J7.4 ANALYSES OF KENNEDY SPACE CENTER TROPOSPHERIC DOPPLER RADAR WIND PROFILER DATA FOR SPACE LAUNCH SYSTEM PROGRAM CERTIFICATION

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1. INTRODUCTION

This paper documents the methodology and results of analyses used to certify the Kennedy Space Center (KSC) Tropospheric Doppler Radar Wind Profiler (TDRWP) as input to launch commit evaluations for the National Aeronautics and Space Administrationôs (NASA) Space Launch System Program (SLSP). These analyses, and the requirements that they address, were designed by the Marshall Space Flight Center Natural Environments Branch (MSFC NE) to certify that the TDRWP provides data of sufficient accuracy and resolution for SLSP, and that the instrument provides enough reliability to support Day-of-Launch Initialization Loads Update (DOLILU) operations. On day-of-launch (DOL), space launch vehicle operators have used data from wind profilers to reverse a previous GO call in prelaunch loads and trajectory assessments due to the profilerôs ability to quickly identify changes in the wind profile within a rapidly changing wind environment. Certification of the TDRWP would allow SLSP to use DOL wind data generated by the TDRWP to design the vehicle trajectory and to verify trajectory and load constraints during the countdown for launch commit decision.

The TDRWP comprises of a completely new antenna field, beam configuration, and updated computational hardware and software from the previous 50-MHz DRWP. The TDRWP replaces the previous three-beam system made of coaxial cables and a copper wire ground plane with a four-beam system that uses Yagi antennae with enhanced beam steering capability. In addition, the TDRWP contains updated user interface software while maintaining the same general capability as the previous system. The TDRWP continues to use the Median Filter First Guess (MFFG) algorithm (Schumann, et al., 1999) to generate a wind profile from Doppler spectra at each range gate. The TDRWP upgrade Statement of Work (Team Qinetiq North America, 2012) contains further details on the upgrade.

The TDRWP system performance and data generated had to be evaluated through a series of tests prior to the system being certified for use at the Eastern Range (ER) and for launch vehicle operations. Tests were segmented into an Operational Acceptance Test (OAT) and a comprehensive year-long Certification Test. MSFC NE performed two OATs in an effort to approve TDRWP data for situational awareness purposes at the ER during launch operations while, at the same time, collecting data for the year-long certification analyses. The OATs showed that end users can utilize the TDRWP in a similar manner to the previous 50-MHz DRWP during launch operations in the midst of a long-term certification process. Details of the OATs and other activities leading to TDRWP certification are contained in Marshall Space Flight Center Natural Environments (2014), Barbré, et al. (2016), DeTect, Inc. and Radiometrics, Inc. (n.d.), and Barbré (2016). Additionally, Barbré (2018) provides the genesis of this paper and additional details of the TDRWP certification analyses.

This paper describes MSFC NEôs ana verify the quality and accura wind data output for SLSP as compared to the TDRWP certification requirements. Ultimately, each launch vehicle program has the responsibility to certify the system for its use.

2. CERTIFICATION REQUIREMENTS

Table 1 presents the SLSP specific TDRWP certification requirements, as well as their criteria and rationale. The variables of interest consist of validating the specified time interval, vertical data interval, data collection period, wind accuracy, altitude, and effective vertical resolution (EVR). The

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Table 1: Requirements for TDRWP certification for DOLILU operations.

Requirement	Criterion	Rationale
Time Interval	5 min	Supports DOL timeline
Vertical Data Interval	150 m	Consistent with database used for SLS design
Data Collection Period	One year	Analyzing available data over one year of continuous operation produces statistically significant results over all seasons
Wind Accuracy	1.5 m/s RMS component difference	Accuracy of heritage balloon and DRWP systems
Altitude	2,700-15,250 m	Consistent with database used in SLS design
Reliability	No criterion. Will report the percent of usable profiles.	Consistent with the method Shuttle used to certify AMPS
Effective Vertical Resolution	700 m	Based on maximum wavelength of gust analyses during SLS design

