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6060

ATMOSPHERIC LIMITATIONS ON ELECTRONIC DISTANCE MEASURING EQUIPMENT

by

Moody C. Thompson, Jr., Harris B. Janes, and Frank E. Freethey

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
BOULDER LABORATORIES
Boulder, Colorado

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NATIONAL BUREAU OF STANDARDS REPORT

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The development of electronic distance measuring techniques during the past twenty years has resulted in radical changes in both the technical and economic aspects of surveying. The measurement of base lines which formerly required many man-days or weeks may now be made to the same precision by two men literally in a matter of minutes in many cases.

The geodesists are to be commended for their willingness to adopt these new methods and for the effective manner in which they have employed the equipment made available to them.

The physical basis for these techniques is essentially the simple expression that distance is the product of speed and time. More specifically, if we know the speed at which a radio or light signal travels through the atmosphere, and the time required for it to progress from one point to another, we can easily calculate the distance as the product of these two quantities. It follows immediately that the precision of this calculation is dependent upon the precision with which we can make these two independent determinations.

Each of these measurements involves an area of physics which is of importance to the National Bureau of Standards. The time measurement involves the sciences of electronics and time standards; the speed measurement is a problem fundamental to electromagnetic wave propagation. Consequently, our work at the Bureau has led us to detailed consideration of these problems and particularly to a study of the factors which limit the precision of such measuring techniques. Although means may later be developed to circumvent what appear to be "basic" limitations today, it is felt that some of the presently recognized factors will influence significantly the practical limits of precision for all of the systems which have been publicly described to date.

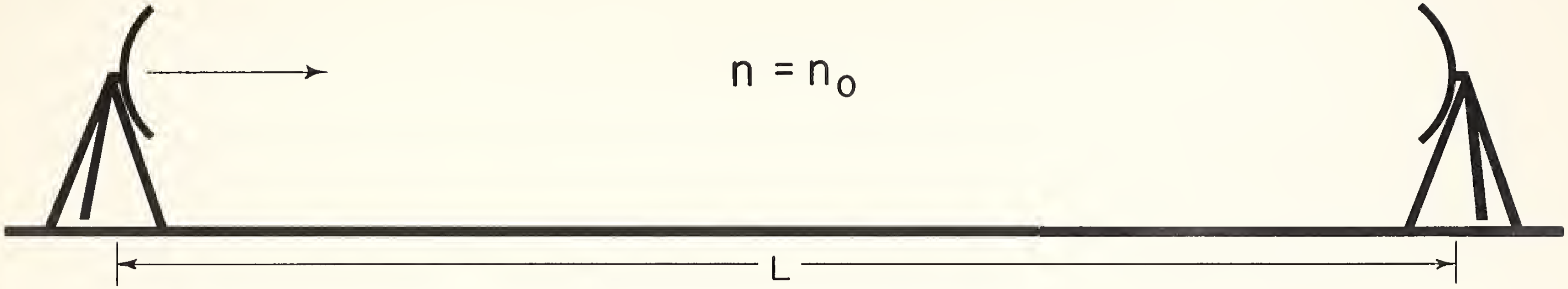
Historically, the Radio Propagation Engineering Division of the Boulder Laboratories, National Bureau of Standards, has been conducting an experimental and theoretical study of the general problem since November 1954. During this time, the work has been supported almost completely by the United States Air Force and, because of the needs of the sponsor, was directed almost exclusively at one aspect of the general problem, namely the specific question of the effect of atmospheric turbulence.

Because the lower atmosphere of the earth is generally turbulent, the air density and composition at every point vary with time. Similarly, at any given time these physical characteristics vary from point to point. Since the speed of propagation of radio or optical signals through the atmosphere depends upon the composition of the latter, several effects are observed in actual atmospheric propagation paths which restrict our use of such signals. Accordingly, the Bureau's work in this area has been generally aimed at evaluating and, wherever possible, systematically classifying these atmospheric effects.

The following will be confined chiefly to a discussion of these atmospheric characteristics. We can express this in another way by stating that we will neglect the uncertainties in $\underline{t}$ in the following equation, and assume that errors in $\underline{L}$ are due solely to errors in $\underline{v}$.

$$L = vt$$

Now consider the physical situation shown in Fig. 1. This is the



$$T = \frac{L}{v_o} \qquad n_o = \frac{c}{v_o}$$

$$T = \frac{n_o L}{c}$$

PROPAGATION THROUGH IDEALIZED HOMOGENEOUS ATMOSPHERE

Figure I

idealized, but trivial case in which the speed is a constant value v_0 at all points along the path. If we knew this situation to exist, we would need only to measure v_0 at any point in the medium to make the necessary conversion of our time measurement to distance. Furthermore, the error in our calculated distance would be determined by the precision with which we could measure v_0 .

