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Accuracy of Aircraft Velocities Obtained From Inertial Navigation Systems for Application to Airborne Wind Measurements

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SUMMARY

An experimental assessment was made of two commercially available inertial navigation systems with regard to their inertial-velocity measuring capability for use in wind, wind shear, and long-wavelength atmospheric turbulence research. The assessment was based on 52 sets of postflight measurements of velocity (error) during a "Schuler cycle" (84 minutes) while the inertial navigation system (INS) was still operating but the airplane was motionless.

Four INS units of one type and two units of another were tested over a period of 2 years after routine research flights similar to airline-type operations of from 1 to 6 hours duration. The maximum postflight errors found for the 52 cases had a root-mean-square value of 2.82 m/s with little or no correlation of error magnitude with flight duration in the 1- to 6-hour range.

INTRODUCTION

During the development of a recent research program involving the measurement of atmospheric turbulence to very long wavelengths, system evaluations emphasized the need for accurate aircraft velocity measurements, which were extracted from an inertial navigation system in references 1 and 2. As described in the references, the method of measurement consisted of determining incremental airflow relative to the airplane by means of angle-of-attack and angle-of-sideslip flow vanes and a sensitive airspeed system. These measurements are then corrected for linear and angular airplane motions by use of the inertial navigation system. Airliners routinely use inertial navigation systems (INS) for guidance, particularly for overwater flights, and also for the measurement of winds. Such wind measurements (limited to a low frequency) use the airplane's pitot-static system and outside air temperature measurement system to determine true airspeed. The true airspeed (generally obtained by means of a so-called "air data computer") is then fed into the INS computer where the true airspeed vector is subtracted from the ground speed vector to obtain the wind speed vector for display by the INS. In the same manner as turbulence measurements, these wind measurements are also primarily dependent upon the INS-derived aircraft velocity for their accuracy.

Several recent accidents during landings in the vicinity of thunderstorms (refs. 3 to 5), believed to be due to wind shear (an unusually large change in wind velocity and/or direction as a function of altitude), have resulted in an enhanced research effort by the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and others on wind shear and turbulence associated with the so-called thunderstorm "gust front" (refs. 6 to 11). The measurements needed for such research can be acquired by means of an airplane equipped with instrumentation similar to that described in reference 1, which includes an INS.

In view of the preceding factors, an investigation was undertaken to determine the accuracy of aircraft velocities obtainable from typical existing inertial navigation systems which could be employed in wind and turbulence research measurements. The purpose of this paper is to present experimental results obtained from 52 sets of data, or cases, collected from two types of INS (which are commercially available and currently in use) after routine research flights (refs. 12 and 13). The accuracy assessments were made by recording the velocity error of the INS at the end of each flight while the aircraft was motionless but the INS was still operating.

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INERTIAL SYSTEMS AND TESTS

Inertial navigation systems presently used by the airlines consist of gyros, torquing devices, a computer, and orthogonal accelerometers mounted on a stabilized element. The torquing devices maintain the stabilized element perpendicular to the local vertical as the airplane maneuvers and travels following the curvature of the Earth. So-called "Schuler tuning" (see ref. 14) is required to successfully isolate the INS from the effects of airplane imposed accelerations. In reference 15, it was pointed out by Schuler that, if it were possible to build a mechanical device having a natural period of oscillation equal to 84 minutes, the device could be moved about in any fashion near the Earth's surface without causing it to be excited into oscillation. A result of Schuler tuning is that the INS stabilized element has an undamped natural period of 84.4 minutes, or the period of a simple pendulum whose length is equal to the radius of the Earth. The angular error of the stabilized element (usually extremely small) thus shows up as a sine wave with an 84.4-minute period. This very small angular error of the stabilized element results in a component of the gravity vector being erroneously sensed by the two orthogonal horizontal accelerometers as airplane motion in the horizontal plane.

The predominant velocity error noted during the postflight measurements is that associated with the Schuler tuning of the INS. In addition, a long-term trend or drift is sometimes present so that the total error has the appearance of a sine wave with an 84-minute period and a slightly offset and tilted zero axis.

