximum wind speeds are 28±4.0 knots. Since the year to year variation is so small, we will assume that the summit winds measured during the Summit Year are representative of normal conditions. This is decidedly different from the number of clear days per year, where the Summit Year was unusually good.

Most of the wind measurements at the Summit Station were made with a hand held precision anemometer, held at eye level at the extreme windward edge of the summit, being the highest and most exposed point within 100 km. For forty days at the end of the Summit Year a permanently installed anemometer about four meters above the ground was used with a chart recorder. The hand held anemometer was used as the standard in the cross calibration of the two instruments. Because of the steep cliff at the west edge of White Mountain, the wind often had an upwards component, and the hand held anemometer was held so as to measure the resultant velocity. As with all the measurements we report, the winds were measured during a random sample of days, by virtue of a man living at the Summit Station during all kinds of weather.

Median wind speeds were carefully determined from the 40 days of chart records for the night time intervals 1800 to 0600 PST and for the daytime intervals 0600 to 1800. There is very little correlation between individual nighttime median speeds and the following sunrise handheld anemometer measurements, but the distribution functions of those quantities are the same at the .25 level of significance. The median of the 40 nighttime median windspeeds is the same as the median of the spot measurements at the following sunrise, being 11 knots over parts of April through June.

Therefore we assume that any modest sized sample of sunrise spot measurements has the same distribution as the set of preceding nighttime medians. On that basis we will compare the White Mountain windspeed measurements with those from Mauna Kea in section II D.

Figure II A-3 shows the distribution of windspeed at White Mountain Summit, using our usual breakdown into summer and not-summer. The hand held anemometer had a maximum reading of 52 knots, so windspeeds above that value were determined with limited accuracy. The high speeds were measured on an existing inexpensive anemometer, but its uncertainties do not affect the distribution below the 85th percentile in not-summer or at all in summer. Median windspeeds are 9 knots in summer and 23 knots in not-summer, and all weather is included.

The only way to measure gust velocities or daily maximum velocities is with a recording anemometer. The calibration of the recording anemometer was done below 43 knots, so we are unsure of its extrapolation to higher velocities. Nevertheless, the highest recorded windspeed on the chart was a gust of 90 knots during a time when the one hour sustained windspeed was 50 knots. On the basis of anecdotes by the observers, we believe that there were higher gust velocities on days before the chart recorder was in operation but we have little idea of their magnitude.

The winds at the Barcroft Station are more nearly representative of less exposed regions on White Mountain, where there is some shielding from the prevailing west winds and some drag from the wind blowing across the ground. As noted above, only the daily maximum one hour sustained windspeed was logged. A spot check of a few of the original strip chart records indicates a tendency to log the instantaneous daily maximum instead of the sustained maximum. In either case the logged quantity is much higher than the median windspeed, which is analyzed in earlier paragraphs.

Figure II A-4 shows the distribution of these daily maximum windspeeds at the Barcroft Station for summer and winter, further broken down by 8 AM cloud cover being less or greater than 50%. The small relationship between windspeed and cloud cover is statistically significant at the .05 level, because of the large number of observations, but it is not operationally significant. The fall and spring distributions fall between those shown, and were left off for clarity.

There is an important difference in winter between the Summit daily median winds, as shown in Figure II A-3, and the Barcroft daily maximum winds as shown in Figure II A-4. The Summit 90th percentile is at 58 knots and the Barcroft 90th percentile is at 42 knots. We expect the relationship between median and maximum to be in the opposite sense. Therefore the high Summit winds are overestimated and/or the reduced exposure at Barcroft has a large effect, since

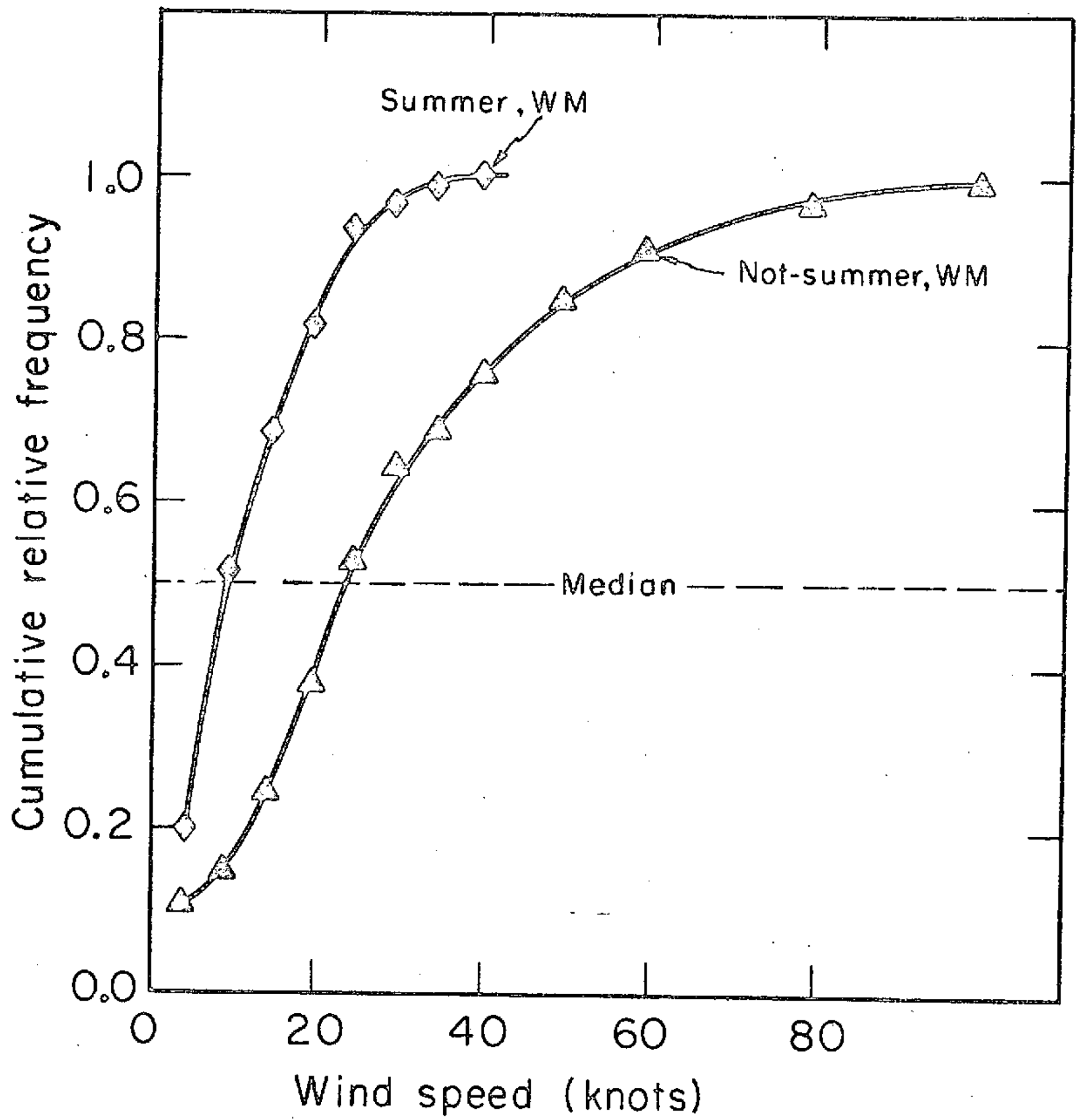
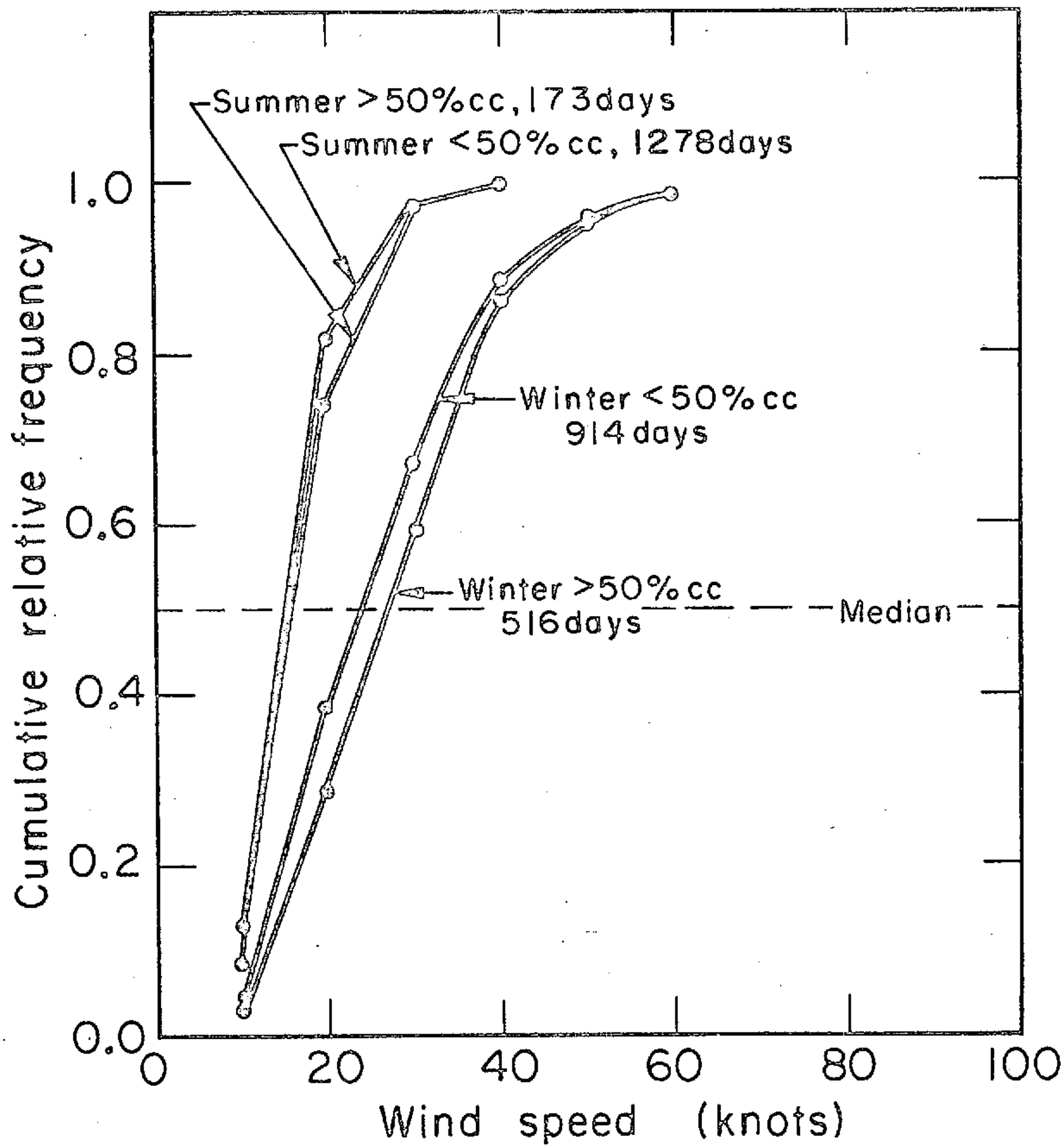


Figure II A-3. Cumulative distribution of sunrise instantaneous wind speed (same as distribution of nighttime median wind speed) at White Mountain summit.



XBL737-3540

Figure II A-4. Cumulative distribution of daily maximum wind speed over 21 years at Barcroft Station, broken down by summer and winter and further by cloud cover greater or less than 50%.

altitude alone does not have that big an effect. Sites are available with similar wind shielding as at Barcroft, including places just below the Summit, so the Barcroft windspeed distribution may be relevant to those sites.

Over the sixteen years of wind measurements at Barcroft, the maximum recorded one hour persistent windspeed was 82 knots. We do not know how much higher the gust velocities were.

5. Stellar Seeing

Seeing observations have been made at the Summit Station only, using a telescope patterned after those used by Walker (1965, 1970, 1971) in his seeing surveys. The particular telescope we used was built in connection with the earlier White Mountain survey under the Space Science Lab, but it was not used before that survey was terminated for lack of funds.

At the beginning of the survey this telescope was temporarily installed at Mount Hamilton and the linear size of its image at the focal plane was calibrated against one of Walker's telescopes there. That in turn was calibrated against eye estimates of seeing disk size at the Coude focus of the 120 inch telescope. This calibration and the subsequent development and reduction of the film with White Mountain seeing measurements were generously done by Dr. Merle Walker.

I have never even seen any of these films of Mt. Hamilton calibration or White Mountain seeing, so I can not bias their interpretation. The individual seeing measurements should be directly comparable with those from Walker's earlier surveys, with the critical questions being related to selection effects and statistical interpretation.

Many factors went into selecting the nights on which seeing measurements were made. The nights on which a man was at the Summit Station were randomly selected out of the year, as discussed in section II.A.2 and a further random selection of clear nights had seeing measurements. Measurements were not made because of observer fatigue, alarm clock failure, high wind, low temperature, and water condensation inside the lens followed by removal for drying. The number of nights with seeing measurements as a percentage of number of clear sunrises was 56% in summer and 79% in not-summer.

We test to see if the distribution of wind speed at sunrise after seeing measurements can be a random sample from the distribution of wind speed for all clear sunrises. The chi square test shows this is a random sample for summer and not-summer separately, with a significance of .15 and .50 respectively, so the seeing measurements were not biased toward calm nights.

A possible source of bias could lie in my rejection of observations where either Walker or the observer reported telescope vibrations due to wind. All the observations were so rejected on eleven nights scattered over the period 1972 July through November. During the course of the survey we several times successively reduced this vibration by piling rocks on and around the telescope mount so the wind speed at which the vibration started varied with date. Vibrations were reported only once after 1972 November. Figure II A-5 shows all seeing observations, which were not rejected because of vibration, plotted against wind speed at the position of the telescope objective. All rejected measurements are shown at the measured wind speed and the upper edge of the seeing graph. Since all seeing measurements are shown, including multiple measurements on many nights, this graph alone does not give a valid picture of the probability of various categories of seeing or wind speed.