In reality, this situation is not even approximated often and we are, in general, faced with the case illustrated in Fig. 2 in which, due to the heterogeneity of atmospheric composition, the speed of propagation is a function of location. If we express this fact mathematically as $n = n(x)$ then the actual conversion factor from our time measurement to distance should be the space-average defined as

$$\bar{n} = \frac{1}{L} \int_0^L n(x)\, dx$$

Now since we are always limited, physically, to determining $n(x)$ at some finite number of values of x, the above expression may be interpreted to mean that even though we made errorless determinations of the index at each of k sampling points, our average would always be subject to a finite sampling error to the extent that

$$\frac{1}{k}\left(n_1 + n_2 + \ldots . + n_k\right) \neq \frac{1}{L} \int_0^L n(x)\, dx$$

This is the error which our experiments are aimed at evaluating.

The early experiments were conducted in the Pike's Peak region of Colorado. [1] Subsequently, a series of measurements were made on the island of Maui, T.H., and we are presently set up in the Boulder area.

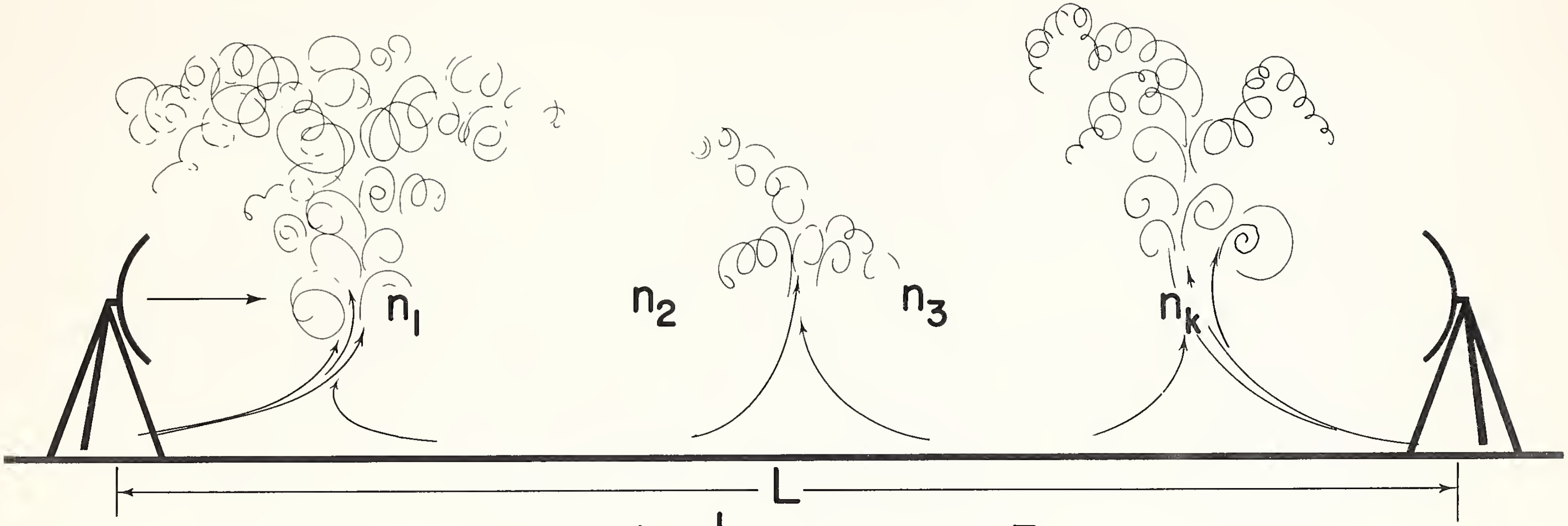
The experimental approach has consisted of a rather straightforward process in which the two radio instruments were set up on rigid pedestals. These latter varied with the particular antennas being used, but generally they were columns about 2 feet across and from 2 to 5 feet high. Fig. 3 shows 4 feet and 18 inch diameter dishes. The signal from the electronic time measuring circuit was recorded continuously by means of both paper chart and magnetic tape recorders. In addition to the slow variations, such as day to night, variations in transit time up to the 10 cycles/second components were quantitatively measured.