time interval criterion of five minutes supports the DOL timeline. Criteria for the vertical data interval (150 m) and altitude range (2.70-15.25 km) are consistent with the 50-MHz DRWP database used in SLS design (Leahy, 2014). Data needed to be collected over one year of continuous operation to allow analysis that produces statistically significant results over all seasons. MSFC NE assessed wind accuracy by evaluating the root-mean-square (RMS) wind component differences from concurrent balloon measurements from the Automated Meteorological Profiling System (AMPS) (Leahy & Overbey, 2004). MSFC NE determined the 1.5 m/s criterion using the results from AMPS wind accuracy studies (e.g., Leahy & Overbey (2004)) and a similar evaluation of the legacy 50-MHz DRWP system after an instrument upgrade (Pinter, et al., 2006). MSFC NE elected not to set a criterion against which to assess reliability. Rather, MSFC NE decided to report the percent of usable profiles, where the term “usable” is defined as a profile containing data that pass specified quality control (QC) checks. This approach is consistent with the method that the NASA Space Shuttle Program used to certify AMPS (Leahy, 2007). The EVR criterion is based off the maximum wavelength of gust analyses when accounting for an assessment 30 minutes before launch. Inserting 30 minutes into the equation that MSFC NE and collaborators use for determining the scale between persistent and non-persistent wind features (Spiekermann, et al., 2000) yields a boundary wavelength of 768 m. Rounding down to add conservatism produced the EVR criterion of 700 m.

The analyses presented herein address the requirements to certify the TDRWP for SLSP. MSFC NE developed and vetted these requirements (Barbré, 2017) through multiple NASA SLSP and inter-governmental working groups.

3. DATA

The TDRWP certification analyses utilized appropriate datasets from the TDRWP and AMPS balloon measurements. Data were collected from 22 June 2016 to 22 June 2017 from both the TDRWP and AMPS.

3.1 *AMPS Balloon*

MSFC NE utilized AMPS one-second balloon data as ground truth for the analysis to determine TDRWP wind accuracy (Section 4.4). The Cape Canaveral Weather Station (CCWS) released all balloons under normal synoptic and mission support operations, and made available to MSFC NE the binary (.w9k) files containing all one-second data for each balloon release. MSFC NE then created specialized text files using Win9000 for analysis. Having the .w9k files enabled MSFC NE to use the Global Positioning System (GPS) coordinates of the balloon to determine its position and timestamp at each altitude. The CCWS provided 1,159 balloon profiles sampled during the analysis period. Data quality checks initially removed 98 profiles which did not reach 15,240 m. Nine of these profiles also contained a vector shear exceeding 0.15 s^{-1} over 30.5 m somewhere in the profile. An additional 31 balloons were released less than five minutes after the previous balloon. Implementing these checks left 1,030 profiles available for analysis.

3.2 *TDRWP*

MSFC NE utilized TDRWP data that were transmitted in the Meteorological Data Transfer Format (MDTF) via the Meteorological Interactive Data Display System (MIDDS) for the certification analysis. The MDTF of TDRWP output files contain altitude, wind speed, wind direction, radial shear, vertical velocity, signal power, noise level, number of first guess propagations (FGP), and QC flags for each profile. The number of FGPs represent the number of consecutive instances in which the same first guess velocity (FGV) is used to estimate the wind as part of the MFFG algorithm (Schumann, et al., 1999).

The TDRWP is a four-beam system, but the MDTF formatted output file format could not be changed from the previous three-beam system. Therefore, the oblique beam signal, noise, and spectral width fields represent opposing-beam averages and the vertical beam field represents averages over all beams. In addition, the FGP field represents the opposing-beam maximum, and the QC field (DeTect, Inc., 2014) contains indicators that relate to any TDRWP internal data quality checks that were tripped. Approximately five minutes exist between temporally adjacent profiles, and altitude coverage ranges from 1,798-19,430 m, at near 150 m intervals. This analysis utilized data files produced by the MSFC NE meteorological data archive process (Brenton, 2016), which combines all of the TDRWP files from MIDDS into files containing TDRWP data for individual days. This analysis used TDRWP data with and without implementing QC screening techniques. The following subsections describe each dataset.