Inspection of Figure II A-5 shows that there may be a small tendency for seeing to get worse with wind speed increasing above 25 or 30 knots. Below 25 knots the seeing is independent of wind speed. In view of the median wind speed in any season being within the region of independence of wind speed and seeing, I conclude that my statistics of seeing are not significantly biased by the rejection of observations when the telescope was vibrating. Whatever bias does exist is in the upper quartile of wind speeds, and has no effect on the probability of excellent seeing.

There were two adjacent nights in January and one night in April with abominable seeing between 10" and 20". The winds were mostly around 50 knots, but no telescope vibration was recorded. In all of these cases and in no other cases at night, alto cumulus standing lenticular clouds were recorded. These were clearly times when the Sierra Wave existed, and the wave apparently devastates seeing.

Inspection of the log shows that other times when lenticular clouds were recorded in daytime were adjacent to nights which were too cloudy to make seeing measurements. The abominable seeing measurements are not shown in Figure II A-5 because they represent a radically different domain of atmospheric conditions. Nevertheless, the nights with abominable seeing are included in the statistics on seeing given below since no telescope vibration was reported.

After the rejection of measurements when the telescope was vibrating, there remained 116 seeing measurements on 64 nights. 25 nights had only one measurement. The average seeing for each night was taken by a simple mean, regardless of number of measurements per night. The frequency distribution for simple means was corrected by weighting by number of measurements during each night, giving about the same frequency distribution as without weighting.

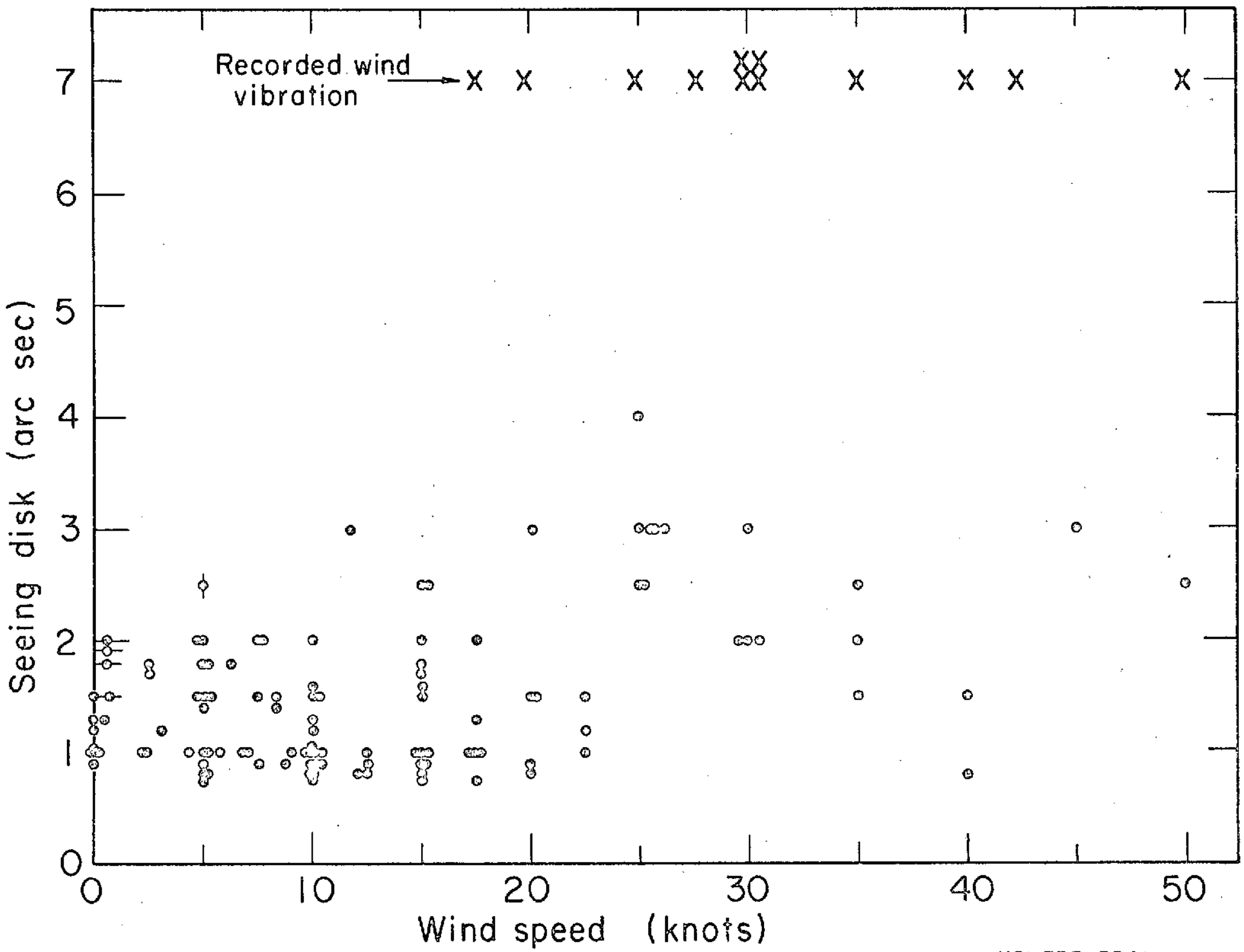


Figure II A-5. Stellar seeing as a function of wind speed at White Mountain summit.

Although nights with single measurements tended to have them before midnight, the trends during the night went in both directions, so the averaging technique is satisfactory.

On one night I did not take a simple mean because of an extreme change of seeing from 1".2 to 7" between two measurements separated by 4.5 hours. The winds were below 10 knots all night. In this one case I arbitrarily assigned 2".0 as the average seeing.

Figure II A-6 shows the average seeing for each night as a function of date of sunset. It appears that winter and spring have worse seeing than summer and fall, where median seeing in winter and spring is 1".5 and in summer and fall is 1".2. First ten percentile seeing is 0".8 in both of those pairs of seasons. Nevertheless, the difference in medians is not significant, having about 20% probability of being due to sampling variation. Figure II A-6 also shows the cloud cover at time of sunrise.

In order to compare White Mountain seeing with that at other sites, we take our entire year's data together. Table II A-3 shows the frequency distribution for seeing at several sites, in the format of Walker's Table IX (1971). Junipero Serra, Cerro Tololo, Kitt Peak, San Pedro Martir, and Piper Mountain are displayed in the same way as in Walker's table.

TABLE II A-3

Percentage of Observed Nights with Average Seeing as Indicated

Location	≤1".0	1".1 to 1".5	1".6 to 2".0	>2".0	Total number of nights observed
White Mountain - best	55	20	16	10	64
White Mountain - average	36	31	17	16	64
White Mountain - worst	27	21	17	35	75
Junipero Serra	26	38	13	23	558
Cerro Tololo	24	32	22	22	509
Kitt Peak	15	30	16	39	253
San Pedro Martir	15	25	17	42	52
Piper Mountain	9	30	20	42	164

Although White Mountain heads this table in apparent quality of seeing, that is not at all significant. χ^2 tests of the White Mountain seeing compared

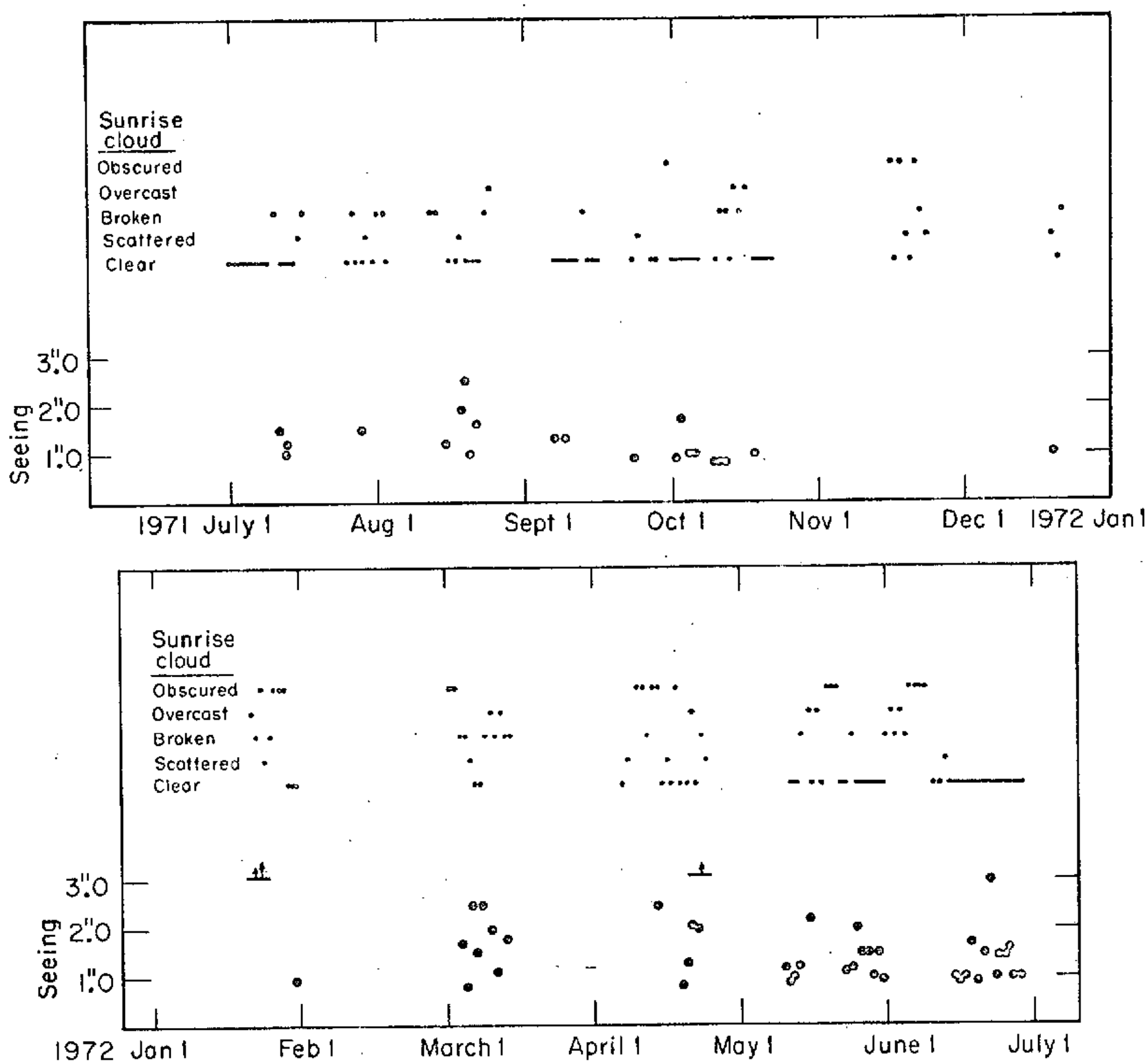


Figure II A-6. Stellar seeing and cloud cover at White Mountain summit as a function of date.

with the other sites one at a time show no significant difference with Junipero Serra or Cerro Tololo when possible sampling variations are taken into account. This decision is made at the threshold significance of .05. However, White Mountain seeing is significantly better than at Kitt Peak, San Pedro Martir, or Piper Mountain at the same level of significance. Because Junipero Serra and Cerro Tololo both have about the same large number of measurements, the χ^2 test shows Junipero Serra to be better than Cerro Tololo.

The distribution of average seeing does not show the spread of seeing conditions nor is the average necessarily a valid parameter, so Table II A-3 also displays the distribution of best and worst seeing on each night at White Mountain. The best seeing comes from simple selection. The worst seeing is organized to give an unreasonably bad description, by assigning seeing greater than 2".0 to all times when there was telescope vibration. This includes the eleven nights which were rejected in formation of average and best seeing because all of the observations during the night had telescope vibration. Some of these nights probably had seeing better than the assigned >2".

Again applying χ^2 tests to find significant differences between White Mountain and other sites, we find that the best seeing out of each night at White Mountain is significantly better than the average at any other site. On the other hand, the worst possible description of the measurements shows only Junipero Serra to be significantly better than White Mountain. Table II A-4 shows the relative standing of White Mountain with several other sites, the decision being made at the .05 level of significance. Best, average, and worst seeing are displayed, using (+) for White Mountain better, (-) for White Mountain worse, and using (x) where a decision cannot be made.

TABLE II A-4

White Mountain Seeing Relative to Other Sites

Station	Best out of night	Average over night	Worst Description
Junipero Serra	+	x	-
Cerro Tololo	+	x	x
Kitt Peak	+	+	x
San Pedro Martir	+	+	x
Piper Mountain	+	+	+

The distribution of various categories of seeing, using the dubious technique of averaging over each night, shows White Mountain to be better than any place measured by Walker except for Junipero Serra and Cerro Tololo. It is perfectly possible that the seeing could be better or worse than at those two stations, but a decision cannot be made with the existing number of observations.

No matter how badly I describe the White Mountain measurements, the seeing is better than at Piper Mountain, 38 km to the southeast and 2.00 km lower. This could be due to any of at least three differences, being in altitude, epoch of measurement, and upwind topography. The latter point could be quite significant, since the prevailing winds at Piper Mountain blow over a ridge which is 27 km away and 1 km higher.

The upwind obstructions at White Mountain range from 40 to 80 km away in the Sierra Nevada, depending upon direction, and are normally about 600 meters lower. Occasional peaks stick up to the height of White Mountain but the sum of their angular widths is a few degrees spread over the entire western semicircle. Both the distribution of wind speed and the distribution of abominable seeing suggest that the Sierra Nevada affect seeing only about 5% of the time when the sky is clear.

6. Sky brightness

We have made measurements of the brightness of the sky close to the sun, using a comparison visual photometer. This was provided by the High Altitude Observatory and calibrated by the Sacramento Peak Observatory. 377 observations were made with this instrument over the summit year, but they have not yet been subjected to careful statistical analysis. The minimum value of the sky brightness was 11×10^{-6} of the photosphere brightness, which is identical with the minimum measured by Walker at Junipero Serra. The analysis of sky brightness will appear in a later report.

