Pub. Astron. Soc. Pacific, Volume 83, August 1971

POLAR STAR-TRAIL OBSERVATIONS OF ASTRONOMICAL SEEING IN ARIZONA, BAJA CALIFORNIA, CHILE, AND AUSTRALIA*

MERLE F. WALKER
Lick Observatory, Board of Studies in Astronomy and Astrophysics
University of California, Santa Cruz

Received 17 April 1971

The results of polar star-trail seeing observations at Kitt Peak and Flagstaff (Arizona), San Pedro Mártir (Baja California), Cerro Tololo (Chile), and Mount McKinlay (Australia), are presented. Seeing and observing conditions at these sites are compared with those at Junipero Serra Peak and Piper Mountain, in California, published earlier (Walker 1970). The best seeing conditions occurred at Junipero Serra and Cerro Tololo. The frequency functions of the average nightly seeing were very similar at these two sites, although the percentage of photometric hours was somewhat higher at Cerro Tololo. The seeing conditions at all of the other sites were appreciably poorer than at Junipero Serra and Cerro Tololo. Seeing conditions at Kitt Peak, San Pedro Mártir, and Piper Mountain were all roughly the same, while at Mount McKinlay and at Flagstaff, the seeing was slightly, and appreciably, poorer still, respectively.

These results appear to strengthen the conclusion that at least between latitudes 30° and 40° N and S, the best seeing occurs at sites on peaks near seacoasts having cold ocean currents offshore that reduce the height of the inversion layer, and where the laminar airflow set up over the ocean still persists. In addition, the observations suggest that a fairly typical seeing distribution may exist on isolated peaks of about 7000-foot altitude in the interior arid regions of any land mass in this range of latitude. Those sites or regions that should, on the basis of these conclusions, have the best seeing conditions, are discussed.

Key words: astronomical seeing

I. Introduction

Following the completion of the California Site Survey (Walker 1970), the Polaris star-trail seeing telescopes used in that survey have been employed to measure the optical turbulence, or astronomical seeing at: Kitt Peak and Flagstaff, Arizona; San Pedro Mártir, Baja California; and Cerro Tololo, Chile. The purpose of these observations was twofold: (1) to determine the seeing at several existing observatories, or potential observatory sites, on the system established for the California Site Survey, and (2) to further investigate the conditions required for the best seeing. This paper presents the results of these observations, together with some earlier observations made at Mount McKinlay, Australia, using the same method.

The technique of using star trails of Polaris, photographed with a six-inch refracting telescope, to measure the seeing has been described by Harlan and Walker (1965) and Walker (1970). With certain modifications, this method may also be used for observations in the Southern Hemisphere. At the present epoch, the star σ Octantis has very nearly the same angular distance from the south celestial pole as does Polaris from the north celestial pole. Thus, comparable trailing rates can be obtained using a fixed telescope and the diurnal motion. The magnitude of σ Oct is, however, $m_v = 5.5$, whereas Polaris is $m_v \simeq 2.0$. Trails comparable in density to those of Polaris obtained with the emulsion and filter described earlier (Harlan and Walker 1965) can be obtained for σ Oct by using Kodak Plus-X film and photographing through a filter consisting of 2 mm of Schott GG-14. The observations in Australia and in Chile were all made using the same telescope, modified in the above manner. The calibration of this telescope was rechecked before it was sent to Chile by installing a 3.5 mag. neutral filter, in addition to the GG-14, between the enlarging lens and the focal plane and making simultaneous measurements of Polaris with this telescope and the regular

*Lick Observatory Bulletin, No. 617.

Polaris telescope used for the observations on Kitt Peak.

II. Observations

With the exception of the measures in Australia, the observations described in this paper were all obtained through the cooperation of the Directors of the various observatories, who very generously arranged for the seeing and related weather observations to be made by the regular observing assistants on their staffs. Since the availability of such assistance was different at each location, the amount and type of data collected varied considerably from one site to another. Consequently, the observations obtained at each site are described separately, below.

A. *Cerro Tololo, Chile*

The most complete set of observations is that obtained at the Cerro Tololo Inter-American Observatory ($\lambda = 70°49'.2$ W, $\phi = 30°10'.2$ S, altitude = 7250 feet). Cerro Tololo is located on the western edge of the Andes range and is some 35 miles inland from the Pacific Ocean. The situation of the site is somewhat similar to that of sites along the California coast. As in California, a cold ocean current flows along the Chilean coast and this current has the effect of lowering the height of the inversion layer to about 3300 feet. Observations at Cerro Tololo are of considerable interest both because of its similarity to the California coastal sites, and because this site has a reputation for having extremely good seeing conditions.

The seeing telescope was set up and observations begun during the writer's tenure as Senior Resident Astronomer at CTIO. The series extends from 10 October 1968 through 31 August 1970 UT. The seeing telescope was mounted on a poured concrete pier, located at the northeast edge of the flat area on top of the peak, on the concrete pad on which the 36-inch reflector was installed before it was mounted in its dome. This point is about 30 feet southeast of the No. 2 16-inch telescope. This location was chosen to put the telescope on the up-wind edge of the peak, since the nighttime wind at Cerro Tololo is nearly always from the north (see Table III). The objective of the telescope was situated about eight feet above the flat surface of the top of the peak.

Weather observations were made simultaneously with each observation of the seeing. Temperature and humidity were read from the Observatory's regular recording thermograph and hydrograph, housed in a U. S. Weather Bureau design louvered box which was located on the concrete pad beside the seeing telescope. These readings were also checked against those of a psychrometer operated at the same location. The wind velocity was measured at ground level at the seeing telescope site, using a hand-held anemometer, until 21 March 1969. Subsequently, the velocity was read from the regular observatory wind guage, located on a tower standing just off the east edge of the peak.

The observations were made by one of the night assistants on duty on a particular night, so that during the course of the program, observations were made by all of the Cerro Tololo night assistants. The observers associated for the longest time with the program were: Srs. Carlos Bolelli, Edguardo Figueroa, Arturo Gomez, Ricardo Gonzales, and Patricio Zamorano. The seeing and weather observations had to be made as the regular work of the night assistants permitted. However, as far as possible, an effort was made to obtain three observations each night at 01:45, 04:45, and 07:45, UT, and on the great majority of nights all three observations were obtained and at approximately the indicated times. The processing and measurement of all of the σ Oct trail films were carried out by the writer.

For all of the locations discussed in this paper, the seeing observations have been treated in the same way as those given in Walker (1970). That is, all seeing observations for each night were combined to give the average seeing for the night, and histograms were prepared for each month giving the number of nights with different average seeing. As in Walker (1970), the average nightly seeing is grouped by $0''.5$ intervals in the histograms. As before, the limits of these intervals are: $0''.5$ to $1''.0$, $1''.1$ to $1''.5$, $1''.6$ to $2''.0$, etc. Those nights with average seeing $> 7''.5$ have been entered on the histograms in the $7''.1$ to $7''.5$ interval, with a notation above giving the value of the average seeing for the night.

