Army Research Laboratory

A Revisit of the Field Artillery's Time-Space Wind Variability Equation

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13. ABSTRACT (Maximum 200 words)

The U.S. Army has derived artillery accuracy error budgets based on a time-space ballistic wind variance formula. The wind algorithm uses a midlatitude wind profile to derive the expected ballistic wind component variance. This time variability equation is reevaluated using 190 hourly upper air profiler soundings collected over Platteville, CO, representing 8 days of diverse weather conditions. Comparisons between the computed ballistic wind time variability and the equation estimated variability reveal the formula to be an unbiased estimator with 1 kn precise agreement at a staleness of 1 h. The equation accuracy ranges from 1.5 to 3.0 ballistic kn depending on a time staleness of 2 to 4 h, ballistic line, and season.

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Preface

The U.S. Army uses a ballistic wind time-space variance formula to estimate the expected ballistic wind component errors given an input wind profile. The errors are then used to calculate artillery accuracy budgets. The formula is based on analysis of 960 soundings made over a 2-month period at Fort Huachuca, AZ. Because its validity is so important to establishing artillery accuracy budgets, it is imperative to verify it with an independent data set. Hourly wind profiler data taken simultaneously at both Denver and Platteville, CO, not only provide the requisite independent data set but also include a high temporal resolution, enabling wind variance errors to be tested at time intervals down to 1 h. This data set also incorporates a variety of weather conditions and a reasonable amount of seasonal variation.

The results of this study indicate that the variance equation is an unbiased estimator with a precise accuracy of 1 kn for a 1-h time interval. This accuracy increases for larger time intervals but is still in the range of from 1.5 to 3 kn for time intervals of from 2 to 4 h regardless of ballistic line and season. Thus, the currently used coefficients and time staleness trend in the ballistic wind component variance equation are corroborated by this study.

In view of expected time stalenesses and spatial separations between observation and application points, future wind sensing accuracy is also discussed.

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Executive Summary

The U.S. Army derives artillery accuracy budgets by using a time-space ballistic wind variance formula. The expected variance of the ballistic wind components is obtained by using midlatitude wind profile. To reevaluate the time variablity with an independent data set, 190 hourly profiler soundings of upper-air winds at Platteville, CO, are used. These observations represent 8 days of diverse weather conditions as well as three of the four seasons. Comparisons between the computed ballistic wind variability and that estimated show the formula is an unbiased estimator with a 1 kn precise agreement for a time staleness of 1 h. The equation's accuracy ranges from 1.5 to 3.0 ballistic kn depending on time stalenesses of 2 to 4 h, ballistic line, and season.

1. Introduction

1.1 Purpose and Overview

This report presents results of testing the U.S. Army Field Artillery's ballistic wind time-space variance formula. [1] The formula is initialized with a mid-latitude wind profile and defines the expected ballistic wind component errors used in calculating artillery accuracy error budgets. [2,3] A new evaluation of the wind variance formula was required in order to ensure that the equation-derived results are valid in defining enhanced meteorological (met) measuring accuracy requirements.

Hourly wind profiler soundings are used to compute actual ballistic wind time variabilities; these are compared to the wind variance formula estimates. The results show that the variance equation is an unbiased estimator with 1 kn precise accuracy at a time staleness of 1 h. The rms accuracy range increases from 1.5 to 3 kn depending on increasing time staleness (2 to 4 h), ballistic line, and season.

Future expected wind sensing accuracy is also discussed in terms of expected time stalenesses and spatial displacements between the point of measurement and its application.

1.2 Background

All effective artillery fire includes met aiming adjustments to compensate for wind, temperature, and density variations. The development of met data systems providing accurate representation of these variations is leading toward unobserved first-round fire for effect and immediate suppressive fire. Currently, the timeliness of the weather information is constrained by the launch preparation time and the ascent rate of the balloon lifting the met sensors.

This revisit of the ballistic wind variance formula addresses the following: empirical coefficients, time-space relationship, and the least squares fit. The first concern is to identify each coefficient in the variance formula. Lowenthal and Bellucci presented a generalized formulation to compensate for weather and seasons by including a dependence on wind speed and altitude in their empirical formulation for estimating wind variance. [4] Using Fort Huachuca, AZ, experimental met data, correlation coefficients were derived to define the wind variance formula. Then, for a particular ballistic wind speed profile, one can compute the expected wind variance.

A combined temporal and spatial relationship is assumed in order to simplify the arithmetic. For flat terrain, the formula defaults to the assumption that a 1 h variance is equivalent to that obtained for 30 km of spatial separation. This assumed equivalence may not be representative over complex terrain, in which case the terrain factor should be changed appropriately.

The time-space formula must be used with appropriate values for both the time and space parameters to obtain correct results. For example, if one wants to obtain the effective time variability of a rawinsonde observation (RAOB) report, both the time staleness and the balloon drift (ascent time effect) must be included. Conversely, it is incorrect to consider only the time staleness since a significant component of variability due to the spatial separation between where an observation is made and where it is used is then ignored.

The other ballistic met concern addressed in this report is the functional expression used in the least squares fit. Different functional relationships are fitted to the actual wind variance data. For the large zone (200, 300, 500, 1000, and 2000 m) wind averages and within the time staleness range of the actual computed standard deviation, the results reveal no significant difference between derived estimates using a time trend based on time staleness raised to the 1/2 or 1/3 power. [5,6,7] Significant differences occur for time stalenesses of less than 1 h (where the knee of the curve is more pronounced with the one third power fit); however, it is believed that the differences will decrease once the instrument error is applied at the zero hour time staleness and included in the least squares fit.

This report addresses use of the ballistic wind variance formula to give expected ballistic wind accuracy for future met equipment. Since extensive hourly upper-air balloon soundings were not available, upper-air wind profiler data was used to compute actual wind variances during 8 days chosen to represent different seasons and a fairly diverse set of weather conditions in Colorado. In this study, the Platteville, CO, profiler wind data is used to complete the time variability analysis; simultaneous Platteville and Denver wind profiler data will be used to complete a future spatial variability analysis. The Denver station location was selected because each day contains about 24 complete wind soundings reaching the height of ballistic line 13 (14 km). Comparisons between actual and estimated wind variances reveal that the field artillery wind variance formula represents an unbiased estimator with 1 kn precise accuracy at 1 h time staleness for all seasons and at all ballistic lines.

