743 TEMPORAL VARIABILITY OF UPPER-LEVEL WINDS AT THE EASTERN RANGE, WESTERN RANGE AND WALLOPS FLIGHT FACILITY

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1. INTRODUCTION

Space launch vehicle commit-to-launch decisions include an assessment of the upper-level (UL) atmospheric wind environment to assess the vehicle's controllability and structural integrity during ascent. These assessments occur at predetermined times during the launch countdown based on measured wind data obtained prior to the assessment. However, the pre-launch measured winds may not represent the wind environment during the vehicle ascent. Uncertainty in the UL winds over the time period between the assessment and launch can be mitigated by a statistical analysis of wind change over time periods of interest using historical data from the launch range. Without historical data, theoretical wind models must be used, which can result in inaccurate wind placards that misrepresent launch availability. Using an over-conservative model could result in overly restrictive vehicle wind placards, thus potentially reducing launch availability. Conversely, using an under-conservative model could result in launching into winds that might damage or destroy the vehicle. A large sample of measured wind profiles best characterizes the wind change environment. These historical databases consist of a certain number of wind pairs, where two wind profile measurements spaced by the time period of interest define a pair.

The Natural Environments Branch at The National Aeronautics and Space Administration's (NASA) Marshall Space Flight Center (MSFC NE) generated wind pair databases at the request of NASA's Launch Services Program (LSP), Databases were produced for five time intervals (0.75-, 1.5-, 2, 3, and 4 hours) at NASA's Kennedy Space Center co-located with the United States Air Force's (USAF) Eastern Range (ER) at Cape Canaveral Air Force Station, USAF's Western Range (WR) at Vandenberg Air Force Base and NASA's Wallops Flight Facility (WFF) from historical data at each location (Figure 1). This paper presents database development procedures as well as statistical analysis of temporal wind variability at each launch range

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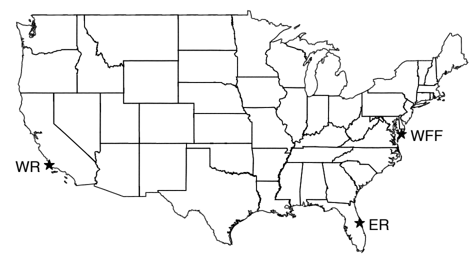


Figure 1: Location of space launch ranges where temporal wind pair databases were developed.

2. DATA SOURCES

The space launch ranges have multiple instrument systems taking UL wind measurements. All three ranges use a rawinsonde system, which measures the wind with a balloon-lofted instrumented package that transmits the data back to a receiving system. The ER and WR also use high-resolution (100-ft interval) wind measurement systems with specially designed balloons known as Jimspheres (Wilfong et al. 1997). Both ranges have multiple vertically pointing Doppler Radar Wind Profiler (DRWP) systems that sample different regions in the troposphere. A splicing technique was developed to merge wind profiles from a 915-MHz Boundary layer DRWP with a 50-MHz mid-tropospheric DRWP to generate a wind profile from roughly 600-60,000 ft (0.183-18.3 km) for use in launch vehicle assessments (Barbré 2013).

Rawinsondes provide the only source of wind data at WFF. MSFC NE obtained two databases of rawinsonde profiles from WFF. The first database consists of profiles from the National Climatic Data Center (NCDC) Integrated Global Radiosonde Archive (IGRA) (Durre et al. 2006) data for the October 1963 through January 2000 period of record (POR). The IGRA data for WFF consists of balloons released from the National Weather Service. MSFC NE obtained the other database of rawinsondes directly from WFF. This database has a POR of February 2000 through January 2013, and consists of rawinsondes released at the NWS site and at WFF in support of mission operations. The IGRA database includes the rawinsonde data that was directly obtained from WFF personnel, which implies that no reason exists to include the IGRA data post December 1999 in the WFF wind pairs database that MSFC NE generated. .

