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Final Report

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"Infrared Sky Noise Study"

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Principal Investigators

J.A. Westphal

Gerry Neugebauer

Robert B. Leighton

Prepared by J.A. Westphal

Introduction

In 1969 NASA began to consider funding a large ground-based IR telescope. The geographic location is of prime importance in such a project, since IR observations are particularly sensitive to the amount and variation of water vapor in the earth's atmosphere and, in certain cases, to the presence of "sky noise". It was clear that a comparison of these parameters at various potential observatory sites was very desirable.

Early in 1970, we proposed that CIT organize and supervise a survey of several sites. We were very concerned as to how to measure the sky noise in some uniform, unbiased way since very little was really understood about its nature. Therefore, we also proposed a study of sky noise itself to be made concurrently with the preparations for the multiple site survey. This proposal was funded by NASA beginning 1 June 1970. This document is the final report of the work conducted under Grant NGR 05-002-184 which ultimately expired 31 May 1972.

Development of a Sky Noise Instrument

From the earliest days of modern 10 micron IR observations, investigators have been plagued with slow variations in the difference in flux between the two sky positions sampled by the optical modulator or "chopper". These variations, with periods longer than about one second, were labeled "sky noise", although it is now known that much of this noise was due to the modulation scheme and should be properly called "modulation noise". As IR technology improved much of the problem of sky noise disappeared, primarily by using very small focal plane displacements of "throws" and by careful attention to the design of the modulator. However, when large throws were needed, as in the case of planetary measurements, sky noise again became a serious problem.

Sky noise is most serious when an attempt is made to conduct 10μ sky surveys with large focal plane apertures, even when the most effective modulators are used. In this case the very large throughput of the system makes it extremely susceptible to small variations in sky emission. An example of this problem can be seen in Figure 1, which shows the variation in sky noise as a 10μ detector on the 62-inch f-1 telescope used for the CIT 2μ Sky Survey is moved from 11 mm outside the stellar focus to 24 mm inside that focus. If the sources of the sky noise are far from the telescope and if they have steep spatial flux gradients, then one would expect to be able to "focus" on these sources. The fact that the noise is a maximum at the stellar focus indicates that the noise sources are far away. This is a very convincing experiment, since any "modulation noise" should be independent of the focal position.