The INS velocity amplitude was measured after each flight. To do this, the aircraft was parked at a convenient location, and the INS was left operating in its navigation mode for the time required to obtain a maximum and a minimum value for both horizontal (north and east) velocity components. The time required for this varied between 42 and 84 minutes, since a random phase relation exists between the two components. Since the velocity values were changing at a very slow rate, it was found to be quite practical to extract them from the INS computer (via the control display unit) and to record them manually at

5-minute intervals. A typical plot of north and east velocity (error) is shown in figure 1.

The data were collected over a 2-year period from typical research flights similar to operational airline flights, which involved a few atmospheric turbulence encounters but no violent maneuvers. The results from the postflight measurements are given in table I. Maximum positive and negative values and peak-to-peak values for each component are tabulated. Data were obtained from six INS units, four of one type and two of another, which were installed in three different airplanes. The duration of each flight is listed, since the performance of an INS is generally believed to be somewhat dependent upon the length of time spent in the navigation mode, and particularly the time spent in maneuvering flight. Most data for the type B INS were collected three cases at a time because three units were installed in the same airplane. A so-called "performance index" is also tabulated and requires an explanation. The manufacturer of the type A INS provides the capability of setting a performance index between 0 and 5, with 0 providing the best performance and 5 the poorest. The purpose in setting performance index 5 as opposed to performance index 0 is that considerably less alignment time is generally required before the INS can be switched to the navigation mode. In addition, performance index 5 may be appropriate for situations where airplane motion (due to gusty winds, cargo loading, etc.) prevents the alignment from progressing to performance index 0. (The increased navigation performance associated with performance index 0 may not always be required.) The performance index for the type B INS is not controllable, nor is it displayed. (See footnote b of table I.) The INS cannot be placed in NAV mode, however, until a condition equivalent to type A's performance index of 0 is attained.

RESULTS AND DISCUSSION

Error Assessment

The maximum velocity error, positive or negative in either north or east component, associated with each flight is shown plotted in figure 2 as a function of flight duration. One-half the peak-to-peak values, indicative of the amplitude of only the Schuler error (i.e., without long term trend), could have been plotted and would have been slightly less in many of the cases. In an overall assessment, it seemed desirable however, to include the trend error. It is apparent that no strong correlation exists between the velocity error and flight time and that a considerable amount of scatter is present. Results from INS units of types A and B are shown as separate symbols. No data were obtained with the type A INS for flights of over 3 1/2 hours duration, whereas the type B data flights extended to 4 hours, with one additional flight of 6 hours. The type B data, since it was collected three points at a time (i.e., three INS units installed side-by-side on the same airplane and thus experiencing the same flight environment), tend to indicate no strong correlation between velocity error and the flight environment. The solid symbols shown are for data obtained on seven occasions when a degraded INS performance index was employed. The velocity error does not appear to have been affected for these values.

Statistical Description

The random character of the data of figure 2 indicates that a statistical description would be appropriate. For that reason, a cumulative frequency distribution was determined for the data of figure 2 (i.e., both A and B), and the probability of exceeding given error levels (in the positive direction) was computed and plotted on figure 3. (The grid is scaled in such a way that a normal or Gaussian probability distribution appears as a straight line.) An increase in the effective size of the sample (and a corresponding reduction in scatter) has been accomplished by supplementing each collected data point with a data point of identical magnitude but of opposite sign. Such a procedure results from an assumption that the sign of the collected data point is not significant. The assumption appears justified when it is recalled that the maximum error values are peak values of a sine wave and that an approximately equal point would have been obtained, but with opposite sign, one-half Schuler cycle later. The resulting probability distribution is therefore symmetric. (The latter reasoning does not apply to the small long-term trend error present; however, the experimental data do not indicate a tendency toward either positive or negative trend error for the individual INS units. Thus, the assumption of nonsignificance for the sign appears to be valid.)

The straight line appearing on figure 3 was determined from the computed standard deviation (root-mean-square value) and a normal (Gaussian) distribution standard area table. The computed standard deviation for the maximum velocity error values of figure 2 was 2.82 m/s. As can be seen in figure 3, the measured probability distribution is well represented by the straight line. A practical estimate of the probability of exceeding any given level of velocity error can thus be obtained from the straight line of figure 3, that is, the assumption of a normal probability distribution with standard deviation of 2.82 m/s.