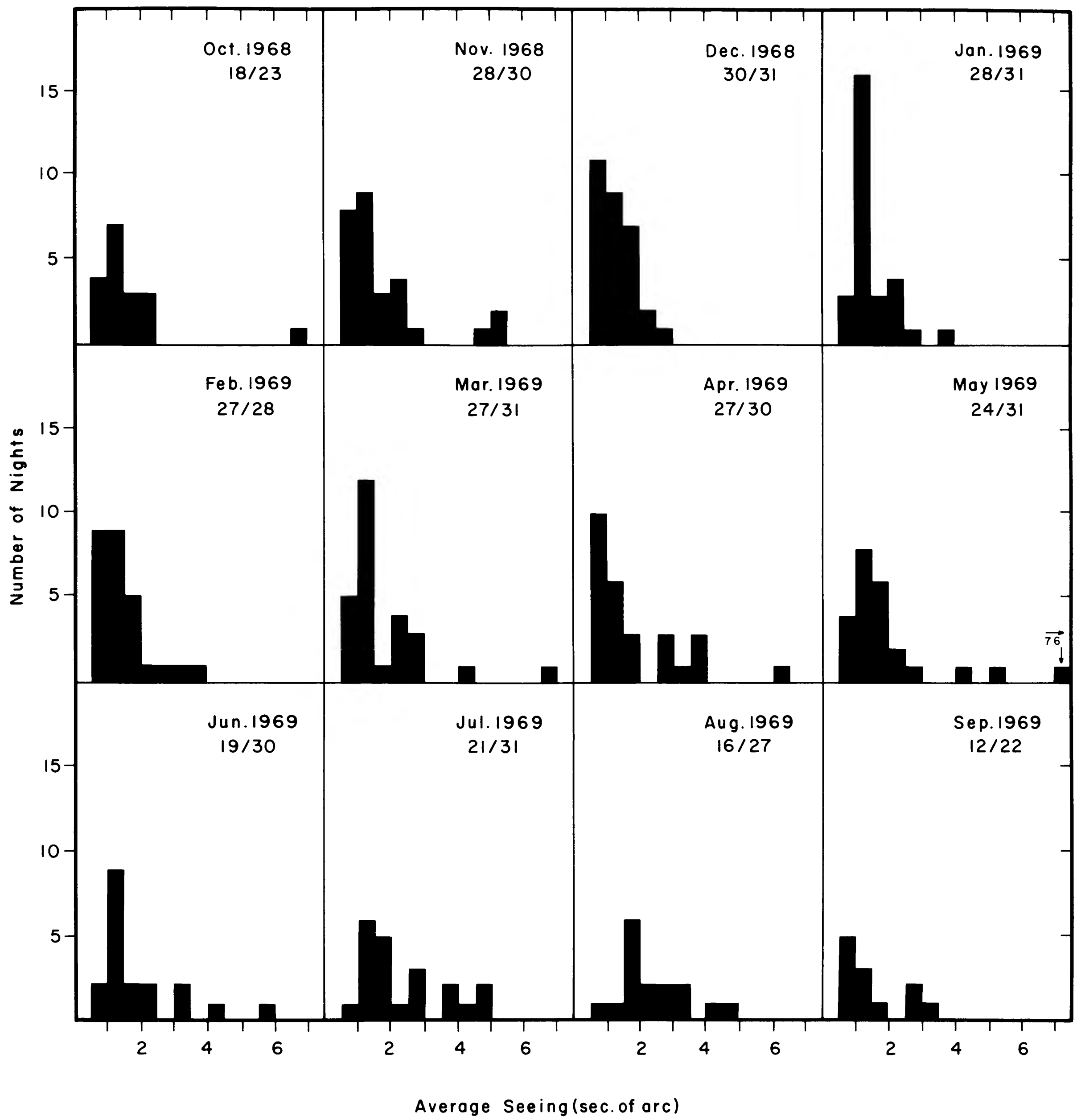

FIG. 1 — Frequency distributions of average nightly seeing observed at Cerro Tololo. Ordinate is the number of nights; abscissa, the average seeing for the night. The fractions given for each month indicate: numerator, number of nights when at least one observation was made; denominator, number of nights with observer present.

The Cerro Tololo seeing histograms are reproduced in Figures 1 and 2. The fraction given for each night indicates, as in Walker (1970), in the numerator, the number of nights on which at least one seeing observation was obtained, and in the denominator, the number of nights on which an observer was present, ready to observe if conditions permitted.

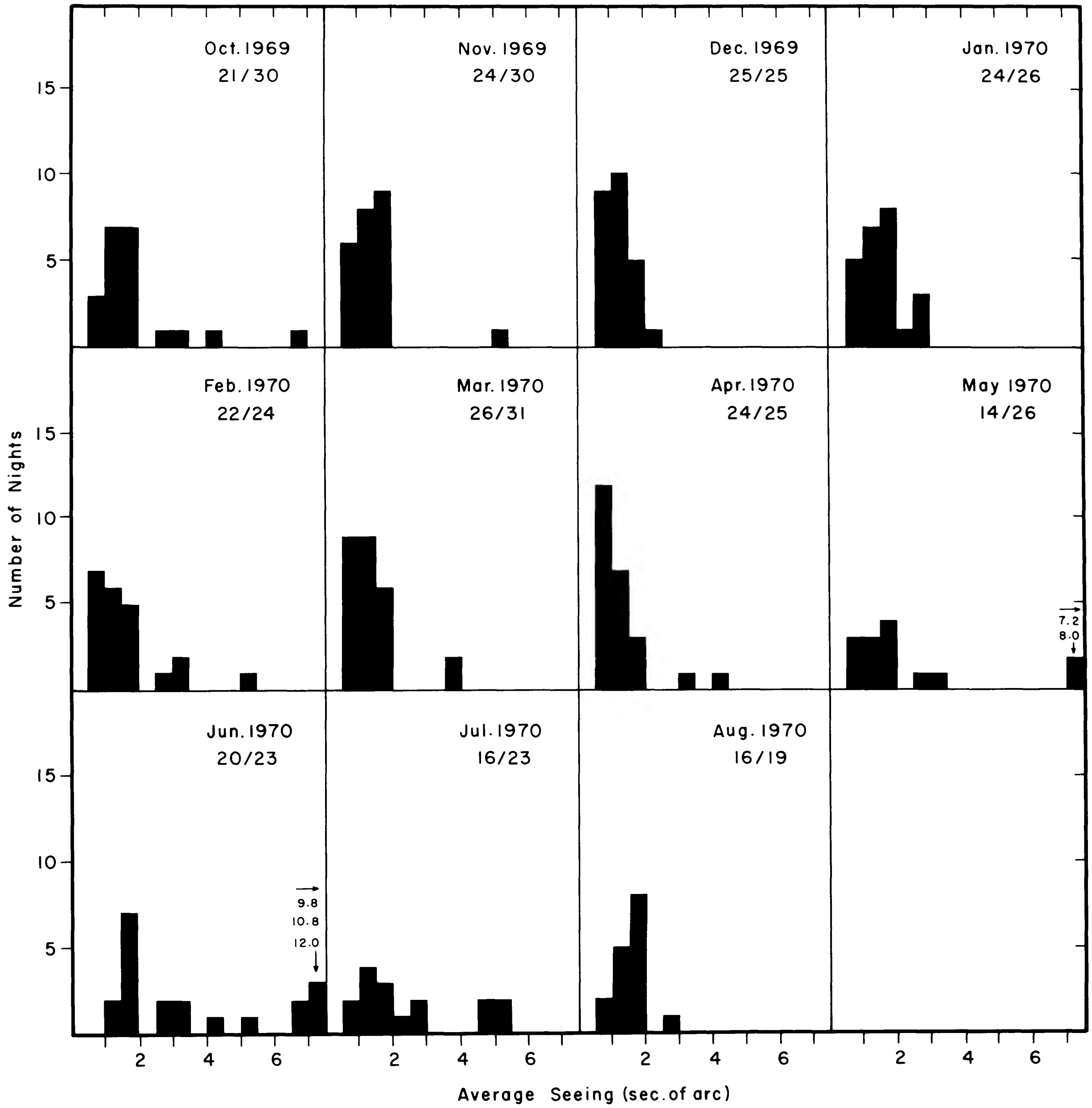

FIG. 2 — Frequency distributions of average nightly seeing observed at Cerro Tololo. Ordinate, abscissa, and notation as in Figure 1.

Since the format of the observing program at Cerro Tololo was nearly identical to that of the observations made during the California Site Survey, it appears of interest to present here, in addition to the seeing data, summaries of the weather observations in the same form as given earlier for Junipero Serra Peak and Piper Mountain (Walker 1970). These data are given in Tables I–III. It will be noted that in Table II the number of nights in each month when weather data were recorded differs occasionally from the number of nights with an observer present as shown in Figures 1 and 2. These differences are due to incomplete records, or to camera malfunction on some nights; in preparing Table II, only those fractions of nights for which weather data were recorded have been used.

TABLE I

NIGHTTIME WEATHER OBSERVATIONS AT CERRO TOLOLO

Date	Temperature, °F Highest	Lowest	Average	Average Δ Temp. During Night, °F	Relative Humidity, % Highest	Lowest	Average
1968							
Oct	60	30	47.4	3.9	75	0	26.0
Nov	65	41	53.9	2.6	75	0	24.8
Dec	62	45	55.2	3.3	75	0	36.3
1969							
Jan	66	50	57.9	3.0	84	3	47.9
Feb	66	50	57.7	2.8	78	23	45.5
Mar	66	42	56.3	2.3	79	0	36.1
Apr	64	44	54.4	2.8	100	13	35.2
May	63	27	51.3	2.8	100	2	32.9
Jun	60	22	44.3	2.4	100	4	38.4
Jul	62	32	48.4	2.4	55	4	16.0
Aug	60	23	48.0	2.6	100	3	29.0
Sep	65	31	50.7	2.5	100	0	31.1
Oct	58	30	50.0	2.2	100	8	35.4
Nov	60	36	50.7	2.3	100	5	39.4
Dec	60	50	55.6	2.0	73	9	43.1
1970							
Jan	70	46	54.9	3.3	85	1	42.8
Feb	68	48	58.1	2.3	82	15	43.4
Mar	70	46	56.5	2.7	84	0	37.6
Apr	66	50	59.3	2.5	38	3	18.0
May	60	30	46.5	2.3	91	0	39.5
Jun	58	32	44.6	2.9	90	0	19.3
Jul	62	29	45.1	3.1	100	0	30.6
Aug	58	30	47.1	2.6	100	0	19.9

B. *Kitt Peak, Arizona*

A long series of observations was obtained at the Kitt Peak National Observatory ($\lambda = 111°35'.7$ W, $\phi = 31°57'.5$ N, altitude = 6772 feet), extending from 18 June 1968 through 29 October 1970 UT. Seeing measures at this site were undertaken because Kitt Peak represents an inland or "continental" observing site, carefully selected to have the best possible observing conditions.