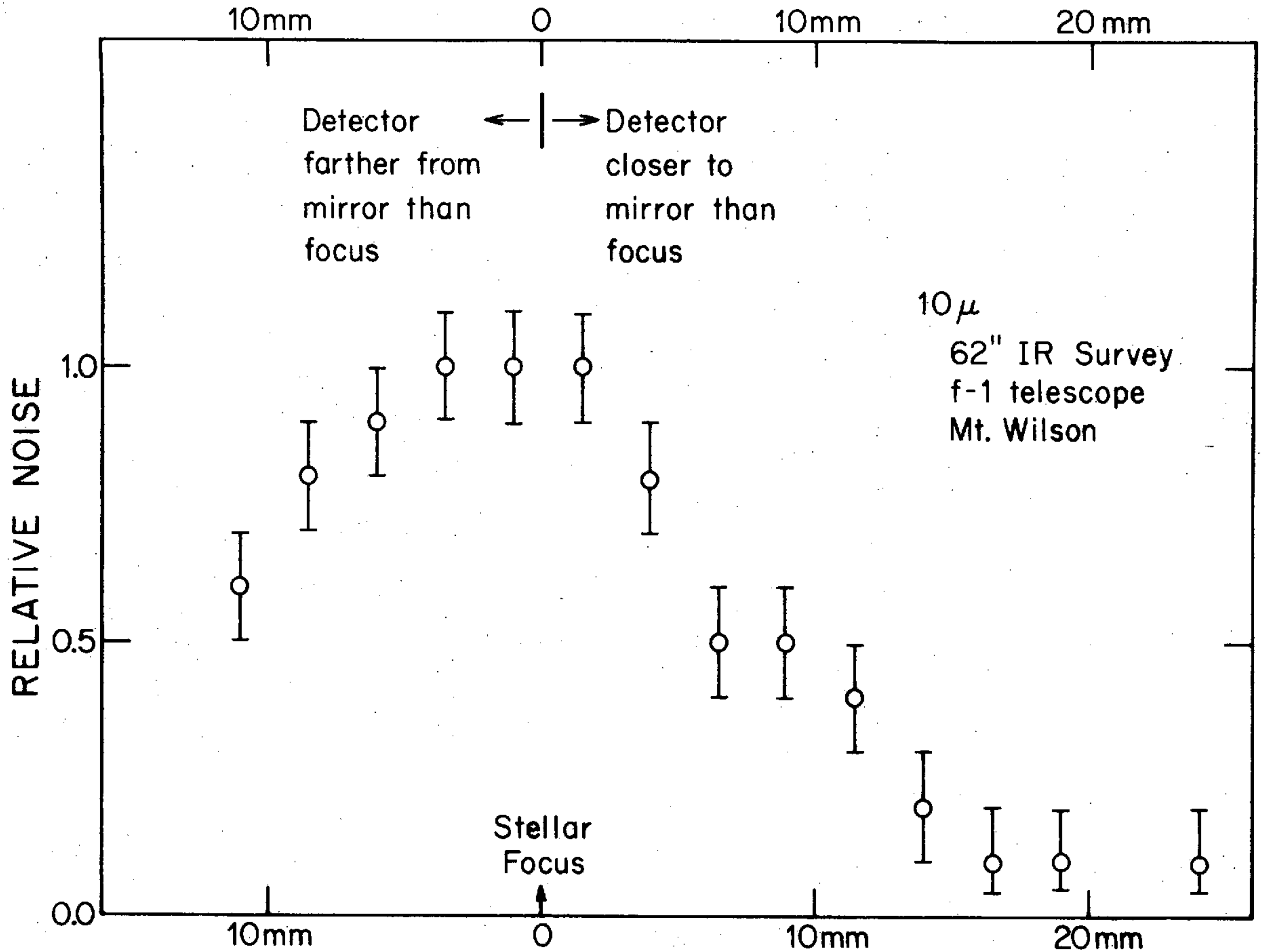
10mm
0
10mm
20mm
Detector farther from mirror than focus
Detector closer to mirror than focus
10 μ
62" IR Survey
f-1 telescope
Mt. Wilson
RELATIVE NOISE
1.0
0.5
0.0
Stellar Focus
10mm
0
10mm
20mm

FIGURE 1

At the time of our proposal, the "lore" of sky noise was summarized as follows:

"1. The sky noise seems generally to be most severe in the 8-14 atmospheric window, although it is often seen at 5μ and in the $16-25\mu$ region.

2. The noise is often, but not always, correlated with the quality of the visible "seeing": when the seeing is very bad the sky noise is usually severe, but when the seeing is quite good the sky noise may be either moderate or low. Examples of strong anti-correlation are also know.

3. Clouds, particularly high cirrus, almost always produce high noise levels. Some observers feel that the major source of sky noise is "invisible cirrus"; however, our own experience strongly suggests that other sources are also present.

4. Sudden shifts in wind direction or increase in velocity usually cause increases in sky noise; however, wind velocity is not obviously correlated.

5. Measurements of the microthermal structure of the lower 30 meters of the atmosphere indicate temperature variations large enough to produce the flux levels commonly seen in sky noise; however, the correlation between these temperature fluctuations and the sky noise, based on very limited data, is not clear.

6. Limited studies, conducted during an attempt to conduct a 10μ sky survey at Mt. Wilson, show that it is possible to "focus" the telescope on the noise sources. If one places the detector at the infinity focus of the telescope, notes the sky noise amplitude, and then moves the detector toward the mirror, the sky noise output drops drastically. Conversely, if one moves the detector away from the mirror the sky noise first increases then as one moves farther away it gradually decreases again.