Implications

The indications in reference 2 are that power spectra of atmospheric turbulence extended into the long wavelength region (15 000 m or greater) are not significantly affected by errors of this magnitude unless the overall turbulence intensity level is quite low (i.e., less than 1 m/s standard deviation).

For research-type measurements of wind shear, the "shear" itself is not appreciably affected by the INS error, since wind shear is generally understood to be change per unit time (or distance) and the INS error is changing very slowly, with an 84-minute period. The magnitude of the wind velocity time history will be offset from its correct value by the magnitude of the INS error, however. Such an offset error could be significant for some applications. An example might be a measurement error in wind velocity near the ground resulting in an erroneously calculated ground or landing speed.

The accuracy of inertial navigation systems for use in the determination of wind speed (and/or ground speed) during routine airline operations appears to be adequate for the prediction of way-point or destination arrival time. The reason for this is that the INS errors, as determined herein, are relatively insignificant in comparison to the large wind velocities and wind velocity variations experienced by airliners flying at jet stream altitudes (particularly for long flights). Stated another way, even if the INS velocity-measuring capability were perfect, arrival time predictions would not be perceptibly improved, due to the variability in wind velocity with time and space.

The operational use of an INS in monitoring ground speed during landings in a predicted high wind shear situation has been advocated by some airline pilots (see ref. 16). The essence of the method is that it reassures the pilot and keeps him from dangerously cutting back airspeed in situations where a buildup in airspeed is caused by wind shear (increasing head wind component). On the other hand, if the noted ground speed is high due to descending through a wind shear of increasing tail wind component, the pilot is alerted to the possibility of landing "long and hot."

An airline pilot using the INS to determine minimum landing speed could get into trouble if a large error in INS velocity were present. A "2-sigma error" (i.e., two standard deviations), which according to a normal probability distribution would occur with a probability of about 5 percent (or more exactly, 4.55 percent), would be 5.64 m/s, or 11.0 kts. A positive error of this magnitude (or one which caused the pilot to believe ground speed was 11 kts faster than it actually was) would seem to be more serious than a negative error and could conceivably cause the pilot to land short of the runway in a wind shear situation of increasing head wind. A negative error would cause the pilot to believe the ground speed was slower than it actually was, which could also be dangerous in a marginal situation if it caused him to make a "too hot" landing or land too far down the runway.

CONCLUDING REMARKS

As assessment of principal errors in inertial velocity determined from two contemporary aircraft navigation systems resulted in a root-mean-square (or standard deviation) maximum error of 2.82 m/s for the 52 cases examined. Little correlation was found between error magnitude and flight duration for flight lengths of from 1 to 6 hours.

It is believed that the error quoted above is acceptable for research-type applications such as the measurement of wind shear and long-wavelength atmospheric turbulence with airborne systems. The long-wavelength region of atmospheric turbulence power spectra (15 000 m or greater) could be affected appreciably only if the overall turbulence intensity level is quite low (i.e., 1 m/s or lower standard deviation). Wind shear measurements, in particular, would not be affected to any appreciable extent due to the very long-wavelength character of the error (84-minute period), since wind shear is defined as change per unit time, or distance. The wind velocity time history, however, would contain errors equivalent to those present in the inertial-velocity measurements.

The accuracy of inertial navigation systems for use in the determination of wind speed during routine airline operations appears to be completely adequate for the prediction of way-point or destination arrival time. The use of an INS in monitoring ground speed during landings in a predicted high wind shear situation (as has sometimes been advocated) could lead to landing speeds which are dangerously high or low.

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TABLE I.- POST-FLIGHT VELOCITY ERROR