3.2.1 *TDRWP Data Without QC*

The TDRWP dataset without QC consists of all data strictly as received through MIDDS. This dataset contains temporal data gaps corresponding to the frequency of data reception, as well as any suspect or erroneous data that were recorded. The analyses used TDRWP data without QC to assess the requirements for time interval, vertical data interval, data collection period, and reliability.

3.2.2 *TDRWP Data With QC*

The TDRWP dataset with QC consists of applying QC checks to the TDRWP data in a similar manner to generating DRWP climatologies. Using this dataset attempted to mimic the DOL QC process which consists of adjusting the FGV in real-time to ensure good quality of the wind produced by the Doppler return spectra. MSFC NE could not replicate this QC process, as the spectra were not available over the period of record (POR). Thus, automated and manual QC checks were applied in an attempt to remove the suspect and erroneous features that would likely be removed by the DOL QC process from adjusting the FGV. These checks were based largely from Barbré (2012), but some modifications were made for the TDRWP data. The QCôed TDRWP dataset was used requirements for wind accuracy, altitude, reliability, and EVR.

The TDRWP data were screened for convection prior to implementing the subsequent checks. Following Barbré (2012), this process first identified periods of convection at each time and altitude using the automated algorithm derived for the previous 50-MHz DRWP. The QC implementation then manually removed parts of profiles that contained extensive vertical regions of flagged data that corresponded to suspect characteristics in the wind field.

The automated process applied the checks described in

Table ***2*** in sequence to all profiles. Temporal data gaps exceeding five minutes were filled with missing data, and the thresholds for unrealistic wind, spectral width, internal shear, vertical velocity, meteorological shear, small median, missing signal, and isolated datum are identical to Barbré (2012). The manual QC process entailed visually examining multiple variables over each day during the analysis period, and removing instances of leftover suspect or erroneous data that the automated process did not flag. Note that this assessment did not include the vertical beam checks in Barbré (2012) as the TDRWP does not have a vertical beam. This assessment included additional checks for inconsistent data, and did not include a check for excessive FGP. Barbré (2018) contains further details on the analyses performed to derive the inconsistent data check and that generated result for the FGP check.

Table 2: Automated QC descriptions and thresholds for the TDRWP dataset with QC.

Auto QC Description	Threshold
Convection	Data flagged following (Barbré, 2012)
Missing Profile	Log missing profiles
Unrealistic Wind	Wind Speed < 0.0 m/s Wind Direction (0ÒÁ 3Ò60Á)
Spectral Width	Spectral Width > 3.0 m/s
Internal Shear	Radial Velocity Shear > 0.1 s^{-1}
Vertical Velocity	|w| > 2.0 m/s
Inconsistent Data, Check 1	QC_{int} Ó4, QC_{int} ~= 64, and |w| > 0.5 m/s
Meteorological Shear	Vector Shear > 0.1 s^{-1}
Small Median	$T1 = -0.06z^2 + 1.35z + 3.26$, $T2 = 0.02(WS + WS_{med})$ Wind Speed > max([T1, T2]) See (Barbré, 2012)
Missing Signal	Missing Signal or Noise value
Isolated Datum	Report which is completely surrounded by missing or flagged reports (Merceret, 1997)
Manual	See text
Inconsistent data, Check 2	QC_{int} Ó4, QC_{int} ~= 64, and |w| > 0.8 m/s
FGP	No check

4. ASSESSMENTS OF CERTIFICATION REQUIREMENTS

This section provides the assessments of the Certification requirements presented in Table 1.

4.1 *Time Interval*

The TDRWP time reporting interval passed the criterion of five minutes under nominal operations. Personnel at KSC / ER communicated any significant deviations from this reporting interval, and MSFC NE expected that the instrument would have periodic outages exceeding five minutes.