7. The amplitudes of the various frequencies in the sky noise seem to vary in a roughly 1/f fashion down to very low frequencies (1 hr.). Both clouds and microthermal variations have a similar frequency spectrum. Unfortunately, this property of sky noise makes conventional signal averaging (integration) very ineffective as a technique for improving the signal-to-noise ratio of an observation. Although some clever techniques have recently been developed to alleviate this problem, it is important to find superior sites and better techniques, particularly for observations of extended objects.

8. At some sites, on occasion, the sky noise is smaller than the detector noise. In our personal experience this has been observed at Cerro Tololo where during all three nights of 10μ and 20μ observing during a 1968 run the sky noise was less than cell noise. The significance of a three-night sample is probably very low, but encouraging."

It was with this background that we started to study sky noise and to develop hardware and techniques to measure and compare sky noise at several sites.

It was extremely important that we devise a device that would maximize its output for sky noise and minimize its output for modulation, detector and other noise sources. Experience, particularly with the 62" f-1 sky survey telescope, had indicated that an ideal modulator would be one that rocked or "wobbled" the primary mirror. However, the 62" required a fixed tripod above the wobbling primary to support the detector dewar, and we were concerned that this tripod/dewar assembly might be a source of excess noise. We felt that an off-axis paraboloid would be an ideal telescope since nothing would be in the optical path except the primary mirror itself. We were able to obtain a 16-inch f-4 metal off-axis paraboloid with about a 1 mm blue circle for a reasonable cost and a prototype instrument was built.

This telescope consisted of a 2 mm liquid helium cooled Ge:Hg detector with a 8-14μ cooled bandpass filter and a f-4 cold radiation baffle looking down at the 16-inch off-axis primary which was wobbled at 15 hz. The 15 hz Ac detector output signal was amplified, synchronously detected and smoothed with a 1-second time constant. By displaying this output on a strip chart recorder, we could then study the variations in the difference in flux between two 2mm diameter spots in the focal plane of the telescope. Figure 2 shows such a recording for several hours looking at an elevation angle of about 45° in a northerly direction. The distance between the sampled spots in the focal plane was about 6 mm. Large variations in the sky noise on this record are representative of the changes seen at Palomar when the sky is visually clear. Of particular interest are the long period variations seen around 0400 and the sharp increase and change in character of the noise just after midnight.

If the output of the telescope is rectified and averaged for about 400 seconds, it is possible to record only the envelope of the variations and produce much more compact records for long periods of time. This was done for the routine survey instruments and Figure 3 shows some results from two of these instruments. The small differences are doubtless due to the telescopes pointing in slightly different direction. At this point it seemed important to compare the output of the sky noise telescope with the output of a more conventional IR telescope with a modern modulation system and a state-of-the-art detector.

With the assistance of Dr. Frank Low, we were able to arrange to set up the telescope about 50 feet west of the 28-inch 10μ sky survey telescope on Mt. Lemmon, Arizona. After a period of several clear days, during which both systems were working properly,