2. Time-Space Ballistic Wind Variability Algorithm

Originally, the wind variability equation was derived from least squares fits to many replicates of experimental data correlating wind speed differences and time staleness. This can be extended to distance by defining a relationship between the temporal and spatial wind variability. Thus, one can compute the distance separation coefficients from the derived time coefficients, thereby simplifying the variance formula to include a single time-space variable. For temperate latitudes, the generally accepted relationship between time and space staleness is that the variability of 1 h in time is equivalent to that of a 30 km distance. [6] Thus, over fairly level terrain, a message taken 30 km away from a location is considered to give the equivalent accuracy of a message measured at that location 1 h previously. In mountainous terrain or in proximity of large bodies of water, this distance should be reduced. The terrain factor (set to 2) appears in equation (1) below within the time-space variable ($t + 2d$). Blanco lists the following two terrain factors: 2 for flat terrain, and 6 for mountainous terrain such as at White Sands Missile Range (WSMR), NM (where there is not much vegetative cover). [1] Other types of terrain may require different terrain factors.

The time-space variance formula contains two terms, the first representing the environmental variance and the second representing the instrumental measurement error (variance). Adding the variances yields the total expected variability. Generally, the environmental variance is greater than the measurement error. Note that no mention of the ballistic wind direction has been addressed in the variance formula. Since artillery targets are generally located within 180° in the forward area, the formula is designed to estimate a normalized component, which represents the same value for the range and cross component with respect to the fire azimuth. Considering many guns and targets, this normalization is valid. The ballistic wind component variance equation is then described as the following:

$$Var = 0.061(1.0 + 0.03445Sb - 0.05846Zb)^2\,(t + 2d) + var \quad (1)$$

where

Var = ballistic wind component variance (kn^2)
Sb = ballistic wind speed (kn)
Zb = top of ballistic line (km)
t = time staleness (min)
d = displacement including balloon drift (km)
var = sensor ballistic wind speed variance (kn^2)

The coefficients in equation (1) were derived from 960 soundings made over a 2 mo period at Fort Huachuca, AZ, and are representative of a variety of weather conditions. [1]

For a given ballistic wind speed, one can derive the expected variance at any time staleness (less than 6 h) and displacement to include met station location and balloon drift. The formula must be initialized with an available ballistic wind profile.

The standard deviation of the sensor is set to 1 ballistic kn. For deriving results at ballistic line 01, equation (1) is modified as described in Blanco. [1]

2.1 Midlatitude Wind Profile

In 1990, the Army Materiel Systems Analysis Agency (AMSAA) requested that a set of midlatitude wind profiles be analyzed to obtain an annual wind summary. It was intended to use the wind summary as the initialization profile for the wind variance formula to calculate upper-air wind error estimates. The request did not include annual wind direction values; however, the study summarized winter and summer wind directions. The Essenwanger study included 10 yr of twice daily wind profiles at Chateauroux, France, and produced wind profiles representing wind speeds in the following cumulative thresholds: the 50th, 68th, 84th, and 95th percentiles. [2] The 68th percentile wind profile is the field artillery's choice because its values are in the middle of the extremes of the 50th and 95th percentile wind profiles. Figure 1 presents the 68th percentile profile in terms of both wind and ballistic wind speeds.

The 68th percentile wind profile (labeled as unweighted) is converted into an artillery ballistic met message. The resulting ballistic wind profile included in figure 1 represents the integrated effect on surface-to-surface unguided projectiles. The ballistic wind is a single value that is ballistically weighted to represent the expected cumulative wind effect on the projectile from the surface to the top of the specific ballistic line. For example, computation of ballistic line 03 requires averaging the unweighted profile into the following three zones: surface to 200 m, 200 to 500 m, and 500 to 1000 m. These averaged zone speeds are then weighted with the corresponding ballistic weights: 9, 19, and 72 percent. The mean of this sum then constitutes the line 03 ballistic wind. Note that the top zone represents the apogee of a particular projectile's trajectory and contains the largest weight. This is because the projectile spends most of its flight time in this zone. The ballistic wind can then be converted into the expected miss on the target by using the unit effect (m/kn) for the specific artillery round.

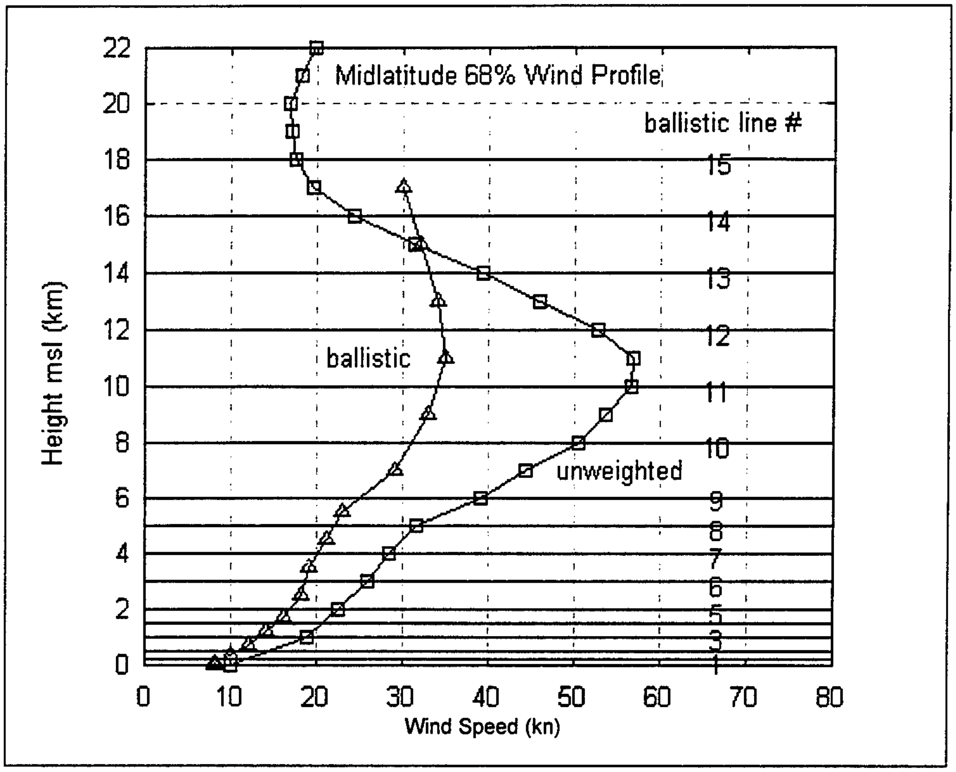

Figure 1. Essenwanger annual midlatitude wind profile.

