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APPLICATION OF 50 MHz DOPPLER RADAR WIND PROFILER TO LAUNCH OPERATIONS AT KENNEDY SPACE CENTER AND CAPE CANAVERAL AIR STATION

Robin S. Schumann * and Gregory E. Taylor

ENSCO, Inc./NASA KSC Applied Meteorology Unit

Steve A. Smith

NASA Marshall Space Flight Center

Timothy L. Wilfong

ITT/FSC, Vandenberg AFB

1. INTRODUCTION

Upper air winds have a significant impact upon space vehicle launches at Kennedy Space Center (KSC) and Cape Canaveral Air Station (CCAS). The estimated stresses the launch vehicle will undergo (referred to as loads in the launch community) due to wind and the vehicle's flight path are computed several hours prior to launch using wind estimates from local rawinsonde and jimsphere balloon releases. The last loads calculation for Shuttle, for example, is made approximately 35 min. prior to the scheduled lift-off and is based upon the balloon released 2 hours prior to launch (i.e. T - 120 min.). The rise rate of the balloons as well as data transfer and computation logistics do not permit the loads to be re-computed using the most recent data prior to launch. Instead, upper air wind measurements closer to launch are used to ensure no significant changes in the winds have occurred that would result in vehicle load exceedences and possible damage to the vehicle. The balloon tracking mechanisms limit the number of balloons in the air at one time and thus limit temporal resolution of upper air wind data available prior to launch to approximately one hour. Significant upper air wind shifts occurring during the hour prior to launch could potentially be missed without using other instrumentation providing better temporal resolution.

In 1990, NASA installed a prototype 50 MHz Doppler radar wind profiler at KSC to perform upper air research and to investigate the potential usefulness of wind profiling technology to launch operations. Theoretically, wind profilers have the capability to provide near instantaneous wind profiles with a temporal resolution much greater than that of the existing balloon tracking system.

Wind profiling radars depend upon the scattering of electromagnetic energy by minor variations in the index of refraction of the air. The index of refraction is a measure of the speed of propagation of electromagnetic energy through the atmosphere and, in the troposphere and stratosphere, depends primarily upon the temperature, pressure, and moisture content of the air.

Small variations in these atmospheric parameters produce minor irregularities in the index of refraction that initiate the scattering of electromagnetic radiation. As the transmitted electromagnetic pulse propagates through the atmosphere, part of the energy is scattered in all directions because of these refractive irregularities. A small portion of this energy is backscattered to the radar antenna where it is received for analysis.

In addition to refractive index irregularities, airborne objects such as airplanes, hydrometeors, and birds also backscatter electromagnetic energy resulting in spurious signals. Electromagnetic energy transmitted by radar sidelobes is often backscattered by refractive index irregularities due to atmospheric changes associated with low and upper level inversions. Standard methods for rejecting spurious radar returns are based upon consensus averaging of several profiles (usually 10 or so) to remove unwanted noise and spurious returns. This technique severely limits temporal resolution and often fails to eliminate persistent interference signals such as radar side lobe returns.

Since its installation, the 50 MHz wind profiler has proven to be useful in detecting wind direction and speed shifts. Its data have been requested for wind persistence calculations for Shuttle launches and for aid in the

*Corresponding Author Address: Robin S. Schumann, ENSCO, Inc., 445 Pineda Ct., Melbourne, FL 32955.

quality control of balloon data for all launch vehicles. NASA is in the process of transitioning the profiler from a research tool to an operational system.

As part of the transition process, Marshall Space Flight Center (MSFC) developed a methodology to extract complete wind profiles at frequent intervals as well as provide for quality control of those profiles prior to their distribution. (Wilfong, et al 1993) NASA KSC's Applied Meteorology Unit then implemented the signal processing algorithm on the existing profiler hardware and is currently assisting in the operational transition of the interactive quality control procedures. This paper describes the technique implemented on the profiler and illustrates its importance to the launch community by discussing a significant wind shift that occurred during the hour prior to the launch of Shuttle mission STS-56 on 08 April 1993.

2. DRWP OPERATING CHARACTERISTICS

The NASA KSC wind profiler operates at 49.25 MHz with an average power-aperture product of 10^8 Wm^2. A wide range of parameter settings provides complete flexibility in the radar operating characteristics. Nominally, an 8-μs pulse consisting of 1-μs code elements is used to yield a range resolution of 150 m over 112 gates. The lowest gate is set to 2 km giving a maximum altitude of 18.6 km.