The seeing telescope was mounted on a concrete-block pier, located just west of the No. 1 36-inch telescope, with its objective about nine feet above ground level. With the exception of a few nights in August 1968 when the measures were made by the writer, all of the observations were made by one of the observatory assistants, Mr. Kelly Cook, and were therefore obtained only during those periods when he was present on the mountain, and at times allowed by his regular duties. From June 1968 to February 1970 two observations per night were made, weather permitting: at about 19:30 MST from April through September (or about 20:30 from October through March), and again at about 00:30 MST. From March 1970 through October 1970 observations were obtained as above, but, in addition, a third observation was obtained at about 04:30 MST. Observations of temperature, relative humidity, and wind velocity were made simultaneously with the seeing observations, using the regular weather instruments of the observatory. Since the number of nights observed per month was usually no more than 15

TABLE II

NIGHTTIME OBSERVING CONDITIONS AT CERRO TOLOLO

Date	No. of Nights*	No. of Dark Hours*†	No. of Photometric§ Hours*†	No. of Nights* With $\geq 6^h$ Cont. Photometric§	No. of Hours*† With Cloud Cover $\leq 60\%$	$\leq 80\%$	No. of Nights* With Wind Velocity Consistently: $\geq 25 \frac{mi}{hr}$	$\geq 30 \frac{mi}{hr}$
1968								
Oct	21.67	187.4	94.9	10.67	130.1	152.1	0	0
Nov	29.33	216.4	130.1	14.0	189.0	191.5	0	0
Dec	31.0	209.2	133.9	17.0	197.8	200.8	0	0
1969								
Jan	31.0	219.4	128.2	16.0	192.0	202.3	0	0
Feb	28.0	225.1	180.4	21.0	193.0	214.8	0	0
Mar	31.0	281.0	163.3	15.0	227.1	242.2	0	0
Apr	30.0	299.1	149.9	12.0	240.1	262.8	2	1
May	31.0	229.2	102.0	6.0	211.0	221.8	8	5
Jun	30.0	327.0	98.0	5.0	185.3	207.1	7	5
Jul	29.67	308.9	95.8	5.0	193.8	200.0	3	3
Aug	30.67	313.7	89.0	6.0	201.5	215.0	2	0
Sep	30.0	282.7	90.4	6.0	185.8	211.2	2	1
Oct	30.0	251.9	93.0	7.0	182.9	188.4	2	1
Nov	30.0	221.3	121.7	12.0	183.2	191.0	3	3
Dec	23.0	155.3	128.2	18.67	155.3	155.3	0	0
1970								
Jan	26.0	189.5	152.3	16.0	175.5	180.1	1	1
Feb	24.0	192.0	113.2	11.0	166.8	172.2	0	0
Mar	30.67	277.8	164.1	15.67	238.8	251.0	0	0
Apr	24.0	237.9	209.1	19.33	227.7	227.7	2	0
May	26.0	276.1	74.0	4.0	169.1	190.6	8	7
Jun	23.33	254.3	130.8	8.33	210.7	210.7	3	1
Jul	24.33	265.4	114.9	9.0	190.0	200.8	4	3
Aug	18.0	177.1	82.3	6.0	123.1	140.4	1	0

*When observing conditions were recorded.

†Based on the interval from the end of astronomical twilight to the beginning of astronomical dawn.

§"Photometric" means zero percent cloud cover.

to 20 and since during most of the program, observations were only taken at the beginning and middle of the night, the complete weather observations have not been included here; a much better impression of the observing conditions can be obtained from the data published in the *Quarterly Reports of the Kitt Peak National Observatory*. The temperature and humidity observations for the period March 1970 through October 1970 have, however, been given in Table IV since, as discussed above, three observations per night were made during this period, so that the results are comparable with those made in California (Walker 1970) and at Cerro Tololo.

TABLE III

FREQUENCY OF NIGHTTIME WIND DIRECTION AT CERRO TOLOLO

Date	Number of Individual Observations							
	N	NE	E	SE	S	SW	W	NW
1968								
Oct	48	8	2	0	1	1	2	3
Nov	32	7	1	0	15	1	4	7
Dec	21	21	0	0	11	6	4	4
1969								
Jan	17	3	5	1	23	6	2	5
Feb	20	1	4	0	20	3	0	3
Mar	42	10	1	0	4	3	1	5
Apr	56	3	0	0	7	1	0	1
May	90	8	0	0	2	0	1	1
Jun	75	8	0	0	4	0	0	0
Jul	73	5	0	0	6	0	0	1
Aug	38	22	1	0	11	0	2	0
Sep	38	17	2	9	8	7	1	0
Oct	29	27	3	9	8	4	0	2
Nov	80	1	1	3	1	0	0	0
Dec	25	7	0	5	5	9	1	1
1970								
Jan	55	3	0	0	11	1	0	1
Feb	7	1	1	0	32	1	0	0
Mar	23	9	4	1	26	2	0	0
Apr	18	10	2	2	19	0	2	0
May	34	28	0	0	4	3	4	0
Jun	20	33	0	0	0	3	0	2
Jul	45	12	0	2	2	0	0	7
Aug	26	11	0	1	2	1	1	3

TABLE IV

NIGHTTIME WEATHER OBSERVATIONS AT KITT PEAK

Date	No. of	Temperature, °F			Average Δ Temp.	Relative Humidity, %		
1970	Nights*	Highest	Lowest	Average	During Night, °F	Highest	Lowest	Average
Mar	21	53	34	42.8	4.4	100	20	72.5
Apr	22	62	32	48.8	4.9	88	14	39.7
May	21	77	46	61.9	5.5	93	24	47.2
Jun	18	77	56	65.7	3.4	94	18	51.4
Jul	14	86	60	68.7	6.5	100	33	75.3
Aug	6	67	60	63.0	4.2	100	76	90.2
Sep	6	69	50	59.9	7.4	99	38	67.2
Oct	11	65	37	49.0	5.5	99	24	64.6

*When weather observations were reported.

The seeing observations are presented in Figures 3, 4, and 5. As before, the fractions given for each month indicate the number of nights on which at least one trail observation was possible and the total number of nights when the observer was present on the mountain; these data are lacking for the months of June, July, and August 1968. It will be noted that the number of nights with the observer present is in some cases smaller than the number of nights on which weather observations were obtained (Table IV). This is due to the fact that on some nights no trail observations were made owing to wind. Since observations under equivalent conditions were made on the other sites, these nights have been treated as nights with no observer in order not to bias the figures for the percentages of nights when seeing observations could be made at Kitt