On over 100 mornings near sunrise we took Kodachrome photographs from a standard position and in a standard direction looking down the Owens Valley. They can be used as a baseline in evaluating any change in haze or smog close to the horizon. They also show the snow cover on the ground along the western edge of White Mountain. Visual inspection of these photographs could not find any time when there was more smog or haze than in the aerial photographs, which were taken with similar elevation and direction of the sun.

7. Sky noise

The raw statistics presented in the Westphal report are of limited value as far as White Mountain is concerned. It will still take considerable effort to understand the nature of the sample of conditions when we had the machine in operation. We suspect that sky noise is correlated with seeing when there are no clouds, and if this is true the sky noise must be very low at White Mountain. However, we have no statistical basis yet to support that belief. Unfortunately the sky noise machine does not separate clouds from high sky noise, so we will in the future go through our records to separate these phenomena. We will derive the distribution of sky noise during clear hours, which can then be multiplied by the probability of clear sky to get the overall probability of low sky noise.

8. Cloud cover

The twenty years of weather measurements at the Barcroft and Crooked Creek Stations include an estimate of cloud cover at 8 AM. This is categorized as clear, less than 10% cover; scattered, between 10% and 50% cover; broken between 50% and 90% cover; overcast; and horizontal vision obscured. There is obviously room for large subjective error in this estimate, but during the times one of the astronomical survey observers was at a lower station, he reported results very similar to those from the station maintenance man. However, from 1958 through 1961 the man at the Barcroft Station never reported the sky as overcast, but as broken or obscured.

In Figure II A-7 we show the cumulative relative frequency of the five categories of cloud cover, pooling all the observations for each month separately over the twenty year run. Note that the median cloud cover is clear over five months and between clear and scattered over the rest of the year. This is certainly very good weather. However, these 8 AM data do not show the common afternoon cumulus buildup in summer, although 8 AM is representative of the rest of the day in not-summer.

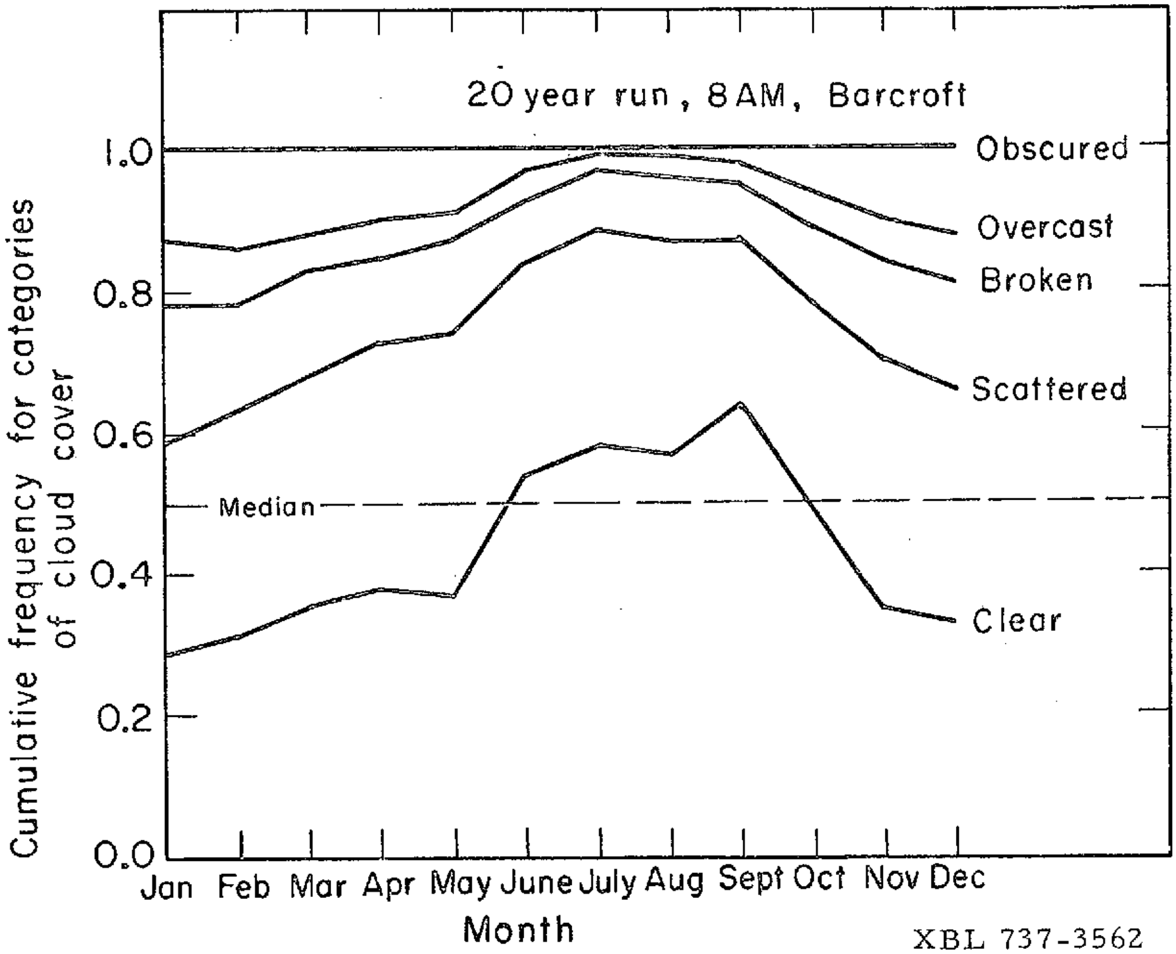
In Figure II A-8 we show the same data arranged by year, in order to show trends in the weather. There are many years where the median cloud cover is clear, even when pooling all the days in the year. A most serious point is the trend of the clear contour, however.

The year in which we made measurements at the Summit included the last six months of 1971, the clearest year out of the entire twenty, so all of our results must take that into account. Interestingly enough there were somewhat more broken and overcast days in that year than in most, and there was a typical number of scattered days. Summer alone does not show so much year to year variation.

In our further discussion of cloud cover we will adjust Summit Year measurements to what they would have been in a normal year. We suggest that other sites may have similar but unmeasured trends from year to year.

There is considerably more cloud cover at the Barcroft Station than at the Crooked Creek Station, especially in winter and spring. Pooling all days in the twenty year run, it is clear at Barcroft only about 76% of the time it is clear at Crooked Creek. That certainly would make us expect more clouds still at the Summit. Going South and downhill from Crooked Creek, cloud cover may not get appreciably less, on the basis of casual observations from the Owens Valley.

On the 169 mornings in the Summit Year when we observed cloud cover at both the Summit and Barcroft Stations, it was clear at Barcroft about 10% more than at



XBL 737-3562

Figure II A-7. Cumulative distribution of 8 A. M. cloud cover at Barcroft Station, arranged by month. Same data as Figure II A-8.

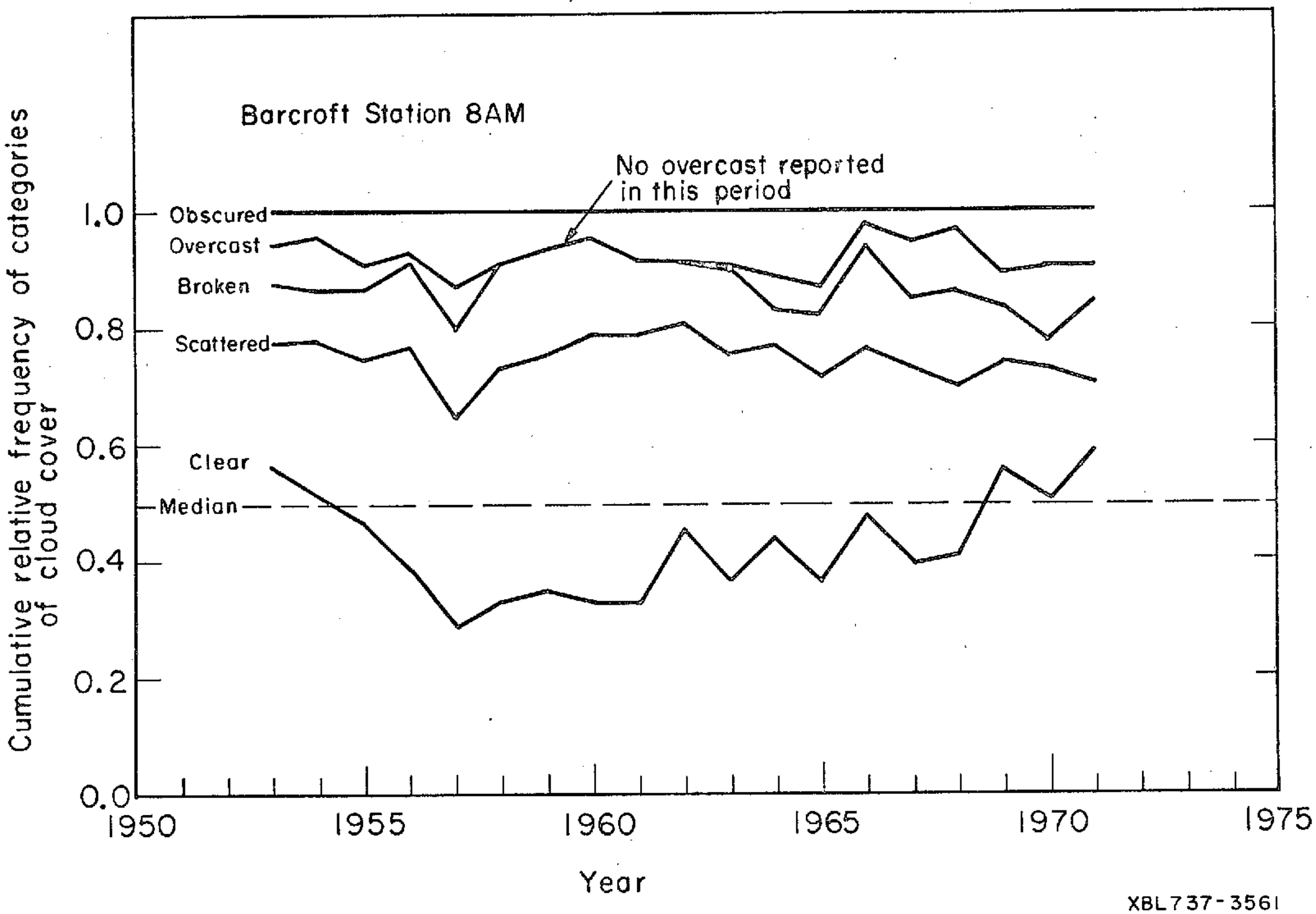


Figure II A-8. Cumulative distribution of 8 A.M. cloud cover at Barcroft Station, arranged by year. Same data as Figure II A-7.

the Summit, with the discrepancy being biggest in winter. After storms there is a tendency for a cloud cap to hang in at the Summit after it has disappeared at Barcroft.

When the observer made seeing measurements at night, we have cloud cover data through the night. With a significance of .20 the clear sunrises are preceded by nighttime cloud measurements a random sample of the time. 78% of all clear sunrises have preceding nighttime cloud measures. We define a photometric night as one with clear sky except for distant clouds appearing near the horizon over a period of at least six hours. In not-summer there are the same number of photometric nights as there are clear sunrises, and in summer the number of photometric nights is 85% of the number of clear sunrises. This is due to occasional delay into the night of the clearing of afternoon cumulus. Taking a weighted mean over the year, the number of photometric nights is 97% of the number of clear sunrises.

Now we can calculate the fraction of photometric nights in a year at the Summit to be the fraction of clear days at 8 AM at Barcroft multiplied by .90 and then by .97, or by .87. Table II A-5 shows the fraction of photometric nights for several places and periods at White Mountain along with data for other sites (Walker, 1970, 1971; Morrison, et al, 1973).

It is clear that during the survey year White Mountain is quite comparable with San Pedro Martir and Mauna Kea. Over the twenty year period it is comparable with shorter periods at Junipero Serra and Cerro Tololo. Note that none of the other sites listed here have the number of cloud observations which have been made at White Mountain, so their photometric fractions may be less accurately defined. On the other hand the cloud measurements by astronomers at existing observatories may be more perceptive than ours.

At the latitude of White Mountain there are an average of 5.7 hours total darkness in summer and 9.4 hours in not-summer. Taking the 20 year determination of summer and not-summer probability of clear sky at sunrise at the Summit, there are 286 hours of clear, dark sky in summer and 855 hours in not-summer, giving a total of 1141 clear, dark hours in the year. If we include times of scattered clouds, there are 399 dark hours in summer and 1378 hours in not-summer, giving a total of 1777 almost clear, dark hours in the year. To evaluate the total number of clear or scattered hours regardless of darkness, we assume half the day has sunrise cloud cover and the other half has noon cloud cover, although that overweights the fraction of a day which is cloudy. That leads to 2650 clear hours and 4747 clear or scattered hours per year.

Table II A-5

Station	N (days)	Fraction of nights with sky clear down to 15° above horizon for $\geq 6^h$
San Pedro Martir	63	.65
WM Crooked Creek Survey Year	366	.61
Mauna Kea	? in 12 months	.56
WM Barcroft Survey Year	366	.56
WM Crooked Creek 20^y	7222	.55
WM Summit Survey Year Summit Days	169	.54
Piper Peak	203	.52
Junipero Serra	402	.46
Cerro Tololo	633	.41
WM Barcroft 20^y	7222	.42
WM Summit 20^y calculated	--	.38

Bollay, E. 1948, Office of Naval Research, U. S. Navy, Unpublished Confidential Report.

Gringorten, I. F., Salmela, H. A., Solomon, I., and Sharp, J. 1966, Air Force Cambridge Research Laboratory, Report No. 66-621.

Holter, M. R., Nudelman, S., Suits, G. H., Wolfe, W. L., and Zissis, G. 1962, Fundamentals of Infrared Technology (MacMillan), p. 78, 83.

Kuiper, G. P. 1970, Communications of the Lunar and Planetary Laboratory, 8, 121.

Mather, J. C., Werner, M. W., and Richards, P. L. 1971, Astrophysical Journal Letters, 170, L59.