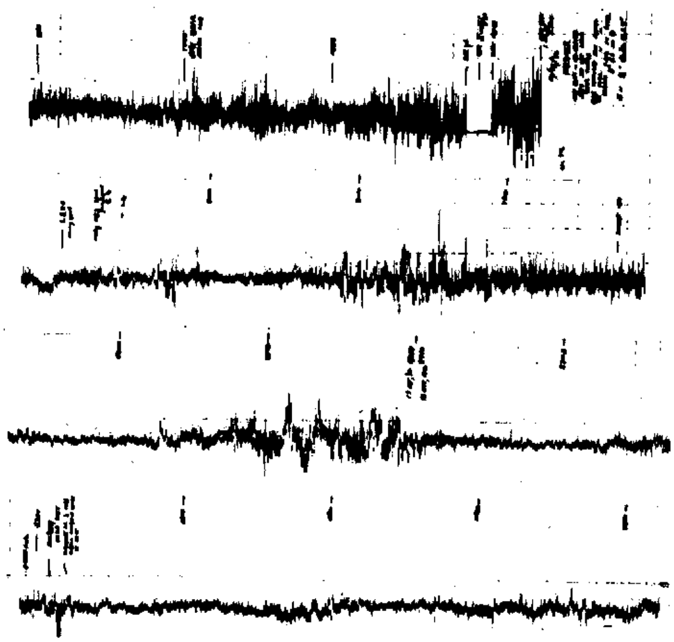

FIGURE 2

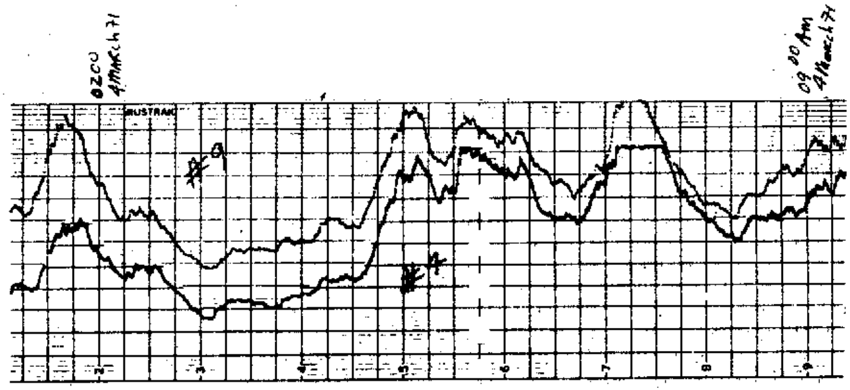

FIGURE 3

we compared the outputs and found a very good correlation, indicating that both systems were measuring real variations in sky emission. As would be expected, the sky noise telescope was somewhat more sensitive for measuring sky noise since the 10μ survey system was designed to minimize its sensitivity to sky brightness fluctuations.

At this point we felt that we had developed a viable system, sensitive to sky noise and capable of operating almost unattended at several possible IR sites.

A more complete description of these instruments and the details of the sky noise survey will be presented in the final report of the grant which supported that activity. The rest of this report will discuss our investigation of the nature of sky noise.

The Nature of Sky Emission and the Fluctuations

The basic source of sky noise is the flux emitted by the various solid and gaseous components of the atmosphere. If this flux was precisely constant over the time required to make a measurement of some astronomical source then it could be simply subtracted from the measured value of object plus sky and would not cause a great difficulty in most cases.

However, even if the long time mean value of the sky emission was constant there would still be variations due to "photon noise", that is, noise due to the random arrival of individual photons. Only very recently have other noise sources in some detectors been suppressed to the point that they are "photon noise limited". Most of the background flux seen by IR detectors in conventional telescopes comes from the optical surfaces and support structure and only a small part from the sky. However, efforts are now underway to design IR telescopes which may be sufficiently "clean" so that the photon noise from the sky would be important. The absolute average sky flux will then be an important factor in the selection of an IR site.

It is, however, the variation spatially and temporally of the sky flux that causes the "sky noise" we have studied.

Gaseous Sources of Sky Noise

Fortunately the "permanent" constituants of the atmosphere, oxygen, nitrogen and the rare gases do not absorb or emit IR radiation in the 1-30 micron region. Only the trace molecules are significant emitters. Of these the most important, particularly at good IR observing sites, are water vapor and carbon dioxide. These gases are responsible for deep absorption bands throughout the mid-IR and define the "windows" through which observations are made.

By far the most variable in both time and space is water vapor, which may change by orders of magnitude on short time scales even at high elevation sites. Because water vapor is so important, the sky noise survey also measured, at least once a day, the amount of precipitable water at each site. The results of these measurements can be seen in the "Preliminary Report on the IR Sky Noise Survey" available from NASA or CIT.

