Use of Smoothed Measured Winds to Predict and Assess Launch Environments

Abstract

Since many of the larger launch vehicles are operated near their design limits during the ascent phase of flight to optimize payload to orbit, it often becomes necessary to verify that the vehicle will remain within certification limits during the ascent phase as part of the go / no-go review made prior to launch. This paper describes the approach used to predict Ares I-X launch vehicle structural air loads and controllability prior to launch which represents a distinct departure from the methodology of the Space Shuttle and Evolved Expendable Launch Vehicle (EELV) programs. Protection for uncertainty of key environment and trajectory parameters is added to the nominal assessment of launch capability to ensure that critical launch trajectory variables would be within the integrated vehicle certification envelopes. This process was applied by the launch team as a key element of the launch day go / no-go recommendation. Pre-launch assessments of vehicle launch capability for NASA's Space Shuttle and the EELV heavy lift versions require the use of a high-resolution wind profile measurements, which have relatively small sample size compared with low-resolution profile databases (which include low-resolution balloons and radar wind profilers). The approach described in this paper has the potential to allow the pre-launch assessment team to use larger samples of wind measurements from low-resolution wind profile databases that will improve the accuracy of pre-launch assessments of launch availability with no degradation of mission assurance or launch safety.

Introduction / Space Shuttle Approach Overview

The approach used to validate the Space Shuttle launch day environments was optimized to be compatible with the available wind measurement systems. The approach assumed a high-resolution, radar tracked "Jimsphere" balloon provided a near perfect measurement of the winds aloft in the vehicle flight path. This balloon system was designed in the early 1960s to provide a measurement of wind profile perturbations with wavelengths as small as 400-500ft. This system provides winds aloft data from the ground to about 55,000ft. The balloon rise time is roughly one hour during which time the balloon may travel as much as 100 miles downwind from the balloon release point. The wind is assumed to represent the actual flight path of the launch vehicle without regard to the temporal and spatial variations inherent in the measurement methodology or inaccuracies of the measurement system. An algorithm is applied to the wind data to remove obvious spurious data and the results are reviewed by a meteorologist at the Cape Canaveral Air Force Station (CCAFS). In the mid-1990s a revised tracking system using GPS eliminated the need for radar tracking.

The unfiltered jimsphere wind measurement is input to a trajectory simulation for assessment of structural loads and guidance, navigation and control (GN&C) response relative to constraints. An increment is applied to the constraint variables to protect for potential adverse dispersions in vehicle subsystems (aero, thrust parameters, thrust misalignment, etc.) and wind in-persistence. Known weaknesses in this approach were addressed through the conservative application of dispersion protection increments and the application of a design gust increment to the certification envelopes prior to the launch day assessment.

Weaknesses in the Classical Approach

1. Assessments of vehicle air loads and controllability on launch day requires the use of high-resolution winds aloft measurement systems which are unique to this application.

2. High-resolution balloon systems are limited to vehicle launch sites (the Eastern and Western Test Ranges), and are typically only used to support simulated and actual launch attempts. Due to this, the sample size for high-resolution wind profiles is relatively small compared to other systems.

3. Wind profiles based on GPS tracked balloons are somewhat unreliable (~20% failure rate) because of data dropouts. Since Space Shuttle methodology is sensitive to data dropouts, two balloons are simultaneously tracked to improve reliability.

4. Wind features with wavelengths less than about 4300ft are not persistent over the 90 minutes between the last pre-launch wind measurement and the actual launch time. Launch day structural constraints are decremented to protect for this temporal uncertainty. An additional increment is developed prior to launch day to account for design gust uncertainty. The design gust represents a worst case wind feature with a wavelength less than 1000ft, which is also in-persistent. To protect for the unknown and unpredictable occurrence of this design gust, the structural loads constraints are decremented by the design gust load increment that is variable through the high air load portion of flight. This methodology protects for a small wavelength wind perturbation that could occur during launch but is not measured at L-90 minutes. This conservatism in the increment methodology may result in a no-go condition caused by the gust that may not necessarily occur at launch i.e. there is the possibility of a false no go.

5. Spatial differences between the balloon and vehicle flight paths may result in additional wind uncertainties, which are not specifically included in the protection increment. No attempt to quantify this uncertainty has been made. It has been assumed that the conservatism discussed in item 4 above adequately envelopes this uncertainty.