The midlatitude ballistic wind profile represents the wind effect to be compensated for in aiming artillery at a particular target. In our line 03 example, if the azimuth of fire includes the ballistic wind as a tail wind, then the expected displacement is expressed as the product between the ballistic wind and the unit effect. In order to hit the target, the gun quadrant elevation angle must be reduced appropriately. Assuming that the ballistic wind profile represents the effect of a measured wind profile, this displacement represents the total wind displacement. But, what if this profile is not representative of the wind experienced by the round projected through the atmosphere? The uncertainty then is due to the measurement error and the time-space staleness of the wind profile.

2.2 Field Artillery Ballistic Wind Error Requirements

By initializing the wind variance formula with the above midlatitude wind profile, one can estimate the expected wind variability as a function of time staleness and distance between the measurement and the application. By knowing the anticipated capability of a met system, one can define the expected artillery accuracy. Alternatively, the met system requirements can be assigned according to the desired gun accuracy. AMSAA reported the current and expected observational temporal and spatial capabilities as follows: base case as 2 h staleness and 20 km spatial separation; mid 1990's case as 1 h staleness and 20 km spatial separation; and the year 2000 time frame as ½ h staleness and 10 km spatial separation. [3] The expected wind errors for these capabilities are listed below in table 1.

Table 1. Ballistic component wind errors (kn) for different scenarios

Line number	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**
Top height (km)	**0.2**	**0.5**	**1.0**	**1.5**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**8.0**	**10.0**	**12.0**	**14.0**	**16.0**	**18.0**
2 h 20 (base)	5.3	4.5	4.6	4.8	4.9	5.0	5.0	5.1	5.2	5.9	6.3	6.4	6.1	5.5	4.8
1 h 20 (1990's)	4.7	3.6	3.7	3.8	3.8	3.9	4.0	4.1	4.2	4.8	5.2	5.5	5.3	4.8	4.2
½ h 10 year 2000)	3.9	2.7	2.6	2.7	2.8	2.8	2.9	3.0	3.2	3.8	4.4	4.8	4.7	4.3	3.8

Returning to the line 03 example, one can identify the current midlatitude ballistic wind profile total effect as 14 kn with an uncertainty of 4.6 kn, or one standard deviation. Note that the midlatitude ballistic wind profile contains the maximum value and maximum uncertainty at line 12. Equation (1) has been designed in this manner based on empirical results. As the wind speed increases so does the variability. The negative coefficient then reduces the variability at the higher levels.

3. Wind Profiler Database

3.1 Platteville, CO, Profiler Data

Denver-area profiler data was obtained for two sites: Denver and Platteville, CO. Eight days that incorporate a variety of weather conditions were selected for use in this study from a set of days in which Global Spectral Model (GSM), upper-air, and surface data had previously been collected. Dan Wolfe of the National Oceanic and Atmospheric Administration (NOAA), Environmental Technology Laboratory (ETL), was the contact source for the Denver profiler data (915 MHz), while Doug Van de Kamp provided data from both the 50 and 404 MHz radars located at Platteville. The Platteville radars overlap in their vertical coverage, enabling their merger into one profile extending from the ground to about 17 km above the ground. Meanwhile, the Denver wind data extends typically from the ground to about 6 km above the ground and also includes temperatures between the ground and 1.5 to 2 km above the ground.

The study days include a diverse set of weather conditions. On several days, upper-level winds were up to and in excess of 100 kn, and on one day (13 December 1995) the observed winds briefly exceeded 160 kn. In addition, several days with light and variable large scale winds are also included, and with clear skies the effect of differential heating on the Rocky mountain surfaces affects the low and (sometimes) mid-level flow fields. There are also a couple of days during which clouds and precipitation occurred.

The Platteville data is analyzed to evaluate accuracy of the time variability estimates derived from the time-space variance formula. In this regard, this data set is very appropriate because it includes soundings at higher levels and includes wind profiles every hour during a 24 h period.

3.2 Artillery Formatted Met Messages

The profiler wind data was translated into the artillery computer and ballistic met message formats. In so doing, the winds are averaged into the appropriate zones for each type of message and then ballistically weighted to provide a single value representative of the expected total wind effect. Figure 2 presents these two kinds of met messages for the 24 soundings collected during 13 December 1995, a day during which the strongest winds of the 8 selected days occurred and which also contains one of the higher variabilities.