During this period of radio observations psychrometer and barometer observations were made from which the corresponding values of radio refractive index could be computed.

In the Maui experiments recordings were made of temperature, pressure and relative humidity at three intermediate stations in addition to the two ends of the radio path. The path geometry and the locations of these stations are shown in Figs. 4 and 5. These data have been analyzed in the following way.

At each hourly interval the variation in path length was calculated in two ways; first, by using the index measurements from only the two end points as the velocity correction and then by using the data from all five meteorological stations weighted according to their differences in elevation. Fig. 6 shows these two curves as well as the uncorrected variations. For each curve the standard deviation has also been computed.

The effects of averaging the observations to different degrees are illustrated in Fig. 7. The ordinates in these curves are the running averages of the points plotted in Fig. 6. The results of this process are summarized in Fig. 8 which shows the decrease in standard



$$T = \frac{1}{c} \int_0^L n(x)\,dx = \frac{L\bar{n}}{c}$$

PROPAGATION THROUGH REALISTIC TURBULENT ATMOSPHERE

Figure 2

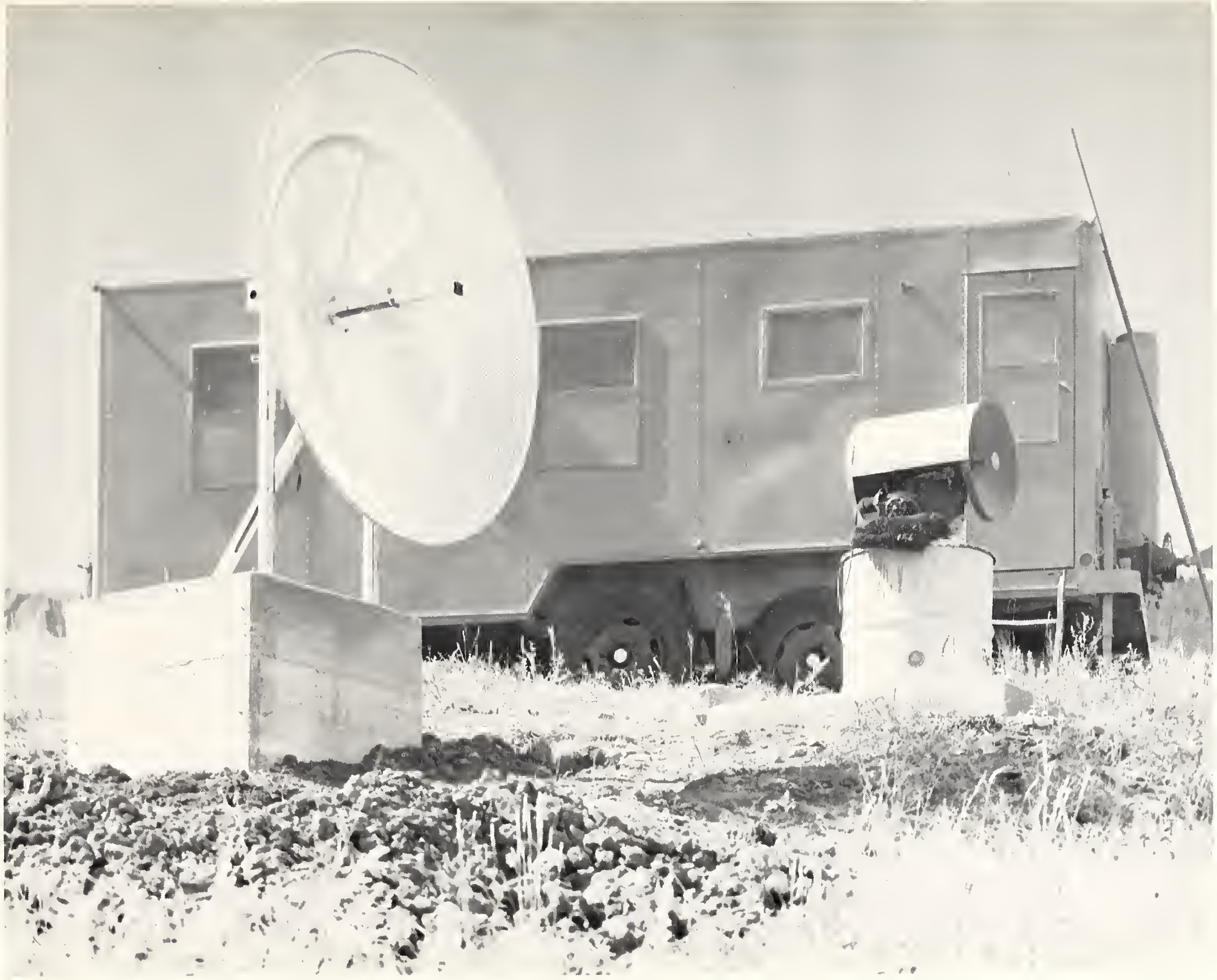


Figure 3 GREEN MT. MESA TERMINAL

TERRAIN PROFILE FOR MAUI PHASE MEASUREMENTS

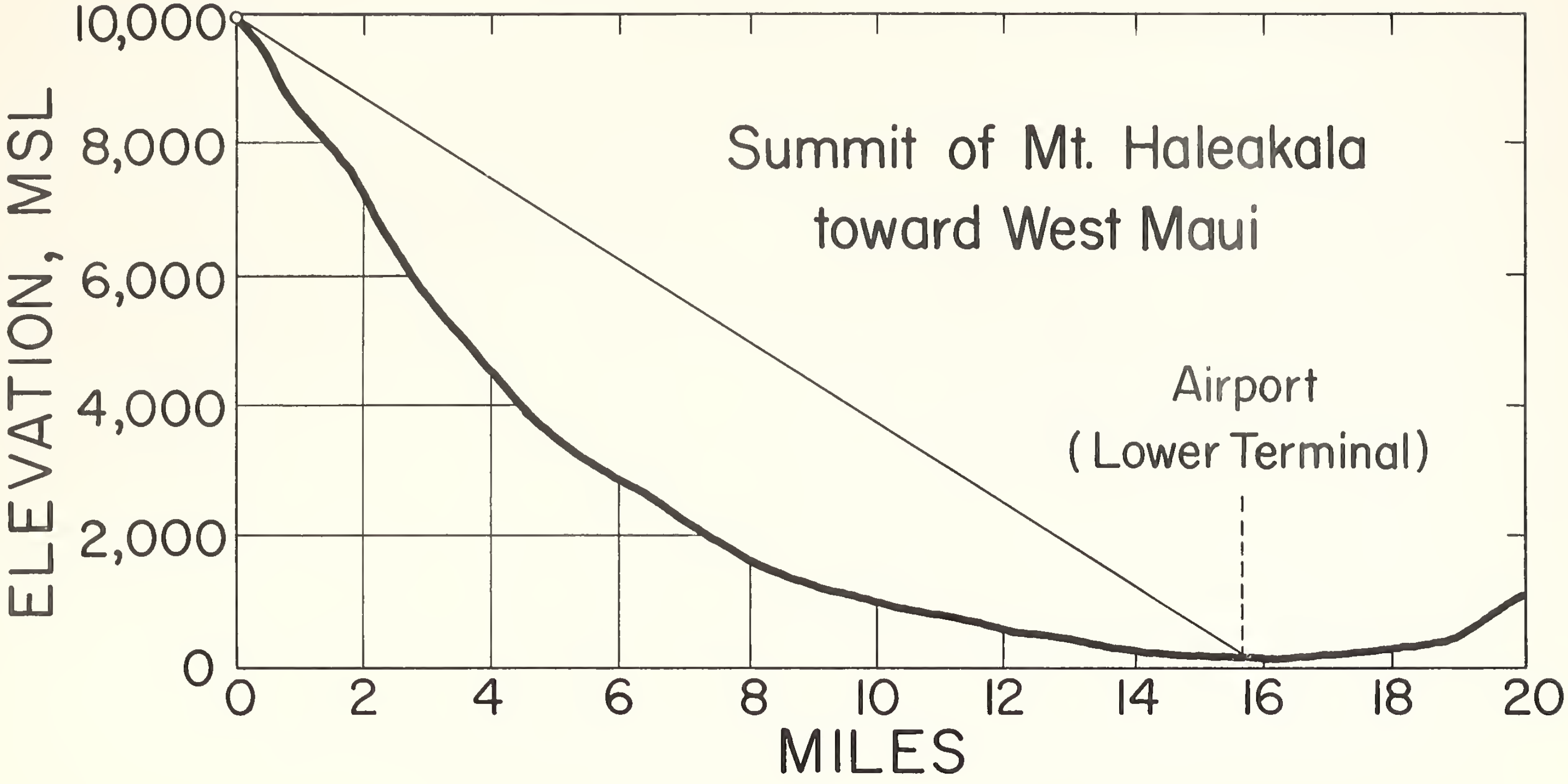
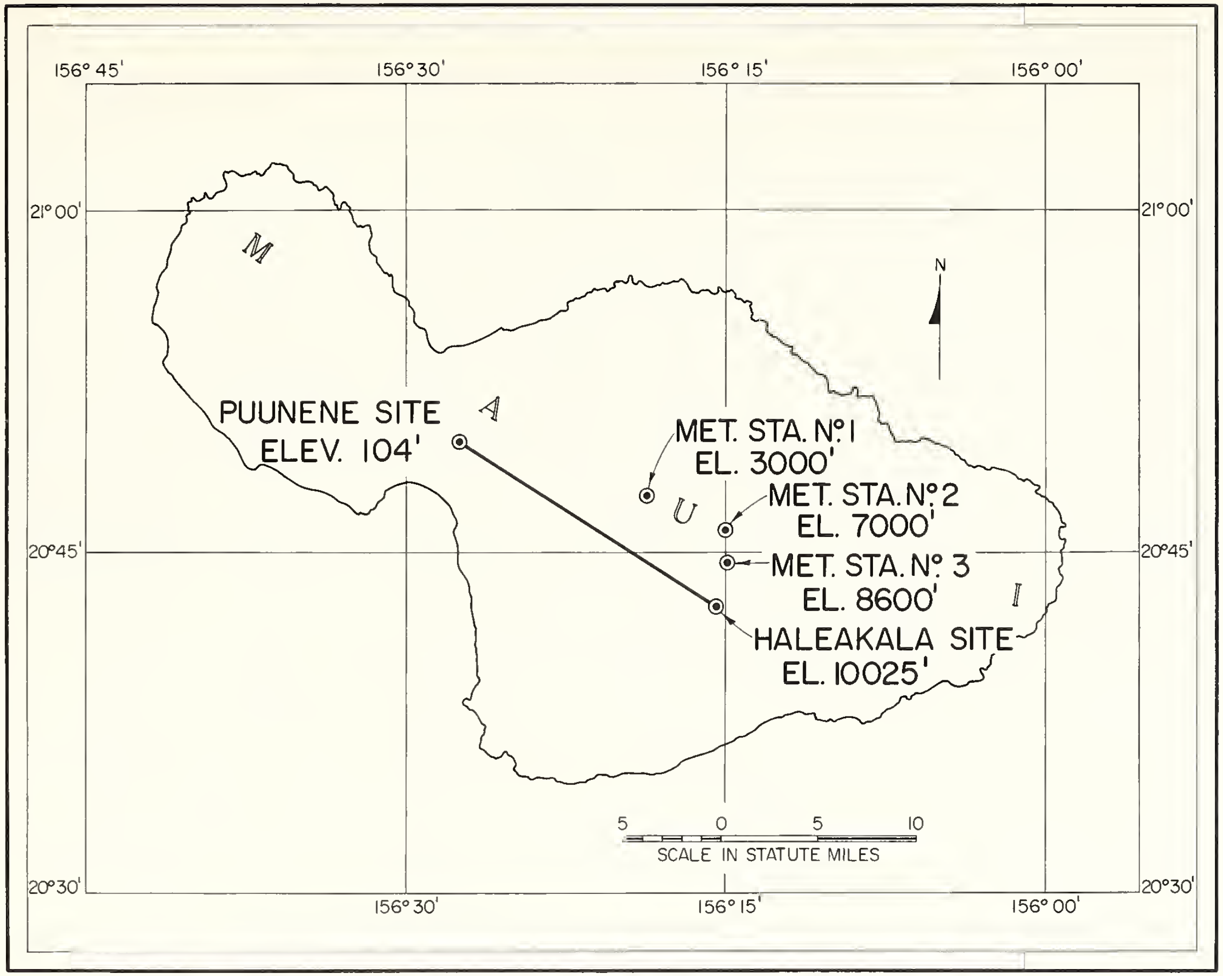


Figure 4



LOCATION OF PROPAGATION PATH
USED IN MAUI EXPERIMENT

Figure 5

TIME VARIATIONS IN APPARENT DISTANCE

MAUI PATH NOMINAL DISTANCE : 15.46 mi.