The water vapor emits IR radiation not only in the well known deep absorption bands but also in a broad continuum far removed from the deep bands. Even if one observes far from these deep bands, substantial flux is still seen from the atmospheric water vapor. If the amount of water vapor present varies, then one sees "sky noise" due to this source. Using reasonable values for the emissivity of the water vapor and the scale of the spatial variations, it is easy to calculate that all of the sky flux variations seen at the telescope could be due to this effect. As we shall see, this is also true of a number of other sources and the surprise is that the sky noise level is generally as low as we observe.

The wings of the CO_2 absorption bands and many weak CO_2 lines are scattered through the normal IR "windows". These lines and wings act just as water vapor does if there are variations in the quantity of CO_2 moving past the telescope. However, the CO_2 concentrations, particularly at sites that have little local vegetation, are probably quite uniform so this may not be a major source of noise.

If the moving air in the optical path has local variations in temperature, then even uniform concentrations of CO_2 or water vapor give rise to sky noise since the flux emission is a strong function of temperature. Such temperature variations have been well established by microthermal studies and usually are on the order of a few degrees Celsius near the ground with "blob" sizes from a few cm up to very large sizes. Again simple calculations based on these numbers yield noise flux values large enough to explain the observations.

Aerosol Sources of Sky Noise

Aerosols are present in the air over most IR sites and can be a major source of sky emission particularly at the lower sites or near cities, mining and smelting activities, dirt roads, etc. Most aerosols are black body emitters in the 1-30μ region and usually are non-uniformly distributed. Aerosols are therefore strong sources of sky noise due both to non-uniformity and to their presence in blobs of warm and cool air moving across the optical path. Clouds are of course aerosol particles of either liquid or solid water and cause very severe sky noise problems. Any cloud visible to the eye is extremely noisy. Often preceding the visible clouds, particularly cirrus clouds, the sky noise instrument will indicate rapidly increasing noise levels suggesting presence of very thin cirrus. Simple calculations again indicate that aerosols can cause all the sky noise normally observed.

Experiments to Further Define Sky Noise

Several experiments were undertaken to further understand the detailed nature of sky noise.

1. Measurement of high speed humidity and temperature changes. In connection with the installation of the new 60-inch telescope, a survey of two sites on Palomar was conducted during 1967. Two 30-meter towers were erected and four high speed thermistor sensors were installed on each tower at 6 m, 10 m, 20 m, and 30 m. The variations in air temperature in the period range from 0.25 to 100 seconds at each station on each tower were recorded for several months. The relative humidity and windspeed/direction were also recorded. Comparison of this data with the sky noise values often indicated correlations, but it was clear that much sky noise originated higher than 30 meters. An attempt was made to measure the microthermal and humidity variations at heights up to 300 m on a tethered balloon, but it was unsuccessful due to logistic problems. Short runs of data, however, indicated that the microthermal amplitudes decreased vertically with scale height of perhaps 25 or 30 m.

2. Variation of sky noise with "stroke". In conventional IR photometry, one normally chops between two sky positions just far enough apart to allow total separation of the source

from the sky. For small objects, stars, satellites, etc., it is common to use strokes of about 5 arc sec. or 10 arc sec. depending on the size of the telescope and the quality of the seeing. However, for planets and other extended sources it is very desirable to use a stroke somewhat larger than the diameter of the source. This leads to strokes of up to 1 arc min. for planets and 30 arc min. for the moon. It seemed important to know how the sky noise varies as a function of the stroke under various conditions, since an optimum stroke might possibly exist for a given problem.

Figure 4 shows how the sky noise varied for strokes between 3 arc min. and 35 arc min. using the sky noise telescope. This data was derived by operating two identical telescopes, looking along almost the same path for several days, one with a fixed 8 arc min. stroke, the other with each of four different strokes. Data was collected for at least one day under clear conditions with each stroke value. The data were then normalized against the fixed stroke values.

The bar on the 8 arc min. point represents the reproductability of the two instruments and the bars at other stroke values show the range of observed values. The data is consistent with a linear variation of noise with stroke and extrapolates nicely to the values recorded at small strokes with conventional photometers. This means that one should use the smallest possible stroke for IR photometry.