The antenna is a phased array of coaxial-collinear dipoles which the radar uses to create three beams - one vertical and two orthogonal. The orthogonal beams are 15 deg. off the zenith on azimuths of 135 deg. and 45 deg. The pulse repetition period (PRP) is 160×10^{-6} s. A typical radar cycle is completed by integrating in each beam for 1 min. In each of the orthogonal beams, the radar real-time processor coherently integrates 320 pulses. A Fast Fourier Transform is then applied to 256 of these points to produce the spectral estimates. Four sets of spectral estimates are then incoherently averaged to produce the final 1-min. estimates. In the vertical beam, only one spectral estimate is formed over the entire minute after coherently averaging 1400 pulses. The one minute spectral estimates from each of the three beams comprise a complete radar cycle which requires approximately three minutes to generate. (Tycho, 1990).

The spectral estimates are then used to compute each beam's radial velocity. The velocity from the vertical beam V_W can be used directly while the radial velocity estimates in each of the oblique beams are converted to horizontal velocities using the relation

$$V_{h45} = V_{r45}/\sin(15 \text{ deg}) \quad (1a)$$

$$V_{h135} = V_{r135}/\sin(15 \text{ deg}) \quad (1b)$$

where the subscripts 45 and 135 refer to the oblique beams' pointing azimuths. To combine the radial velocities into a vector wind, one assumes a homogeneous wind field over the horizontal area sampled by the radar for the duration of the sample time (usually three minutes for an entire radar cycle). In situations where there is a significant large scale vertical velocity, the vertical velocity contributes considerably to the radial velocities in the oblique beams and must be accounted for in the horizontal velocities. If the vertical velocity is consistent over time, as is the case near mountains in a standing wave situation, the vertical velocity can be removed from the oblique beams' radial velocities before they are combined to form the horizontal velocity. Significant vertical velocities are rare in central Florida except when associated with strong convection (in which case the wind field homogeneity assumption is also suspect). Therefore, the vertical velocity measured by NASA's 50 MHz DRWP is generally used as a quality control indicator.

The horizontal winds obtained in Eq. (1) are combined to form the u and v components using the equations:

$$u = -V_{h135}\sin(135) - V_{h45}\cos(45) \quad (2a)$$

$$v = -V_{h45}\cos(45) + V_{h135}\sin(135) \quad (2b)$$

In this case, the radial velocity is positive if it is towards the radar.

Prior to the implementation of MSFC's algorithm, the single cycle velocity estimates were quality controlled by applying a consensus average. After ten cycles, the 30-min. consensus is formed at each of the 112 gates by searching the ten computed radial velocities for four or more observations whose differences are less than 2 m/s (radial velocity). If four or more observations are found they are all averaged. Consensus radial velocities are then used to form the horizontal wind vector in the consensus averaged profile..

For most cases, the consensus averaging method performs well. However significant problems arise for launch support operations. The consensus averaging method is particularly susceptible to persistent interference signals. If the interference signal affects several of the single cycle velocity estimates throughout the half-hour averaging window, the consensus averaging technique will produce an erroneous wind. Furthermore, since the 30 min. consensus is roughly equivalent to block averaging the data, small scale wind fluctuations can be severely attenuated.

3. IMPROVED WIND VELOCITY COMPUTATION METHODOLOGY

Review and analysis of many profiler spectral samples when the single cycle velocity computation produces erroneous winds due to spurious echoes, have shown there is a weaker but identifiable atmospheric signal in the radar spectral data. More sophisticated algorithms and techniques are required to extract the true atmospheric signal while still retaining the potential temporal resolution the profiler offers.

The methodology MSFC developed to improve the quality and temporal resolution of the DRWP wind profiles consists of several elements that distinguish it from the consensus average technique. First, a temporal median filter is applied to the one minute spectral estimates before they are processed. Then the search for the atmospheric signal is constrained to a window about a first guess velocity. Finally, after the radial velocities are estimated, they may be manually quality controlled by overlaying the radial velocity estimates on the one minute averaged spectral estimates.

3.1 *The Median Filter*

The intent of the median filter is to reject transient signals, such as returns from airplanes, from consideration in the evaluation of the atmospheric signal while still retaining the ability to detect rapid shifts in wind speed or direction. The algorithm allows for any size median filter to be used. We have found, however, that a 3 point temporal median filter applied to the spectral estimates effectively eliminates many of the spurious echoes from the spectral data. In this case, the medians of the one minute spectral estimates from three consecutive radar cycles are used to compute the beams' radial velocities.