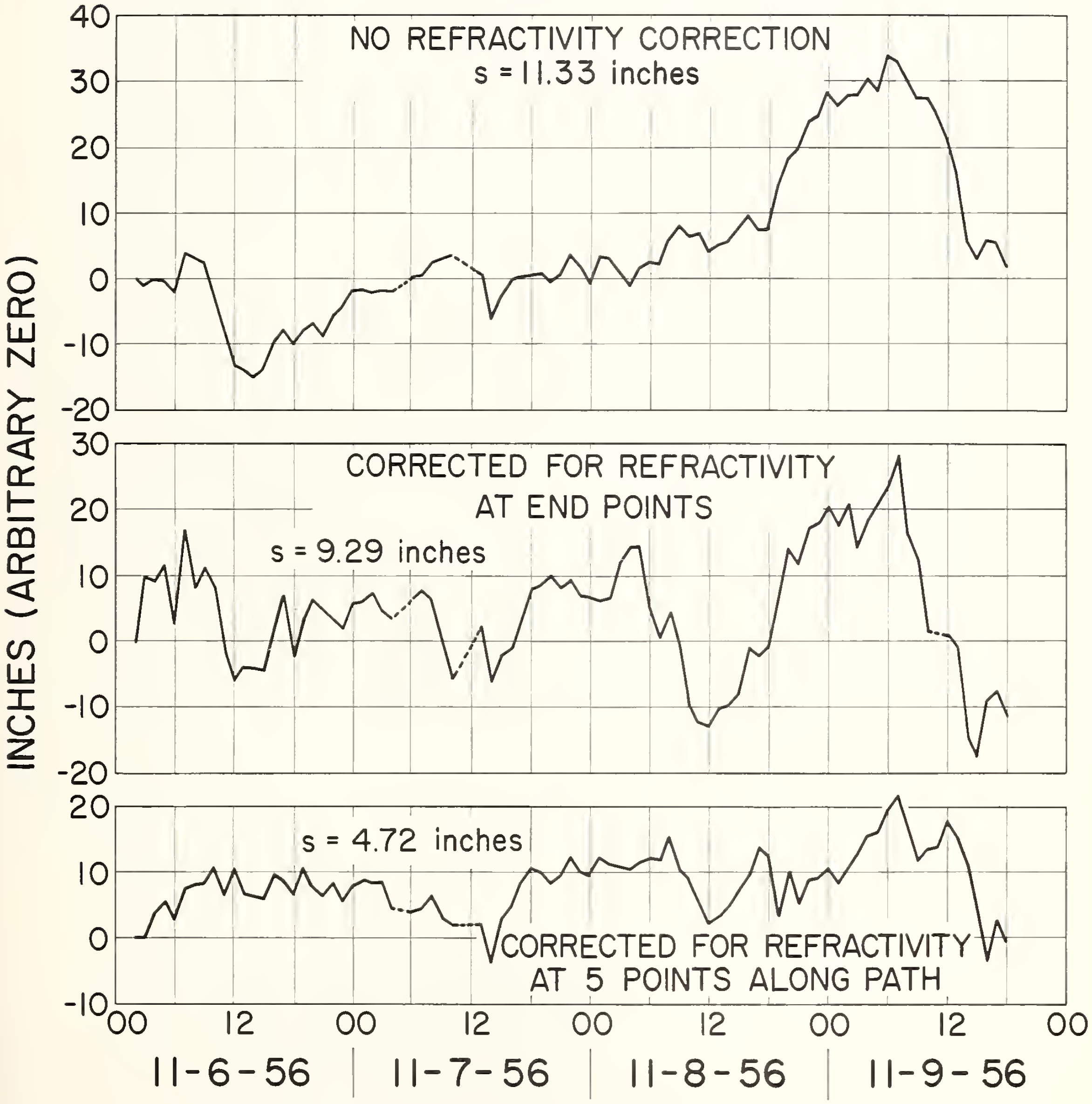


Figure 6

EFFECT OF AVERAGING VARIATIONS IN APPARENT DISTANCE