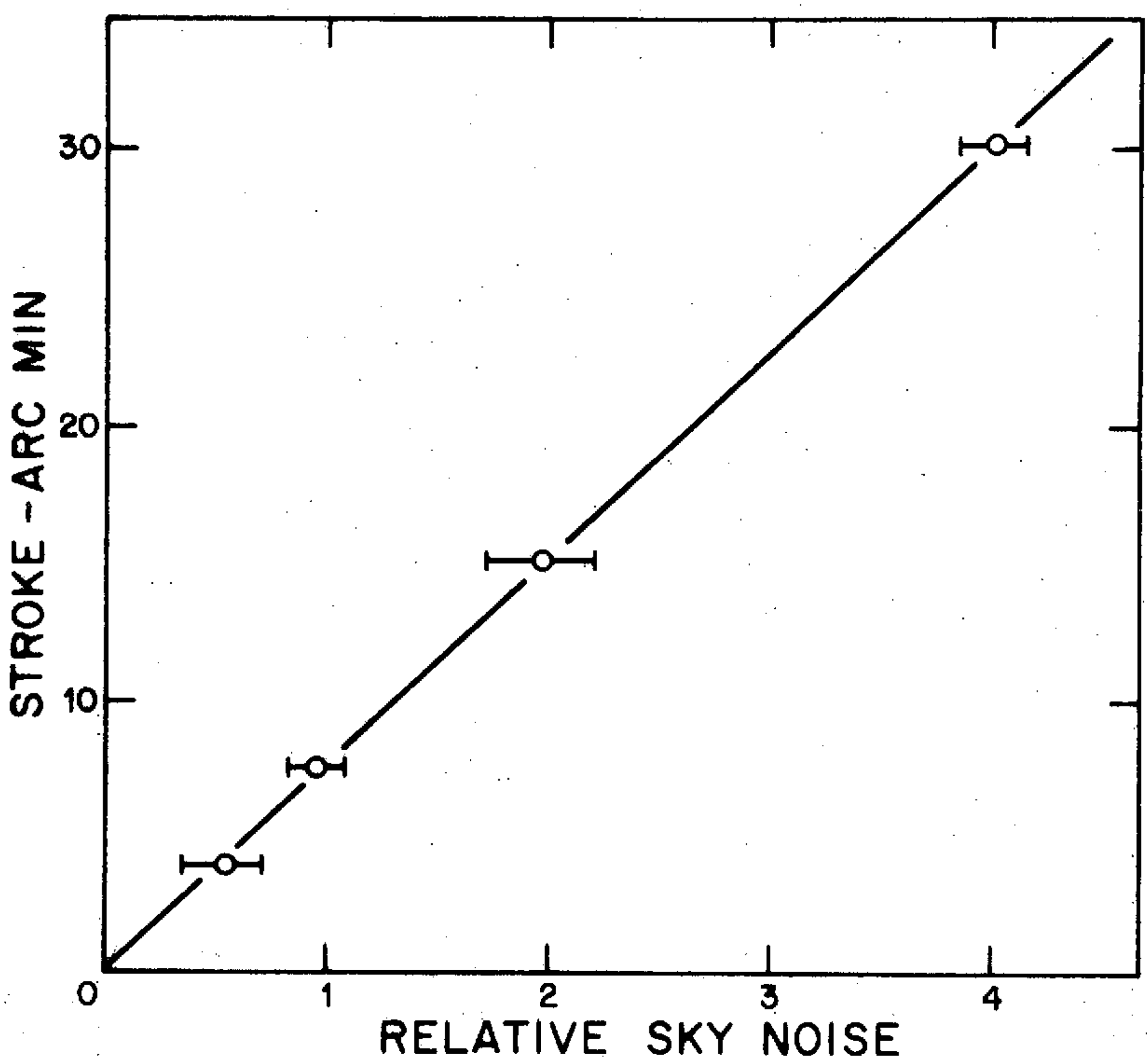

FIGURE 4

3. <u>Attempts to correlate meteorology with sky noise</u>.