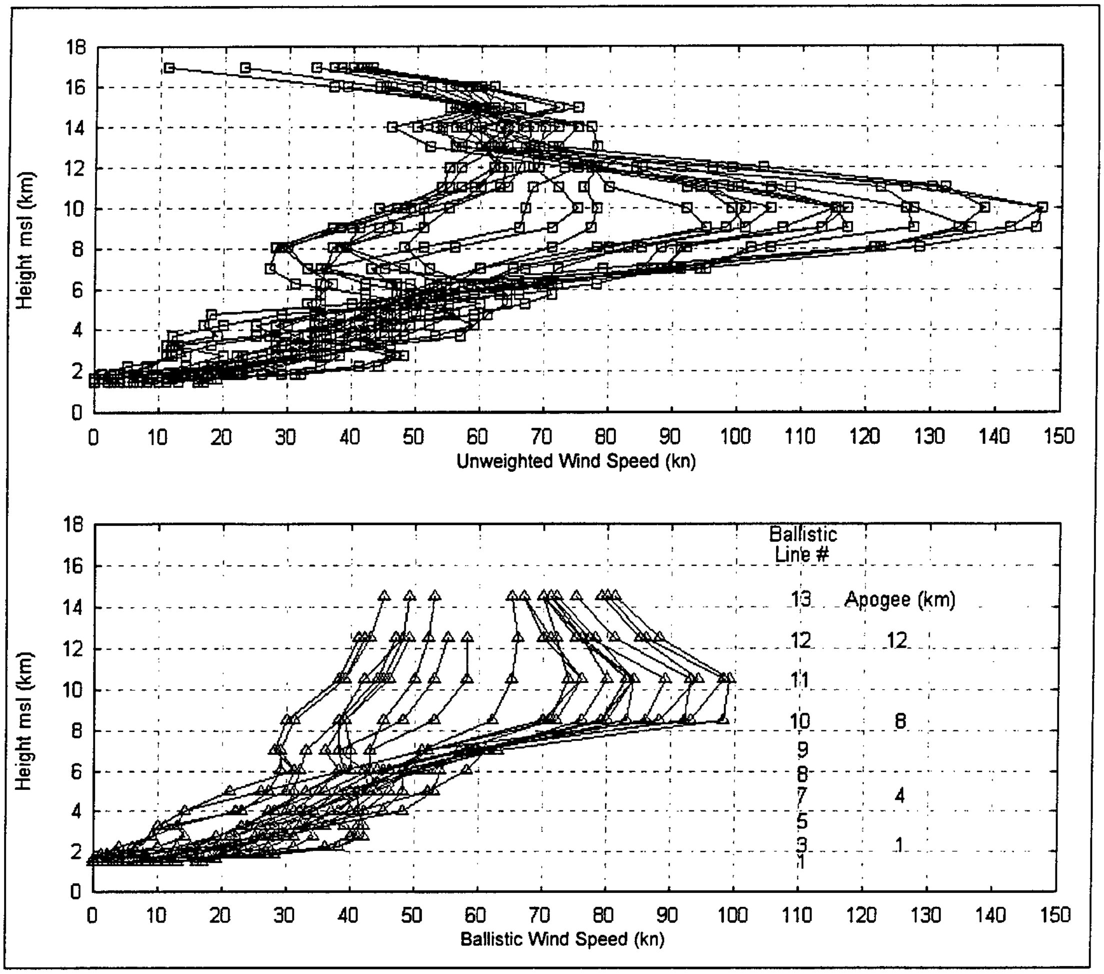

Figure 2. Platteville, CO, artillery met messages for 13 December 1995.

Figure 3 is included to interpret how the ballistic message is applied when aiming artillery. Using a rocket-assisted round, trajectories are simulated from the Platteville met datum plane using standard conditions (no wind) to present the expected range and apogee of the round fired. Again, using our example for ballistic line 03, the effect from the highest tail wind profile (38 kn) is about 312 m. At line 10, the strongest ballistic wind (99 kn) should cause a 2,640 m displacement from the standard impact. These displacements pertain only if the measured met data is applied at the time of aiming; hence, spatial and temporal changes are not included. In general, however, with current capabilities, artillery is being aimed with data that is stale by 2 h and 20 km away. Thus, it is necessary to determine the effect of the expected wind variability so that new wind measurement requirements can meet the desired artillery accuracy.

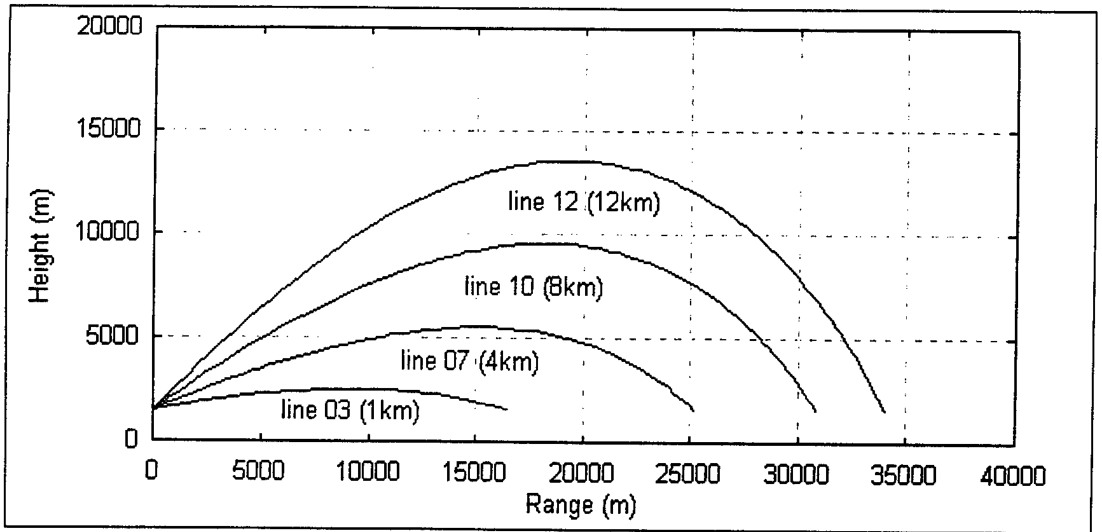

Figure 3. Projectile apogees and ballistic line numbers.

Figure 4 presents the artillery met messages for 30 March 1995, the day containing the lowest wind variability. With the exception of 2 days that include a frontal passage of the observation sites, all the other days contain wind variabilities within the limits presented in figures 2 and 4. The exceptional days are 24 March and 14 April, which exhibit greater variabilities.