Approach used for Ares I-X

Due to limited analysis time leading up to the launch of the Ares 1-X vehicle, it was not feasible to address all of the weaknesses in the classical approach described above. Development of protection increments for vehicle structural air loads and controllability needed to be done with the databases available at that time. However, the methodology to compute wind in-persistence protection increments was revised in order to allow the use of all measurement systems available. A proposal was made to develop a launch day assessment methodology around the use of profiles from low-resolution GPS-tracked balloons instead of the previously used high-resolution profiles. The low-resolution profiles include measured winds and atmospheric temperature, pressure, density and dew point. The system has the capability to measure wind features with wavelengths as small as 2000ft. The profiles measured from the CCAFS weather station more closely resemble the profiles obtained by the National Weather Service in support of weather prediction, whereas the high-resolution profile measurement systems are only available at Eastern and Western Test Ranges. Advantages of low-resolution profiles over the high-resolution versions include the potential for reduced cost due to increased commonality with commercial products, a significantly higher termination altitude, and reduction in the number of GPS sonde balloons needed to support launch day assessments.

Development of a wind in-persistence increment requires a database of wind profile pairs separated in time that will represent the time interval between the go/no-go assessment time and the launch time. For the Shuttle program, this database consists of high-resolution wind profiles pairs separated by 2 and 3.5 hour pairs. Approximately 200 CCAFS wind pairs for each time increment are available for each season (winter, summer, and fall/spring). For Ares I-X launch day operations, the go/no-go assessment was conducted about 2 hours before the scheduled launch time. However, low confidence in the results of this assessment due to the small sample size suggested that the increment should be based on the 3.5 hour wind pairs. Trajectory and constraint parameter assessments were made using the first of the pair (pre-launch assessment), which has been smoothed with a filter, and compared to results for the same parameter when assessed using the unfiltered second of the pair (launch environment). The amount of smoothing done on the first of pair was chosen such that that wind features with wavelengths less than about 6700ft were removed. Removal of wavelengths of 6700ft and below effectively removes wind features that are incoherent over a 3.5 hour period (Spiekermann et. al., 2000). Smoothing was accomplished by using a 44th order Gaussian filter, with forward and backward implementation. Figure 1 depicts the magnitude response of the filter and figure 2 shows an example of an Ares I-X launch day wind. The wind in-persistence increment was determined by differencing the maximum deviation from nominal of the second of the pair from the same for the first of the pair. The load data wind in-persistence increment was developed and applied over 10-second intervals. This methodology was intended to provide an uncertainty increment which accounted for wind change from the assessment wind measurement to the actual winds aloft during the ascent phase and for changes in the high frequency content of the wind profile.

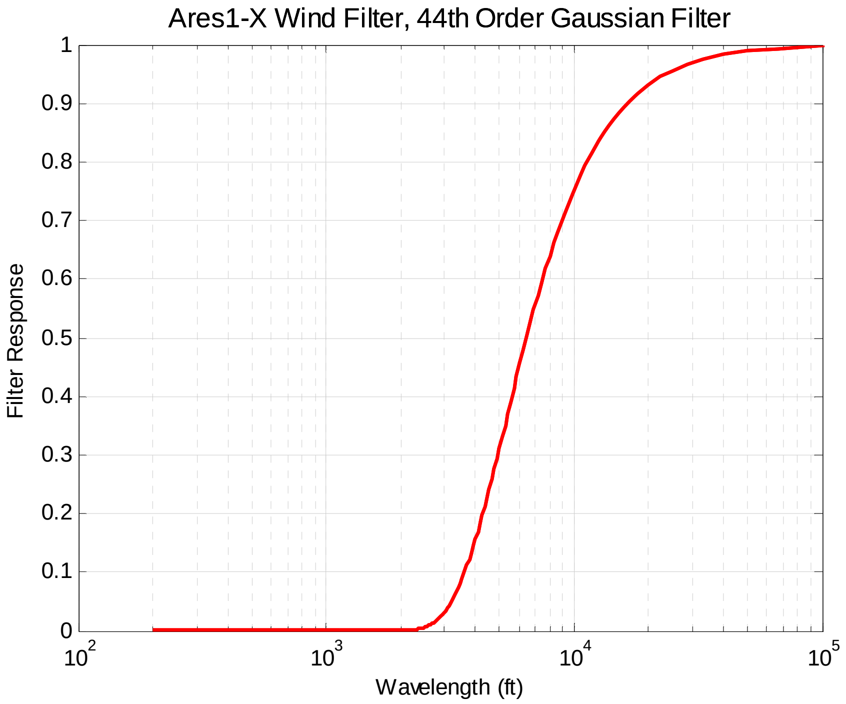

Figure 1. Magnitude response of the filter used to smooth Ares I-X launch day wind profiles.