As quoted earlier the sky noise "lore" suggested that local meterological conditions affect the sky noise in complex ways. To learn more about this, we conducted a series of experiments with the sky noise telescope at Palomar. For several long periods we took IR time lapse movies of the sky in the region near our measuring beam. These movies were made by exposing 16 mm Kodak High Speed IR Film 2481 through the recommended filter, one frame each 4 seconds during daylight hours. We had hoped to see very faint cirrus clouds by this technique. Unfortuantely the exacting exposure requirements were such that it was only rarely that we saw cirrus not visable to the eye. In every such case the sky noise had increased markedly before the cirrus was visable. An interesting effect was seen, however, in those cases where the cirrus was dissipating instead of forming, in these cases the sky noise was low in the clear spaces between the clouds.

We believe this means that "invisable" cirrus does exist and is commonly present when cirrus clouds are forming, but that it is absent when they are dissipating.

This photographic work also lead us to understand another serious source of sky noise. Very often in recent years the "smog" from the Los Angeles Basin blows over Palomar Mountain. When this happens, the IR movies show the advancing aerosols before they are visually obvious and explain many of the observed sudden increases in sky noise when the sky looks clear. These aerosols plus the nitrogen oxides, water vapor and carbon dioxide also contained in smog, are a major source of sky noise at Palomar. Undoubtedly the copper smelter aerosols and gases which often invade the Kitt Peak, Mt. Hopkins and Mt. Lemmon observatory sites, the volcanic polutants sometimes present at Manna Kea and the smoke from agricultural burning sometimes seen at White Mountain, California are also sources of severe sky noise.

Many hours were spent just watching the behavior of the sky noise output in attempts to find unknown correlations. Many times, particularly at night, large changes in sky noise were observed without obvious cause. Often when the sky noise became very high on moonless nights, observations at dawn found the sky covered with thin cirrus even though a careful visual search had found no clouds while it was dark. We feel that a simplified model of the sky noise telescope could become a very useful permanent observatory cloud sensor to aid all kinds of photometric observations. We are now developing such a monitor with other funds.

Summary

We believe the following conclusions are justified by the large mass of data from the Sky Noise Survey and the special experiments to understand sky noise conducted under this grant.

1. Sky noise really exists, i.e. both spatial and temporal variations in the local sky emission flux field are commonly present even at the best known IR observing sites.

2. Sky noise has approximately 1/f properties both temporally and spatially with a wide range of frequencies.

3. There are many sources of sky noise, the most common are:

   (a) blobs of hot or cold air of finite emissivity blowing across the optical path.

   (b) blobs of increased or decreased water vapor, carbon dioxide or aerosol content blowing by, even at constant temperature.

   (c) any visible clouds.

   (d) "invisible" cirrus when the cirrus cover is forming.

4. The spatial distribution of the sky noise sources are such that the observed noise values are linear function of chopping stroke, therefore the minimum stroke is the best.

5. IR sky noise measurements are a very effective way to detect cloudiness at an observatory and can be used to monitor the photometric

quality of the sky for both IR and visible photometry.

6. It is unlikely that sky noise levels can be significantly decreased by any technique except choice of site. The most desirable site would have at least these properties:

(a) high and dry (to decrease total water vapor)

(b) isolated (to decrease man made aerosols)

(c) away from both polar and tropical regions (to decrease cloud cover)

(d) barren (to decrease locally generated water vapor and carbon dioxide variations)

(e) good visual seeing (an indication that the microthermal activity is low)

Of these (e) is clearly the most important particularly for photometry of small sources where the focal plane aperture size and therefore the stroke are defined by the seeing blur circle.

7. The study of sky noise is especially frustrating, since one is trying to measure a non-stationary phenomenon.

Acknowledgment

This study would not have proceeded without the invaluable assistance of E.O. Lorenz. We also thank Dr. Frank Low for his cooperation and the mountain staff at Palomar for their support.