The median filter is applied to the spectra from the oblique beams only. It is generally desirable to observe short time-scale variations in vertical velocities. Therefore filtering of the data is not desirable. As mentioned earlier, the vertical velocity estimates on KSC's 50 MHz profiler are generally used as indicators of the horizontal wind estimates' quality.

3.2 *The First Guess Velocity Profile*

The first-guess technique effectively prohibits most interference signals from affecting the radial velocity calculations. Since the radial velocity calculated for a given beam must lie within the constraining window about its first guess velocity, the first guess velocity must be close to the true atmospheric signal or the wind algorithm will produce erroneous velocity estimates. The implementation of this methodology on KSC's profiler allows for user specification of a first guess velocity for each range gate as well as the width of the corresponding constraining window.

The first guess velocity profile for any radar cycle is usually the previous cycle's computed velocity profile. Under ideal conditions, the first guess window is set to 20 frequency bins (or about 5 m/s, radial velocity). Occasionally, radar side lobes generate strong returns within the first guess constraint window. Under such circumstances, the size of the first guess window must be decreased accordingly.

Also, associated with the size of the first guess window width is the integration window width. Normally, the spectral peak is integrated down to the noise level. If a secondary peak associated with a consistent interference signal, is within the first guess window it may affect the integration of the signal peak. Constraining the integration window will prevent the secondary peak from inclusion in the signal peak integration.

The first guess velocity profile can either be initialized with the winds from a recent sounding or the algorithm can be used to generate an initial first guess profile. In the latter case, the algorithm selects the strongest peak within each range gate for the first guess velocity. The first guess profile generated from the algorithm in this manner usually requires considerable manual editing before it reflects the true atmospheric signal at all range gates. Once the first guess velocity profile reflects the atmospheric signal, however, it provides an excellent mechanism for eliminating spurious signals from subsequent velocity calculations. The manual monitoring and editing of the first guess velocity profile comprises the interactive quality control procedure described below.

3.3 *Interactive Quality Control*

For daily forecasting, manual quality control of the velocity profiles is largely unnecessary. An occasional comparison between the velocity profile and the spectral data to ensure the first guess velocity is not leading the velocity calculation astray is all that is necessary. Accurate upper air wind estimates are essential, however, when they are used to affect launch decisions. Continuous quality control of the first guess velocity profile is necessary during the hours preceding a launch to ensure the wind estimates provided to the launch decision team are not erroneous.

The quality control procedure implemented for the KSC 50 MHz profiler consists of overlaying the radial velocity profile on top of a plot of the spectral estimates color coded by signal strength. Color coding the spectral estimates in this manner allows the entire vertical profile to be displayed at once enabling the quality control to be done in near real-time. Individual profiles generated by the wind velocity are never modified before release for distribution. Instead, profiles that include spurious wind estimates are withheld from distribution, and the first guess velocity and associated constraining window width and integration window width are modified accordingly. The wind algorithm is then allowed to generate the next profile which is released if it tracks the true atmospheric signal.

4. DRWP IMPACT ON SHUTTLE MISSION STS-56

As mentioned earlier, the last pre-launch loads estimates for the Shuttle are based upon the balloon released 2 hours prior to the actual launch (i.e. T - 120). Other vehicles' loads estimates are done based on data measured earlier or later in the count. Upper air measurements taken after the loads calculations are performed are used primarily to ensure the wind conditions have not changed sufficiently to render the loads estimates non-applicable. Wind shifts occurring after the vehicle loads estimates are calculated are scrutinized carefully, and if necessary, the launch is scrubbed to ensure vehicle and/or crew safety.

The current operational upper level wind instrumentation consists of rawinsonde and jimsphere balloons. The number of available radars for tracking limit the number of balloons in the air simultaneously resulting in a temporal resolution of about one hour between upper level wind measurements. The last balloon released prior to a Shuttle launch is a jimsphere released at about 1 hr 10 min. prior to the scheduled lift-off (i.e., T-70). Another jimsphere is released 15 min. after lift-off (i.e., T+15) and is used to estimate the winds experienced by the Shuttle during its flight.