Archived data from rawinsondes and Jimspheres were available for developing the WR wind pair databases. The data came from three sources: IGRA data from January 1965 through January 2013, USAF-provided WR data from February 2008 through April 2012, and a WR Jimsphere database from January 1965 through September 2001. The time overlap between the IGRA and USAF provided WR databases was necessary because the USAF WR archive contains additional rawinsonde data from the Real-Time Automated Meteorological Profiling System (RTAMPS) that is not archived in the IGRA database. The WR wind pair databases do not contain DRWP measurements because extensive time would be required to process the DRWP systems.

Data from the ER DRWP systems provide the largest sample size and are the sole source used for database development. The spliced ER DRWP profile database has a POR of April 2000 through December 2009. This POR results from the availability of quality controlled (QC'd) data for both the 50-MHz and 915-MHz DRWP at the time of wind pair database development. No rawinsonde or Jimsphere data were used because adding these data would have only increased the sample size of the ER database by 0.5%.

3. DATA PROCESSING AND QUALITY CONTROL PROCEDURES

Extensive QC of wind profile data was required to remove suspect data in individual profiles as well as in profile pairs. Automated and manual QC checks were applied on the data from each measurement source (Decker and Barbré 2013). The automated QC checks differed between the measurement sources and consisted of general and task-specific checks. The latter checks were necessary because all of the general QC checks evaluated the data in single profiles and did not check consistency within a profile pair. The development process rejected a profile that failed a given QC check.

Wind pairs can consist of two Jimsphere profiles, two rawinsonde profiles, a Jimsphere and a rawinsonde profile, or two spliced DRWP profiles. A Jimsphere/rawinsonde combination contains an issue in that a difference exists in the smallest resolvable wavelengths between these two wind profiles due to the different systems' sampling intervals. The small-scale wavelengths were removed through a filtering algorithm in order to maintain an equivalent effective vertical resolution between the rawinsonde and Jimsphere systems (Wilfong et al., 1997). An 800-ft filter was applied to the Jimsphere based on a mean normalized power spectrum density (PSD) analysis of the Jimsphere and rawinsonde data (Figure 2). Filtering the Jimsphere data was necessary to use wind profiles from either system interchangeably in assessing wind affects on vehicle performance (Wilfong et al.1997). The RTAMPS mean normalized power spectral density likely contains additional noise in the 500-2000 ft wavelength range. The additional noise was not removed from the RTAMPS data contained in the database since filtering the Jimsphere data to ~2000-ft would remove valid spectral content that is necessary to assess wind affects on vehicle performance.

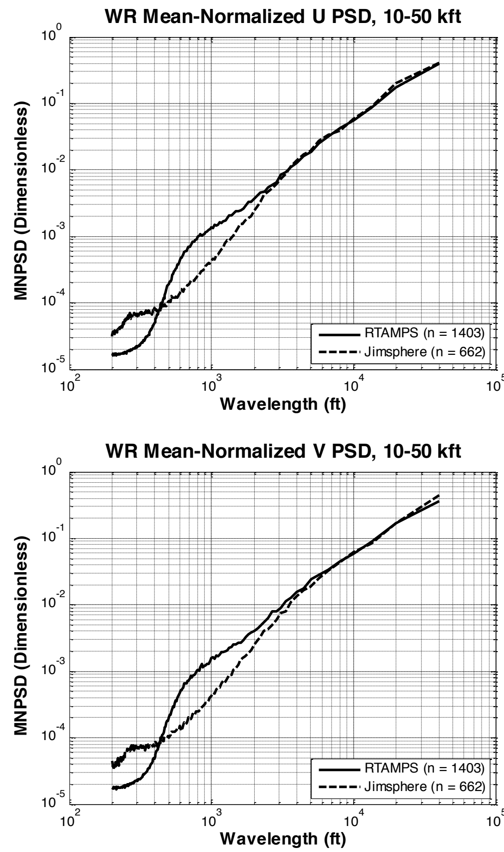


Figure 2: Mean-normalized power spectral density for the WR Jimsphere and RTAMPS rawinsonde systems.