Airplane	INS		Flight duration	Performance index	North component, m/sec			East component, m/sec			Footnote
	Type	Unit no.			Max. pos.	Max. neg.	Peak to peak	Max. pos.	Max. neg.	Peak to peak	
A	A	1	1:00	0	0.46	0.34	0.79	0.24	0.21	0.46	
A	A	1	1:00	0	1.04	.34	1.37	.58	.64	1.22	
A	A	1	1:00	0	.70	.34	1.04	.21	.24	.46	
A	A	1	1:00	5	.46	.58	1.04	.82	.82	1.65	
A	A	2	1:02	0	.70	1.92	2.62	.43	.12	.55	
A	A	2	1:05	0	.58	1.46	2.04	.94	.43	1.37	
A	A	1	1:05	5	.27	2.01	2.29	4.82	4.11	8.93	
A	A	1	1:05	2	.34	.06	.40	.73	.52	1.25	
A	A	1	1:13	0	.64	.18	.82	.55	.91	1.46	
A	A	1	1:15	0	.43	.37	.79	.73	.67	1.40	
A	A	1	1:22	0	.82	1.25	2.07	1.22	1.22	2.44	
A	A	1	1:25	5	.46	.94	1.40	.34	.18	.52	
A	A	1	1:30	5	.03	.46	.49	.91	.61	1.52	
A	A	1	1:35	1	.67	.82	1.49	.49	.37	.85	
A	A	1	2:00	0	1.22	1.52	2.74	1.07	1.01	2.07	
A	A	1	2:00	5	1.46	.49	1.95	.00	.79	.79	
A	A	2	2:09	0	1.13	.61	1.74	.55	.46	1.01	
A	A	1	2:30	0	.98	.18	1.16	1.68	1.52	3.20	
A	A	1	3:30	0	3.47	2.74	6.22	2.65	2.99	5.64	a
B	A	2	2:50	0	1.31	1.28	2.59	3.08	2.99	6.07	
	B	1		0	1.16	3.84	5.00	3.90	.91	4.82	b
	B	2		0	.94	1.22	2.16	1.25	.55	1.80	
B	B	1	1:03	0	1.68	1.68	3.35	1.22	1.04	2.26	
	B	2		0	1.83	1.74	3.57	.46	.73	1.19	
	B	3		0	2.83	1.01	3.84	.46	2.56	3.03	
B	B	1	1:20	0	2.01	.82	2.83	1.34	1.04	2.38	
	B	2		0	1.52	1.37	2.90	2.19	2.35	4.54	
	B	3		0	2.16	+.21	1.95	.82	2.93	3.75	
B	B	1	1:23	0	.34	1.07	1.40	3.20	.73	3.93	
	B	2		0	.79	.70	1.49	2.01	2.26	4.27	
	B	3		0	1.92	+.43	1.49	.70	2.44	3.14	
B	B	1	1:40	0	2.83	2.13	4.97	3.38	.64	4.02	
	B	2		0	1.07	.91	1.98	1.25	1.28	2.53	
	B	3		0	2.01	+.76	1.25	-.61	2.23	1.62	
B	B	1	2:37	0	1.40	3.05	4.45	3.17	.09	3.26	c
	B	2		0	1.62	2.01	3.63	1.22	1.10	2.32	
B	B	1	3:00	0			7.13			4.15	d
	B	2		0			7.53			2.29	
	B	3		0			9.14			15.24	
B	B	1	3:01	0	1.89	1.22	3.11	.94	.46	1.40	
	B	2		0	.61	.46	1.07	2.65	2.56	5.21	
	B	3		0	2.10	+.94	1.16	-.76	2.77	2.01	
B	B	1	3:40	0			2.44			4.18	d
	B	2		0			2.74			4.75	
	B	3		0			3.05			16.95	
B	B	1	4:00	0			2.93			1.46	d
	B	2		0			3.17			3.78	
	B	3		0			2.44			2.32	
B	B	1	4:00	0			3.29			4.02	d
	B	2		0			2.74			5.97	
	B	3		0			7.13			10.39	
C	B	4	6:00	0	2.74	2.16	4.91	3.32	2.41	5.73	

a - The 3½ hours indicated under "flight duration" actually consisted of a sequence of approximately 1 hour in the air, 1½ hours parked on the ramp at a location different from that of take-off, and another hour in the air.

b - For type B INS, the performance index is not controllable, nor is it displayed. The INS cannot be placed in NAV mode, however, until a condition equivalent to type A's performance index of "0" (or best performance) is attained.

c - Of the 2 hours 37 minutes indicated under "flight duration," 1 hour 18 minutes was spent parked at another airfield with INS units in NAV mode and operating.

d - Peak-to-peak Schuler velocity error for this flight was estimated based on data taken for only 25 minutes of the 84.4-minute Schuler cycle and is believed to be accurate to approximately ±0.3 m/s.

