5.12-P Profiler Support for Operations at Space Launch Ranges

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1. Overview. Accurate vertical wind profiles are essential to successful launch or landing. Wind changes can make it impossible to fly a desired trajectory or avoid dangerous vehicle loads, possibly resulting in loss of mission. Balloons take an hour to generate a profile up to 20 km, but major wind changes can occur in 20 minutes. Wind profilers have the temporal response to detect such last minute hazards. They also measure the winds directly overhead while balloons blow downwind. At the Eastern Range (ER), altitudes from 2 to 20 km are sampled by a 50-MHz profiler every 4 minutes. The surface to 3 km is sampled by five 915-MHz profilers every 15 minutes.

The Range Safety office assesses the risk of potential toxic chemical dispersion. They use observational data and model output to estimate the spatial extent and concentration of substances dispersed within the boundary layer. The ER uses 915-MHz profilers as both a real time observation system and as input to dispersion models. The WR has similar plans.

Wind profilers support engineering analyses for the Space Shuttle. The 50-MHz profiler was used recently to analyze changes in the low frequency wind and low vertical wavenumber content of wind profiles in the 3 to 15 km region of the atmosphere. The 915-MHz profiler network was used to study temporal wind change within the boundary layer.

2. Requirements. Vehicle operators would like errorless wind measurements and infinitely fine spatial and temporal resolution. In practice, the accuracy of balloons (1 m/s RMS with essentially zero bias) is acceptable and readily achievable with modern profilers and software. Users must be assured that data will be available and will meet advertised accuracy and timeliness specifications. Anything less than 98% reliability is unacceptable for spaceport operations.

Vertical resolution is Nyquist-limited to twice the sampling interval. If the atmospheric signal is weak, then the effective resolution will be noise-limited to scales large enough to produce measurable signals. The ER 50-MHz profiler is Nyquist-limited to 300m resolution. The performance of the 915-MHz profilers is consistent with Nyquist limitation at 200m. Recent analyses have shown that 300m resolution is more than adequate for operational use (*e.g.* Spiekerman, C.E., B.H. Sako and A.M. Kabe,2000: Identifying slowly varying and turbulent wind features for flight loads analysis, *J. Spacecraft and Rockets*, **37**, 426-433.).

Near jet streams, small motions of the jet boundaries can cause rapid wind changes at a given location. Changes large enough to cause mission failure have been observed in 30 minutes or less over the ER in the winter and spring. On the other hand, changes over periods less than five minutes will not be large enough to violate the safety margins built into operational launch constraints. Thus, the 4 to 15 minute temporal sampling rate of the current operational profilers is adequate.

3. Current state of the art. Wind profilers have been used on launch ranges for over a decade and today support launch and landing operations as well as personnel and property protection functions. The ability to make accurate measurements directly overhead at time scales of a few minutes makes the technology uniquely suited to real time decision processes.

Commercial signal processing software handles interference and low signal to noise ratios poorly. Therefore, the ER and WR implemented their own unique signal processing and quality control software. The Median Filter First Guess algorithm (Wilfong,T.L., S.A. Smith and R.L. Creasey, 1993: "High temporal resolution velocity estimates from a wind profiler", *J. Spacecraft and Rockets,* **30(3)**, pp 348-354.) for the 50-MHz profilers provides frequent, precise profiles of sufficient quality to feed directly into a vehicle loads program. The 915-MHz profilers use commercial consensus software, so the data must be manually interpreted or passed through a post measurement QC process like that reported by Lambert *et al.* (2003, Performance of five 915-MHz wind profilers and an associated automated quality control algorithm in an operational environment, *J. Atm. & Ocean. Tech.,* **20(11)**, 1488-1495).

4. Suggestions. Fully automated signal processing for direct launch support is not acceptable: a single bad measurement could put a vehicle at risk or unnecessarily scrub a launch or landing. However, improved automation could reduce the amount of manual processing required.

Commercial technology suffers from major limitations in software and hardware. Despite many improvements, erroneous measurements remain common. Typically, beams are steered using high-power mechanical relays rated only for about a million cycles. Digital beam steering would enable fast, relay-free switching between four or more opposing oblique beams. Vertical velocities could be precisely computed and the underlying homogeneity and stationary assumptions verified.