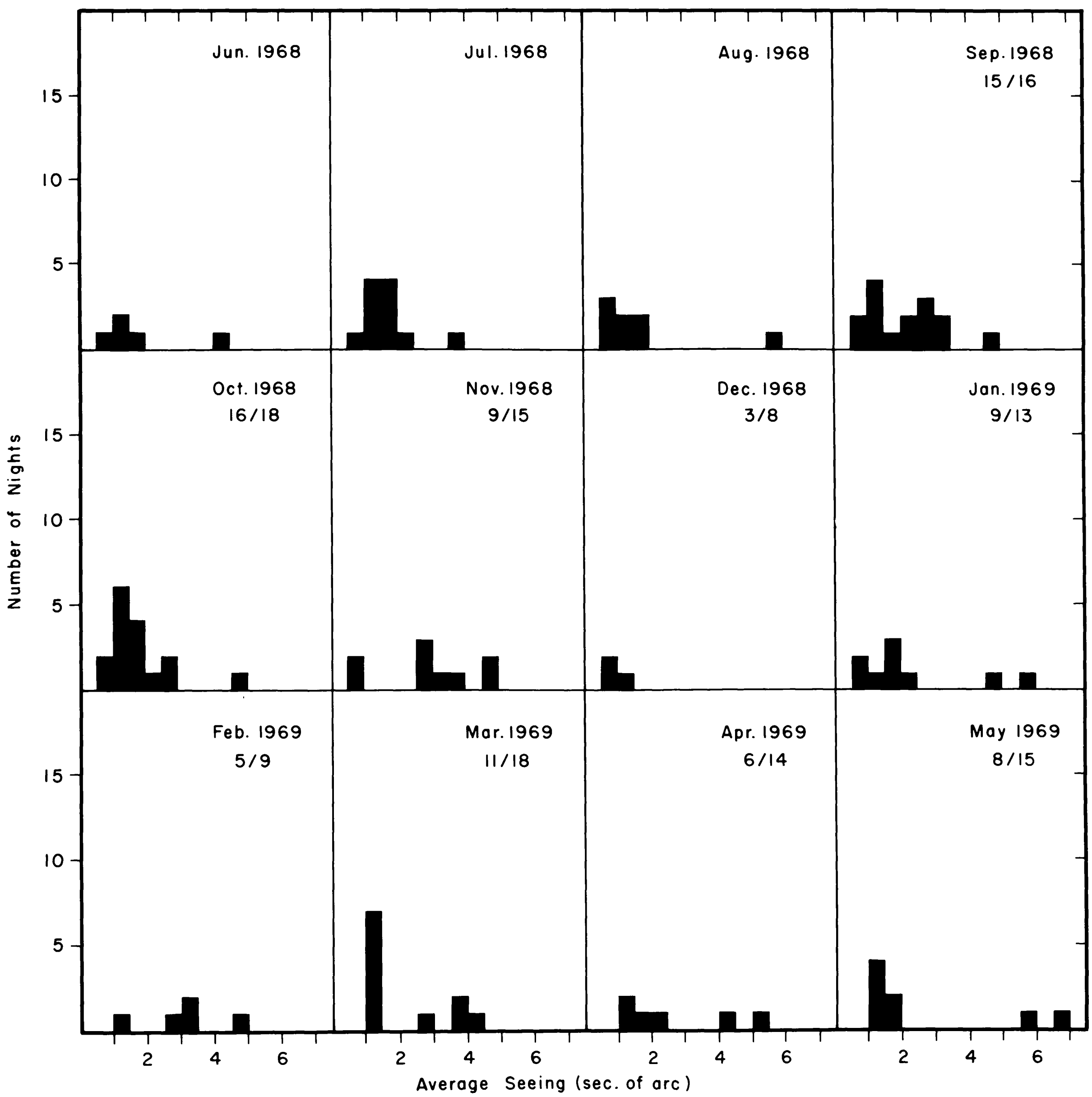

FIG. 3 — Frequency distributions of average nightly seeing observed at Kitt Peak. Ordinate, abscissa, and notation as in Figure 1.

Peak. For the observations through 23 September 1969, the Polaris trail films were processed by the Photographic Laboratory of the Kitt Peak National Observatory; following that date, they were processed by the writer. The measurements of seeing on all of the films have been made by the writer.

C. *Flagstaff, Arizona*

Observations were obtained at the U. S. Naval Observatory, Flagstaff Station ($\lambda = 111°44'.4$ W, $\phi = 35°11'.0$ N, altitude = 7579 feet), between 30 November 1966 and 20 January 1967, between 13 May and 2 July 1967, and during September and October 1968. The seeing telescope

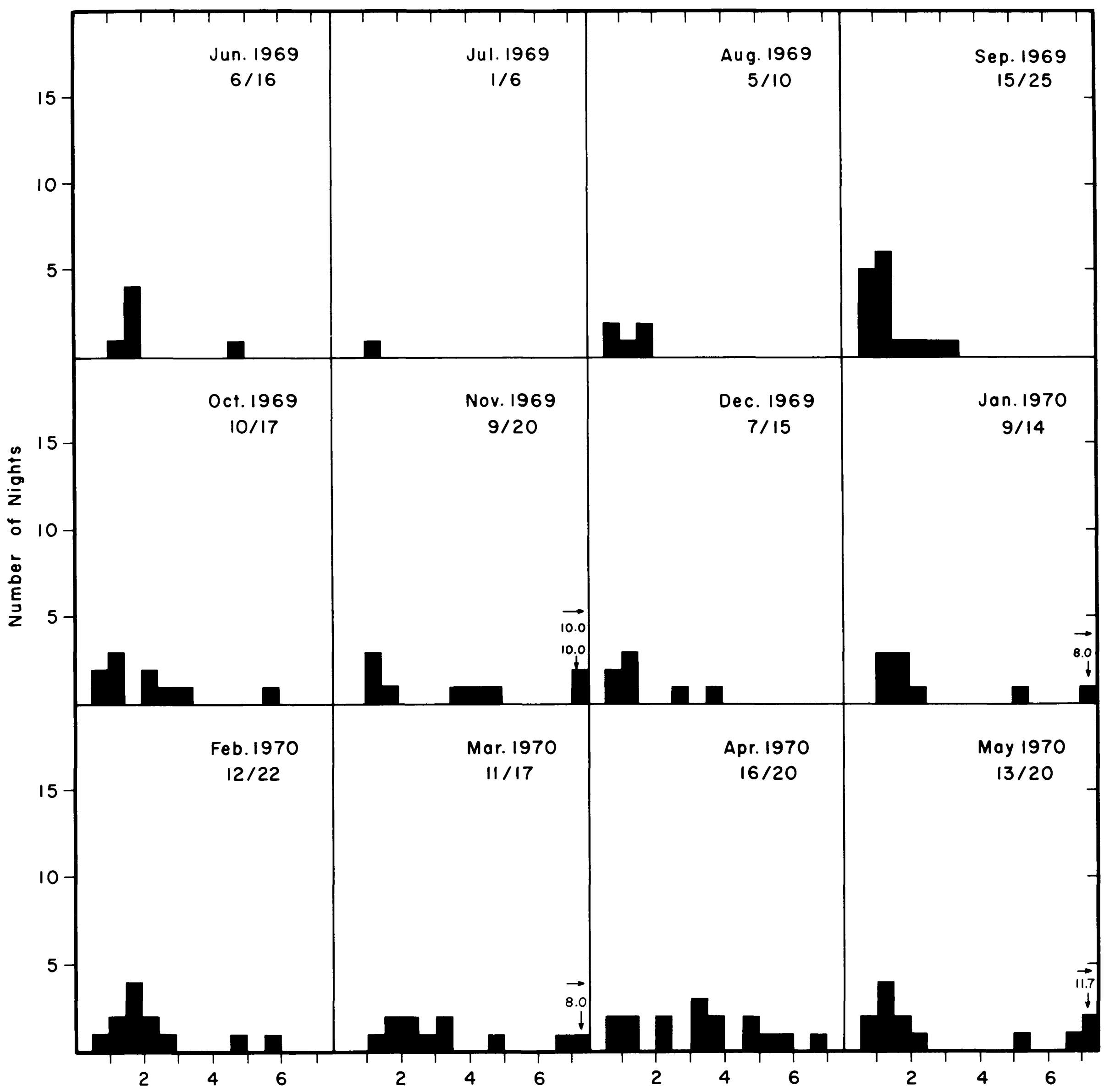

FIG. 4 — Frequency distributions of average nightly seeing observed at Kitt Peak. Ordinate, abscissa, and notation as in Figure 1.

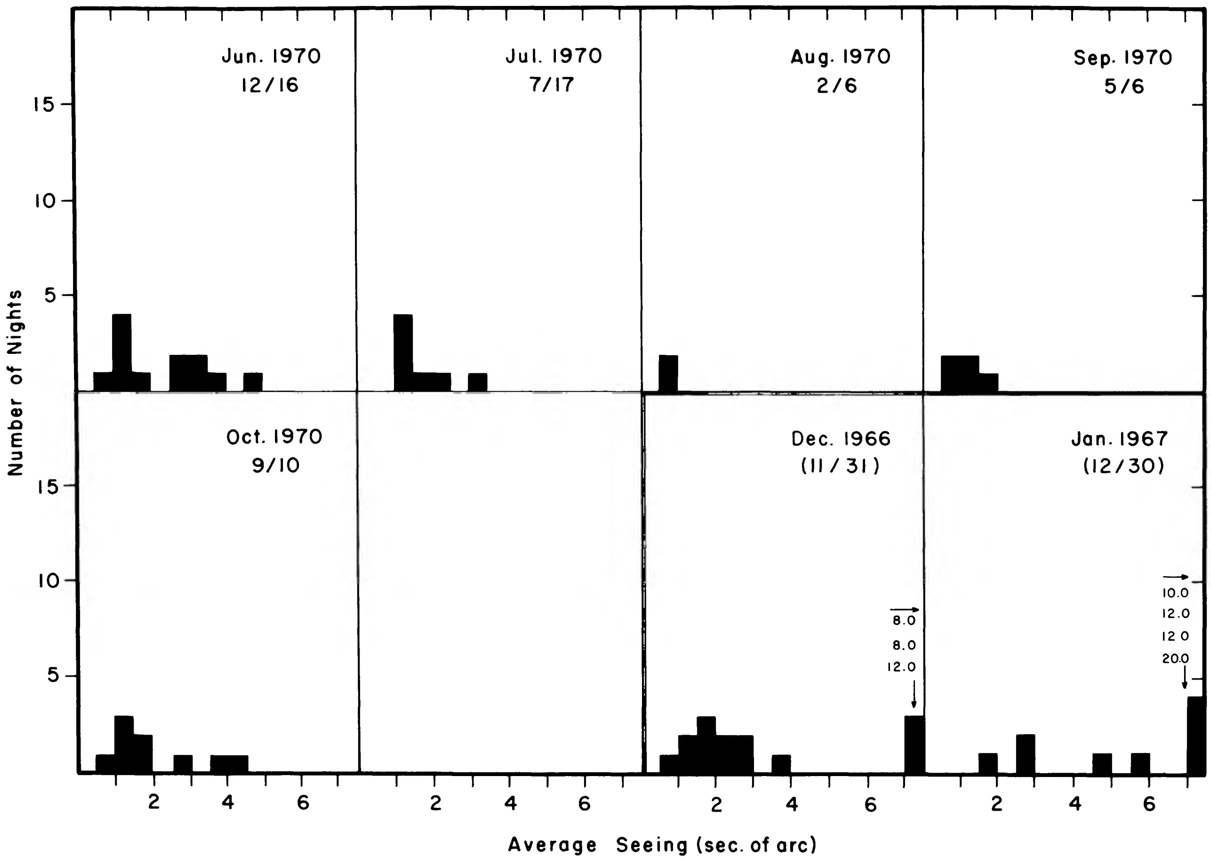

FIG. 5 — Frequency distributions of average nightly seeing observed at Kitt Peak (first five panels) and at Flagstaff (last two panels). Ordinate, abscissa, and notation as in Figure 1, except for the fractions given for the Flagstaff observations; see text. The panel for December 1966 includes observations on 29 and 30 November 1966.