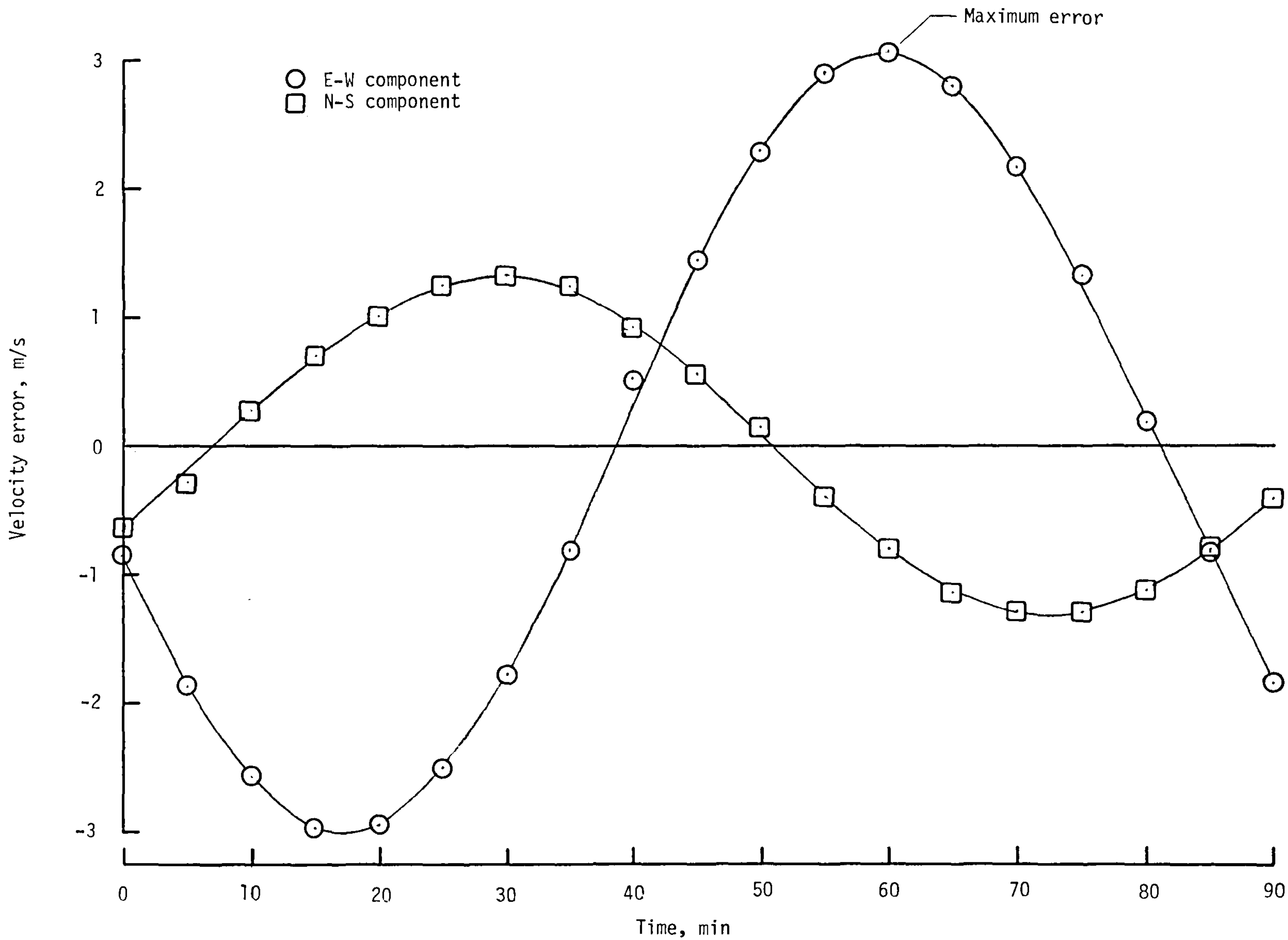

Figure 1.- Typical velocity error for one Schuler cycle, as recorded after 2-hour-50-minute flight.