Ranges require rapid wind measurements. The variability of winds across different antenna beams due to gravity waves, convection, or other causes may generate meteorological noise in the wind component estimates. An assessment of the contribution of meteorological noise should be provided as an error estimate based on separate evaluations of the temporal and spatial variability of the wind. Temporal variability on each beam can be established from time series of measurements. Checking horizontal spatial variability across beams requires four or more beam-pointing directions.

Profiler vendors need to adopt improved real-time methods of separating the wind signal from interference and noise in the Doppler signal. There are several ways this could be accomplished, and at least one of them has already been implemented and thoroughly tested at the ER.

5. Conclusion. Radar wind profilers are an important tool for space launch ranges. The current state of the art is acceptable but significant improvements are possible and desirable, especially in commercial products. For additional detail and references, see the appendix to this paper on the ISTP7 CD.

Appendix

Note to the reader: This "Appendix" is the complete paper for which the two-page print version is an extended abstract.

1. Overview

This paper examines the requirements for high-resolution wind profiling to support launch, landing and ground support operations at space launch ranges. It explains why wind-finding balloons alone are not adequate to provide the level of safety and launch availability obtainable on a modern range. The current state of the art in operational radar wind profiling for support of range operations is discussed, as well as some suggested improvements to the operational systems and software.

Accurate assessment of the vector wind as a function of altitude is essential to a safe, successful launch or landing. Unexpected wind changes can make it impossible to fly the desired trajectory or may impose unacceptable aerodynamic loads on a vehicle. The result can be loss of mission or even loss of vehicle with its payload or crew. Balloons take an hour to generate a wind profile from the surface to 20 km, the region in which a correct assessment of the winds is most critical. Major wind changes can occur in 20 minutes. In addition, balloons blow downwind away from the launch or landing site. Only wind profilers have the temporal response to detect last minute hazards and they measure directly overhead. At the Eastern Range (ER), which provides weather support for both the Kennedy Space Center and Cape Canaveral Air Force Station, the region from 2 to 20 km AGL is covered by a 50-MHz profiler that produces a profile every 4 minutes. The region from the surface to 3 km is covered by a network of five 915-MHz profilers that generate profiles every 15 minutes. A companion paper (Case *et al.* 2006) discusses some of the boundary layer phenomena, including low level jets, which have been observed with the ER profiler network. The Western Range (WR) is scheduled to be similarly equipped.

Range Safety offices at the ER and WR assess the safety risk due to toxic chemical dispersion for their respective spaceports. They use observational data and output from models that calculate the expected spatial extent of substance dispersion and the expected concentrations within the boundary layer. The WR does not yet use profilers but has plans to do so. The ER uses its 915-MHz profilers as both a real time observation system and as input to dispersion models (Boyd *et al.* 2006). They also use the data to modify the lower levels of the most recent sounding taken during an operation, and then use the modified sounding to initialize or nudge their operational dispersion prediction model. ER Range Safety is developing a three-dimensional dispersion model that will be initialized directly by the data from the 915-MHz profilers, wind towers and rawinsondes.

Wind profilers are also used to support engineering analyses for the Space Shuttle Program. The 50-MHz profiler has been used in analyzing change in the low frequency wind content contained in wind profiles in the 3 to 15 km region of the atmosphere. The 915-MHz profiler network has been used in a study of temporal wind change within the boundary layer, 0.5 to 1.4 km.

Long vertical wavelength spectral wind content is used to shape the vehicle's trajectory and determine trajectory dynamics, known as Initialization-Loads (ILOADS), during the first stage of ascent, 3 to 15 km. Large changes in the winds over a ~2.3 km (7500 ft) interval can invalidate vehicle steering commands. 50-MHz profiler data were used to verify balloon-derived wind change boundaries. Those boundaries are used as close to launch as possible on day of launch to evaluate the low wavenumber temporal wind change from the initial wind profile.