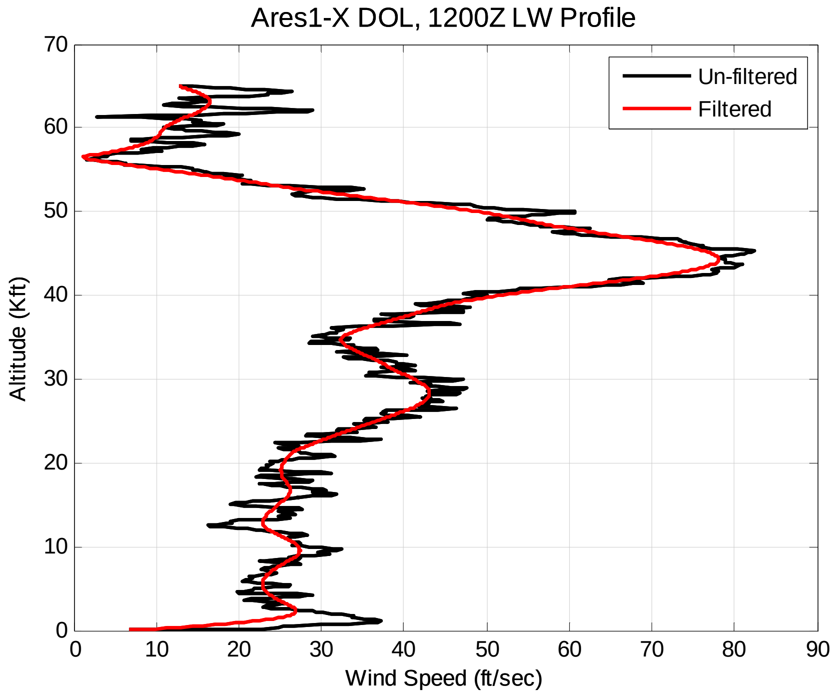

Figure 2. Example Ares I-X launch day wind profile for both the filtered and un-filtered data.

A structural gust load increment for air loads during ascent was developed by application of a design gust at every Mach point. The gust load increment was applied by decrementing the absolute vehicle capability envelope. This increment is intended to conservatively protect for the temporal and measurement uncertainty of a gust throughout the ascent flight profile. This approach is consistent with the approach used by the Shuttle Program.

A Monte Carlo based approach was used to develop vehicle systems and atmosphere dispersion individual load indicator increments. In this approach, 2000 launch simulation assessments were run. Each simulation used a mean monthly wind to ensure that the wind effect was not included in the systems dispersion protection increment. Each run included a 0 to 3 sigma variation of each parameter (aero uncertainty, thrust dispersion, Re-usable Solid Rocket Motor [RSRM] burn rate, thrust misalignment, etc.). The parameter variations were varied to be consistent with each parameter's dispersion distribution. Trajectory and structural loads parameters were assessed for each run. Distributions of each parameter or load were developed such that a 3 sigma dispersion delta could be calculated. Figure 3 depicts the time-based increment for the system dispersion of load parameter Qalpha-total. Load indicator increments are developed and applied over 10-second intervals.

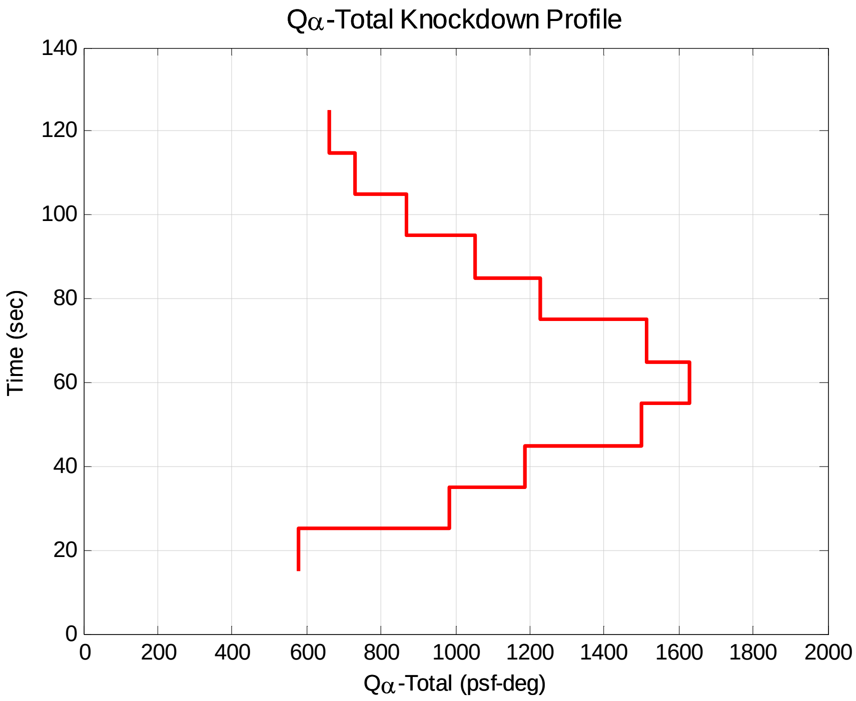

Figure 3. Time-based protection increment for Ares I-X load variable system dispersions.