DATA CORRECTED FOR REFRACTIVITY AT END POINTS

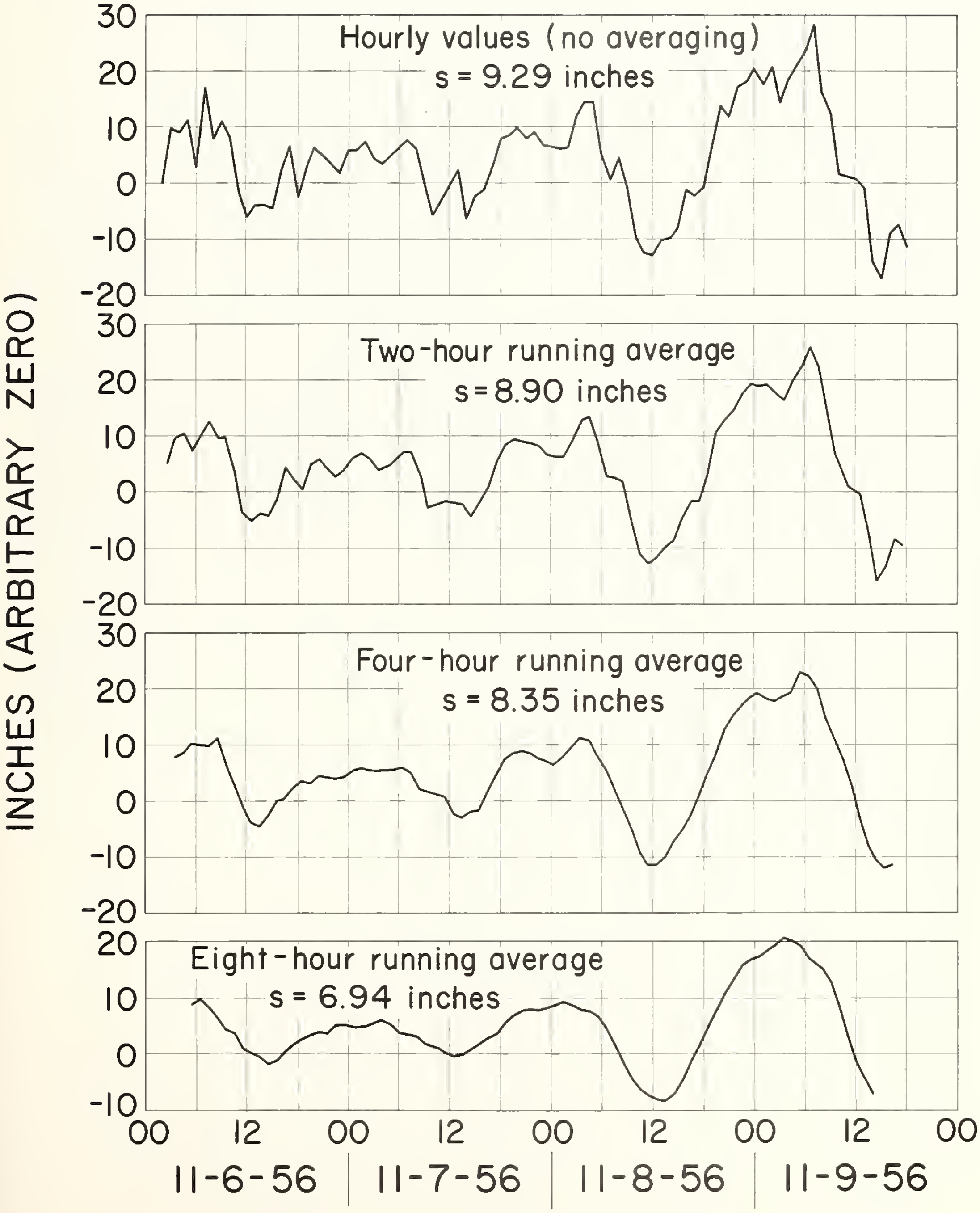
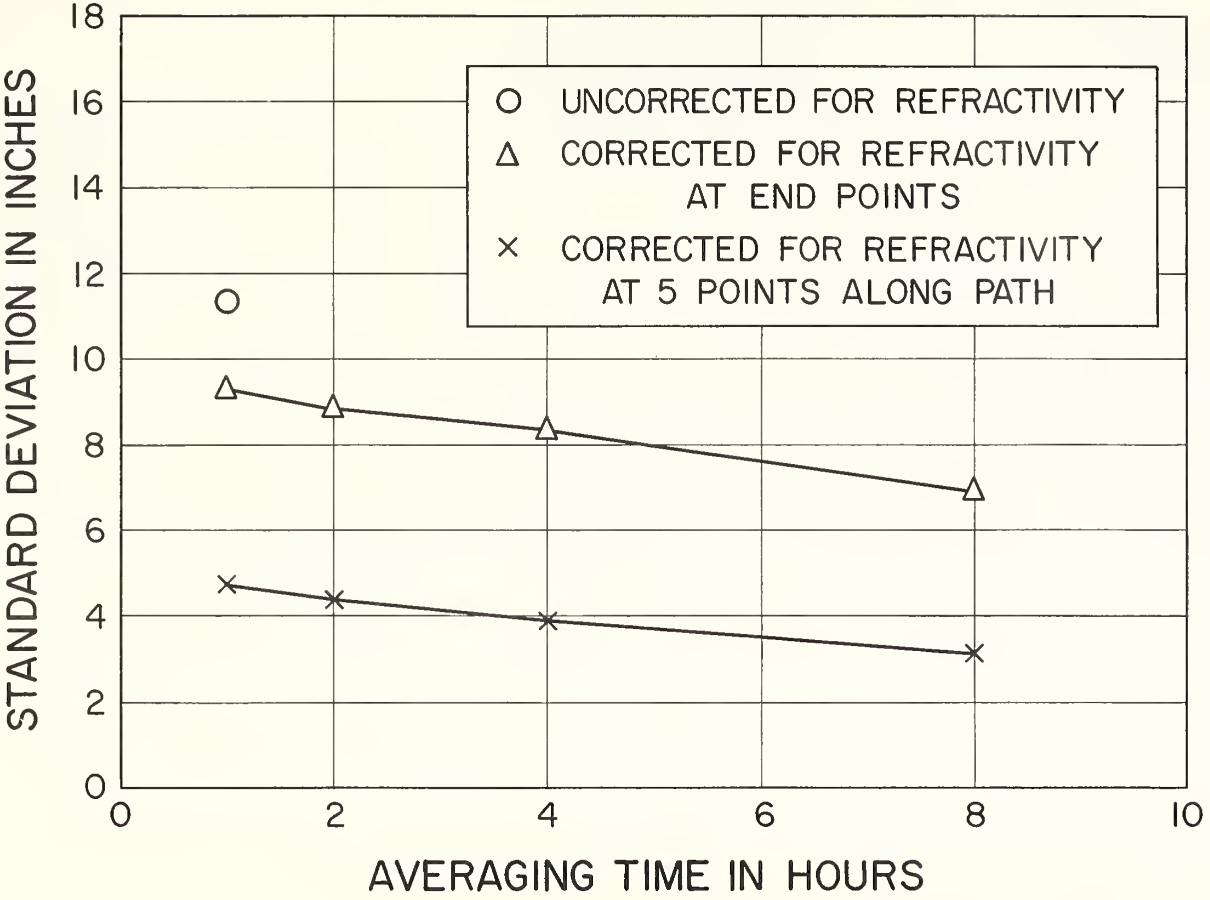