Morrison, D., Murphey, R. E., Cruikshank, D. P., Sinton, W. M., and Martin, T. Z. 1973, Publications, Astronomical Society of the Pacific, 85, 255.

O'Connor, J. T., Welch, W. J., and Tayeb, A. M. 1969, Space Sciences Laboratory, University of California, unpublished report.

Pace, N., Kiepert, D. W., Nissen, E. M. 1971, White Mountain Research Station, University of California, unpublished report.

Plass, G. N., and Yates, H. 1965, Handbook of Military Infrared Technology (Office of Naval Research), 175.

Harlan, E. A. and Walker, M. 1965, Publications, Astronomical Society of the Pacific, 77, 246.

Walker, M. 1970, Publications, Astronomical Society of the Pacific, 82, 672.

Walker, M. 1971, Publications, Astronomical Society of the Pacific, 83, 401.

B. Telescope Sites

1. General description of terrain

The general nature of White Mountain is that of a high north-south ridge with steep sides and a gently sloping crest. The prevailing air flow is from the west, crossing the Sierra Nevada 50 km away. The Sierra Nevada collects most of the precipitation, making storms less troublesome, making ground travel easier because of less snow on the ground, and leaving less water to evaporate into the air. Over the ten year period 1959 July 1 to 1969 June 30 the mean annual precipitation at two places in the Sierra, the Owens Valley, and two places on White Mountain was:

Station	Elevation (m)	Precipitation (cm)
Mammoth Pass, directly on Sierra crest	2900	152
Lake Mary, 4 km east of Mammoth Pass	2720	76
Bishop, 65 km southeast of Mammoth Pass	1250	15
Crooked Creek, 80 km east-southeast	3090	38
Barcroft, 75 km east of Mammoth Pass	3800	53

Eighty six percent of the precipitation at the Barcroft Station is snow, and the median snow depth at that station in winter and spring is 25 cm. The maximum recorded snow depth at the Barcroft Station is 312 cm, occurring on 1969 March 22. Figure II B-1 shows the cumulative relative frequency of snow depth at the Barcroft Station for each season.

Because of the extremely low humidity snow evaporates rapidly from the ground. At the preferred telescope site the wind blows away most of the snow which falls, so that there are many areas with bare rock throughout the winter. However those same winds pile up snow drifts in some places, which can be a considerable operational nuisance and a potential source of added water vapor to the air. We propose to investigate control of those drifts with snow fences in the area of the telescope. There appears to be considerable experience with such control in the alpine areas of Europe.

Since the surface soil is quite thin, it does not stay wet for an appreciable time, especially since so little rain falls. The areas of bare shattered rock dry completely in an hour or so.

The longevity of the snow is shown in the photographs, which were taken on 1973 July 15. The preceding winter had the second highest snowfall in the history of the White Mountain Station, and it can be seen that very little

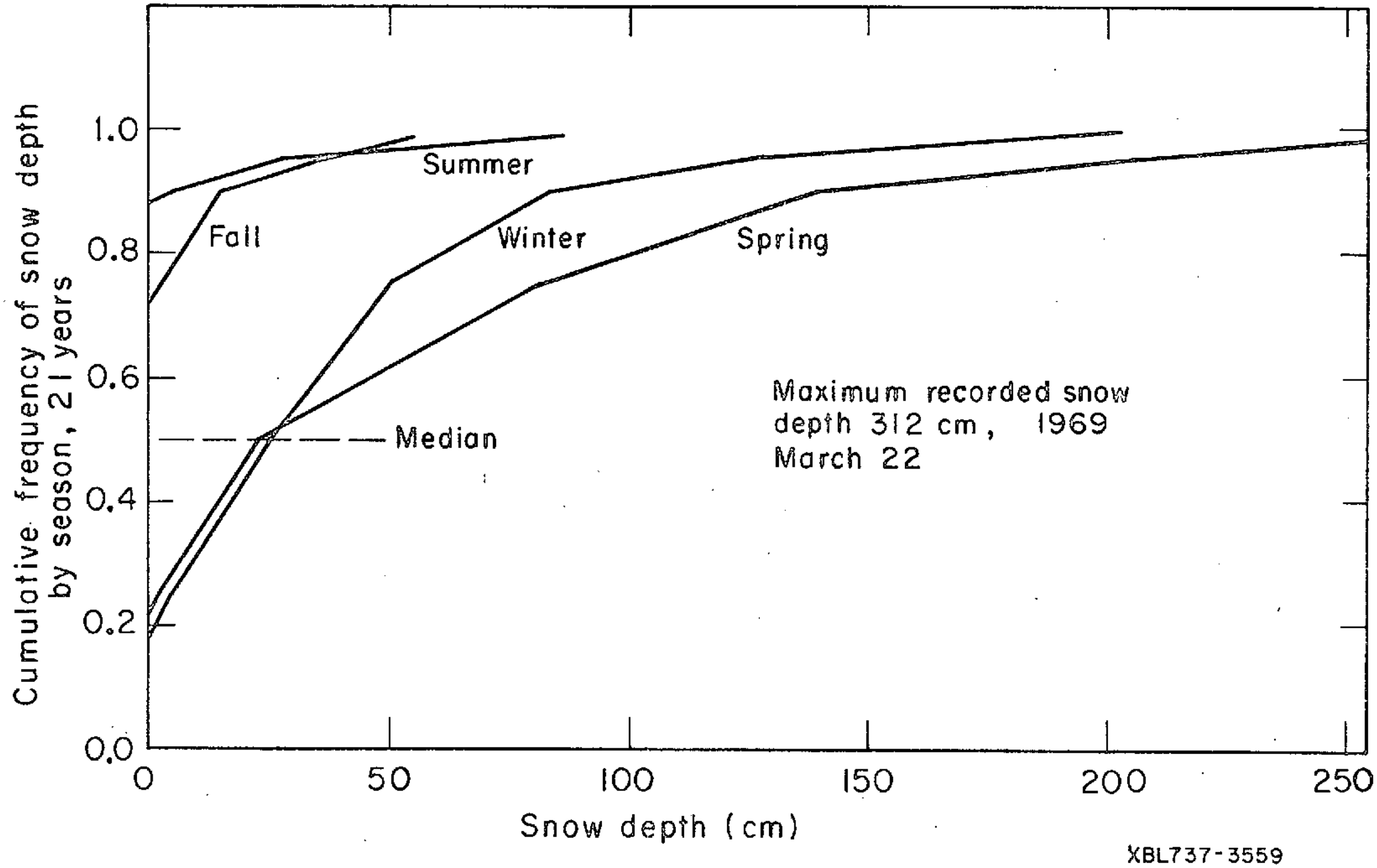


Figure II B-1. Cumulative distribution of snow depth at the Barcroft Station.

remains. Those remaining patches are left from wind blown drifts and they exist for four to six months in any year. However, areas away from drifts are clear of snow 90% of the time in summer, 70% in fall, and 20% in winter and spring at the Barcroft Station.

The nearest trees are 1000 meters below the telescope site, and along the access ridge to the south they are 12 km away. The tallest plants at the site are lichens.

The modest total precipitation and the very small rainfall has led to very little erosion of the crest of the White Mountain ridge. This makes ground travel unusually easy, since there are no gullies to cross at the high altitudes.

Because of the low erosion the surface soil has built up to many inches depth in some places, as can be seen in the photographs. This makes a good part of the road maintenance much easier than it would be on bare rock. In addition the places with bare rock are heavily shattered to depths of a foot or more. There are no places that I am aware of high on the mountain where there is massive rock at the surface, where it can interfere with roads and potential telescope sites.

The potential telescope sites are high on the mountain, where the surface soil has long been sifted by the wind to get rid of the smaller particles. At our preferred site there is a possible upwind source of wind blown particles which is only about 100 meters long, and further upwind the land drops off precipitously. However we believe those particles are quite large and heavy. Therefore we do not expect any problem with wind blown dust or grit, but measurements should be made to confirm that. We expect that wind blown snow picked up from the surface will control the limiting wind speed under which the telescope can be operated.

We do not know much about the subsurface materials, but the photograph of the north face of our preferred telescope site shows massive rock directly below the shattered surface layer. Since all of the rocks are of granitic or metamorphic origin, we expect no problem with footings which penetrate the surface layer.

2. Specific sites

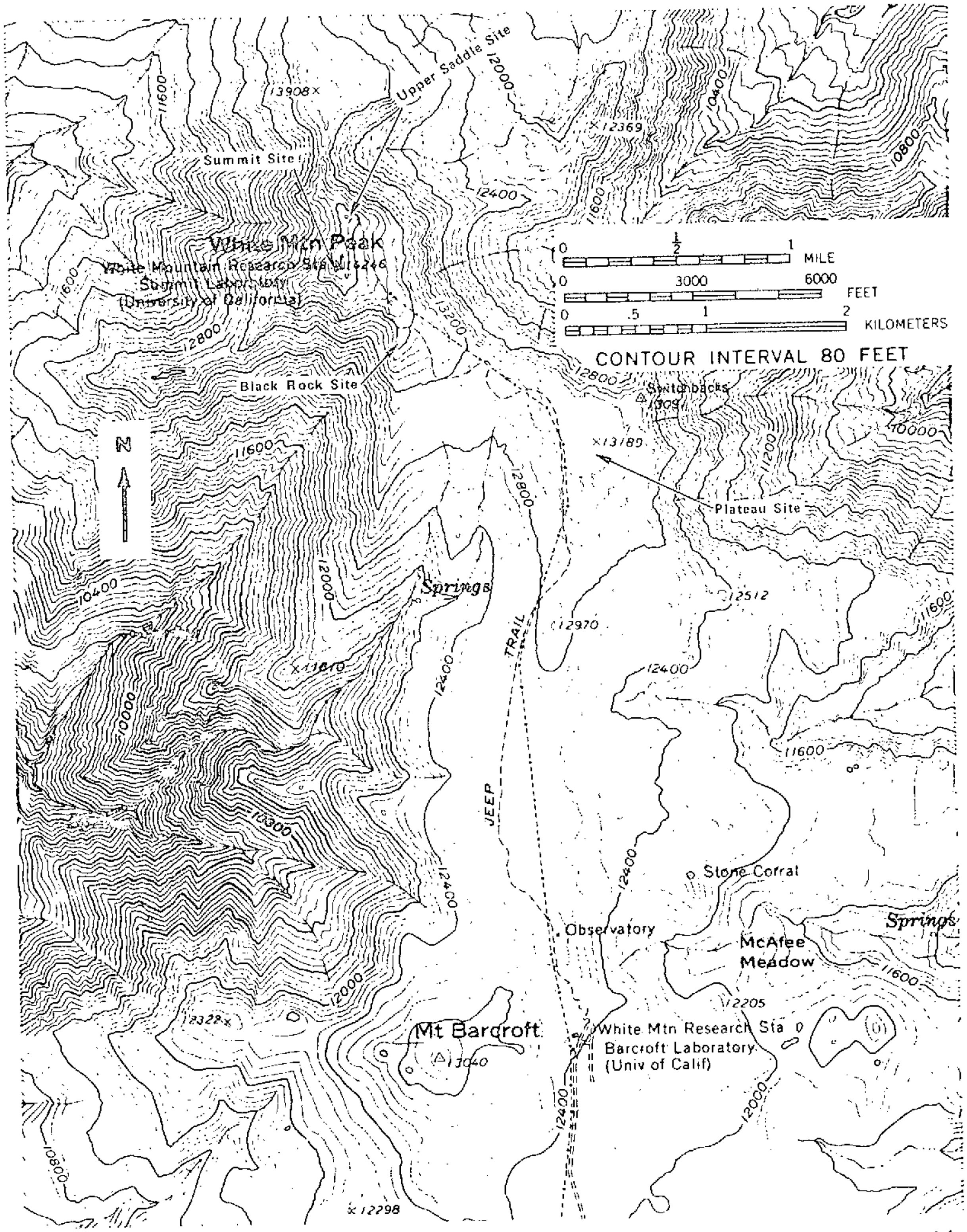
There are four potential telescope sites at high altitude. The local names we give to the sites and their altitudes are: Plateau, 4020 meters; Black Rock, 4176 meters; Upper Saddle, 4267 meters; and Summit, 4342 meters. The site locations are shown on a topographic map in Figure II B-2. Access becomes more difficult as we go to the higher sites, but the decrease in water vapor as we go up has a major effect upon the integration times of observations which are noise limited.

We calculate integration times relative to the Summit on the basis of the time being inversely proportional to the square of the transmission, assuming the same zenith distance. For an average situation we assume an optical thickness of one at the Summit and the standard scale height of 1.6 km. For a worst case we assume an optical thickness of two at the Summit and a winter scale height of 1.0 km. We have often successfully corrected spectra for atmospheric transmission when the line bottoms had an optical thickness of more than two, and the winter scale height may be even smaller than 1.0 km, as described in the section on precipitable water vapor measurements.

The integration times relative to the Summit for the average and worst cases respectively are: Upper Saddle, 1.1 and 1.3; Black Rock, 1.2 and 1.9; and Plateau, 1.5 and 3.6. This makes it seem well worth the effort to go to at least the Upper Saddle. All this assumes that the water vapor difference that we measured between the Summit and Barcroft Stations is accurately represented by an exponential distribution.

The Plateau is appealing because of its very easy access from the Barcroft Station. With only moderate work on the road passenger cars can make the trip there very easily in summer and fall and trucks can make the trip during a large fraction of winter and spring conditions. There is a large flat area of about one by two km and it would be a fine site for our proposed work with infrared aperture synthesis. Its only disadvantage is the above one on integration time with measurements pushing to the limit of wavelength where any measurement at all is an achievement.

The Black Rock is the smallest site except for the very Summit, and its main advantage is a totally unobstructed view to the south. Access is not too bad, and in particular there are no cliffs anywhere along the access route. We expect that a tracked snow vehicle would go directly up the slope to the site, with no sidehill traverse needed.



XBB 738-4861

Figure II B-2. Topographic map showing four possible telescope sites (all above 13,000 ft) in the vicinity of White Mountain.