Wind profiles generated by KSC's 50 MHz DRWP are monitored during the launch countdown to provide wind measurement redundancy and to detect any wind shifts occurring between balloons, especially those occurring after the last balloon is released prior to launch. On 08 April 1993, a significant wind shift within a relatively shallow layer (i.e., the 2 km between 11 km and 13 km) of the atmosphere occurred within the last hour prior to launch. Lift-Off for Shuttle mission STS-56 was scheduled for 0529 UTC on 08 April 1993. The jimsphere used for loads calculations was released at 0329 UTC and the last jimsphere released prior to launch was released at 0419 UTC. Fig. 1 contain the u- and v-component profiles measured by the T-120 min. and T+15 min. jimspheres. Post analysis of the data indicate that significant differences in the u- and v-components between 11 km and 13 km occurred in the 2 hours prior to launch. The last jimsphere released 70 min. prior to launch did not detect this feature indicating that most of the shift occurred during the last hour prior to launch. This shift amounted to a 25.3 m/s (49.3 knot) reduction in the expected tail-wind on the Shuttle (based upon the T-70 min. balloon) which was used in the last loads estimation. Fortunately, this shift was detected by the profiler and the validity of the loads was evaluated prior to the actual launch which occurred on time at 0529 UTC.

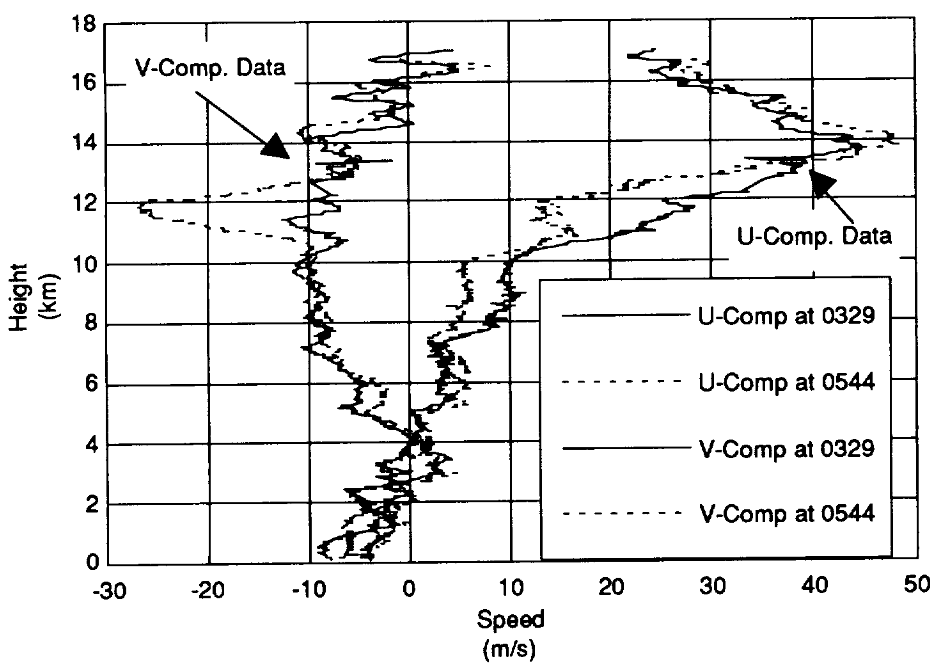

Figure 1. Jimsphere u- and v-component wind speeds at T-120 and T+15 min.

Figures 2 and 3 contain the height profiles of the u- and v-components of the wind velocity measured by the jimsphere at T-70 and T+15, respectively, overlaid with the time coincident u- and v-component profiles generated by the DRWP using the new signal processing algorithm. The differences between the profiler and jimsphere profiles, especially those evident between 11 km and 13 km, are due to the time lag associated with the jimsphere rise rate. (Jimspheres rise at rate of about 5 m/s.)