was mounted on an existing pier just west of the building that houses the 40-inch reflector. The observations in 1966 and January 1967 are shown in the bottom row of Figure 5, and the later observations in the top row of Figure 6. Since only occasional seeing observations were possible, at times permitted by the regular work of the observatory, the fractions shown for each month indicate the number of nights per month that some observations were made with the 61-inch astrometric reflector, which was scheduled for use each night. The Polaris trail films were all processed at the U. S. Naval Observatory, Flagstaff, and all measurements of the seeing on them were made by the writer.

D. *San Pedro Mártir, Baja California*

Observations were made from 24 April through 30 July 1970 on the highest point of the new site of the Mexican National Observatory. The observatory site ($\lambda = 115°27'$W, $\phi = 31°03'$ N, altitude = 9252 feet) is located in the Sierra San Pedro Mártir, about five miles northwest of Cerro de la Encantada (altitude = 10,171 feet), and about 110 miles due south of Mexicali. The site occupies one of the peaks along the main ridge of the Sierra San Pedro Mártir and overlooks the San Felippe Valley to the east. To the west is a high mountain basin (the Vallecito) whose altitude is some 1000 feet lower than that of the site and whose width is about six miles. Seeing and weather observations were obtained at this site from June 1969 through July 1970 by the French site-testing group headed by Dr. Roger Cayrel. A preliminary account of the observations obtained through October 1969 is contained in a preprinted report of the French site-investigation program prepared by the Institut National d'Astronomie et de Géophysique, Meudon.

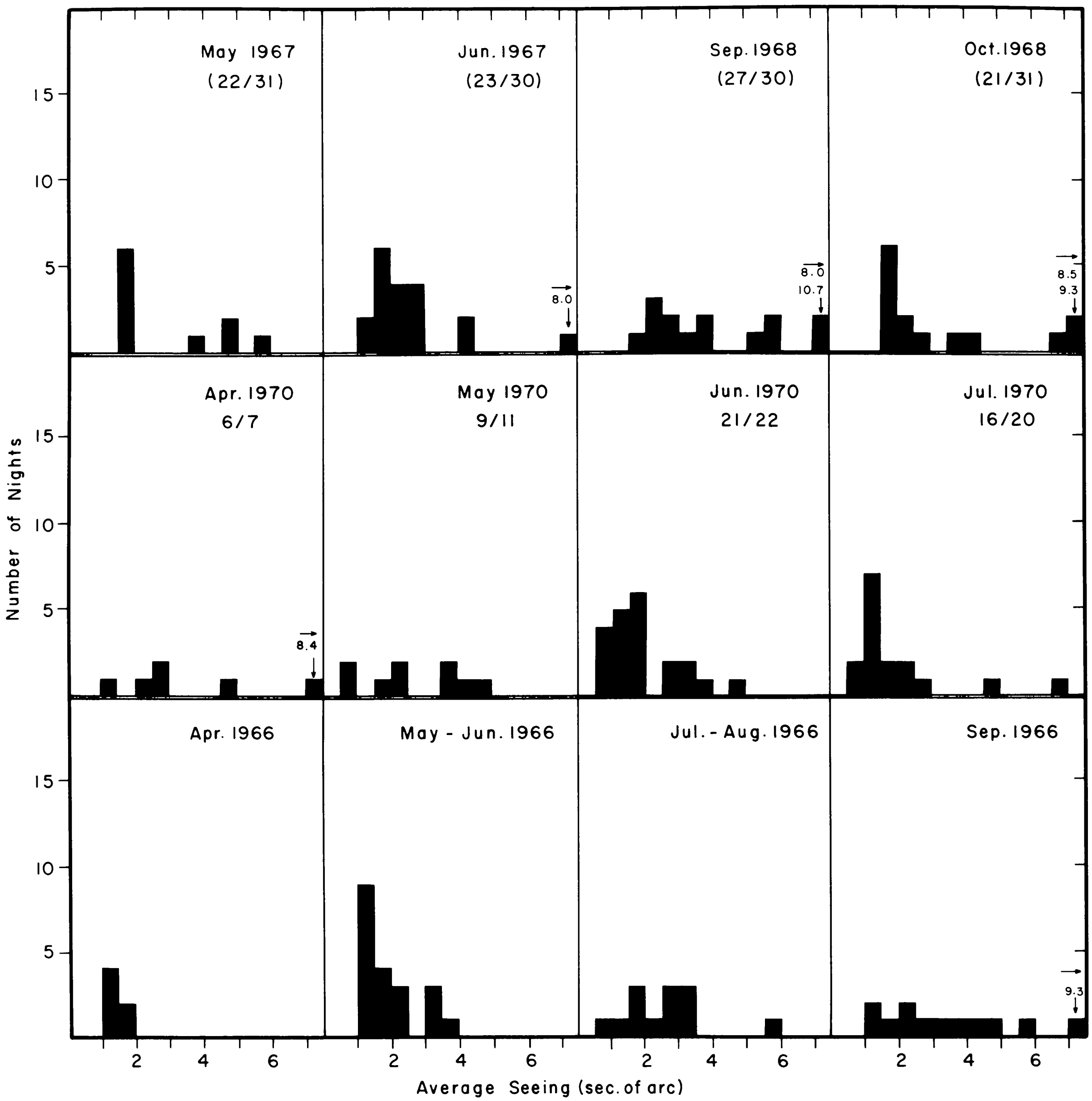

FIG. 6 — Frequency distributions of average nightly seeing observed at: Flagstaff (top row), San Pedro Mártir (middle row), and Mount McKinlay (bottom row). Ordinate, abscissa, and notation as in Figure 5.

The telescope was mounted on a rock-loaded wooden scaffold attached to the concrete pier of the Polaris seeing telescope installed by the French astronomers. The objective of the telescope was at the same height above the ground as that of the French telescope, or about twelve feet. The observations were made by Srs. Manuel Orona and Juan Luna of the staff of the Mexican National Observatory. Since the primary purpose of this program was to compare the California and French seeing scales, five to ten observations were usually made each night, generally between 20:00 and 23:00 PST, although on some nights observations were continued until about 02:30 PST. All of the Polaris trail films were processed and measured by the writer. The resulting seeing histograms are shown in the middle row of Figure 6; the notation is the same as in Figures 1–5.

Weather observations were made simultaneously with the seeing measurements. A summary of these observations is given in Tables V and VI, even though the observations do not cover the entire nights, since to date little information is available concerning conditions at this site. Table V lists the observations of temperature, humidity, cloud cover, and wind velocity, while Table VI gives the frequency of observed wind direction and the relationship between the nightly average seeing and the average wind direction. Since the observations

TABLE V

NIGHTTIME WEATHER AND OBSERVING CONDITIONS AT SAN PEDRO MÁRTIR

Date 1970	No. of Nights*	Temperature, °F Highest	Lowest	Average	Relative Humidity, % Highest	Lowest	Average	No. of Nights* With Cloud Cover 0%	≤60%	≤80%	No. of Nights* With Wind Velocity Consistently: $\geq 25\frac{mi}{hr}$	$\geq 30\frac{mi}{hr}$
Apr	6	39	12	26.6	68	10	40.1	5	6	6	1	1
May	16†	51	35	41.5	84	13	40.5	13	16	16	2	2
Jun	21	66	43	52.8	73	4	30.0	14	21	21	2	1
Jul	20	59	48	53.3	97	48	73.9	9	20	20	0	0

*When weather readings were taken.

†Differs from number in Figure 6 due to camera trouble on several nights.

TABLE VI

DEPENDENCE OF AVERAGE NIGHTLY SEEING ON WIND DIRECTION AT SAN PEDRO MÁRTIR

Average Direction for Night	No. of Nights	Average Seeing for Night ≤1″0	1″1 to 2″0	2″1 to 3″0	3″1 to 4″0	4″1 to 5″0	<5″0
N	4	1	0	1	1	0	1
NE	13	1	5	3	1	2	1
E	6	2	2	2	0	0	0
SE	5	2	2	1	0	0	0
S	6	0	5	1	0	0	0
SW	10	0	4	1	2	3	0
W	5	1	3	0	1	0	0
NW	3	1	1	1	0	0	0

cover only parts of the nights, it is not possible to derive the average change in temperature during the night, nor the number of dark hours with different amounts of cloud cover. Note that the number of nights on which weather observations were made (the second column of Table V) is usually less than the number of nights with an observer present on the mountain, as indicated in Figure 6, since weather observations were not always obtained on nights when observations of Polaris were impossible due to clouds.