The Upper Saddle is a fine site except for an 8° blockage above the horizon by the Summit itself and the need for a sidehill traverse in going there from Black Rock. However, we feel that both of those problems are minimal. This is our preferred site. The water vapor there is 4% higher than the Summit with a 1.6 km scale height and 8% higher with a 1.0 km scale height.

The Summit has the disadvantage of a quite difficult piece of road above the Upper Saddle, which might require major improvements to become suitable even for tracked vehicles in the winter. The winds are probably a maximum there, but we were quite able to cope with those problems during the survey. The Summit is already leveled over an area large enough for our proposed telescope, but use of that area would require tearing down the Summit Laboratory. That is a very useful facility, and we are reluctant to destroy it. Finally, the U. S. Forest Service has requested that we enable hikers to enjoy the Summit, although there would be room for them alongside the telescope.

Our preferred choice of site is the Upper Saddle, even with the small increase of integration time relative to the Summit. However, if we found in a more detailed water vapor survey that the snow banks in the vicinity of the Upper Saddle had a significant effect upon the water vapor in the air, there could be reevaluation. The Summit Laboratory will be of value during the construction of the utility building at the Upper Saddle, and I expect that it will often continue to serve as an easy and amenable retreat from the pressures of work at the Upper Saddle.

C. Facilities and Logistics

1. Site Location

The White Mountain summit site, at an elevation of 14,250 ft, is located on White Mountain Peak in the White Mountain Range of California, approximately 225 airmiles east of San Francisco and 255 airmiles north of Los Angeles. The geographical location at latitude 37°38' N, longitude 118°15' E, is within Mono County and the Inyo National Forest. A map of the immediate area is shown in Figure II C-1.

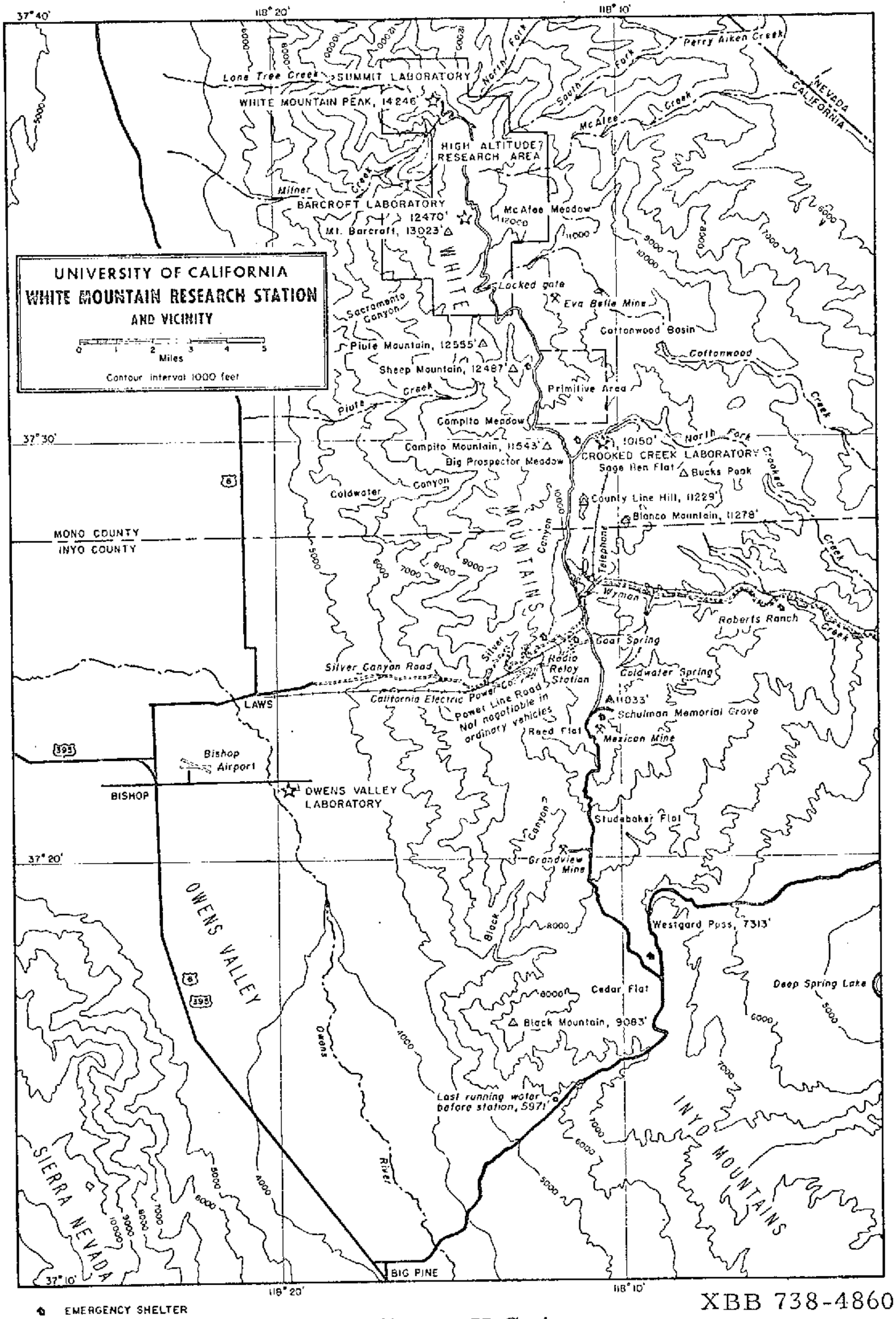
2. Relationship to U. S. Forest Service

The Crooked Creek, Barcroft, and Summit Laboratories of the White Mountain Research Station are located in Inyo National Forest, which is administered from Bishop, California. Within that National Forest is a 5000 acre tract called the White Mountain Scientific Area, and the Barcroft and Summit Laboratories are in that area. The order establishing the Scientific Area states, "Principal values in the area are for its high elevation scientific purposes and for its representation of an arid to semi-arid alpine flora and fauna." In further detail in Forest Service documents and in conferences with Forest Service administrators it is made clear that astronomical research can be a highly suitable activity for use of the Scientific Area.

Any major development within the Barcroft and Summit Laboratories and any development outside of those laboratories will require a use permit from the Forest Service. In order to protect the natural values of the area, the Forest Service wants to limit use of the area to programs which require the conditions there. Any program must be planned in such a way as to minimize ecological disturbance. The evaluation of proposed programs will be made by the Pacific Southwest Forest and Range Experiment Station of the Forest Service.

We have discussed our instrumental plans, including plans for millimeter and ten micron wavelength angle measuring interferometers with kilometer baselines, with the Forest Service. They state orally that those plans can very well be compatible with their management goals, and they will be happy to receive requests for use permits.

Use agreements between the U. S. Forest Service and the University of California have long been established to permit the construction and operation of research laboratories and access roads by the University of California, White Mountain Research Station, at three locations in the National Forest, including the summit site.



XBB 738-4860

Figure II C-1

3. White Mountain Research Station

The White Mountain Research Station of the University of California comprises four high-altitude laboratories. The highest, the Summit Laboratory, occupies the top of White Mountain Peak, and consists of a stone building, 15' x 30', and a helipad. Electric power is provided by engine-driven generators, housed in an adjacent shed. From the Summit Laboratory an unsurfaced six-mile road descends south to the Barcroft Laboratory of the UC White Mountain Research Station, at an elevation of 12,470 ft. This well-equipped laboratory operates on a year-round basis, providing dormitory, laboratory and shop services. The Summit and Barcroft Laboratories lie within the White Mountain Scientific Area.

In addition to the previously mentioned Barcroft and Summit Laboratories of the White Mountain Research Station, a third high-altitude laboratory is located in the Inyo National Forest outside the Scientific Area. The Crooked Creek Laboratory, at an elevation of 10,150 ft, is a fully-equipped, year-round operating facility, providing dormitory, laboratory, and maintenance shop services. It is located ten miles south by unsurfaced road from the Barcroft Laboratory, along the same road to the summit. From this Laboratory the access road continues for an additional ten miles to Schulman Grove in the Ancient Bristlecone Pine Forest, and by paved road and highway to Bishop for another 38 miles.

The Owens Valley Laboratory of the University of California's White Mountain Research Station is located on the outskirts of Bishop, at an elevation of 4,050 feet. This 580 acre facility contains laboratories, dormitories, classrooms, and a regularly operating helicopter service to the high-altitude laboratories.

Altogether, the four laboratories of the White Mountain Research Station have an estimated capital asset value of $3,000,000. The White Mountain Research Station high-altitude laboratories have been operated by the University of California for a period of 23 years. The facilities, interconnecting roads, helicopter, power and communication systems are maintained by White Mountain Research Station personnel, supplemented by contracted services. The personnel of this organization are particularly well qualified in the operation of facilities in this environment.

4. Adjacent Communities and Facilities

The proposed sites overlook the Owens Valley and nearby city of Bishop, California, in the valley, at an elevation of 4,147 ft. Bishop is located on

U. S. Highway 395, which is the primary surface route connecting Los Angeles and Reno. This community, including adjacent residential area, has a population of 8,500. An all-weather airport serves Bishop, and is capable of handling most general aviation aircraft.

An important asset of the Bishop area is the presence of the California Institute of Technology Owens Valley Radio Observatory. At the very least the staff at that observatory makes life in Bishop more intellectually interesting, but in addition there are many opportunities for cooperation, consultation, and shared use of facilities.

5. Accessibility

The proposed sites are easily accessible, year around, from the metropolitan areas of San Francisco, Los Angeles and Reno. Several modes of travel are available for observers, dependent upon the preference of the travelers.

a. Surface transit. Surface travel by car or bus from the metropolitan areas to Bishop is practical year around on paved roads. In the summer months, private car travel is practical as far as the Barcroft Laboratory, to within six road miles of the summit. Due to present road surface and slopes (not over 15%), surface travel over the remaining distance to the summit necessitates the use of four-wheel drive vehicles. Surface travel in winter (December-May), beyond Westgard Pass is possible only by tracked snow vehicles at the present time, because of the unstabilized road surface and lack of snow removal equipment. The current level of operations of the White Mountain Research Station has not warranted the expenditures necessary to stabilize the road surface for approximately 26 miles and acquire and operate snow removal equipment for this purpose. Logistic support of the high-altitude laboratories, during winter, by helicopter has proven to be highly successful and more economical than surface vehicles for the current level of operations.

Table II C-1 illustrates various routes and travel times from three metropolitan areas by surface vehicle.

An alternate road to the summit from Bishop is feasible during the summer period. This route is more direct than the primary road. However, due to steep grades and switchbacks, it is not recommended for normal access. This Silver Canyon route is designated as a "primitive road" but is easily traversed by four-wheel drive vehicles. The distance by this route, from Bishop to the summit, is approximately 40 miles.

b. Winter Surface Transit. The primary mode for logistic support of operations of the proposed infrared telescope observatory, during winter, is by

Table II C-1

Surface Travel to Proposed Site

FROM	TO	ROUTE	DISTANCE (miles)	TRAVEL TIME
Berkeley	Bishop	Sacramento/Tahoe, via US80, CAL89, CAL28, US50, US395 (year around)	393	9:30
"	"	Sacramento/Reno, via US80, US395 (year around)	414	9:30
"	"	Sacramento/Tahoe/Echo Summit, via US80, US50, CAL89, US395 (summer, winter?)	347	10:00
"	"	Lodi/Carson Pass/Monitor Pass, via US50, CAL88, CAL89, US395 (Summer)	356	10:00
"	"	Sonora/Ebbetts Pass/Monitor Pass, via US50, CAL120, CAL108, CAL49, CAL4, CAL89, US395 (summer)	363	10:00
"	"	Sonora/Sonora Pass, via US50, CAL120,CAL108,US395 (summer)	308	9:00
"	"	Sonora/Tioga Pass, via US50, CAL120, US395 (summer)	287	8:30
Bishop	Summit	Big Pine/Westgard Pass, via US395, CAL168, Access (summer - improved road)	64	3:00
		TOTAL TRAVEL	351 to 478	11:30-13:00 Hr
Los Angeles	Big Pine	Palmdale/Lancaster, via US405, CAL14, US395 (year around)	251	5:00
Big Pine	Summit	Westgard Pass, via CAL168, Access (summer - improved road)	49	2:40
		TOTAL TRAVEL	300	7:40
Reno	Bishop	Via US395 (year around)	206	4:00
Bishop	Summit	Westgard Pass, Access (summer -- improved road)	64	3:00
		TOTAL TRAVEL	270	7:00
SCHEDULED BUS SERVICE				
Berkeley	Bishop	Via Reno - Daily	--	11:40 Hrs
Reno	Bishop	Direct - Daily	--	4:00 "
Los Angeles	Bishop	Direct - Daily	--	7:00 "

helicopter. To assure continual year-around logistic support of operations and construction, surface vehicle access is required, as an alternate mode. This entails the resurfacing of approximately 26 miles of the existing gravel access road, to provide for a minimum standard of summer and winter trafficability. Resurfacing would include the construction of adequate drainage and gravel surface for travel by all types of vehicles. Further details and costs for this construction are provided in Section II.C.7.

With such a stabilized road surface, year around travel by surface vehicle can be accomplished with reliability. Washouts from thaws would be minimized. The White Mountain Research Station has operated "Weasel" type snow vehicles at the Laboratories for a number of years. Replacement parts for these military surplus vehicles are no longer available. Replacement of these vehicles with newer and higher performance snow vehicles is necessary for reliable winter surface transportation. Utility type snow vehicles, such as the Thiokol Spryte models, equipped with hydraulically controlled snow blades, are presently being utilized successfully by public utility service companies, under worse climatic and snow conditions in the nearby Sierra mountains. This type of vehicle has the performance and climbing ability necessary to transit the slopes. The vehicle carries a 1900 lb payload of cargo and/or up to six passengers at top speeds of 14 or 23 miles per hour, as determined by the track width selected. Low ground pressure of the tracks (0.86 lbs/sq in), permits travel over deep snow without the necessity of plowing. The self-contained plow and low center of gravity of this vehicle provides good sidehilling ability, particularly in drifts along the slopes. Level sidehill travel is sustained by "notching" of the drifts, with the plow. This self-contained capability effectively eliminates the need for expensive snow removal maintenance of access roads to the proposed sites in winter. The track configuration of these vehicles is also satisfactory for travel on the frequently bare road surfaces.

c. Air Transit. Commercial airline connections from the University of California, Berkeley, to the vicinity of the proposed site, are scheduled daily (except weekends). Flights originate from the nearby Oakland Airport and terminate at Mammoth, California, within 42 miles of Bishop.