Recently the Shuttle program implemented safety margins for vehicle loads at altitudes between 0.5 and 1.4 km to account for wind temporal uncertainty in the atmospheric boundary layer. A study was conducted to determine if time of day influence on wind persistence in the atmospheric boundary layer is adequately represented in the certified wind change databases. Data from the 915-MHz profilers at the ER were used as a verification tool to assess the variability in wind change over a 2-hr period.

2. Requirements

Vehicle operators would like wind measurements with no error and infinitely fine spatial and temporal resolution taken along the planned flight track of the vehicle. In practice, the accuracy of balloons, 1 m/s root mean square (RMS) with essentially zero bias, is acceptable and readily achievable with modern profilers and software (Wilfong *et al.* 1993; Schumann *et al.* 1999).

Vertical resolution is limited to twice the vertical sampling interval by the Nyquist theorem. If the atmospheric signal at the smaller scales is smaller than the RMS noise of the measurement, then the effective resolution will be noise limited to scales large enough to produce measurable signals. The ER 50-MHz profiler is usually Nyquist limited to 300m resolution. No quantitative evaluation of the resolution of the 915-MHz profilers has been made, but their performance appears consistent with Nyquist limitation at 200 meters. Although high resolution wind finding balloons can resolve scales as small as 100m, recent analyses have shown that 300m resolution is more than adequate for operational use (Spiekerman *et al.* 2000; Merceret 2000). For engineering analyses and the development of statistical data, the higher resolution of the balloons can be useful.

For safety and mission assurance, it is necessary to have complete profiles at intervals smaller than that over which significant wind changes can occur. Near jet streams, small motions of the jet boundaries can cause rapid temporal wind changes at a given location. Changes large enough to cause a mission failure have been observed in less than half an hour over Cape Canaveral in the winter and springtime (Merceret 1997). On the other hand, changes over periods less than five minutes will not be large enough to violate the safety margins built into operational launch constraints. Thus the 4 to 15 minute temporal sampling rate of the current operational profilers is adequate.

Wind profiles should be taken as close to the flight track as is feasible to minimize the effects of spatial variability on the degree to which the measurements are representative of the environment through which the vehicle will fly. In the vicinity of jet stream boundaries there are large horizontal gradients that can cause large differences between balloon-measured profiles and radar profiles because the balloon blows downstream and the resulting profile is not truly vertical, but slanted. Ideally, an operational wind profiler will be located as close to the launch or landing site as feasible.

Operational users must be assured that the data will be available and the data will meet the advertised accuracy and timeliness specifications. The major cause of unreliability with operational profilers on the ER has been outages associated with maintenance or communications. Maintenance outages can be reduced by designing reliability into the instruments and also by designing them to facilitate quick diagnosis and repair when they do fail. Anything less than 98% reliability is unacceptable for spaceport operations.

3. Current State of the Art

Wind profilers have been used on the ER and WR for over a decade (*e.g.* Beran and Wilfong 1998) and today support virtually all phases of launch operations as well as personnel and property protection functions. The ability to make accurate measurements directly overhead at time scales of a few minutes makes the technology uniquely suited to real time decision processes.

Although current commercial wind consensus-based profiling software is inadequate for operational range use, the current state of the art has some significant strengths. First, the Median Filter First Guess (MFFG) algorithm used on the ER 50-MHz profiler provides profiles that are both more frequent and more accurate than the commercial software (Wilfong *et al.* 1993; Schumann *et al.* 1999). In addition, it permits (but does not require) real-time interactive manual quality control (QC) of the data. Real-time manual QC is an essential requirement for any wind measurement that will be fed directly into a vehicle guidance or loads analysis program because a single bad datum could either unnecessarily scrub a launch or landing or permit an attempt under unsafe conditions. The MFFG algorithm has proven adequate to support Atlas, Shuttle and Titan operations at the ER for a decade.

Second, there are post-measurement automated QC algorithms that work very well. The QC package tested by Lambert *et al.* (citation) passed fewer than one erroneous measurement in 3000. The most significant drawback to their use is the delay between the measurement and availability of the QC'd data. Many of these algorithms use temporal continuity as a component of the QC process, and QC of the current profile requires the following profile to be available. For some operational applications, this delay and error rate is acceptable, allowing fully automated use of the instruments.