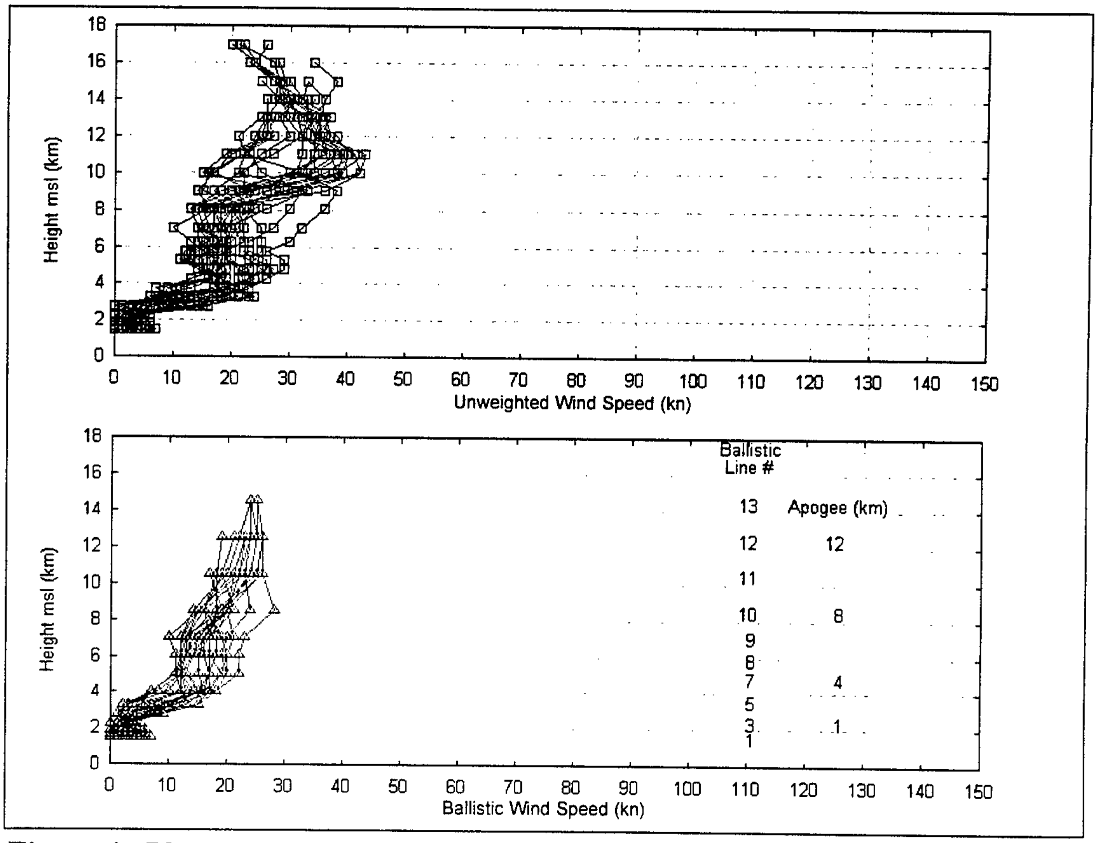

Figure 4. Platteville, CO, artillery met messages for 30 March 1995.

3.3 Variability Computation Methodology

By inspecting figures 2 and 4, one can interpret the actual variability. Each profiler sounding was collected during every hour of the day. Paired soundings are used to compare quantitatively the variability between all possible profiler soundings collected with 1, 2, 3, and 4 h of time staleness. With 24 profiler soundings, there are 23 pairs of 1 h staleness and 20 pairs of 4 h staleness. These pairs are not partitioned between day and night, and the statistics are performed for each wind component at all ballistic lines. All paired differences are calculated, and the resulting mean and standard deviation are used to compute the root-mean-square (rms) of each wind component for every ballistic line.

The ballistic wind variance formula must be initialized with a ballistic wind speed profile. The ballistic rms speeds at each ballistic line are computed for each of the 8 days. These initialization profiles are used to estimate the daily expected wind variability at all ballistic lines.

Since the wind variance formula is used to derive the ballistic wind component uncertainty, the actual range and cross-component rms are averaged to represent a mean component value. The difference between the actual and estimated rms is then used to evaluate the worth of the wind variance formula.

4. Results

4.1 Actual/Estimated Ballistic Wind Variability

Paired statistics for all ballistic lines were calculated; however, the reported results below are for lines 03, 07, and 12 only. Table 2 lists the statistics for a sample size of 8 days (the averaged rms ballistic wind component versus the estimated value).

Table 2. Statistics for actual minus estimated variability comparisons with assumed balloon drift.

	Time Staleness							
	1 h		2 h		3 h		4 h	
Line no.	**mean**	σ	**mean**	σ	**mean**	σ	**mean**	σ
03	0.4	1.0	1.0	1.7	1.4	2.0	1.7	2.2
07	-0.6	1.1	-0.2	1.5	-0.1	1.7	0.0	2.1
12	-2.9	1.9	-2.8	1.9	-2.4	2.4	-1.5	3.6

The comparison results for ballistic line 12 show the largest differences; however, they include as much as 64 km in assumed balloon drift even though all the data was collected at and above Platteville. Therefore, the ballistic wind variance equation needs to be adjusted to represent results applicable to profiler data that have no spatial displacement. Meanwhile, zero balloon drift was used in initializing the variance equation; this assumption is valid since the collection of profiler data is almost real time. Recomputing the variability estimates yields the new statistics listed in table 3, and the new estimated trend is reduced to within the range of the actual computed results.

Table 3. New statistics using no balloon drift

	Time Staleness							
	1 h		2 h		3 h		4 h	
Line no.	**mean**	σ	**mean**	σ	**mean**	σ	**mean**	σ
03	0.5	1.1	1.1	1.7	1.4	2.0	1.7	2.2
07	-0.1	1.1	0.2	1.5	0.2	1.7	0.2	2.1
12	-0.8	0.8	-1.1	1.2	-1.0	1.8	-0.2	3.0

Using the mean ballistic wind speed profiles for each day from the Denver profiler, the variance formula was initialized to compute the variability at Platteville (40 km away). Since the Denver observations only extend to 6 km, these comparisons can only be done for lines 03 and 07. Because the data does not extend to line 07 on 3 days, the data sample size is 5 days instead of the 8 total days. Table 4 shows that the accuracy is as good as the results derived from using Platteville data.

Table 4. Results using Denver mean ballistic winds to compute Platteville variability with no balloon drift

	Time Staleness							
	1 h		2 h		3 h		4 h	
Line no.	**mean**	σ	**mean**	σ	**mean**	σ	**mean**	σ
03	-0.8	0.8	0.1	1.5	0.7	1.8	1.1	2.0
07	-1.1	0.8	-0.3	1.1	-0.3	1.4	-0.2	1.8

Figure 5 presents the actual computed rms ballistic wind component versus the time staleness. The actual variability results are connected with straight lines. In all cases, the variability increases with time staleness. Figure 6 presents the estimated rms ballistic wind component versus the time staleness and includes provision for balloon drift of up to 64 km at line 12, or effectively a time staleness of slightly more than 2 h. The trend of the estimates are mostly within the actual computed results except for the results at ballistic line 12. Balloon drift affects the line 12 results significantly and needs to be removed because the profiler data is not subject to drift. Taking the drift into account, the trend of the estimates at all lines fall mainly within the distribution of the actual data.