Commercial airline connections are also scheduled daily from the Los Angeles area to Mammoth, departing from Burbank Airport. There are no scheduled connections from Reno to the proposed site vicinity.

Chartered aircraft service is available on an as-required basis by the White Mountain Research Station for travel from Oakland to Bishop. This service is capable of transporting five people.

The White Mountain Research Station helicopter service, operating from the Owens Valley Laboratory at Bishop, has provided regular logistic support to the high-altitude laboratories for a period of 9 years. The Bell helicopter being utilized at this time operates approximately 150 flying hours per year. It regularly carries payloads of 540 lbs to and from the high-altitude laboratories. In FY 1972/1973, this service transported 294 passengers and 37,950 lbs of cargo. Larger payloads are feasible by sling. This service has been free of a major accident since 1966, notwithstanding the mountainous terrain and frequently severe winter environment of flight operations. The good safety record, reliability and economy of this logistic support service is attributable to strict standards established for helicopter maintenance, and pilot operating procedures.

Development of this highest altitude regularly operating helicopter service in the United States was a pioneering effort by the White Mountain Research Station in conjunction with the helicopter manufacturers. Improved maintenance procedures, operating procedures and equipment have resulted from this unique development program.

Table II C-2 provides transit times and costs for the several above modes of air travel.

The feasibility of operation of STOL (Short Takeoff and Landing) aircraft at the Barcroft Laboratory has been demonstrated by the White Mountain Research Station. If warranted by traffic requirements, an adequate landing area within six miles of the Summit is available for logistic support of the proposed sites by this means.

6. Housing and Support Facilities

a. General. Dormitory type housing for staff and observers is available at the Summit Laboratory, and at the Barcroft, Crooked Creek and Owens Valley Laboratories within 6, 16 and 64 miles, respectively of the Summit. Permanent housing is available in the city of Bishop, within commute time of the Summit by surface vehicle or helicopter. Support facilities are available at Barcroft, Crooked Creek and Owens Valley Laboratories.

b. Summit Laboratory. The Summit Laboratory building, approximately 15 x 30 ft, has sleeping accommodations for four people. This building has oil heat, kitchen facilities and generator-supplied electric power. There is no water supply or sewage facilities. Chemical toilets are provided and water is transported from the Barcroft Laboratory.

Table II C-2

Air Travel to Proposed Site

FROM	TO	TRAVEL MODE	ONE WAY TRAVEL TIME	COST/PERSON
Oakland	Mammoth	Commercial Airline -- Via Burbank	3:00 Hrs	$43.50
Mammoth	Summit	Helicopter -- Direct	:40	38.00*
		TOTAL	3:40 Hrs	$81.50
Burbank	Mammoth	Commercial Airline	1:15 Hrs	$27.00
Mammoth	Summit	Helicopter -- Direct	:40	38.00*
		TOTAL	1:55 Hrs	$65.00
Oakland	Bishop	Chartered Air Service	1:10 Hrs	$46.60**
Bishop	Summit	Helicopter -- Direct	:30	29.00*
		TOTAL	1:40 Hrs	$75.60

* Prorated for 1 passenger (capacity - 2)

** Prorated for 1 passenger (capacity - 5)

c. Barcroft Laboratory. Housing at the Barcroft Laboratory is provided in one of the large Quonset type buildings and one separate smaller building. The main two-story Quonset building has complete sleeping quarters, library and recreation rooms, bathroom, dining and kitchen facilities. In addition, this building includes laboratories, oil heat, water supply, commercial electric power, and radio communications with the other laboratories. The sleeping quarters will accommodate 20-25 men. The smaller building has sleeping accommodations for 6-8 women with bathroom facilities. The total facility, consisting of seven separate and/or attached buildings, has a total floor space of 10,000 square feet. Commercial electric power for the facility is supplemented by standby, diesel-powered generators. Water is supplied by an intermittent well during summer and by snow melting tanks in winter. The water supply is supplemented in summer by tank truck from a spring source at the Crooked Creek Laboratory. A 10,900 gallon water storage tank is presently under construction at Barcroft. Sewage at the Barcroft facility is processed by a 1500 gallon septic tank.

Work space is available for staff and observers in the main building. The outlying buildings are also available for work space. Approximately 2000 sq ft of work space is available in the main building and another 2000 sq ft is available in the outlying buildings.

d. Crooked Creek Laboratory. Dormitory accommodations for 20 people are provided in a wood frame and Quonset type building. This 1200 sq ft building also includes a kitchen and dining area, living room and laboratory. Oil heat, commercial electric power, a spring-fed water supply, and 1000 gallon septic tank sewage system is also provided. Outlying buildings consist of a large Quonset type vehicle maintenance shop, of 1200 sq ft. Several smaller buildings are also located on the facility. Work space in the main building is 710 sq ft. Telephone and radio communications are also available at this facility.

e. Owens Valley Laboratory. Dormitory space for 28 people at the Owens Valley Laboratory is provided in a modern, air-conditioned building, with bathroom facilities. Three travel trailers are also equipped to sleep an additional six people. Work space is available in a 720 sq ft classroom, and two separate laboratory buildings of 1140 sq ft and 495 sq ft. A Quonset type building of 1274 sq ft serves as a helicopter hangar and repair shop. Commercial electric power, and a year-round well support these facilities. Sewage is processed through 2500 gallon septic tanks. Radio and telephone communications facilities are also available.

f. Bishop. Housing is available for staff and observers in Bishop and the adjacent residential area in 26 motels and 33 apartments. In addition, private homes are available for rent, or sale on a more permanent basis. Public and private schools, from elementary through high school, are also available in this community, as well as a community hospital.

7. Site Development Needs

a. Road Construction. Stabilization of the existing access road to the Summit, as previously described, is necessary for year around logistical ground support of the proposed sites. Road construction and maintenance would be contracted with the Ecology Corps, Division of Forestry, State of California.

b. Power and Communications. A 12,000 volt, three conductor, pole line constructed in 1957, provides commercial electric power from a 60,000 volt power line, approximately 6 miles south of the Crooked Creek Laboratory to the Barcroft Laboratory. An extension of this 13-1/2 mile line approximately four miles toward the Summit from Barcroft, has been disconnected due to damage from winter storms. Although the reliability of this electric power, supplemented by diesel generators, has been adequate for the purposes of the White Mountain Research Station, maintenance costs of the power line are high due to line damage from the winter storms and summer lightning strikes. This damage occurs primarily over a 4-3/4 mile portion of the line above the 11,000 ft elevation, as well as the disconnected 4 mile section above Barcroft.

To assure continuous reliable commercial electric power to the proposed site, it is necessary to bury the existing power line for this length and install lightning rods at the transformer locations and diverter lightning rods on several high peaks in the area adjacent to the power lines. The underground cable, equipped with grounding wires, would be three conductor, #2 aluminum A.W.G., power cables having 175 mil high molecular polyethylene 15 KV insulation. The cable would be buried at least 24 inches, in half-mile lengths, with suitable terminations and connecting links above ground, to facilitate testing and location of possible faults.

Existing overhead telephone lines, which are subjected to breakage and failures from storms, would be buried underground with the power lines. At the same time, the telephone line capability would be increased to provide for adequate communications and data transmission. Armored type cable of 100 pairs, designed to provide lightning and gopher protection, is recommended for this purpose. Similar to the underground power line, the telephone cable would have above-ground terminals at half- or one-mile intervals, dependent upon reel lengths.

Installation of underground power and communications lines would be contracted with an installation contractor by the University of California and the Continental Telephone Company.

c. Water. Enclosed water storage and snow melting tanks would be required at the proposed site, to provide a year around water supply for the observatory. Servicing of the water tanks would be accomplished by tank truck from Barcroft Laboratory in summer, and supplemented by snow melting in winter.

d. Sewage. The requirement for construction of a sewage disposal system is not anticipated for the proposed observatory. The use of chemical toilets and water drain ditches appears to be adequate for the requirements of this facility. Refuse from the chemical toilets would be transported to Barcroft Laboratory for disposal.

8. Costs of Site Development

Road Construction

Construction of road drainage, surface grading and gravel surfacing of existing roadway.

Construction by: Ecology Corps, Division of Forestry, State of California.

Costs: Labor, equipment and material, 26 mi @ $2,000/mi	$ 52,000

Underground Electric Power Lines and Telephone Cable

Bury underground, two sections of existing overhead power lines and telephone cable to Summit.

Engineering by: Professional engineer.

Construction work: University of California selected contractor.

Costs:

Underground electric cable, 9 mi @ $10,650/mi	$ 95,850
Cable plowing, 9 mi @ $660/mi	$ 5,940
Electrical installation labor, 50 man-days @ $87.50	$ 4,375
Lightning diverters, 12 @ $375	$ 4,500
Telephone cable, 9 mi @ $2500/mi	$ 22,500
Terminal boxes, 25 @ $13 ea	$ 325
Telephone cable connection labor, 40 man-days @ $130	$ 5,200
Sub-Total	$138,690
Contingencies @ 10%	$ 13,869
Engineering, design, inspection - 5%	$ 6,935
Total	$159,494

Snow Vehicles

Acquisition cost:

Thiokol Spryte, 45" track, with plow, radio

1 ea 2 Passenger	$ 18,000
1 ea 6 Passenger	$ 18,000
Total	$ 36,000

TOTAL SITE DEVELOPMENT COSTS $247,494

D. Comparison with other sites

In comparing the precipitable water vapor between White Mountain Summit and Mauna Kea we use the sea level equivalent amount, since the altitudes are so similar. By reading the values off the 1973 July plots sent by Westphal, we derive the following median values for summer and not-summer noontime, respectively, in mm: White Mountain, 2.36 and .89; Mauna Kea, 1.84 and 1.92. Using the χ^2 test, the not-summer difference between the sites is significant at the less than the .001 level and the summer difference is not significant at the .2 level.

The ratio of the median water vapor at White Mountain to that at Mauna Kea is about 0.5 in not-summer and 1.3 in summer, although the latter is not significant.

As we discussed earlier, the sunrise water vapor at White Mountain in the summer is .56 that at noon. We tentatively suggest that the convection which makes this big difference may not exist so strongly at Mauna Kea, because of the high albedo cloud layer instead of absorbing rocks below the summit. The summer sunrise water vapor at White Mountain may be well below that at Mauna Kea, and give a ratio more like that in not-summer.

There is no question that White Mountain has much less water vapor than Mauna Kea at noon in not-summer, and it is possible that this is true at other times.

A comparison between the integration times (to achieve the same signal to noise ratio) at Mauna Kea (MK) and White Mountain (WM) is shown in Figs. II D-1 to II D-4. The $\log_{10}$ ratio of integration times at the two sites is plotted against hour angle for assumed values of the ratio of precipitable water vapor (WM/MK) and the zenith optical depth (QZ) at Mauna Kea. Four curves are plotted on each graph for declinations of $-23\overset{\circ}{.}5$, $0\overset{\circ}{.}0$, $+23\overset{\circ}{.}5$ and $40\overset{\circ}{.}0$.

The zenith optical depth is taken to be proportional to the ratio of precipitable water vapor, the integration time proportional to the square of the opacity and the opacity increasing exponentially with the product of zenith optical depth and the secant of the zenith distance.

Points falling below the ordinate = 0 line favor White Mountain.

It is clear that the White Mountain water vapor during not-summer being half that at Mauna Kea more than makes up for the zenith distance, even at