That said, the operational use of wind profilers is generally far from totally automated. Commercial implementations of profiling technology still suffer from poor performance in the presence of persistent interference and low signal to noise ratios. The demand for high quality products at high temporal frequency drove the ER to implement the unique signal processing and QC software described above. Although these improved algorithms are available in the open literature for general use, commercial vendors have not elected to adopt them, nor have they developed their own.

4. Suggestions

Although, as noted above, fully automated signal processing for direct launch support is not acceptable because a single bad measurement could put a vehicle at risk or unnecessarily scrub a launch or landing, improved automation could reduce the amount of manual processing required. For routine operations and model initialization, fully automated signal processing is both practical and desirable. Much progress has been made in the past decade (*e.g.* McLaughlin and Merritt 2005 or Weber et. al. 2004), but changes have been slow to appear in commercial products. The advent of powerful, inexpensive computers and digital receivers has driven many improvements (*e.g.* Wilfong *et.al.* 1999), but erroneous measurements still are common. Commercially available technology suffers from two main limitations – signal processing methods and hardware.

A major hardware/firmware improvement we recommend is the adoption of digital beam synthesis and switching. Typically today, beams can only be steered to pre-determined positions (fixed zenith and azimuth) and the high-power mechanical relays needed to switch the pointing of the array are only rated for one to two million cycles. The very presence of a mechanical beam steering unit mandates a less than optimal dwell strategy to minimize the maintenance problems associated with the mechanical relays. Digital beam steering would permit fast economic switching between opposing oblique beams (4+ beam systems). That would allow vertical velocities to be more precisely computed or eliminated and the underlying homogeneity and stationarity assumptions to be verified.

On the software side, while some systems today are capable of pointing in five directions, the signal processing implementations do not use the opposing beams to compute vertical velocities, or indeed, to verify the underlying assumptions of horizontal homogeneity and stationarity implicit in all Doppler beam swinging wind profilers. Instead, it has traditionally been assumed either that uniform conditions exist or that time averaging (typically 30 minutes to an hour) will significantly reduce errors from these effects. Of course, neither assumption may be valid. In particular, range applications require high-time-resolution wind measurements that preclude averaging long enough to satisfy the assumption. Spatial variability of radial velocities across different antenna beams (*e.g.* due to gravity waves, convection, or precipitation) may generate meteorological noise in the wind component estimates. An assessment of the contribution of meteorological noise should be provided in the form of an error estimate based on separate evaluations of the temporal and spatial variability of the wind. Temporal variability on each beam can be established from time series of measurements. Checking horizontal spatial variability across beams requires four or more beam pointing directions.

Profiler data often contain multiple signals, *none* of which may be due to radar return from the atmosphere. A limiting assumption in most current implementations is that the atmospheric return is the only signal present. Contamination can obscure or be mistaken for clear-air return from the atmosphere, resulting in erroneous or even meaningless measurements. Traditionally, radial velocities are submitted to such a consensus-type filtering which require relatively long (typically 30-60 min) averages in order to eliminate spurious measurements. While the widespread consensus technique is effective at eliminating intermittent spurious data, it is ineffective in the presence of persistent contamination.

A quick improvement for commercial profilers would be to incorporate the range-tested MFFG algorithm discussed in Section 3 in their off-the-shelf software. More sophisticated approaches that take advantage of the power and speed of modern desktop computers might include the capability to recognize and track multiple Doppler signals coupled with algorithms to determine which signal is the atmospheric signal.

5. Conclusion

Wind profilers are important Range assets. Their ability to make rapid, accurate measurements in the immediate vicinity of ascending or landing spacecraft gives them substantial advantages over the older balloon-based technologies. Although the ER has implemented substantial improvements over previously available signal processing and automated quality control algorithms, the commercial market has not yet adopted them. Digital beam synthesis and steering coupled with next-generation signal processing software has the potential for even greater improvement of data quality and opportunity for increased automation.

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