4. WIND PAIR DEVELOPMENT AND ANAYLSIS

Constraining the pair selection to the exact time spacing with the balloon-based WFF and WR profiles limits the number of pairs since balloons are released infrequently. Therefore, for each pair the time range was expanded by +/- 15 minutes to increase the wind pair sample size. For example, profile pairs spaced between 2.75 to 3.25 hours were treated as 3-hour pairs. For the ER, two profiles defined a pair if the desired time separation of the pair +/- two minutes separated the profiles' timestamps. For example, a 0.75-hour (45-minute) pair has two profiles spaced anywhere from 43-

47 minutes apart. The pair selection process used a two-minute window because a large number of DRWP profiles existed and, nominally, at least three minutes existed between adjacent DRWP profiles.

Table 1 presents the resultant number of pairs at each time interval and location that passed the QC screening. The disparity in the magnitude of samples at the ER is due to the continuous operation of the DRWP versus the discrete measurements from the balloon systems used at WR and WFF. The WR's history of supporting space launch operations that require frequent balloon releases attributes to the difference between the number of WR and WFF pairs.

Time Interval (hours)	ER	WR	WFF
0.75	273,265	435	78
1.5	260,878	401	54
2	297,490	548	75
3	273,189	508	127
4	276,108	366	74
TOTAL	1,380,930	2258	408

Table 1: Total number of wind pairs at each location.

The most frequent application of wind pair databases is to apply the empirical maximum zonal (u) and meridional (v) wind change components of each profile into a persistence assessment to determine the effects of wind change over a specific time period on vehicle performance (Smith et al. 1992). Therefore, a large sample size must exist in order to capture the largest range of maximum wind change possible. Several analyses were conducted to determine how well the sample population at each location characterized the wind change extremes.

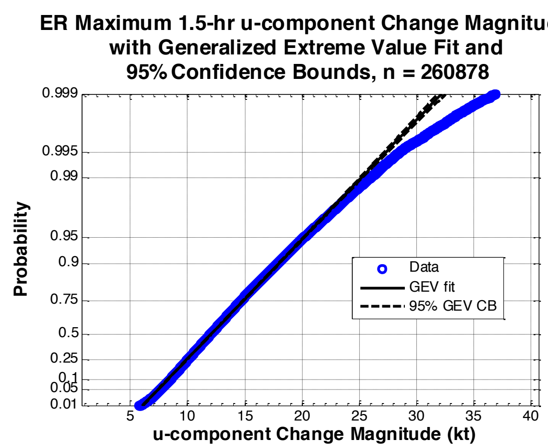
The analyses results quantify the distribution and the confidence bound (CB) in the empirical maximum wind change from the various sample sizes of each pair set. Extreme wind change population distributions are usually non-Gaussian (Merceret 1997), so the use of an extreme theoretical probability function was used to fit the data. The generalized extreme value (GEV) probability distribution function (PDF) (Coles, 2001, Kotz and Nadarajah, 2000) provided a good fit of the extreme u- and v-component wind changes in each pair up to roughly the 99th percentile level. The GEV PDF is expressed by:

$$y = f(x|\, k, \mu, \sigma) = \left(\frac{1}{\sigma}\right) \exp\left\{-\left[1 + k\frac{(x-\mu)}{\sigma}\right]^{-\frac{1}{k}}\right\}\left[1 + k\frac{(x-\mu)}{\sigma}\right]^{-1-\frac{1}{k}} \quad (1)$$

for $k \neq 0$ and $1 + k\frac{(x-\mu)}{\sigma} > 0$,

where x represents each value in a distribution of maximum wind changes, and k, μ, and σ denote the scale, shape, and location parameters, respectively, of the GEV estimate. Using the results from the GEV, 95% CB at various percentile levels were calculated using the Asymptotic Distribution of Percentiles (ADP) method (DasGupta 2008). The ADP equation produces a width of uncertainty as a function of the CB, sample size and percentile level of interest. The analysis uses the 95% CB as a conservative approach to assess the range of extreme wind change for selected percentile levels.