4.2 *Vertical Data Interval*

The TDRWP vertical data interval passed the criterion of 150 m between vertically adjacent reports. The unique differences between adjacent reporting altitudes during the POR was found to be either 149 m or 150 m.

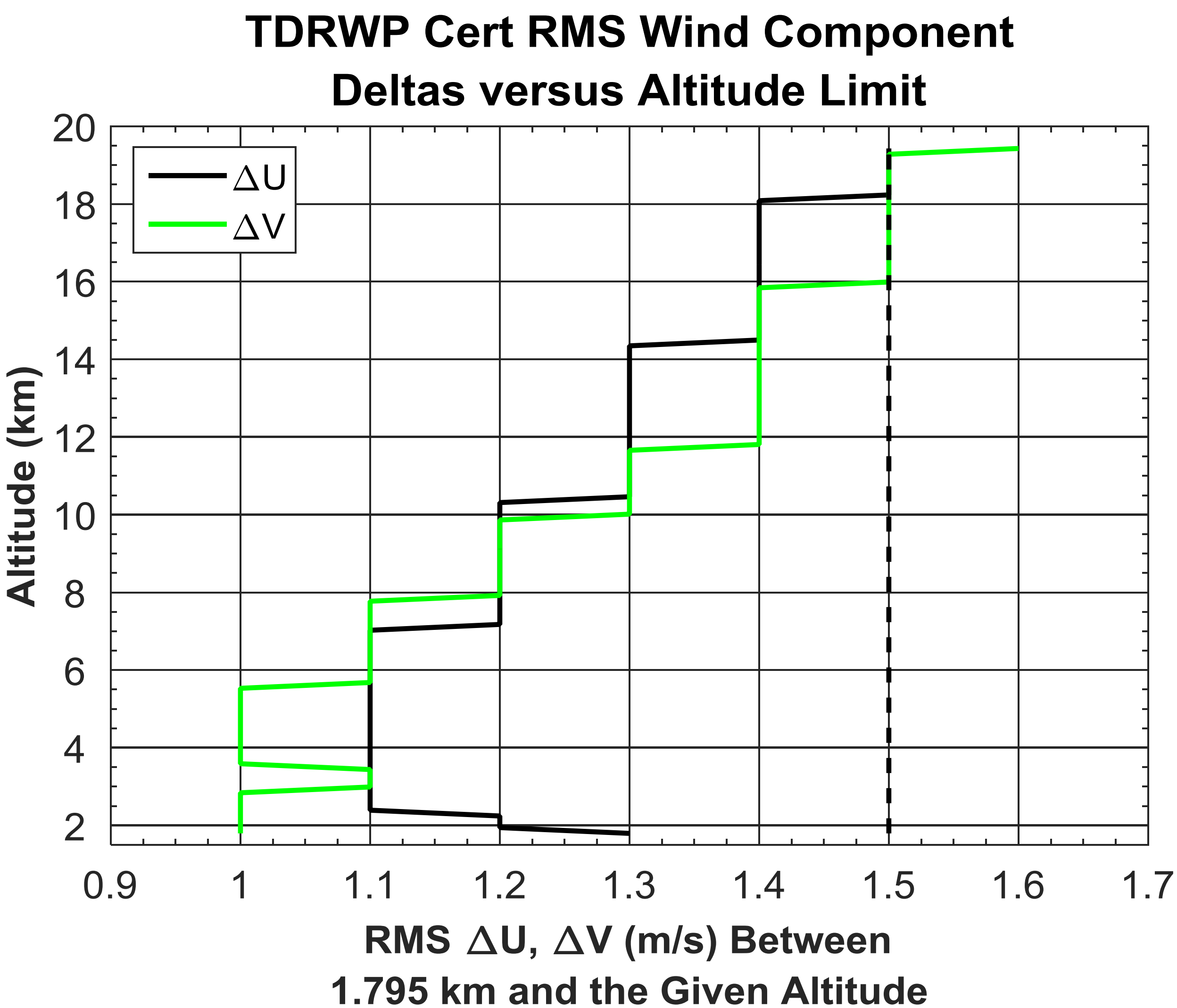
4.3 *Data Collection Period*

The TDRWP certification data collection period passed the criterion of one year. Data were collected over one year for 348 days, which provides enough data to produce statistically significant results over all seasons. The TDRWP was operating continuously under nominal conditions, and MSFC NE understood that periodic outages would exist.

