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EMPIRICAL ESTIMATES OF ERRORS IN DOUBLE-THEODOLITE WIND MEASUREMENTS

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ABSTRACT

This paper presents the results of an empirical study conducted at White Sands Missle Range, New Mexico, to estimate the errors in winds obtained by the manual double-theodolite wind system.

A series of pilot balloon flights was conducted as a part of the tests. Each balloon was tracked simultaneously by the double-theodolite system and the very precise Contraves cinetheodolite system. The cinetheodolite system was used as a standard for evaluation of the double-theodolite system. Differences between the two systems were considered to be errors in the double-theodolite system.

An observation interval of 20 seconds was used for the manual double-theodolite system; the observation interval for the cinetheodolite system was 1 second. Each balloon was tracked for 520 seconds. The double-theodolite data were reduced for observation intervals of 20, 40, 60, 80, 100, and 120 seconds. The reduced data, wind speed and direction, were compared with the cinetheodolite data for corresponding time periods. Similar evaluations were made by comparing the mean winds, measured independently by the two systems, through specified altitude layers. Layer thicknesses of 100, 200, 300, 400, and 500 feet were considered.

The paper presents a discussion of the tests, the data reduction procedures, and results obtained. The decrease in errors for increased observation interval and increased layer thickness is discussed. The variation of measurement error with altitude is also presented.

CONTENTS

INTRODUCTION

The manual double theodolite system for pilot balloon tracking is one system presently used for wind measurement at White Sands Missile Range (WSMR), New Mexico, in support of rocket firings. This system consists of two manually operated theodolites which track a pilot balloon, i.e., at discrete intervals of time, the azimuth and elevation angles from each theodolite are recorded. These data are then reduced either by plotting board (1) or by computer (2) techniques to obtain wind data.

Many of the rockets fired at WSMR are highly wind sensitive. Thus it is desirable to know the error distributions of the various wind measuring systems. This paper describes a series of tests -- and presents the results thereof -- performed at WSMR to estimate the accuracy of the manual double-theodolite system.

The evaluation was based on analysis of routine manual double-theodolite observations furnished by the Meteorological Support Division, Atmospheric Sciences Laboratory, WSMR, New Mexico. Thirty-six balloon ascents of 9-minute duration during the period 12 October 1965 to 10 February 1966 were used in the evaluation. Each balloon (a hundred-gram pilot balloon inflated for an ascent rate of approximately 1000 feet per minute) was also tracked by the Contraves photo-theodolite system. The data obtained from the Contraves system were used as a standard for the comparison.

All data were collected in the vicinity of launch complex 36 (LC-36),WSMR. The relative position of the trackers is shown in Figure 1. Four photo-theodolites (G107, G108, G109, and G110) were used by the Contraves system. The readings from the manual double-theodolite system were recorded every 20 seconds. The observation interval for the Contraves system was one second. Precise timing was provided by IRIG-B timing (10 per second) at the LC-36 blockhouse and the photo-theodolite positions. The 20-second timing interval for the manual theodolites was coordinated by voice communication over the Range Command Network.

CONTRAVES PHOTO-THEODOLITE SYSTEM

Photo-theodolites are angle measuring instruments used to determine the trajectories of moving aerial targets. These theodolites, placed at known distances from each other, measure and record on