First of all, Figures 2 and 3 provide reassurance that the wind shift detected by the jimsphere and profiler is real. This is an obvious benefit from having two

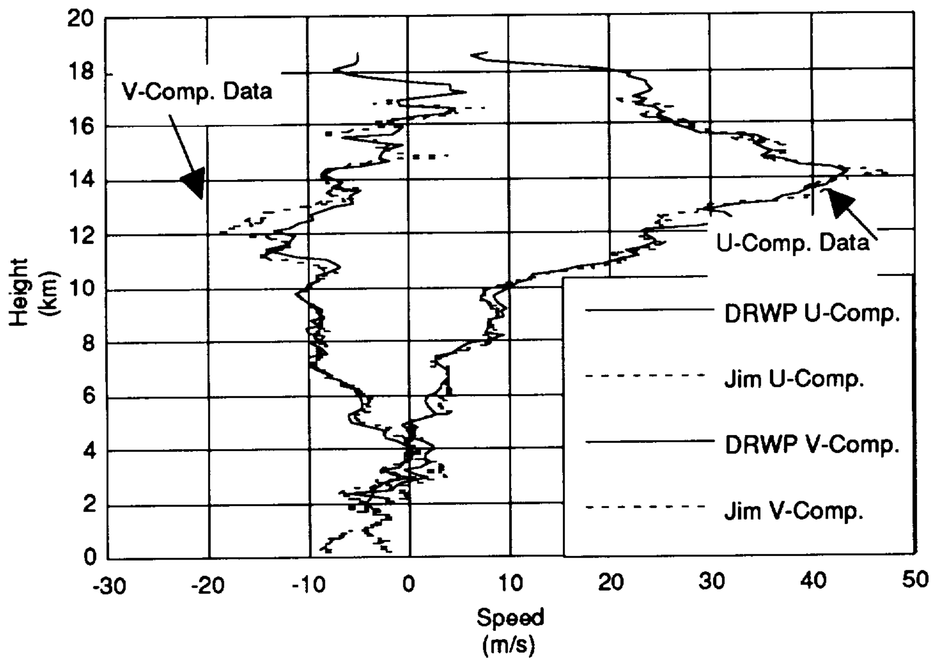

Figure 2. u- and v-components of the wind velocity profiles from the jimsphere at 0419 UTC and from the profiler at 0421 UTC.

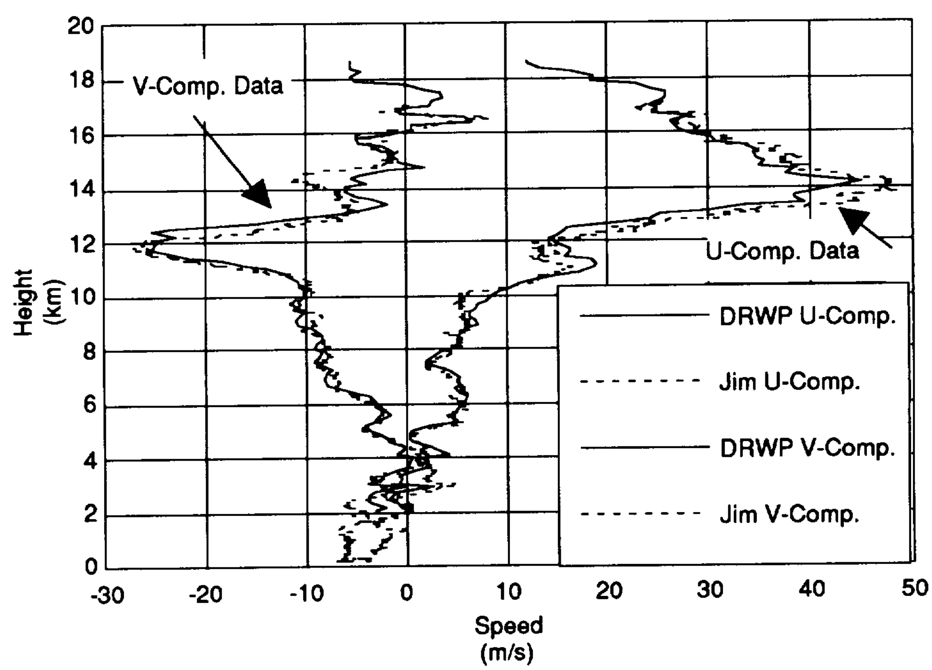

Figure 3. u- and v-components of the wind velocity profiles from the jimsphere at 0544 UTC and from the profiler at 0544 UTC.

independent instruments measuring critical winds. More importantly, however, Figures 1 through 3 illustrate the importance of having higher temporal resolution in the measurement of upper level winds for launch missions.