Two distribution plots of the maximum change in wind component magnitudes are presented in Figures 3-4 to illustrate difference in CB as a function of sample population. The cumulative probability, drawn from the probability density function (Wilks 2006), is along the y-axis and the magnitude of the wind component's change is along the x-axis. The sample size of the pairs is correlated to the width of uncertainty at the 95% CB for the highest percentile levels in the sample population (Figures 3-4). As the sample size increases the width of uncertainty at the 95% CB decreases. In addition, a small probability density at a selected percentile level increases the width of uncertainty. The WFF 1.5-hour pairs plot (Figure 4) shows this attribute – where the 95% CB in the v-component change significantly exceeds the bounds in the corresponding u-component change even though the sample sizes for both u- and v-changes are the same.



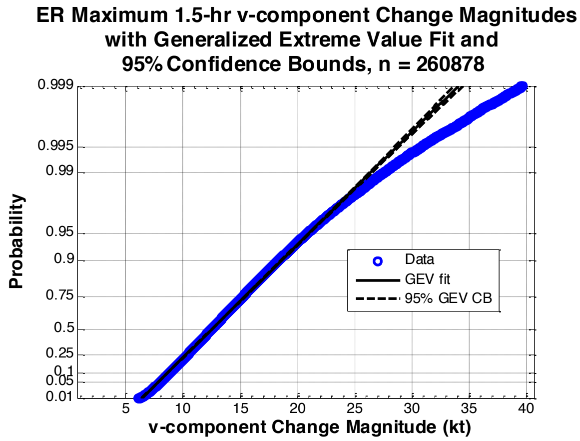
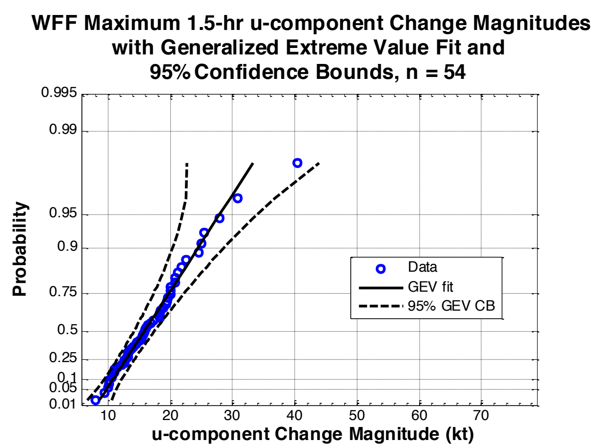


Figure 3: Illustration of a narrow spread in the 95% CB associated with a large sample population. Maximum wind change from the 1.5-hour wind pairs at the ER with 95% CB for the u-(top) and v-component (bottom) wind changes. The magnitude of the wind component change is on the x-axis and probability is on the y-axis. The number of pairs (n) in the analysis is 260,878.

The width of uncertainty in the CB for all the ER pairs (Figure 3) is small due to the large sample size. The deviation of the CBs from the empirical distribution above the 95th percentile level is an artifact of the CB being calculated from the GEV distribution, which does not fit the empirical distribution well. However, the poor fit is not an issue since the sample size is large enough to justify using the empirical percentiles for almost any flight vehicle assessment. The samples of the WFF and WR pairs do not provide this luxury, so the GEV fit must be utilized to characterize extreme wind changes. For the WR and WFF pairs, the 95% CB width of uncertainty increases noticeably at higher probability levels because of both databases' small sample size (e.g., Figure 4).