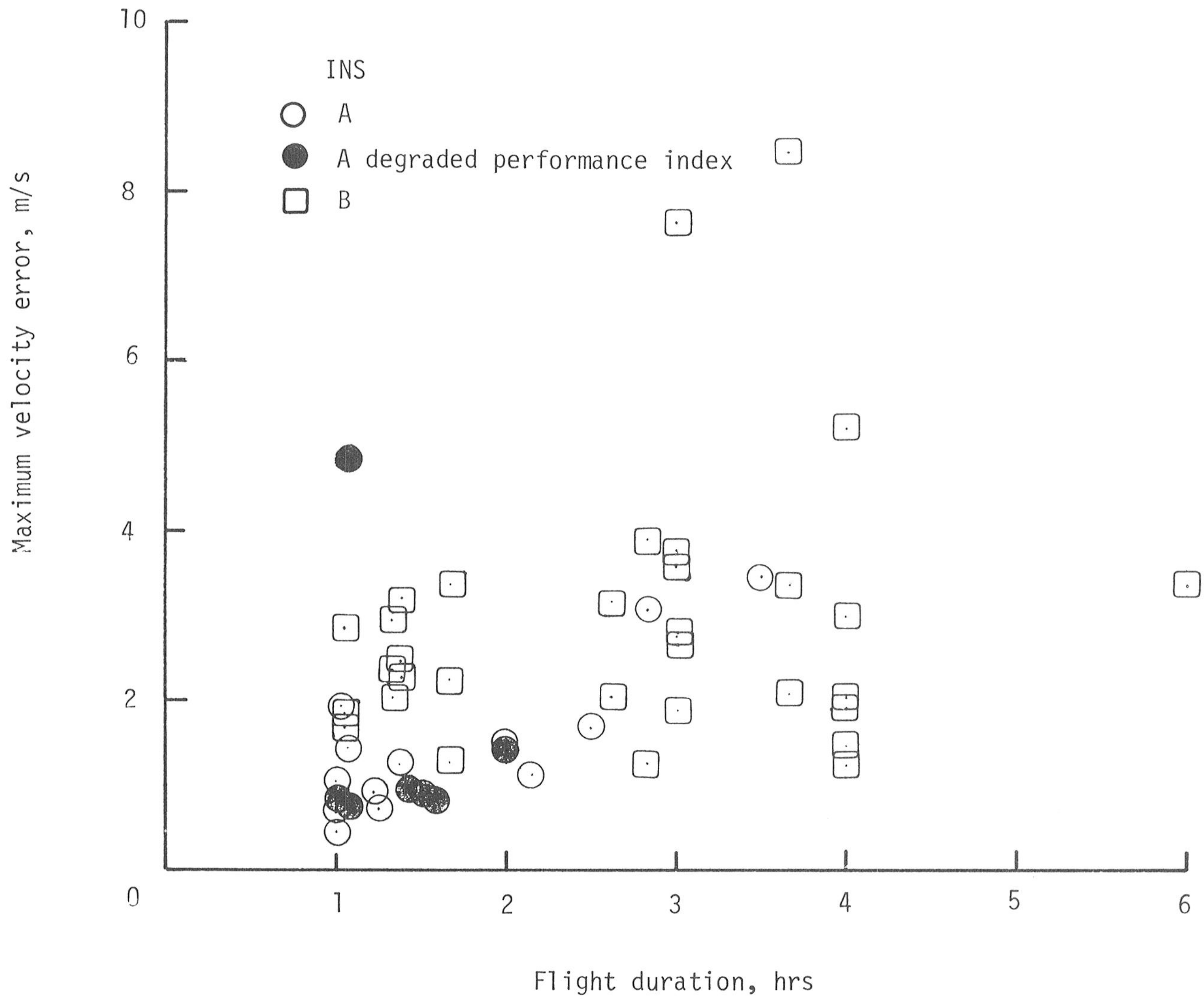

Figure 2.- Maximum velocity error (either north or east component) as function of flight duration.