Measurements of the night sky brightness at San Pedro Mártir were obtained by the writer on two nights, 26 April and 27 April 1970 UT, using the same instrument that was employed for the sky brightness measures given in Table IX of Walker (1970). The results of these observations are shown in Table VII.

E. *Mount McKinlay, Australia*

Mount McKinlay ($\lambda = 139°06'$ E, $\phi = 30°31'$ S, altitude = 3442 feet) is a peak in the North Flinders range that was investigated during the course of the University of California Southern Hemisphere Site Survey, conducted by Dr. A. E. Whitford. Observations were made at this site for a period of about two years. However, star-trail observations of σ Oct were only obtained during the last five months of that interval, from 24 April 1966 through 26 September 1966. Generally, four observations were obtained each night, at about 20:00, 23:00, 02:00, and 05:00, local time. The films were processed by Mr. E. Harlan at the Lick Observatory, and the seeing measurements were made by the writer. The seeing histograms are reproduced in the bottom row of Figure 6.

TABLE VII

OBSERVATIONS OF NIGHT SKY BRIGHTNESS AT SAN PEDRO MÁRTIR

Zenith Distance Degrees	Direction	Sky Brightness Magnitude/Square Second of Arc: 1970 Apr 25/26* V	B	1970 Apr 26/27† V	B
10	N	21.83	22.88	21.87	22.88
13	N	---	---	21.78	22.82
30	N	21.83	22.88	---	---
31	N	---	---	21.73	22.77
32	N	---	---	21.78	22.77
45	N	21.70	22.77	21.60	22.73
60	N	21.42	22.55	21.45	22.52
70	N	21.26	22.44	21.23	22.37
80	N	21.14	22.44	21.07	22.30
85	N	---	---	21.20	22.48

*Between 21:15 and 22:38, PST.

†Between 22:55 and 23:08, PST.

TABLE VIII

NUMBER OF NIGHTS PER YEAR WITH INDICATED AVERAGE SEEING

	Tololo				Kitt Peak				San Pedro Mártir				Flagstaff				McKinlay			
Year	1*	2*	3*	4*	1*	2*	3*	4*	1*	2*	3*	4*	1*	2*	3*	4*	1*	2*	3*	4*
1966	--	--	--	--	--	--	--	--	--	--	--	--	1	2	3	14	1	16	10	50
1967	--	--	--	--	--	--	--	--	--	--	--	--	0	2	13	38	--	--	--	--
1968	23	25	13	76	13	18	11	65	--	--	--	--	0	0	7	28	--	--	--	--
1969	58	95	53	271	13	33	14	92	--	--	--	--	--	--	--	--	--	--	--	--
1970	40	43	47	162	11	25	16	96	8	13	9	52	--	--	--	--	--	--	--	--

*1. Seeing $\leq 1''.0$.

*2. Seeing $1''.1$ to $1''.5$.

*3. Seeing $1''.6$ to $2''.0$.

*4. Total number of nights with seeing observations.

III. Discussion

The seeing observations in Figures 1–6 are on the same system as those given in Walker (1970), and represent the visual angular diameter that the star image would have had if viewed on the slit of the coudé spectrograph of the 120-inch reflector. As in Walker (1970), the observations have not been reduced to the zenith, for the reasons discussed therein. Furthermore, no corrections have been applied for the differences in the altitudes of the pole stars at the different sites. Since the total range in the altitude of the pole stars for all of the locations discussed here and in Walker (1970) is only from about 37° to 30°, this correction should not be very large, amounting to a factor of $\leqq 1.1$ if we suppose that the image size varies as $(\sec z)^{1/2}$, or $\leqq 1.2$ if it varies as $\sec z$.

Seeing conditions at Cerro Tololo, Kitt Peak, San Pedro Mártir, Flagstaff, and Mount McKinlay are also compared in Table VIII, which gives for each year the total number of observed nights when the average seeing was $\leqq 1''.0$, $1''.1$ to $1''.5$, and $1''.6$ to $2''.0$, as was given earlier for Junipero Serra Peak and Piper Mountain (Walker 1970). In Table IX, all of the sites so far investigated are intercompared, the sites being listed in order of decreasing seeing quality as indicated by the data in the table. This table shows the best seeing observed at each site and the percentage of observed nights when the average seeing fell within the limits given above. Since the observations at San Pedro Mártir, Piper Mountain, Mount McKinlay and Flagstaff cover only parts of years, the comparison of these sites given in Table IX may be affected to some extent by the

TABLE IX

COMPARISON OF SEEING AT INVESTIGATED SITES

Location*	Best Seeing Observed	Percentage of Observed Nights With Average Seeing as Indicated ≤1″.0	1″.1 to 1″.5	1″.6 to 2″.0	>2″.0	Total No. of Nights Observed
Junipero Serra†	0″.5	26	38	13	23	558
Tololo	0″.70	24	32	22	22	509
Kitt Peak	0″.75	15	30	16	39	253
San Pedro Mártir	0″.75	15	25	17	42	52
Piper Mountain†	0″.75	9	30	20	42	164
Mt. McKinlay	0″.75	2	32	20	46	50
Flagstaff	1″.0	1	5	29	65	80

*In order of decreasing quality of seeing.

†Data from Walker (1970).

seasonal variation in the quality of the seeing. In order to minimize this source of error, Table X was prepared summarizing those observations at Kitt Peak and/or Cerro Tololo obtained during the same or corresponding seasons of the year as those at the sites mentioned above.

Comparing the seeing histograms in Figures 1–6 and in Walker (1970) together with the data in Tables IX and X, it is immediately evident that the seeing conditions at Cerro Tololo were very similar to those at Junipero Serra Peak, and that both of these sites were appreciably better than any of the others. The figures show that the improvement in seeing during the summer and fall months observed at Junipero Serra Peak also occurs at Cerro Tololo. During those months, the seeing at both Cerro Tololo and Junipero Serra Peak was concentrated between 0″.5 and 2″.0, with a slightly better concentration toward small image diameters at Junipero Serra Peak. The best seeing observed at Cerro Tololo was 0″.70. As discussed in Walker (1970), the best seeing observed on Junipero Serra Peak was somewhat better than this, and has been assumed to be about 0″.5; precise determination is not possible since the calibration of the seeing telescopes extends only to 0″.75 in the direction of good seeing.

TABLE X

SEEING AT KITT PEAK AND TOLOLO DURING THE SAME OR COMPARABLE INTERVALS AS THE OBSERVATIONS AT SAN PEDRO MÁRTIR, PIPER MOUNTAIN, MOUNT MCKINLAY, AND FLAGSTAFF.

Location	Percentage of Observed Nights With Average Seeing as Indicated: $\leq 1''.0$	$1''.1$ to $1''.5$	$1''.6$ to $2''.0$	$>2''.0$	Total No. of Nights Observed
Kitt Peak*	10	29	8	52	48
Kitt Peak†	14	33	7	46	137
Tololo§	13	26	27	35	158
Kitt Peak**	11	26	15	48	85
Kitt Peak††	16	33	18	33	142

*April - July 1970. Observed during the same time interval as the measures at San Pedro Mártir.

†March - October, 1969 and 1970. Same season of the year as the observations at Piper Mountain.

§May - September, 1969, plus May - August, 1970. Same months of the year as the observations at Mount McKinlay.

**November, 1968 - March, 1969, plus November, 1969 - March, 1970. Season of the year corresponding to the interval of the observations at Mount McKinlay.

††June, September, October, December, 1968; January, May, June, September, October, December, 1969; January, May, June, September, October, 1970. Same months of the year as the observations at Flagstaff.

As discussed in section II, the wind direction at Cerro Tololo is nearly always from the north. Since the general air circulation pattern should give a prevailing wind from the southwest in this region, it appears that the wind at Cerro Tololo may be a local phenomenon, perhaps related to the presence of the great barrier of the Andes just to the east. Thus, it seems possible that Cerro Tololo may be slightly too far inland and/or too close to the Andes to receive a completely undisturbed airflow in off the ocean. It would be of considerable interest to obtain simultaneous measurements of the seeing at Cerro Tololo and on another peak closer to the shoreline in Chile in order to investigate this point. In this connection, it should be noted that the frequency distribution of the seeing at Cerro Tololo does not vary markedly with wind direction. As at Junipero Serra Peak, seeing observations were obtained unless the wind velocity exceeded about 50 mi/hr, and a slight correlation between seeing quality and wind velocity is observed. At Cerro Tololo, the average of all of the individual measures of seeing, during the two-year observing period, increases more or less linearly from $1''.4$ at 0 mi/hr to $2''.2$ at 30 mi/hr.