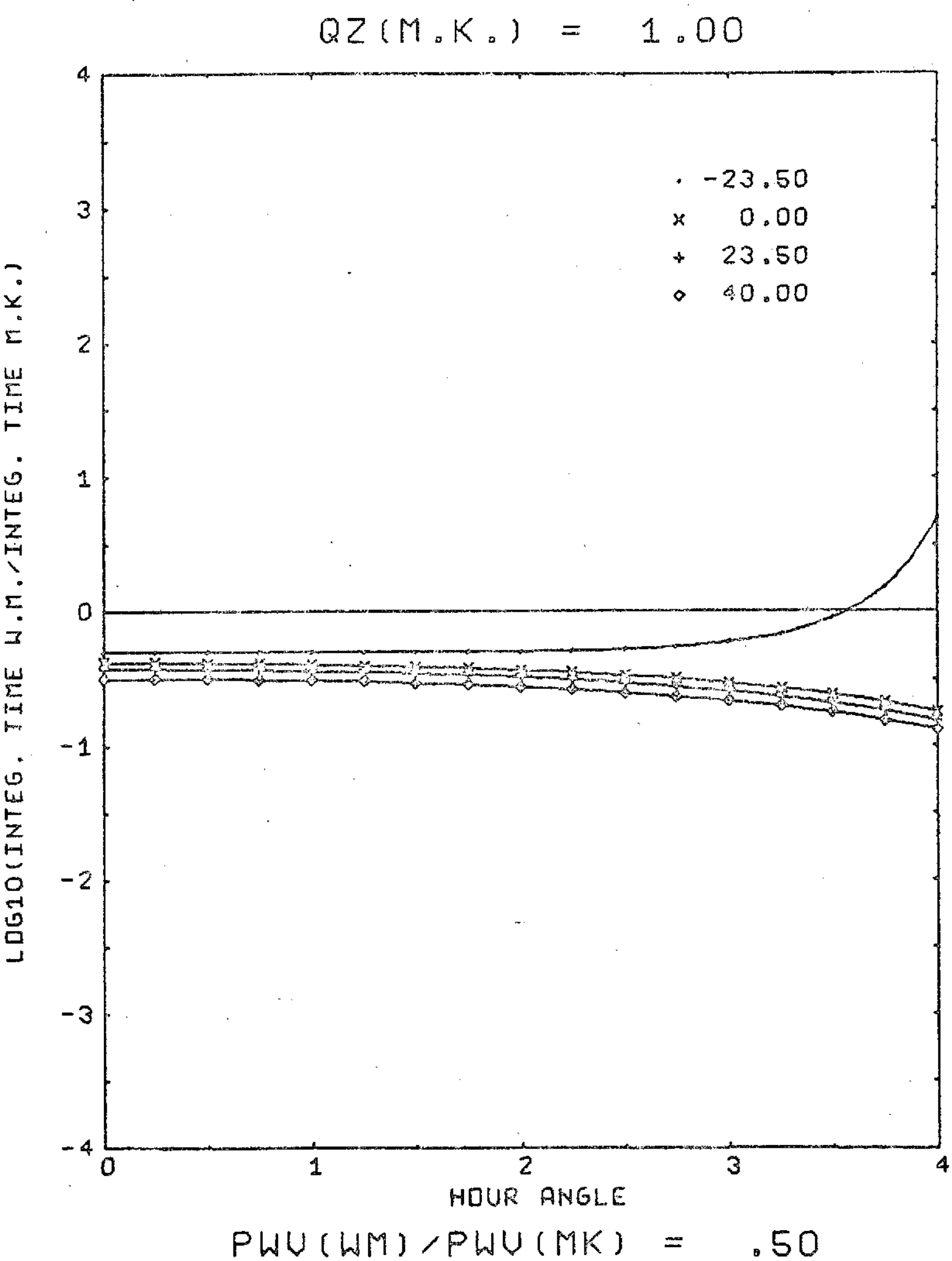


Figure II D-1

XBL 738-1078

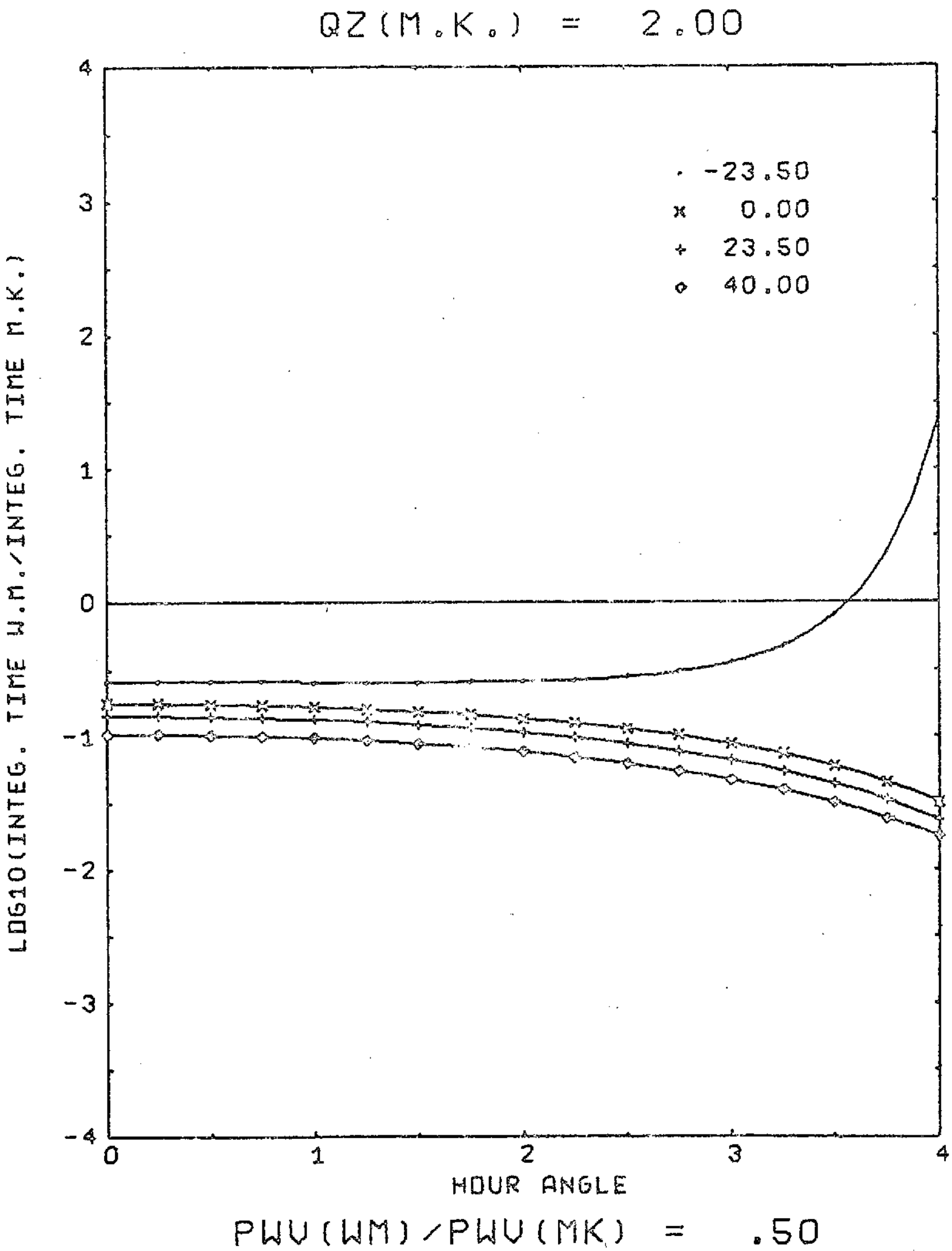


Figure II D-2

XBL 738-1077

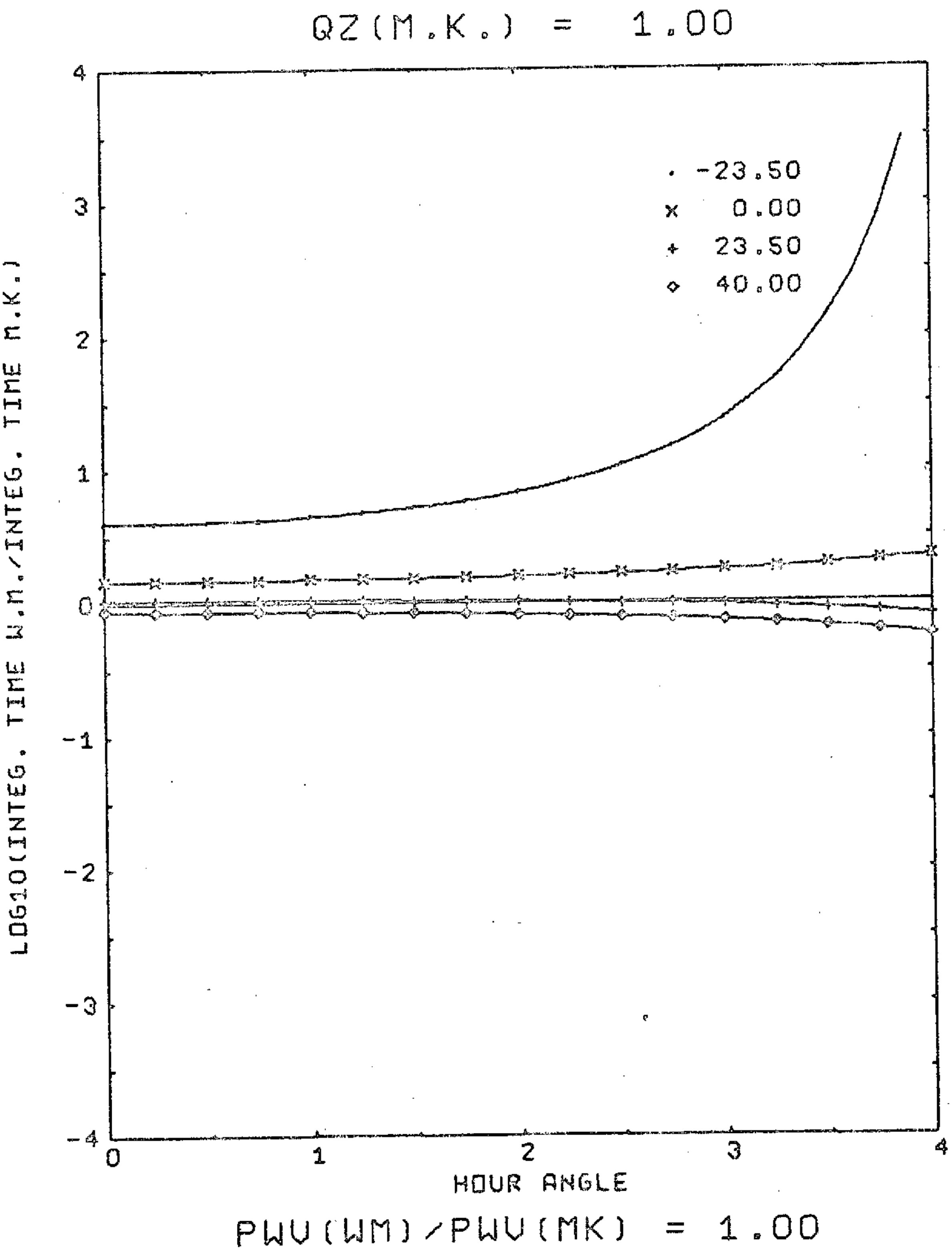


Figure II D-3

XBL 738-1076

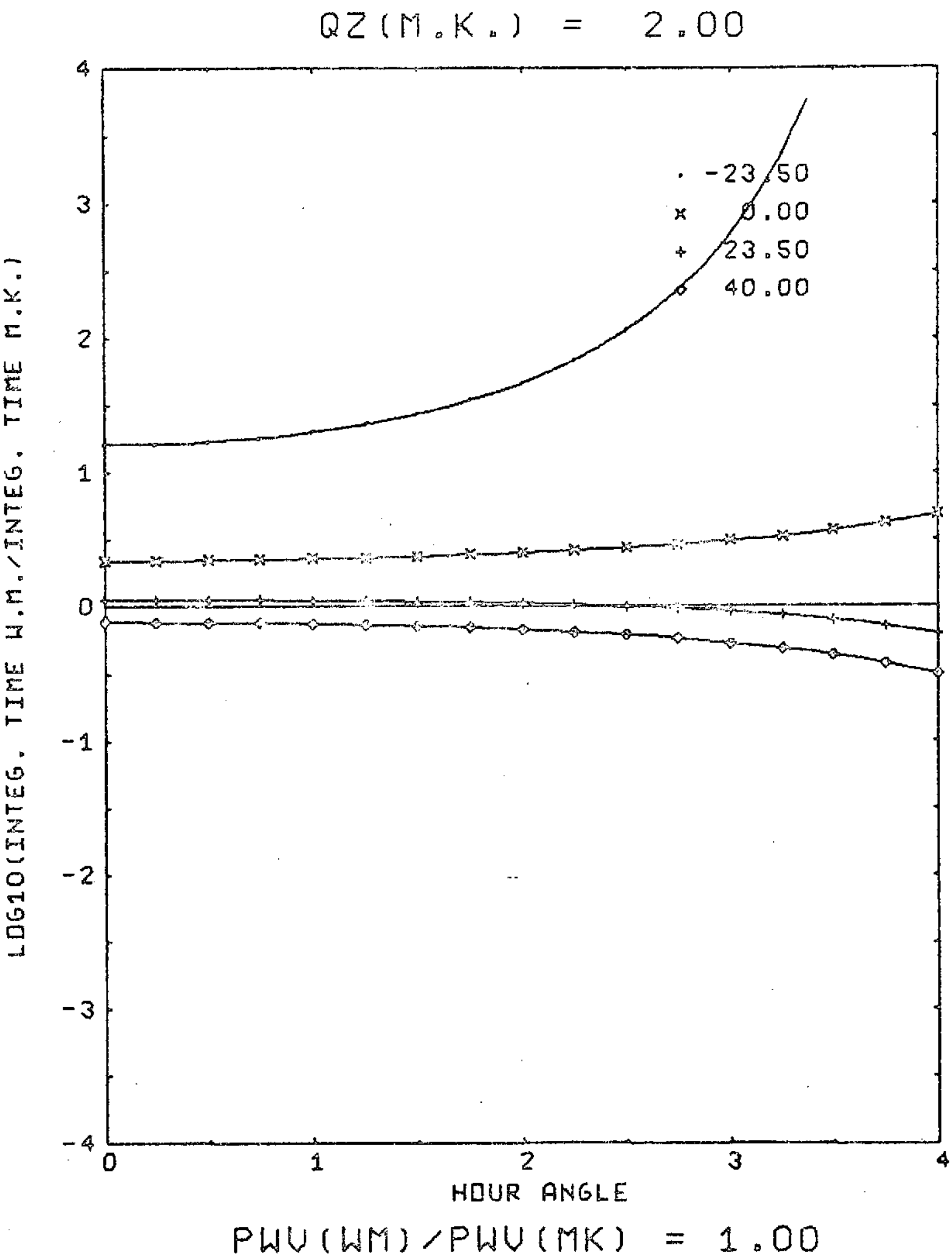


Figure II D-4

XBL 738-1075

the southern limit of the ecliptic. This advantage is compounded at the higher values of optical thickness. When the water vapor is the same at the two sites, as it is during summer noontime, there is no advantage at White Mountain, even at the northern limit of the ecliptic. If our suggestion above, that the summer nighttime water vapor at White Mountain is half that at Mauna Kea, is valid, then during all seasons White Mountain is superior.

Nevertheless, since not-summer is nine months long, even if we did not observe at all during summer, the integration time advantage for optical depths greater than one would give more information than twelve months of observing at Mauna Kea. In addition, the integration time advantage overwhelms small differences in cloud cover. At these optical depths only water vapor is significant.

For optical depths less than about 0.1, zenith distance or small difference in water vapor has little effect. Then only cloud cover is significant. As we discussed in section II A-8, the cloud cover at White Mountain is about the same as at Mauna Kea, during the year of the survey. If we look at that year alone, White Mountain is equivalent to Mauna Kea at wavelengths where water vapor is not important. Since White Mountain has a marked variation over 20 years, it is important to know what kind of variation might exist at Mauna Kea.