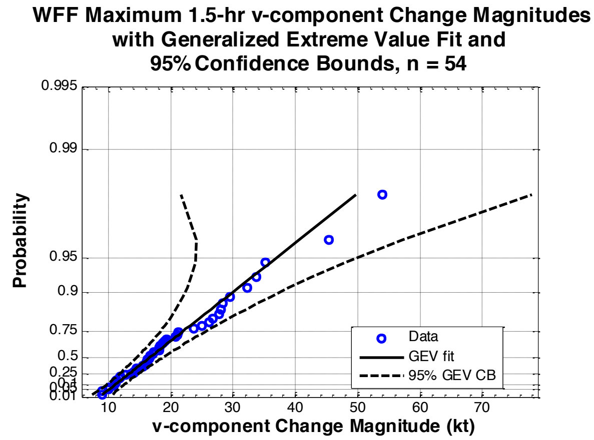


Figure 4: Illustration of a large spread in the 95% CB associated with a small sample population. Maximum wind change from the 1.5-hr wind pairs at WFF with 95% CB for the u-(top) and v-component (bottom) wind changes. The magnitude of the wind component change is on the x-axis and probability is on the y-axis. The number of pairs (n) in the analysis is 54.

Because of the large uncertainty at the extreme empirical percentile for all WFF and WR wind pairs, another approach was applied to quantify the confidence of the empirical wind change data. For example, the WR 95% CB width of uncertainty at the sample size's maximum empirical probability level was approximately 30 kt for both wind components in all the pairs except for 4 hours where the width of uncertainty is ~80 kt (Decker and Barbré 2013). This approach uses a function from Smith and Adelfang (1998) that approximates the probability level of a sample population with a specified sample size to a probability level of the universal population. The function makes no assumption to the form of the probability distribution function of the wind change and is defined as

$$P_u = 1 + \left[(n-1) - \frac{n}{P_s}\right] P_s^n \qquad (2)$$

where P_u is the probability that the sample contains the universal population at the sample probability P_s given the sample size, n. Stated another way; a certain sample size is required to be P_u percent confident the sample contains the P_s value of the universal population. Table 2 presents the confidence level of the sample containing the universal population at various sample probability levels based on the sample size in each WR wind pair interval. For the 366 4-hour wind pairs, there is 88.1% confidence that the pairs contain the 99th percentile of wind change during this time interval. The confidence level exceeds 90% for the other four time periods. These samples are large enough for most vehicle performance applications; however, a low confidence exists that these samples capture wind changes at extreme (e.g., > 99th percentile) levels.

Sample Probability	Time Interval (Sample Size)				
	0.75 hours (435)	1.5 hours (401)	2 hours (548)	3 hours (508)	4 hours (366)
0.500	1.0000	1.0000	1.0000	1.0000	1.0000
0.750	1.0000	1.0000	1.0000	1.0000	1.0000
0.900	1.0000	1.0000	1.0000	1.0000	1.0000
0.950	1.0000	1.0000	1.0000	1.0000	1.0000
0.990	0.9318	0.9102	0.9734	0.9628	0.8813
0.995	0.6400	0.5960	0.7592	0.7215	0.5466
0.999	0.0711	0.0617	0.1050	0.0925	0.0525

Table 2: Confidence levels of the universal population for arbitrarily selected sample probability levels and the WR sample size for each wind pair time interval (Smith and Adelfang 1998).

The WFF samples contain the smallest number of pairs of the three locations. Due to the small sample sizes for each time period, the 95% CB for the observed wind change extremes (~>40 kt) have a large uncertainty, which is more pronounced for the v-component (Decker and Barbré 2013). At each time period the 95% CB for the v-component wind change width is at least 40 kt. The maximum 4-hour v-component wind change of 74 kt exists at the 98th percentile level in the sample population's distribution. The 95% CB for the 4-hr v-component wind change at the 98th percentile level ranges from 40.2 to 89.3 kt (Decker and Barbré 2013).