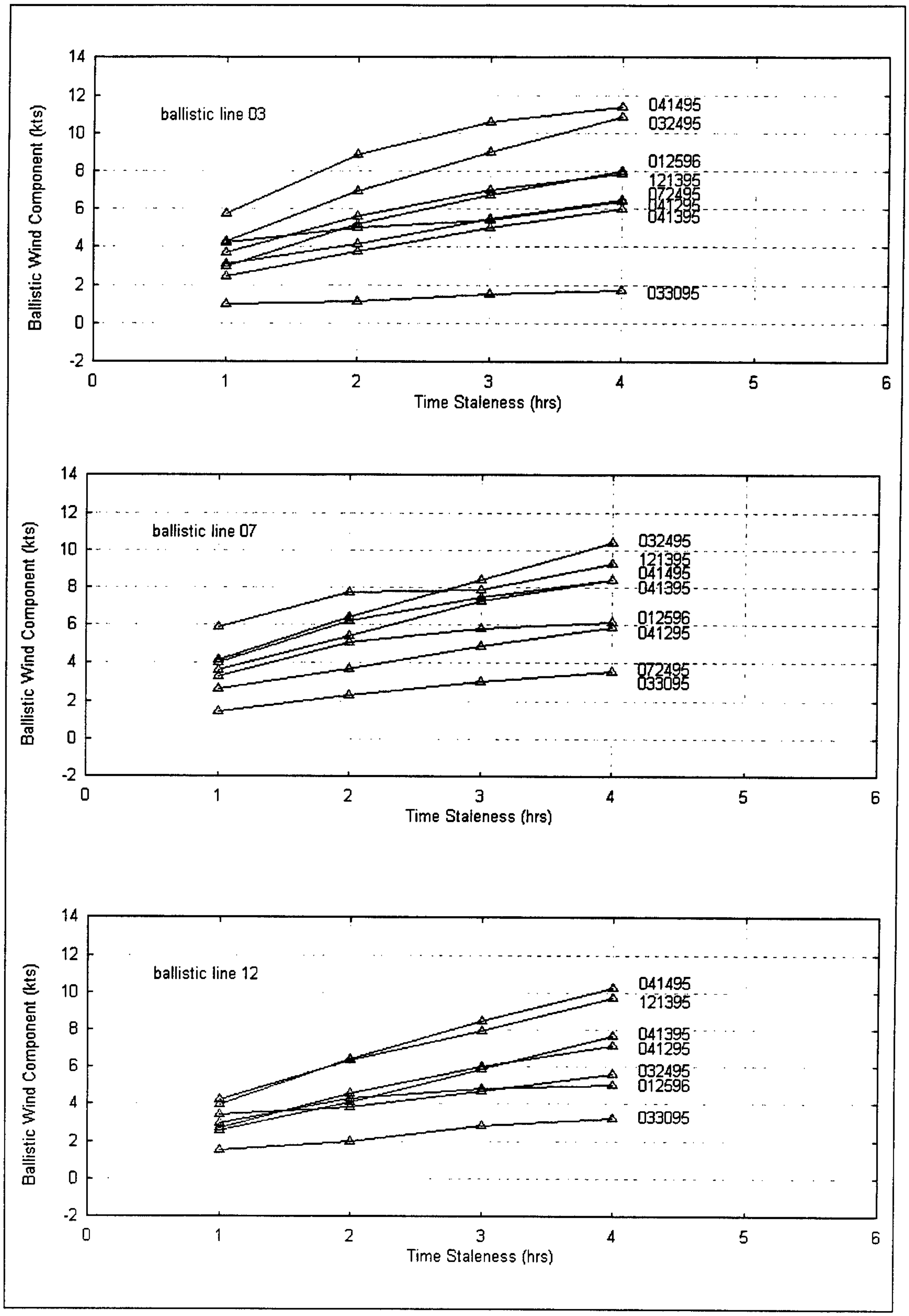

Figure 5. Actual wind variability for the 8 days.