4.4 *Wind Accuracy and Altitude*

The TDRWP was found to pass the wind accuracy criterion over the required altitude range. Comparisons to concurrent TDRWP and balloon data addressed both the TDRWP wind accuracy and altitude requirements. The approach to verify the altitude requirement entailed defining an altitude range over which the wind accuracy requirement is met using an analysis technique introduced in Barbré (2016). This technique entailed examining the RMS wind component delta between concurrent TDRWP and balloon measurements as a function of altitude range from the bottom of the TDRWP profile.

The TDRWP and balloon comparison utilized data that were both temporally and vertically matched in an attempt to mitigate the differences in measurement characteristics between both systems. Balloon wind profiles were vertically matched to TDRWP data, and multiple TDRWP wind profiles were used to temporally match to balloon data. To vertically match the TDRWP data, one-second balloon wind component, GPS location, and measurement time profiles within 75 m of each TDRWP altitude were averaged to represent the balloon measurement and timestamp at the TDRWP altitudes. This averaging was performed if greater than 15 one-second measurements existed over 135 m within the 150-m altitude interval to ensure a robust calculation of the average winds within the altitude interval. To generate concurrent profiles, the TDRWP timestamp was first subtracted by 7.5 minutes to account for temporal averaging. These timestamps



TDRWP Cert RMS Wind Component
Deltas versus Altitude Limit
ΔU
ΔV
Altitude (km)
20
18
16
14
12
10
8
6
4
2
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
RMS ΔU, ΔV (m/s) Between
1.795 km and the Given Altitude

personnel. Planned outages were determined through examining both operational logs and email notifications that the KSC Weather Office and TDRWP support personnel provided to MSFC NE. Each known outage was categorized as confirmed planned, confirmed unplanned, or uncertain. The outage was classified as uncertain if no confirmation of either a planned or an unplanned outage were found specifically for that outage, and outages classified as uncertain were treated as unplanned outages in this analysis. Wait times not exceeding 10 minutes were also treated as unplanned. Reasons for planned outages included placing the TDRWP in standby for antenna field walk downs, weed control, routine maintenance, and known power outages. Reasons for unplanned outages included memory leakage (resulting in timing issues), profiler health monitor (PHM) heartbeat errors, communication failures between the TDRWP and the MIDDS data distribution node at the ER, and unexpected reboots. Barbré (2018) contains a table with each known outage and further discussion on outages classified as uncertain.

Results of the reliability analysis are presented as a function of desired wait time. Figure 4 displays the probability of waiting a specified time until the next profile. The green line in the plot denotes the probability of obtaining a usable profile containing all valid data within the required TDRWP altitude range, and within the specified time per requirements (Table 1). The blue line in the plot shows the probability of obtaining any profile, regardless of data quality. The probability of obtaining a usable profile by five minutes within the required altitude range per requirements is 86.5%. The probability of obtaining any profile, regardless of data quality, is 93.8%.

4.6 Effective Vertical Resolution

The TDRWP EVR using the certification data passed the criterion of 700 m. The methodology for this assessment followed the methodology of Barbré (2016), Merceret (1999), and Wilfong, et al. (1997). First, five-minute wind component pairs

Figure 4: Cumulative probability of wait times after removing periods of convection and planned outages. The blue line denotes waiting for any profile, regardless of data quality. The green line denotes waiting for a profile that contains good data in the TDRWP altitude range.