Table 3 presents confidence levels of the universal population for various sample probabilities based on the WFF sample size. A 16.9% confidence exists that the 4-hour pairs contain the 99th percentile of all wind changes during this period. The confidence levels ranges from 10-36% at the 99th percentile for the other pairs. Due to the low confidence that the sample contains extreme wind changes and large uncertainty in the confidence intervals at probability levels above 95%, MSFC NE recommends to apply the extreme 4-hour wind component change for all time change intervals of interest in vehicle performance evaluations. Applying this recommendation produces more conservative results for shorter time periods, while generating more under-conservative results as the time period approaches 4-hours.

Table 4 presents confidence levels of the universal population for various sample probabilities based on the ER sample size. The confidence is 100% for all time periods and sample probability levels in the table.

Sample Probability	Time Interval (Sample Size)				
	0.75 hours (78)	1.5 hours (54)	2 hours (75)	3 hours (127)	4 hours (74)
0.500	1.0000	1.0000	1.0000	1.0000	1.0000
0.750	1.0000	1.0000	1.0000	1.0000	1.0000
0.900	0.9973	0.9763	0.9965	0.9999	0.9962
0.950	0.9065	0.7592	0.8944	0.9886	0.8900
0.990	0.1836	0.1018	0.1729	0.3629	0.1693
0.995	0.0584	0.0301	0.0545	0.1332	0.0532
0.999	0.0028	0.0013	0.0026	0.0073	0.0025

Table 3: Confidence levels of the universal population for arbitrarily selected sample probability levels and the WFF sample size for each wind pair time interval (Smith and Adelfang 1998).

Sample Probability	Time Interval (Sample Size)				
	0.75 hours (273,265)	1.5 hours (260,878)	2 hours (297,490)	3 hours (273,189)	4 hours (276,108)
0.500	1	1	1	1	1
0.750	1	1	1	1	1
0.900	1	1	1	1	1
0.950	1	1	1	1	1
0.990	1	1	1	1	1
0.995	1	1	1	1	1
0.999	1	1	1	1	1

Table 4: Confidence levels of the universal population for arbitrarily selected sample probability levels and the ER sample size for each wind pair time interval (Smith and Adelfang 1998).

5. CONCLUSION

Temporal UL wind pair databases were generated for NASA's LSP to incorporate into commit-to-launch decisions based on UL wind assessments. Databases for five time intervals (0.75, 1.5, 2-, 3- and 4 hours) at the USAF ER and WR, as well as NASA's WFF were generated through use of historical data at each location. Multiple sources that measure UL atmospheric winds at the requested sites were used. Databases were compiled using wind profiles from rawinsonde, Jimsphere, and DRWP systems. Extensive QC checks were applied on the data to remove unacceptable profiles, and statistical analyses of the resultant wind pairs from each site were performed to determine if the observed extreme wind changes in the sample pairs represent extreme temporal wind change. The resultant ER wind pair databases yielded sample sizes that characterize the extreme wind change environment and no restrictions on the usage of these databases exist.

The WR wind pair database sample size is large enough for vehicle performance assessments up to the 99th percentile level. However, due to the small sample size for each wind pair time period at WFF, low confidence exists that the observed extremes in each time period characterize the extreme wind change environment. Therefore, for any vehicle performance applications at WFF, the recommendation is to apply the extreme 4-hour wind change values for all time change intervals of interest.

Future work would include increasing the number of WR wind pairs by adding data from the WR DRWP systems into the WR temporal wind pair databases. This process would include, at the minimum, QC of the individual 50-MHz and 915-MHz wind profiles. Acceptable wind profiles from each DRWP system would be spliced to generate vertically complete wind profiles and available pairs would then be incorporated into the existing databases.

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- Mr. Matt McClelland, United Launch Alliance: Provided VAFB Jimsphere and rawindsonde data.
- Dr. Brian Sako, Aerospace Corp.: Provided VAFB Jimsphere data.

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