Launch day structural loads assessments were made using filtered low-resolution balloon wind measurements. The filtered wind profiles were input to a trajectory simulation program. Trajectory simulation results were used to estimate undispersed structural loads during the ascent phase. The structural loads estimates were increased by the root sum square (RSS) of the systems dispersion increment and the wind in-persistence increment previously calculated. The RSS was used since these two dispersions are considered independent. This dispersed load estimate was compared to the adjusted vehicle capability envelope. The adjusted vehicle capability envelope was developed by reducing the full capability envelope by the previously calculated gust increment. If the estimated dispersed loads were contained by the capability envelope, the launch was a "go" from a winds aloft standpoint. The Load is "Go" if the day-of-launch (DOL) simulation load plus the RSS of the systems dispersion and wind in-persistence increments is less than the load capability minus the gust load, as illustrated in the following equation. Otherwise the load is forecast to be larger than capability and the load is “No-Go”.

$DOL\ Sim\ Load(i) + \sqrt{\ }(sys\ dispersion\ load\ inc(i) ** 2 + (wind\ in - persistence\ load\ inc(i) ** 2)) < Load\ Cap(i) -\ Gust\ Load(i)$ where i = 1 through the number of load indicators assessed

Parameters assessed include all available load indicators and significant trajectory parameters, such as, dynamic pressure times total angle of attack (also known as Q_alpha).

Future Refinements to this Methodology

1. Augmentation of the limited wind pair database

The limitations of the size of the high-resolution wind pairs database should be addressed. In combination with the change in methodology suggested by this paper, it is proposed that the database be expanded with the inclusion of a large number of CCAFS Doppler Radar Wind Profiler (DRWP) measurements.

Proper utilization of this expanded database may require that the wind pairs be smoothed in such a way as to reduce or eliminate differences between the resolution of the high-resolution wind pairs and the DRWP wind pairs. It is suggested that all wind features below the maximum resolvable wavelength of the DRWP be removed from both the DRWP and the HR wind pairs data sets prior to trajectory assessments.

A methodology for addressing the missing DRWP wind data below ~7500ft and above 60000ft should be developed. Work is currently underway to build radar wind profiles from near the surface to 60000ft. Data from multiple DRWP sources at the launch site (915-MHz and 50-MHz) can be integrated together to generate wind profiles from 1500ft to 60000ft.

2. Analysis of spatial variations in wind measurements

Up to this time any differences due to the displacement of the balloon to the actual space vehicle flight profile have been ignored or been considered enveloped by the conservative dispersion increment methodology used. An assessment of the trajectory and constraint parameter differences due to spatial variation should be completed in order to take full advantage of this methodology change.

It is proposed that this assessment could be made either by a limited assessment of trajectory and constraint parameter differences between a simultaneously measured/released DRWP (fixed) wind profile and a low or high-resolution balloon wind profile. If the differences are significant when compared to the RSS of the systems and wind inpersistence increment, a more refined assessment and expansion of the spatial variation database may be required.

It may be possible to correlate spatial variation to temporal variation which could simplify development of an increment.

3. Investigate the potential reduction in wind inpersistence protection as the measurement moves closer to launch

An earlier paper (Spiekermann et. al., 2000) showed a relationship between wind measurement time before launch and the wavelength of wind features expected to remain in place (i.e., persist) until launch time. It may be possible to use this relationship to reduce the amount of wind in-persistence protection required to protect for wind change as the wind change moves closer to launch. A meaningful change would require use of a DRWP wind profile taken as close to launch as possible.

4. Develop DRWP wind profile trajectory assessment methodology

Since the DRWP provides wind data between 7500ft and 60000ft, a methodology for either filling the missing data from another wind measurement source or completing an assessment that supports ignoring the missing data is required in order to use the DRWP for any launch day operations.

Summary / Observations

The plan outlined in this paper addresses a number of weaknesses in the traditional methodology used to assess launch day loads due to winds aloft. Implementation of this approach will improve launch availability by reducing conservatism that has been included in the uncertainty protection due to limitations in the measurement systems previously available. In particular, an assessment methodology which relies on a DRWP based final assessment will result in improvements in the realtime understanding of launch day winds aloft impacts to structural loads which will translate directly in to improvements in safety and an increase in launch availability.

References:

C. E. Spiekermann, B. H. Sako, and A. M. Kabe, “Identifying Slowly Varying and Turbulent Wind Features for Flight Loads Analysis,” J. Spacecraft and Rockets, Vol. 37, No. 4, July-August 2000, pp 426-433.