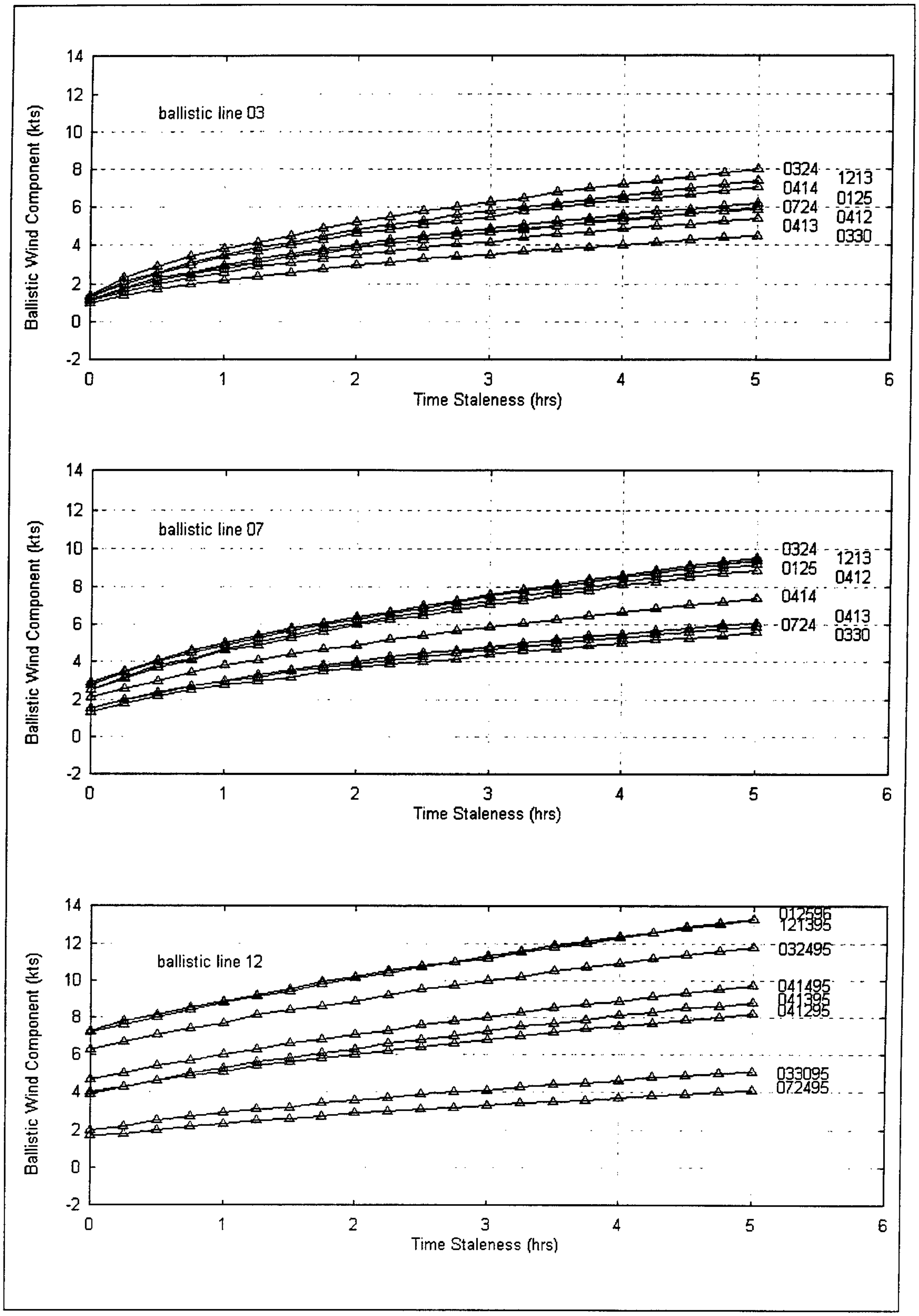

Figure 6. Estimated wind variability for the 8 days.

4.2 Variability/Time Staleness Trend

The day with the maximum wind speed (13 December 1995, which is also a high-variability day) and the day with the lowest variability (30 March 1995) are used to compare the three least squares fits to the actual data. These fits follow the suggestion reported by Lenhard: [8]

$$\sigma = a + bt^{1/2} \tag{2}$$

where

a = instrumental error (kn)
b = coefficient (kn/min)
t = time staleness (min)
σ = estimated error (kn)

Figures 7 and 8 present the comparisons between the three actual data least squares fits and the estimated ballistic wind component time staleness trend. Figure 7 contains the results for 13 December corrected for balloon drift, while figure 8 contains the same information for 30 March. A straight line fit is obtained by replacing the power of t with 1. Following Jasperson, the time trend is also used by replacing the power of t with 1/3. [7] Note that there is no significant difference between the least squares fits for the range in which the variability is computed (i.e., from 1 to 4 h). Extrapolating the fitted curves down to zero time staleness reveals different slopes; however, if the different fits are constrained to a common instrumental error, the interpolated fits are again similar.

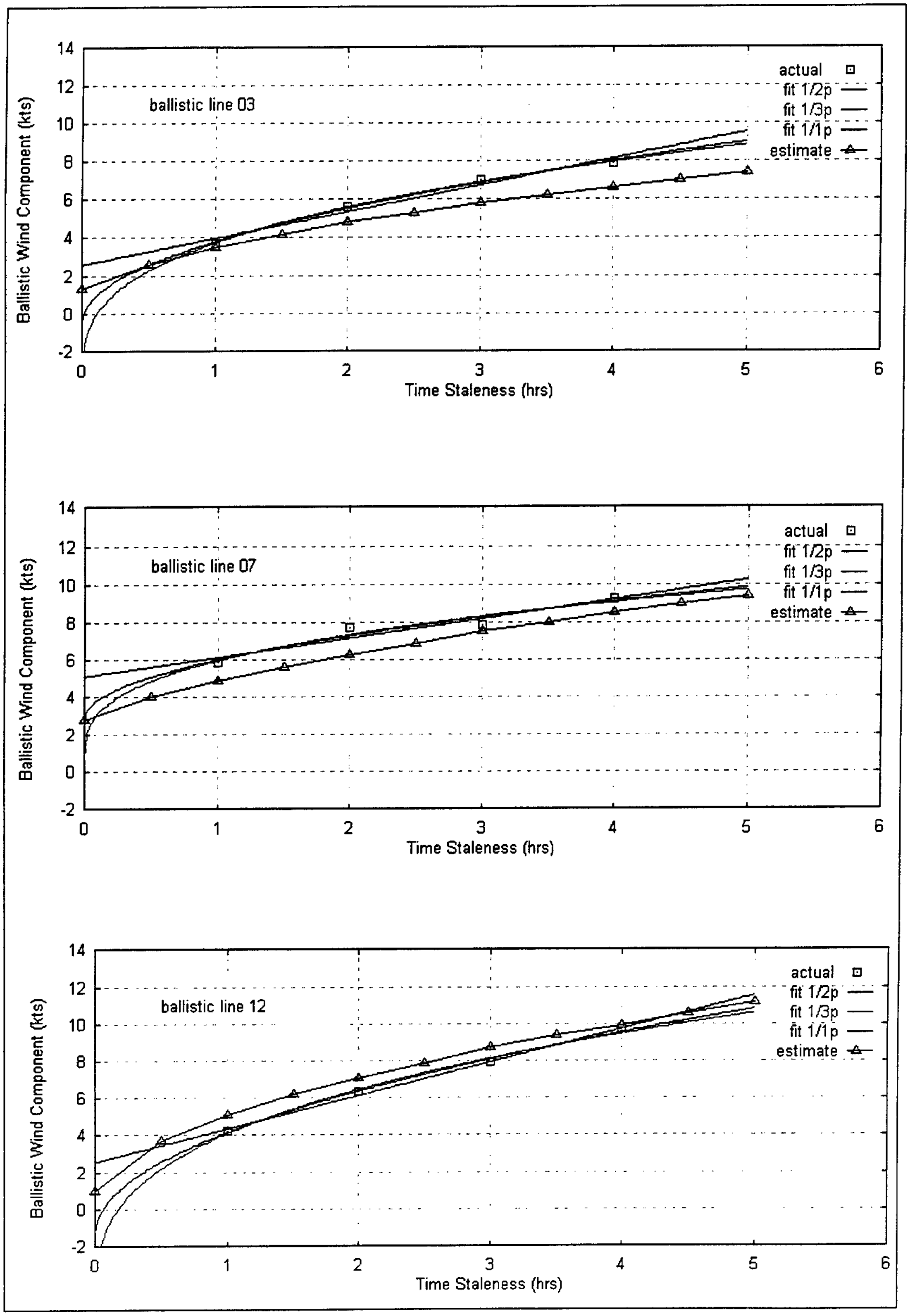

Figure 7. Actual variability fits for 13 December 1995.