Comparing the percentage of dark hours that are photometric at Cerro Tololo and Junipero Serra Peak, we find that during the summer months, about 75 percent of the dark hours were photometric at both sites. However, during the winter about 35 percent of the dark hours at Cerro Tololo were photometric, while at Junipero Serra Peak only about 25 percent were photometric.

The average change in temperature during the night was also very similar at the two sites, averaging about three degrees Fahrenheit at both Cerro Tololo and Junipero Serra Peak. This reflects the fact that at Cerro Tololo, as at Junipero Serra Peak and Mount Hamilton (Walker 1970), the temperature tends to remain constant during the night, presumably due to the stabilizing influence of the nearby ocean.

While the seeing and weather observations for the same season do not differ greatly between the two years covered by the observing program at Cerro Tololo, the possibility of longer-range changes cannot be ruled out. During the last several years the north and central regions of Chile have been undergoing a prolonged drought. Thus, seeing and weather observations obtained during this period could differ somewhat from those obtained in earlier years.

As indicated above, the seeing at Kitt Peak was appreciably poorer than at Junipero Serra Peak and Cerro Tololo. The quality of the seeing varied with the season, as at Junipero Serra Peak and Cerro Tololo, although that change is not as well defined owing to the small numbers of observations during many of the months. The seeing at Kitt Peak was much less stable during the night than at Junipero Serra Peak or Cerro Tololo. At the latter two sites there was a strong tendency for the seeing to remain about the same all night, while at Kitt Peak large changes were frequently observed during the night. It might be expected that Kitt Peak would be more affected by local seeing than the other two sites, since the mountain top is fairly large, with interior areas in which cold air can collect. However, if this is the case, we would expect the poorest or most variable seeing to occur when the wind was blowing from the north or northeast, across the top of the mountain to the site of the seeing telescope; such a correlation was not observed.

At Kitt Peak, the temperature dropped continuously during the night as it did at Piper Mountain (Walker 1970), rather than being constant during the night as at Mount Hamilton, Junipero Serra Peak, and Cerro Tololo. This behavior is reflected in the size of the values of the average temperature change during the night given in Table IV. These changes are of the same size as those observed at Piper Mountain, and are significantly larger than those at the coastal sites.

A good comparison between San Pedro Mártir and Kitt Peak is possible since observations were obtained during the same time interval on both sites, and since the geographical separation of the two sites is only about 235 miles. Tables IX and X show that during the period of the observations, the seeing was quite similar at the two sites, being perhaps slightly better at San Pedro Mártir. This similarity is further brought out in Table XI, which gives the average nightly seeing for each month at each site.

Table VI indicates that during the period of observations, the most frequent wind directions at San Pedro Mártir were northeast and southeast, while the least frequent were north, northwest, and west. Although the data in Table VI are too few to permit definitive conclusions, they indicate that the seeing tended to be poorest when the wind was from the north, northeast, and southwest. As discussed in section II D,

TABLE XI

AVERAGE NIGHTLY SEEING AT SAN PEDRO MÁRTIR AND KITT PEAK

Date 1970	Average Nightly Seeing Seconds of Arc San Pedro Mártir	Kitt Peak
Apr	3.6	3.0
May	2.7	3.3*
Jun	1.9	2.3
Jul	2.0	1.8

*2″6 omitting one night with average seeing = 11″7 the observatory site is located on one of the peaks surrounding a high mountain basin. Thus, there is the possibility that when the wind is from the west or southwest it might pick up the cold air that drains into this basin during the night and carry it up over the observatory site. However, careful analysis of the observing records indicates that the poorer seeing associated with a southwest wind most probably results from the approach or passage of a weak storm front, as indicated by clouds on the observed night or a completely cloudy sky on the night following. Five such nights were observed, the average seeing on these nights being 5″0, 4″6, 4″4, 3″6, and 2″8. If we eliminate these nights, the data in Table VI indicate that in the absence of storm fronts, the poorest seeing tended to occur when the wind was from the north and northeast, and the best seeing when the wind was from the east and southeast. These directions correspond to those in which the distance traveled by the airflow over land is a maximum and a minimum, respectively. This result suggests that the seeing at San Pedro Mártir resembles that at Kitt Peak rather than that at the coastal sites in California and Chile because although the site is near the ocean, the distance traveled by the airflow over land before reaching the site is so great that the laminar flow set up over the ocean is destroyed.

Comparing the measures in Table VII with those given by Walker (1970), we find that the sky brightness at San Pedro Mártir was almost the same as that observed at Mount Palomar, or about 0^m1 to 0^m2 brighter than at Junipero Serra Peak, dispite the great distance of San Pedro Mártir from sources of light. Perhaps the explanation is the same as discussed by Walker (1970) for the brightness of the night sky at Piper and Hunter Mountains. That is, that the brighter sky is due to the amount of starlight reflected from the earth's surface in the general region of the site. The terrain north of San Pedro Mártir, like that of the trans-Sierra region of California, is arid and has a relatively high albedo. The lights of Mexicali and Calexico are readily visible as a glow on the northern horizon at San Pedro Mártir, but are not bright enough to affect the measures at the largest observed zenith distance.

Seeing conditions at Piper Mountain were also quite similar to those at Kitt Peak, as shown in Tables IX and X. This comparison is somewhat less satisfactory than in the case of San Pedro Mártir, since the observations at the two sites were made during different years.

Comparing the observations at Mount McKinlay with those during the corresponding season at Kitt Peak, we find that the percentage of nights with seeing ≦ 2″0 was about the same, but that the percentage of nights with seeing ≦ 1″0 was less, at Mount McKinlay than at Kitt Peak. The altitude of Mount McKinlay is, of course, much less than that of the other inland sites investigated, and this fact may well explain the deficiency of nights with seeing ≦ 1″0.

At Flagstaff the seeing conditions were consistently poorer than at Kitt Peak. This is shown in Figures 3 and 6 which compare observations at the two sites in September and October 1968 and in Tables IX and X. The lower quality of the seeing conditions at Flagstaff compared to those at the other inland or "continental" sites most probably results from the fact that the U. S. Naval Observatory, like the other observatories in the Flagstaff area, is situated on a very extensive plateau, rather than on an isolated peak. It seems likely that much better seeing conditions might be encountered in the Flagstaff area by observing from the top of one of the nearby peaks that rise to considerable heights above the plateau, such as Kendrick Peak, 10,418 feet, or Humphreys Peak, 12,633 feet.

The results for San Pedro Mártir, Piper Mountain, Mount McKinlay, and Flagstaff are clearly of lower weight than those for Junipero Serra Peak, Cerro Tololo, and Kitt Peak since observations were obtained over much shorter periods of time. Consequently, not too much significance can be attached to the small differences between these sites shown in Tables IX and X. In general, we may only conclude that *during those intervals covered by the observations*, seeing conditions appear to have been similar at Kitt Peak, San Pedro Mártir, and Piper Mountain, roughly similar at Mount McKinlay though with fewer nights of seeing ≦ 1″0, and appreciably poorer at Flagstaff.

Table IX shows that the best seeing observed varies much less from site to site than does the form of the frequency function of the seeing.

Thus, the difference between sites is not so much one of the quality of the very best seeing that occurs at the site as it is of the frequency with which nights of good seeing occur.

IV. Conclusions

While it is clear that much more observational work is required before definitive statements can be made, the results of this study, together with those reported earlier (Walker 1970), appear to strengthen the conclusion that, at least in latitudes between 30° and 40° N and S, the best seeing occurs at sites near a coast having a cold ocean current offshore that lowers the height of the inversion layer, and where the laminar airflow set up over the ocean still persists. Further, the similarity of the results at the inland sites suggests that in these same latitudes a fairly typical seeing distribution may exist at "good" inland or "continental" sites, that is, sites on isolated peaks in arid regions having altitudes greater than about 7000 feet. If this is the case, then by careful choice of a site, one might expect to obtain seeing conditions more or less similar to those found at Kitt Peak in the interior arid regions of any land mass in the above range of latitude.

If the best astronomical seeing occurs at locations where there is laminar airflow over the site from a nearby cold ocean then, if we neglect other problems such as accessibility, and meteorological factors such as cloud cover, temperature, precipitation and wind, it is a relatively simple matter to identify those regions of the earth where the best sites will be found. In general there are two types of localities at which the above condition can occur: (1) sites on isolated mountain peaks near the coast of a continent (or large island) having a cold ocean current offshore, and (2) isolated mountain peaks on (small) islands situated in cold oceans.