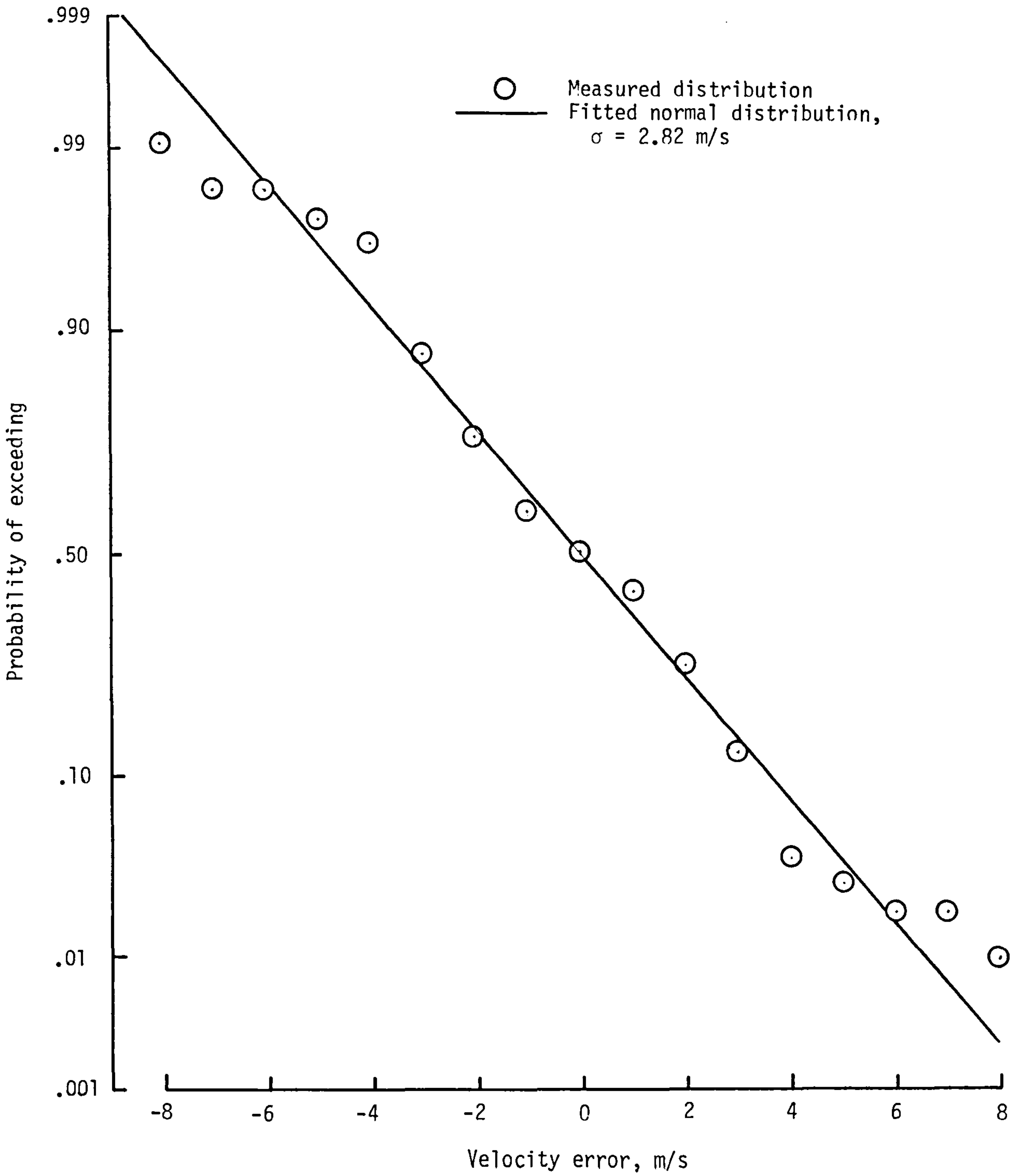

Figure 3.- Probability of equaling or exceeding given values of velocity error (data of figure 2).

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16. Abstract

An experimental assessment was made of two commercially available inertial navigation systems with regard to their inertial-velocity measuring capability for use in wind, wind shear, and long-wavelength atmospheric turbulence research. The assessment was based on 52 sets of postflight measurements of velocity (error) during a "Schuler cycle" (84 minutes) while the inertial navigation system (INS) was still operating but the airplane was motionless. Four INS units of one type and two units of another were tested over a period of 2 years after routine research flights similar to airline-type operations of from 1 to 6 hours duration. The maximum postflight errors found for the 52 cases had a root-mean-square value of 2.82 m/s with little or no correlation of error magnitude with flight duration in the 1- to 6-hour range.

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