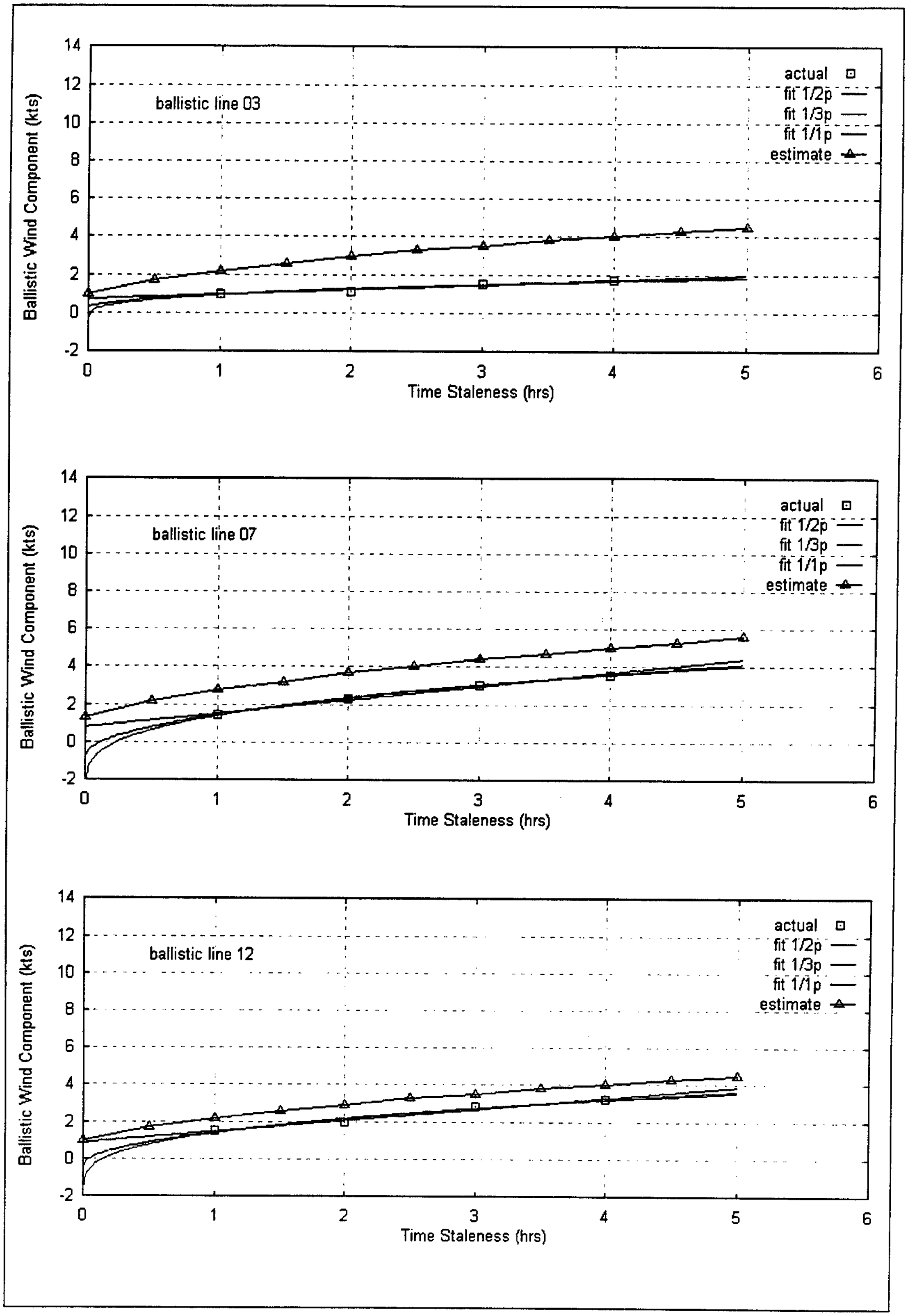

Figure 8. Actual variability fits for 30 March 1995.

5. Conclusions

Hourly profiler sounding data were used to evaluate the accuracy of the field artillery's wind variance equation. In order to compare the profiler data to the variance equation results, it was necessary to adjust the variance equation for a zero wind drift. This is because in contrast to RAOB observations, there is no horizontal displacement associated with a profiler observation. Time and space variability were also evaluated by using the Denver profiler soundings to estimate the variability 40 km away at Platteville for 1, 2, 3, and 4 h periods.

The 8 day wind profiler data set includes diverse weather conditions. Using the 190 hourly upper-air profiler soundings, statistics were calculated with the ballistic wind variance equation. These are shown in table 3. The results indicate that the formula represents an unbiased estimator with a precise agreement of 1 kn with actual variability computed for a time staleness of 1 h. This accuracy ranges from 1.5 to 3.0 ballistic kn depending on 2 to 4 h staleness, ballistic line, and season. The combined time-space variabilities in table 4 show good agreement between the estimated variability calculated with equation (1) and the actual variability of the Platteville observations.

Different least squares fits to the actual computed variability data reveal no significant difference. The 1/2 and 1/3 power time trend results are within the accuracy of the wind variance equation. The current coefficients and time staleness trend used in the ballistic wind component variance equation are corroborated by this reevaluation.

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Acronyms and Abbreviations

AMSAA	Army Materiel Systems Analysis Agency
ETL	Environmental Technology Laboratory
GSM	Global Spectral Model
met	meteorological
NOAA	National Oceanic and Atmospheric Administration
RAOB	rawinsonde observation
rms	root mean square
WSMR	White Sands Missile Range

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