The median noontime sea level equivalent precipitable water vapor in not-summer at Mt. Lemmon and Kitt Peak is 2.19 mm and 2.59 mm respectively, as taken directly from the Westphal plots of 1973 July. No September data are given for either place, and the Mt. Lemmon data are given for only 43 days, so sampling and selection effects need to be considered. In spite of those uncertainties, it appears that the higher altitudes of White Mountain and Mauna Kea lead to considerably less equivalent water vapor, as expected both from radiosonde distribution of water vapor with altitude and from pressure broadening.

After correction for pressure broadening as described in section II A-3, the median noontime actual precipitable water vapor in not-summer is: White Mountain, 1.25 mm; Mauna Kea, 2.67 mm; Mount Lemmon, 2.79 mm; and Kitt Peak, 3.15 mm. Kuiper (1970) has calculated quantities which can be directly compared with these pressure corrected measurements, using radiosonde measurements at unspecified but probably daylight times of day as organized by Gringorten, et al. (1966). A rough estimate of the not-summer median from Kuiper gives: White Mountain, 1.2 mm; Mauna Kea, 1.9 mm; Mount Lemmon, about 3 mm, and Kitt Peak, about 5 mm. We suggest that these differences between water meter and radiosonde measurements show that the effects of sampling, water meter calibration, and local effects due to terrain are still to be understood.

The simplest expectation of the distribution of water vapor is that it decreases with increasing altitude and latitude. There is no question that White Mountain has the highest value of both of those quantities, for all of the sites considered. Therefore we are quite confident that the measurements and expectations agree that the summit of White Mountain has significantly less water vapor than any of the sites measured in the NASA funded survey.

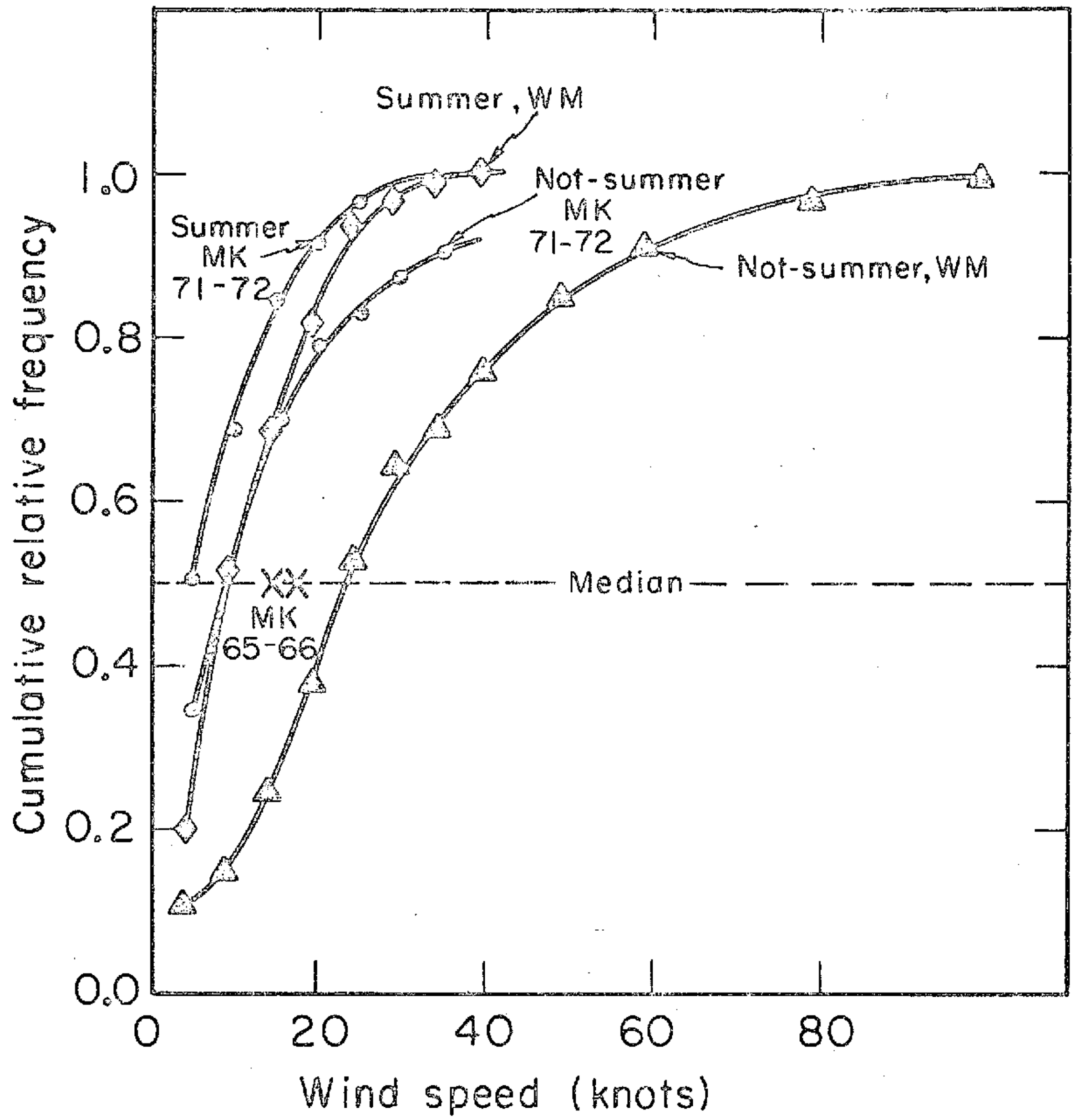
As we discussed in the section on potential telescope sites at different altitudes on White Mountain, if one is pushing as far as possible into normally obscured regions of the spectrum, low water vapor overwhelms all other considerations.

In section II A-4 we justify using the distribution of sunrise spot measurements of windspeed as being equivalent to the distribution of nighttime median windspeed. Figure II D-5 compares the White Mountain and Mauna Kea windspeeds. It is clear that the not-summer winds are much higher than the summer winds at the summit of White Mountain, and that the corresponding seasonal difference is much smaller at Mauna Kea. However, Mauna Kea winds are reported with quite different values for 1965-1966 and for 1971-1972, with the earlier values considerably higher than the later ones (Morrison, et al, 1973).

This yearly variation at Mauna Kea seems quite large compared with the yearly variation at the Barcroft Station at White Mountain, so it is difficult to understand the effects of sampling in comparing the two mountains. Probably the not-summer winds at White Mountain are higher than at Mauna Kea, but the amount of difference is unclear.

We have no information on whether Mauna Kea winds were measured under all conditions or under maximum exposure to the wind, so we cannot compare the severe winds at the two sites.

We complete this discussion of the White Mountain site with our best estimate of an overall comparison with the other sites in the NASA funded survey. The outstanding disadvantage of White Mountain is the lesser logistic development than at the other sites, which are all operating observatories. In addition it is quite possible that the foul weather at White Mountain is worse than at other places, because of its higher latitude, the clear weather windspeed may be higher, and the temperature is lower.



XBL737-3539

Figure II D-5. Cumulative distribution of nighttime median wind speed at White Mountain summit and Mauna Kea. Only monthly medians available for 65-66 at Mauna Kea.

The outstanding advantage of White Mountain is low water vapor. The seeing is objectively compared only with Kitt Peak and San Pedro Martir, and White Mountain is better. Those are the two parameters which finally have major influence on the integration time to achieve a given signal to noise ratio, once an observer is at the telescope, everything is working, and the sky is clear. There is a factor of two integration time advantage of White Mountain over Mauna Kea for objects at the southern limit of ecliptic. For more northern objects, more northern obervatories, and observations at wavelengths with maximum atmospheric opacity, the White Mountain advantage becomes an order of magnitude. Those advantages are equivalent to having two to ten telescopes for the price of one, and the advantage gets even bigger when signal to noise ratio increases less rapidly than the square root of integration time for all sorts of practical reasons.

Those advantages far outweigh the modest capital investment in facilities necessary to make White Mountain more usable. The travel costs at White Mountain including helicopter operation and charter flights from San Francisco or Los Angeles to Bishop are no greater than flying to Hilo and driving to Mauna Kea, and in any case those costs are small compared to other operating costs. Operation is certainly easier at Mt. Lemmon and Kitt Peak, but we estimate that the increase in operating cost necessary to take care of all the unique problems at White Mountain is a few tens of thousands of dollars per year. Again that is inexpensive compared to the increase in telescope output because of low water vapor.

There remain the physiological and psychological problems due to hypoxia, dehydration, remoteness, and travel in less comfortable vehicles than passenger cars. White Mountain is no worse than Mauna Kea in those respects, but Mt. Lemmon and Kitt Peak have a great advantage. It is possible that much of the severe criticism of White Mountain is based on those factors, and if those factors keep people from achieving their goals, they are certainly highly significant. All of those problems have partial solutions involving technological and management techniques. In the 23 years of experience in operating the White Mountain Research Station it has been possible to clearly identify these problems and solutions, but the total activity there has been too small to justify the solutions.

Improvement of the road and purchase of better vehicles will make ground travel more comfortable. Maintenance and partitioning of the dormitories and improvement of their heating and humidifying systems will make nights more comfortable. Easy access to oxygen at the higher stations and maybe in the vehicles will overcome many of the hypoxia symptoms. Normal telephone service will remove much of the sense of remoteness. Even as simple a thing as repainting the interiors of buildings will remove some of the sense of desolation that some users of the Station complain about.

Finally we would like to investigate the cost and benefits of pressurized buildings, especially for use during intellectual work and during sleep at the higher stations. At this time we cannot estimate whether or not such buildings would be worthwhile.

The final support of White Mountain on these physiological and psychological grounds is that many people have enjoyed working there even under the existing hardships. Over three hundred scientific papers have been published on the basis of such work, and many people report that their times there have been very enjoyable.

III. DATA DISPOSITION

The measurements of ten micron sky noise were sent directly to Dr. James Westphal, California Institute of Technology, without any reproduction or analysis. The water vapor measurements were also sent to him, but copies of the data were kept in Berkeley for statistical analysis. These data plus all the other measurements and codings of the verbal descriptions are in machine readable form, and were used in the analyses presented above. A printout of those data has also been sent to Dr. Westphal. Machine readable or hard copies are available on request.

The photographs of star trails, used for determination of stellar seeing, are currently being kept by Dr. Merle Walker, Lick Observatory, who reduced them to derive the quantities given here. The fisheye lens photographs of the sky have been used to verify a sample of the verbal descriptions, which in turn were coded for use in our analyses. Those photographs plus all other data are in the custody of Dr. Cudaback. Further analyses will appear in a published paper, and that may include data from 1971 January through June, largely accumulated at the Barcroft Laboratory.

IV. OPERATIONAL EXPERIENCE

The program at the Summit Laboratory was the first one to be operated there in winter and was far and away the longest program ever there. Accordingly we had to work out some operational details, which are relevant to future operations there.

The provision of electricity for the ten micron sky noise instrument turned out to be straightforward, by operating a gasoline driven generator for two hours per day. That charged lead-acid storage batteries, which then operated the instrument continuously through an inverter. The system worked well, and it showed that gasoline engines can be started readily when cold and at high altitude.

The one problem involving the electrical system indirectly was damage to the inverter when lightning struck an ungrounded part of the building and got into the system. More lightning rods solved that problem.

Lightning was a continuing problem with the anemometer, because we never got to developing a sufficient cage of conductors around it. It does demonstrate that careful attention must always be given to lightning protection, but the techniques for that have been developed at many other places.

Supply of liquid helium proved to be straightforward. Thirty liter, super insulated dewars were used, could be carried easily by two people and occasionally by one, and could be carried easily on the outside of the helicopter. At the start rented dewars were used with helium supplied commercially, and only a small amount of helium arrived at the Summit. Apparently that was due to defective dewars or poor practice in filling and cooling, for a new dewar which we purchased and filled at the University helium plant normally lost only the helium expected from normal boil off, in being carried all the way to the Summit.

The travel facilities at the White Mountain Research Station have been developed for coping with the altitude and climate problems on the basis of 20 years of experience. In particular the use of a helicopter is very effective under a wide range of conditions, especially in travelling to the lower laboratories on the mountain. For the small amount of traffic there now, the use of the helicopter is cheaper and easier than maintenance of the road in winter.

At the Summit Laboratory there are more constraints on helicopter operation, and then ground vehicles become more useful. In addition the terrain above the Barcroft Laboratory and almost to the Summit Laboratory is considerably more gentle than the steep and incised slopes at lower altitudes, and the road distance between those points is only five miles as compared with 33 miles from the nearest plowed road to Barcroft. Since we do not have suitable tracked vehicles now, men occasionally walked between the Barcroft and Summit Stations when helicopter operation was impossible and the road blocked by snow.

For an operating observatory we expect to use the helicopter for carrying people from Bishop to the Barcroft Laboratory in winter, with slower trips being made by tracked vehicles for carrying freight. The helicopter would be used between the Barcroft and Summit Laboratories when possible, with the expectation that tracked vehicles would be used often.

Because at times there was only one man at the Summit Laboratory, we chose to hire only men with engineering training and experience and with serious mountaineering experience. These men coped extremely well with any problems which arose, and accordingly no problems ever became serious. The three men who worked at the summit were all close to thirty years old, two were trained as engineers and one as a physicist, all had led mountaineering trips, and all were used to a variety of activities which had to be done correctly for safety. They provided their own mountain clothing and equipment, and they were prepared to walk to at least the Barcroft Laboratory if necessary under any weather conditions.

In future astronomical operations at White Mountain we believe that there should be usually one man of this experience and caliber with any group above the Barcroft Laboratory in winter and spring, and men with this combination of talents are readily available. Such a man would be assigned to each observing program and care for the needs of the visiting observer in more detail than a traditional telescope operator. He would operate the telescope, drive any specialized vehicles being used, and assure that the operations are safe for both people and equipment. Finally he would be able to make observations without the full-time presence of the visitor, to enable the visitor to stay in a more amenable place. For example the visitor may stay in Bishop, after an initial check of equipment at a telescope, and monitor the observations via a video microwave link.