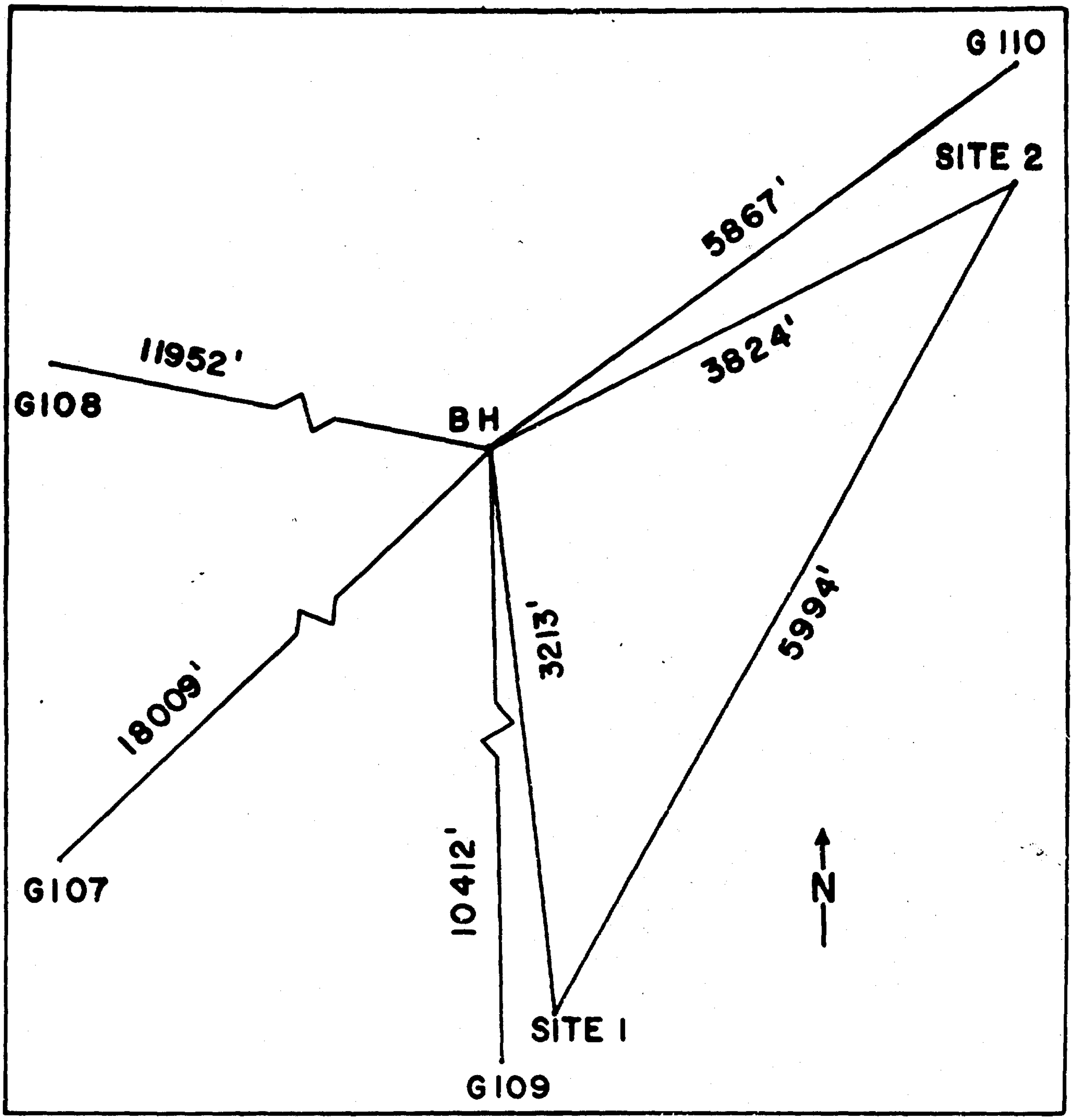

Fig. 1. Relative Geometry of Data Collection Site.

film the azimuth and elevation angles to a target. Since the distance between the theodolites (base line) and the angular measurements are known, the positions of the target can be computed. In the Contraves photo-theodolite system, the target is photographed in a manner which allows time to be recorded along with azimuth, elevation, and target position relative to a pair of cross hairs in the optical path. Measured data are read from film and corrected for errors which include eccentricity, lens sag, reference zero, collimation, mislevel (or tilt), refraction, and bore sight errors.

Corrected rays from the various theodolites will intersect only with zero probability because of unknown sources of error in the Contraves photo-theodolite and in reading the film. Therefore, the problem arises of estimating the position of a target at a given time from observations yielding nonintersecting lines in space. The method of solution (3) at WSMR is based on the theory of least-squares, minimizing the sum of the squares of angular residuals.

Component velocities were computed from the Contraves position data by numerical differentiation. Standard WSMR data reduction techniques (4) were employed. Mean velocities for specific time intervals were computed as simple averages.

Precise error estimates for the velocities obtained by the Contraves system are not available. However, the qualitative results obtained by Kingsley et al., (5,6) indicate that these errors would be quite small.