Figure 7



APPARENT DISTANCE VARIATIONS VERSUS AVERAGING TIME

MAUI PATH NOV. 6-9, 1956

Figure 8

deviation as a function of the averaging interval for the different correction processes.

Although this work has been in progress for more than four years, only a small part of the data has been analyzed in the manner just illustrated. The primary interest of the United States Air Force as sponsor of this work has been, and is currently, with short-term variability rather than actual distance measurement. Consequently, the experiments have always been designed to emphasize the former while making no attempt to pursue the latter. Fortunately, a great deal of the data contains information relevant to the latter application and may be of value in assessing the performance to be expected from distance-measuring systems.

The National Bureau of Standards experiments have been designed from the beginning not simply to observe the turbulence effects, but to study them quantitatively. Thus, we were forced to develop instrumentation whose noise level was significantly lower than the variations in transit time resulting from turbulence.[2/]

One might say that our signal--to be studied quantitatively-- is the electronic surveyor's noise level. This has resulted in equipment whose stability is such that variations of transit time of less than one micro - microsecond can be detected and the normal atmospheric variations can be recorded with an accuracy of a few per cent. At the same time, although for different purposes, we have had to develop instruments such as the National Bureau of Standards microwave refractometer which can record variations in radio refractive index to a few parts in ten million.

In a homogeneous atmosphere, we are, thus, already instrumented to make electronic distance measurements to the order of better than one part per million. However, our experimental observations as described above, indicate that we are limited to accuracy of the order of several parts per million in the field.

It thus appears that we are clearly to the point where our lack of knowledge of atmospheric turbulence is the limiting factor and that, if we are to extend the precision of these electronic techniques, our first approach should be to pursue this area further both experimentally and theoretically.

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1 /

J. W. Herbstreit and M. C. Thompson, Jr., "Measurements of the Phase of Radio Waves Received over Transmission Paths with Electrical Lengths Varying as a Result of Atmospheric Turbulence," Proceedings of the IRE, Vol. 43, No. 10, Pages 1391-1401, October 1955.

2 /

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Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Engine Fuels. Free Radicals.

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