To illustrate the benefit of higher temporal resolution upper air wind data, Figures 4 and 5 illustrate the timing and intensity of the change in the u- and v-components relative to the 0202 UTC profile that were evident using the profiles generated by the 50 MHz DRWP. Wind velocity data generated by KSC's 50 MHz DRWP using the new signal processing algorithm were used to determine the differences in the u- and v-components subsequent to the 0202 UTC profile. The profiler generated data every 6 min.; however, only data every 12 min. were used in the figure to enhance its readability.

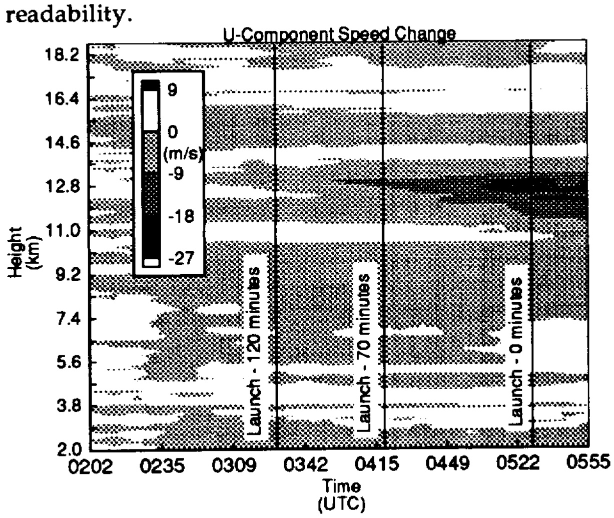

Figure 4. Change in u-component velocity relative to 0202 UTC.

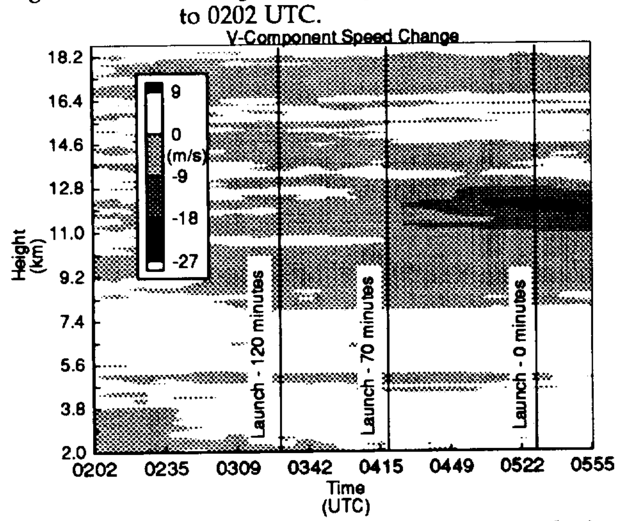

Figure 5. Change in v-component velocity relative to 0202 UTC.

Figures 4 and 5 indicate that not only was the significant wind shift detected by the 50 MHz profiler, but its structure as it developed could also be examined in near real-time providing confidence that the feature was real and not due to instrumentation error. Furthermore, the figures indicate that most all of the change in u- and v-component speed occurred after the T-70 minute jimsphere.

5. CONCLUSION

This paper presented a case study where a significant wind shift, not detected by jimspheres, was detected by the 50 MHz DRWP and evaluated to be acceptable prior to the launch of a Shuttle. This case study illustrates the importance of frequent upper air wind measurements for detecting significant rapidly changing features as well as for providing confidence that the features really exist and are not due to instrumentation error. Had the release of the jimsphere been timed such that it would have detected the entire wind shift, there would not have been sufficient time to release another jimsphere to confirm the existence of the feature prior to the scheduled launch.

We have found that using a temporal median filter on the one minute spectral estimates coupled with a constraining window about a first guess velocity effectively removes nearly all spurious signals from the velocity profile generated by NASA's 50 MHz DRWP while boosting the temporal resolution to as high as one profile every 3 minutes. The higher temporal resolution of the 50 MHz DRWP using the signal processing algorithm described in this paper ensures the detection of rapidly changing features as well as provides the confidence the features are genuine. Further benefit is gained when the profiles generated by the DRWP are examined in relation to the profiles measured by jimspheres and/or rawinsondes. The redundancy offered by using two independent measurements can dispel or confirm any suspicion regarding instrumentation error or malfunction and wind profiles can be examined in light of their respective instruments' strengths and weaknesses.

6.0 REFERENCES

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Wilfong, T. L., S. A. Smith, and R. L. Creasy, 1993: High Temporal Resolution Velocity Estimates from a Wind Profiler. *Journal of Spacecraft and Rockets*, **30**, 348-354.