THE MANUAL DOUBLE-THEODOLITE SYSTEM

The manual double-theodolite system consists of two optical theodolites located at known positions. For these runs two operators were present at each position. Upon signal over the voice network one operator reads aloud the azimuth and elevation angles from the dials and resumes tracking while the second operator records the angles.

The position data for manual double-theodolite solution were computed using the solution such that the sum of the squares of distances from this point to each line of sight is minimized (2). The first 20-second layer of each run was discarded due to large initial errors in balloon acquisition after launch. The 20 through 39-second layer was the first layer used in the comparison and was followed by 24 additional 20-second layers through the 500 to 519-second layer.

The last layer (520-539 seconds) was deleted because Contraves photo-theodolite data were incomplete.

Wind components were computed from the position data using the first differences

$$W_{x_i} = \frac{X_{i+1} - X_i}{T_{i+1} - T_i} = \frac{X_{i+1} - X_i}{20}$$

$$W_{y_i} = \frac{Y_{i+1} - Y_i}{T_{i+1} - T_i} = \frac{Y_{i+1} - Y_i}{20}$$

W_{x_i} and W_{y_i} were considered to be the mean wind components for the time layer (T_i, T_{i+1}).

DEFINITIONS OF ERRORS

For purposes of evaluation of the manual double-theodolite system the winds determined by the Contraves systems were assumed to be correct. Differences between the two measurements were then defined to be errors in the double-theodolite system. The authors realize that this assumption tends to degrade the system being evaluated; however, it is believed that, since the Contraves system is much more precise than the manual double system, the degree of degrading will be insignificant.

The error estimates, expressed in terms of the RMS value σ, were computed for speed and direction. These RMS values are denoted by σ_S and σ_D respectively.

COMPARISON BASED ON TIME INTERVALS

Two separate modes of comparison were used in this study. The first technique was to compare the mean winds obtained for specified time intervals (balloon flight time intervals). Since it is clear that expected error in measuring the mean wind depends upon the observation interval, several different lengths for the time intervals were used in the data reduction. These were all integer multiples of the observation interval -- 20 seconds. Comparisons were made for time intervals of 20, 40, 60, 80, 100 and 120 seconds.

RMS values for the errors were computed separately for each run for the 20-second interval comparisons. These results are presented in Table I and indicate the differences in precision from run to run. Such error estimates were not computed for the larger time intervals due to the small sample sizes (12 or fewer) obtained.

It is apparent, after a moment's reflection, that σ_D is a function of s. To investigate this relationship the estimates of σ_s and σ_D were computed for the entire data sample and for three speed ranges: $s < 5$ fps, $5 \text{ fps} \leq s < 10$ fps, $s \geq 10$ fps. These results are shown in Figure 2.

The pertinent question of whether measurement error varies throughout the flight was investigated by computing σ_s and σ_D separately for each time layer. The results for time intervals of 20 and 60 seconds are presented in Figure 3. The abscissa is the midpoint of the layer.

EVALUATION BY ALTITUDE LAYERS

The evaluations described in the previous section were easy to design and compute. However, most applications of balloon-measured winds require mean winds through specified altitude layers. This is especially true for rocket trajectory analysis. If the balloon ascent rates were invariant from ascent to ascent the results of the preceding section could be interpreted, by suitable change of variable, to yield the desired results. Unfortunately the ascent rate is not invariant.

A natural question arises as to how one should process the original data to compute the mean wind through a given height layer. Numerous techniques can be advanced, and each has its own merit. The following was used for this study:

Let $\{W_{x_i}, W_{y_i}, Z_i, t_i\}_{i=1}^{N}$ be the computed "20-second

TABLE I

Error Estimates for Individual Runs

I.D	σ_D	σ_s	I.D	σ_D	σ_s
1012654	3.25	1.55	0120663	9.98	3.13
1021652	5.91	1.21	0120664	7.24	1.28
1021656	5.51	1.28	0120667	8.14	1.19
1021657	8.00	.80	0125661	4.16	1.56
1102652	21.68	.92	0125662	3.84	2.57
1102653	20.73	1.70	0125663	4.78	3.96
1102654	9.35	1.10	0125664	4.05	2.19
1104651	7.67	2.49	0125665	3.15	2.01
1104653	7.11	2.99	0127662	5.70	4.37
1104654	4.87	1.83	0127664	2.93	2.67
1104656	8.37	3.04	0127665	8.06	3.82
1109654	3.78	1.20	0203661	28.69	.70
1109655	8.01	3.02	0203662	18.29	1.10
1116653	16.33	2.94	0203664	3.22	.81
1116654	27.83	1.52	0203665	7.29	1.04
0111666	3.77	4.32	0203666	15.90	2.25
0113666	7.69	2.69	0210663	5.25	2.05
0120661	15.66	2.70	0210667	3.02	2.99