Examination of a world atlas (e.g., Grosvenor and Darley 1963) shows that the continental coasts having the most strongly developed cold ocean currents offshore are those with which we are already familiar: the coasts of California and Baja California in the Northern Hemisphere, and the coasts of Chile and Peru in the Southern Hemisphere. We would therefore expect good sites to be found on isolated peaks along those portions of these coasts where the direction of the prevailing wind is in off the ocean. Between latitudes 50° N and S, the only other continental coasts with similar conditions are: (1) the coast of Argentina, where the Falkland current runs northward to about the latitude of Cabo San Antonio ($\phi = 37°$ S), (2) the west coast of South Africa and South-West Africa, where the Benguela current sets northward along the coast from the Cape of Good Hope to about latitude 20° S, and possibly (3) the west coast of Australia. The Argentine coast is ruled out by the lack of high mountains near the shoreline. The west coast of Australia also lacks high mountains and, in addition, the ocean current along the coast is neither very strong nor very cold. However, a number of fairly high mountains do occur near the coastline in South Africa and South-West Africa, and it appears possible that some of these might be good sites. Unfortunately, the latitude of these portions of the African coast is such that the prevailing wind appears to be from the south or east, rather than directly in from the ocean, so that it is difficult to judge how good the seeing may be on these peaks without actual tests.

The number of islands having high mountain peaks that are situated in cold oceans between latitudes 50° N and S is very limited. In the Northern Hemisphere, only one, Guadalupe Island ($\lambda = 118°15'$ W, $\phi = 29°00'$ N, altitude of peak = 4257 feet), appears at all suitable. This island, situated some 150 miles west of the west coast of Baja California, is within the cold California ocean current. The altitude of the peak is rather low, but is comparable with the altitude of Mount Hamilton (4207 feet), and is probably high enough to be well above the height of the inversion layer. In the Southern Hemisphere, possible islands include: Alexander Selkirk, or Más Afuera, Island ($\lambda = 80°45'$ W, $\phi = 33°45'$ S, altitude of peak = 5413 feet) in the Juan Fernández group, some 550 miles west of the coast of Chile; Tristan da Cunha Island ($\lambda = 12°17'$ W, $\phi = 37°10'$ S, altitude of peak = 6760 feet) in the South Atlantic Ocean; and Kerguélen Island ($\lambda = 70°$ E, $\phi =$ 49° S, altitude of peak = 6430 feet) in the Indian Ocean. Kerguélen Island is so far south that it is probably ruled out by unfavorable weather conditions, while Tristan da Cunha is, unfortunately, the site of active volcanism.

Alexander Selkirk Island is perhaps somewhat more favorable. The island is located just within the western edge of the cold Peru current that flows along the coast of Chile. The geography of the island is very striking. In the east-west direction, the island is only four miles wide, while the mile-high peak, Cerro de los Inocentes, is located at a horizontal distance of about ¾ mile from the southwest coast of the island. Since the prevailing wind is from the southwest, the site is effectively a natural tower in the ocean. The ocean in this region is generally covered with the same cloud layer observed along the coast of Chile, due to the cold ocean current, and the great uncertainty regarding this site is what fraction of the time the high peak projects above this layer. It is clear from an examination of the vegetation covering El Yunque, the 3002-foot peak on Robinson Crusoe, or Más a Tierra Island ($\lambda = 78°55'$ W, $\phi = 33°40'$ S), that this peak is usually below the top of the cloud layer. How much higher the cloud layer extends is uncertain. On the one occasion when the writer was able to examine Alexander Selkirk Island from the air, the peak was not visible, being within the cloud layer, whose base at that time was at about 3000 feet and whose top was at about 5500 feet.

The most basic requirement for good seeing is probably that of having laminar airflow over the site. The effect of the cold ocean may be simply to decrease the altitude to which one must ascend in order to be above the temperature inversion, and in the region where the airflow is undisturbed. Thus, mountain peaks on (small) islands in warm oceans may be good sites, provided that the peaks are sufficiently high to place the observer above the inversion layer, and provided that the meteorological or physiological conditions do not become too severe at the high altitude required to achieve this condition. Some evidence already exists that this is indeed the case. In 1856, Smyth (1857, 1858) made observations of double stars from stations at altitudes of 8843 feet and 10,710 feet on Pico de Teide on Tenerife ($\lambda = 16°38'$ W, $\phi = 28°16'$ N, altitude of peak = 12,198 feet) during July, August, and September. Using a 7½-inch aperture refractor at the 10,710-foot site, he found that the close components of γ Andromedae were consistently well resolved. In addition, observations with a double-beam seeing telescope (Jefferies and Sinton 1968), at the site of the new Mauna Kea Observatory ($\lambda = 155°28'.3$ W, $\phi = 19°49'.6$ N, altitude of peak = 13,600 feet) on the island of Hawaii, have indicated the seeing to be excellent.

A considerable number of islands having high mountain peaks and located in warm oceans exist. In order to prepare a complete list of possible sites of this type, we would need to know the height of the inversion layer at each island, in order to determine whether the peak rises high enough above that level to be in the region of undisturbed airflow. The height of the inversion will, in turn, depend upon the temperature of the surrounding ocean. Some idea of these heights is given by the fact that the height of the inversion layer is about 4000 to 5000 feet at Tenerife (Smyth 1858) and about 6000 to 8000 feet in the Hawaiian Islands (Jefferies and Sinton 1968). Using these values as a guide, it would appear that, in addition to Mauna Kea, the sites listed in Table XII might have good seeing conditions. This list excludes islands whose high peaks are extremely active volcanos, but includes a few whose peaks show slight volcanic activity as well as islands having active volcanos on them (as does the island of Hawaii). The first two islands listed in Table XII are located in the land-locked Mediterranean Sea. Whether or not conditions at such sites are equivalent to those on islands in the open ocean is not clear, since we do not know how far the air must travel over an ocean before laminar flow is established.

Finally, it is to be noted that the altitudes of all of the inland or "continental" sites investigated so far have ranged about 7000 to 9000 feet in altitude. No information is presently available concerning the improvement in seeing with altitude in such regions, although scintillation studies suggest that the height of the turbulent layer may be greater than 20,000 feet (Keller et al. 1956). Thus, observations at higher inland sites should be made in order to determine whether a significant improvement in seeing will result if observations are made from the tops of the highest available peaks.

It is a pleasure to thank all of the observers who participated in this program. I am especially indebted to Drs. V. M. Blanco, A. A. Hoag, G. E. Kron, and A. Poveda, Directors of the Cerro Tololo Inter-American Observatory; Stellar Division, Kitt Peak National Observatory; U. S. Naval Observatory, Flagstaff Station; and Mexican National Observatory, San Pedro Mártir Station, respectively, for arranging for the seeing observations to be made at their institutions. Permission from Dr. A. E. Whitford to include the results of the observations at Mount McKinlay is likewise gratefully acknowledged. Special thanks are due to Dr. Richard A. Gaard of Modesto, California, for transporting the scientific instruments, and the writer, from San Jose, California, to the Meling Ranch at the foot of the Sierra San Pedro Mártir, Baja California, in his private airplane.

TABLE XII

SOME POSSIBLE ISLAND SITES IN WARM OCEANS

Island	Group	Approximate Longitude Degrees	Approximate Latitude Degrees	Altitude of Peak Feet
Corsica	---	9.0E	42.2N	8891
Crete	---	24.7E	35.3N	8058
Madeira*	Madeira	17.0W	32.7N	6106
La Palma*†	Canary	17.9W	28.8N	7949
Tenerife*§	Canary	16.6W	28.3N	12,198
La Reunion*††	---	55.5E	21.1S	10,069
North Island*§§	New Zealand	174.1E	39.3S	8260

*Volcanic peak.

†An active volcanic region is located some 13 miles south of the high peak; the last eruptions in this district were in 1949 (Neuman van Padang, et.al. 1967).

§Eruptions of subsidiary craters on the slopes of Pico de Teide have occurred in historic times, namely Chahorra in 1798, Garachico in 1706, and Chinyero in 1909. Gas emission presently occurs near the summit of the high peak (Neuman van Padang, et.al. 1967).

††One of the lower peaks on this island, Piton de la Fournaise, is an active volcano.

§§Mount Egmont. Included here because of its location on a point that projects from the island in the direction of the prevailing wind. Occasional volcanic activity occurs.

REFERENCES

Grosvenor, M. B., and Darley, J. M. 1963, *Atlas of the World* (Washington, D. C.: National Geographic Society).

Harlan, E. A., and Walker, M. F. 1965, *Pub. A.S.P.* **77**, 246.

Jefferies, J. T., and Sinton, W. M. 1968, *Sky and Tel.* **36**, 140.

Keller, G., Protheroe, W. M., Barnhart, P. E., and Galli, J. 1956, *Perkins Obs. Reprint*, No. 39, pp. 7 and 9.

Neuman van Padang, M., Richards, A. F., Machado, F., Bravo, T., Baker, P. E., and Le Maitre, R. W. 1967, *Catalog of the Active Volcanos of the World, Part XXI, Atlantic Ocean,* (Naples: International Volcanological Association).

Smyth, C. P. 1857, *M.N.R.A.S.* **17**, 107.

—— 1858, *Teneriffe, An Astronomer's Experiment* (London: Lovell Reeve), pp. 131 and 287.

Walker, M. F. 1970, *Pub. A.S.P.* **82**, 672.