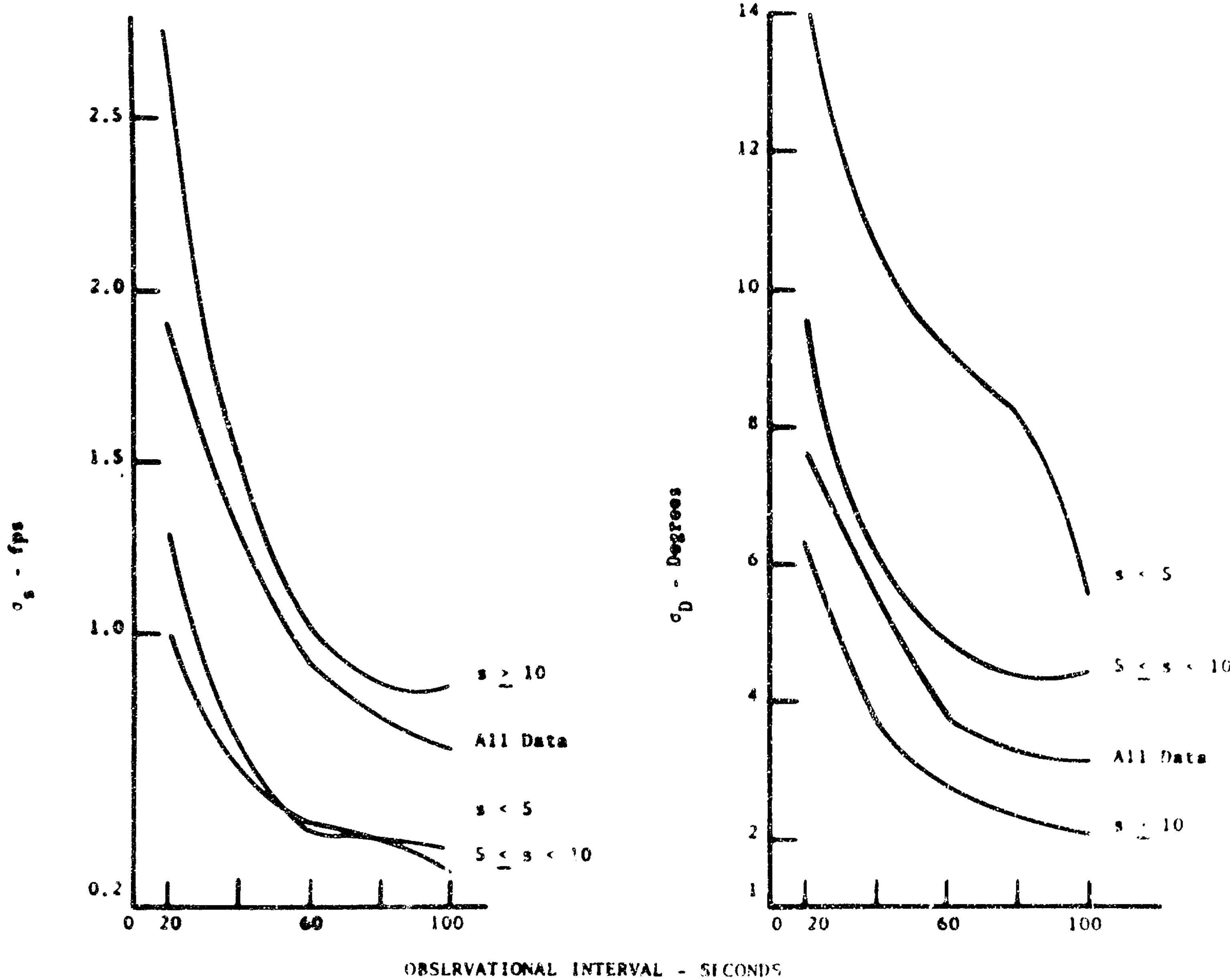

Fig. 2. Variation of Error with Observation Interval

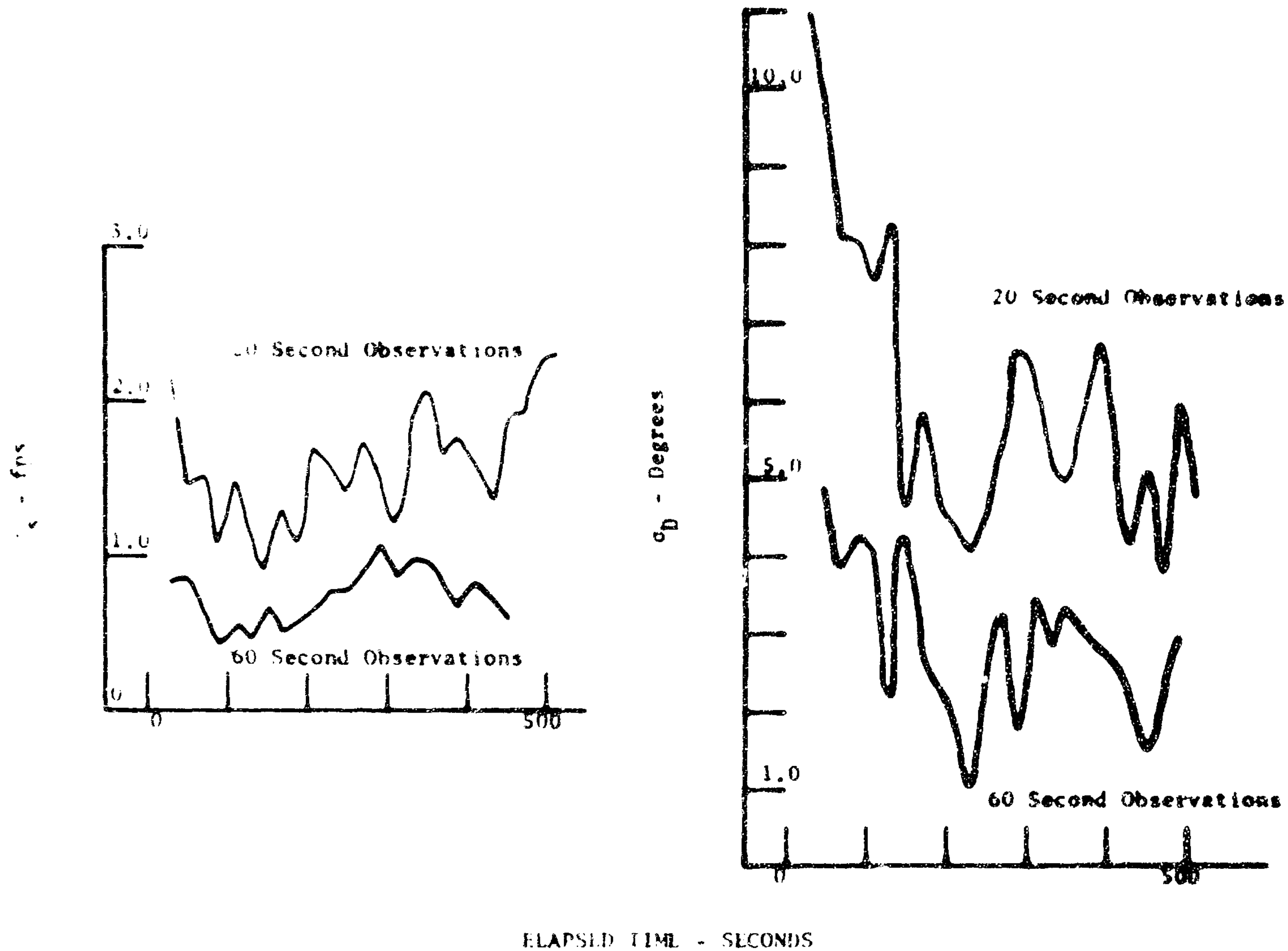

Fig. 3 Variation of Error with Balloon Flight Time

profile" where W_{x_i} is the x-component, W_{y_i} is the y-component, t_i is time, and Z_i is altitude at the end of the 20-second period. Consider the sequence $\{W_i, \bar{Z}_i\}_{i=1}^{N}$ where W_i represents either W_{x_i} or W_{y_i} and $\bar{Z}_i = (Z_i + Z_{i-1})/2$. For an altitude layer $[h_1, h_2]$ let W_1^* and W_2^* be the values obtained from $\{W_i, \bar{Z}_i\}_{i=1}^{N}$ by linear interpolation at h_1 and h_2 respectively.

If there does not exist a value of $\bar{Z}_i$ between h_1 and h_2 the mean wind over the layer, $\bar{W}$, is taken as $\bar{W} = (W_1^* + W_2^*)/2$. Suppose there exists $h_1 < \bar{Z}_i < \cdots < \bar{Z}_{i+n} < h_2$. Then $\bar{W}$ is taken as a weighted average $\bar{W} = \sum_{j=1}^{n+1} \alpha_j \hat{W}_j$ where $\alpha_1 = (\bar{Z}_i - h_1)/(h_2 - h_1)$, $\alpha_{n+1} = (h_2 - \bar{Z}_{i+n})/(h_2-h_1)$, $\alpha_j = (\bar{Z}_{i+j}-\bar{Z}_{i+j-1})/(h_2 - h_1)$ for $1 < j < n+1$, $\hat{W}_1 = (W_i + W_1^*)/2$, $\hat{W}_{n+1} = (W_{i+n} + W_2^*)/2$, and $\hat{W}_j = (W_{i+j} + W_{i+j-1})/2$ for $1 < j < n+1$.

The procedure described above was applied to the profiles measured by both the manual double-theodolite system and the Contraves system to obtain mean winds through adjacent 100-foot thick height intervals. As before, the differences between these profiles were considered to be errors in the manual double system. Profiles for height interval thicknesses of 200, 300, 400 and 500 feet were obtained by taking appropriate averages from the "100-foot profiles." It is easy to see that this procedure yields the same profile that would be obtained by applying the procedure outlined in the preceding paragraph to the original data.

The statistical parameters computed for this evaluation are the same as those discussed in the preceding result. The error estimates for the various speed ranges and layer thicknesses are shown in Fig. 4. The variation of error with altitude, plotted at the midpoint of the layer, is shown in Figure 5 for layer thicknesses of 100 and 500 feet.

SUMMARY AND CONCLUSIONS

The system of tests was designed to determine the accuracy of winds measured by a routine manual double-theodolite system. More accurate results could, perhaps, be obtained by highly skilled operators; however, such results would not be typical of routine operations. One-hundred gram balloons inflated for an ascent rate of approximately 1000 feet per minute were used for the tests. The results presented herein are not necessarily applicable to other balloons or other ascent rates.

The measurement error depends upon both wind speed and layer thickness. This is shown in Figures 2 and 4. If one desires to use a single value for a fixed layer thickness the curves labeled "All Data" should suffice. The variation of measurement error with altitude is shown in Figures 3 and 5. The data presented in Table I show the variation in measurement error that can occur from different balloon tracks.

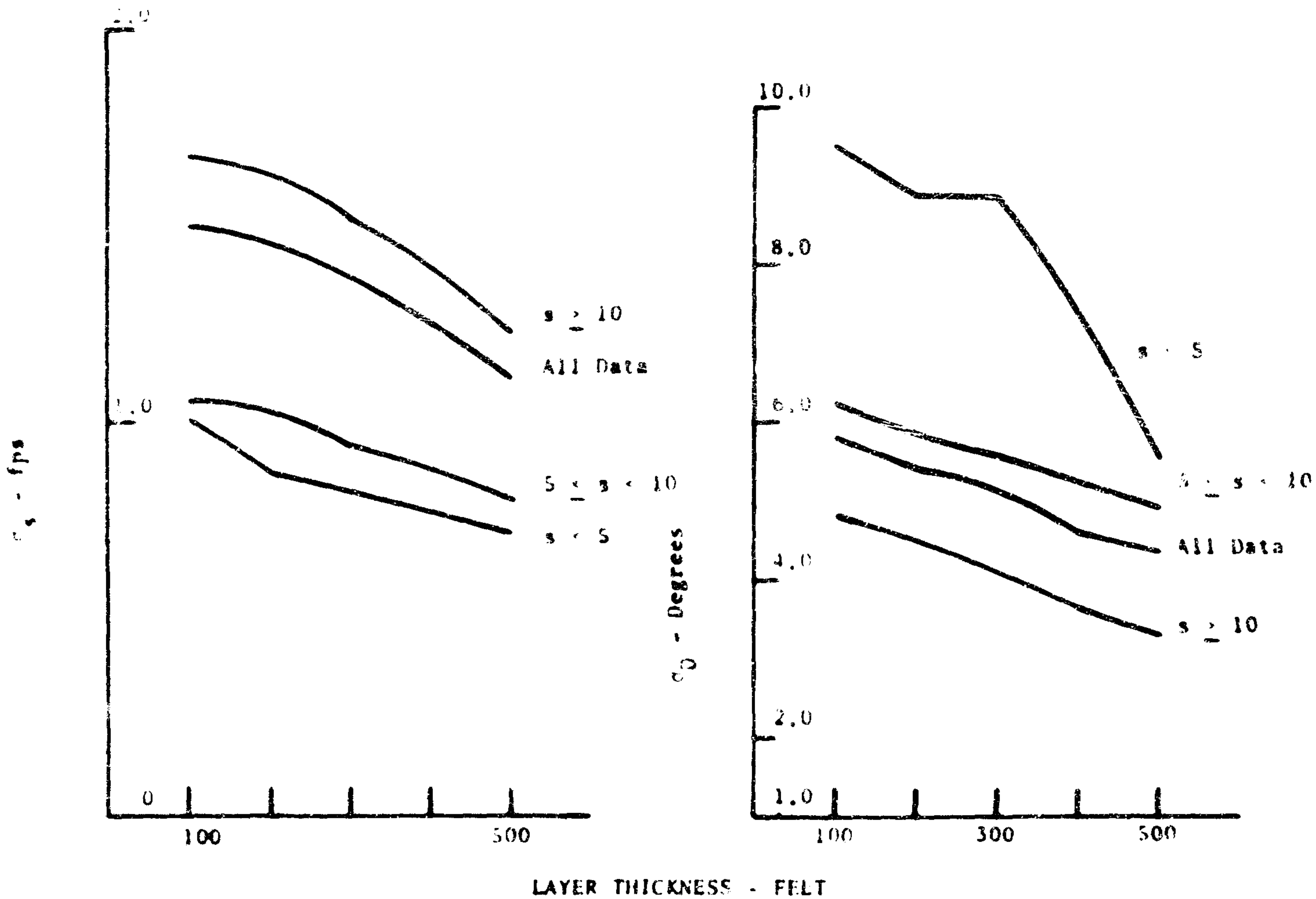

Fig. 4. Variation of Error with Depth of Altitude Averaging Layer

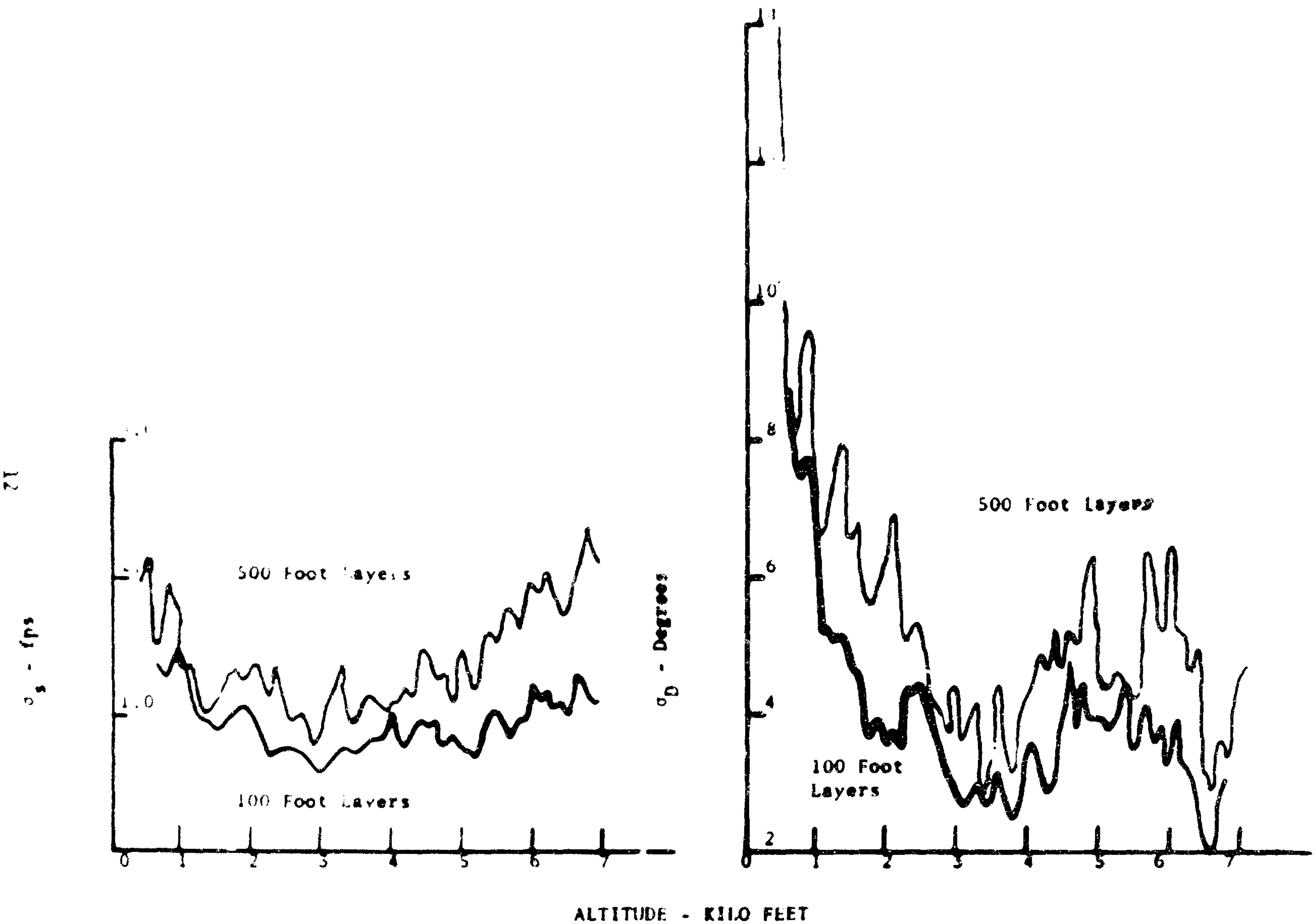

Fig. 5. Variation of Error with Altitude.

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13. ABSTRACT

This paper presents the results of an empirical study conducted at White Sands Missile Range, New Mexico, to estimate the errors in winds obtained by the manual double-theodolite wind system. A series of pilot balloon flights was conducted as a part of the tests. Each balloon was tracked simultaneously by the double-theodolite system and the very precise Contraves cinetheodolite system. The cinetheodolite system was used as a standard for evaluation of the double-theodolite system. Differences between the two systems were considered to be errors in the double-theodolite system. An observation interval of 20 seconds was used for the manual double-theodolite system; the observation interval for the cinetheodolite system was 1 second. Each balloon was tracked for 520 seconds. The double-theodolite data were reduced for observation intervals of 20, 40, 60, 80, 100, and 120 seconds. The reduced data, wind speed and direction, were compared with the cinetheodolite data for corresponding time periods. Similar evaluations were made by comparing the mean winds, measured independently by the two systems, through specified altitude layers. Layer thicknesses of 100, 200, 300, 400, and 500 feet were considered. The paper presents a discussion of the tests, the data reduction procedures, and results obtained. The decrease in errors for increased observation interval and increased layer thickness is discussed. The variation of measurement error with altitude is also presented.

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