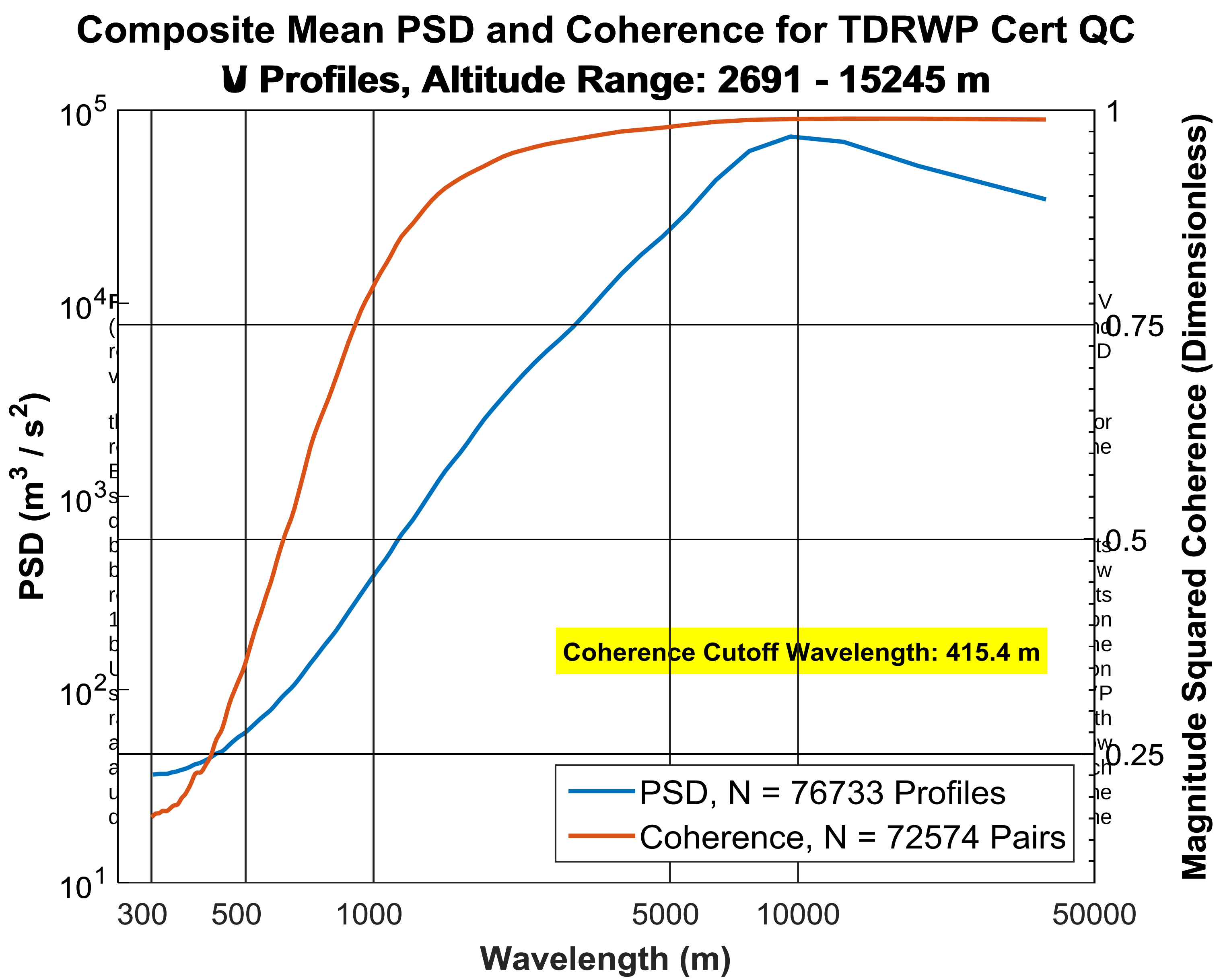
function of wavelength on each individual wind component profile on the entire profile assuming a 150 m sampling interval. Before computing the FFT, the mean and linear trend of each profile were removed and a Hanning window with zero overlap was applied. From the FFTs, each profileôs power spectral density (PSD) and -each pairôs cross spectral density (CSD) were computed. These quantities were then used to compute the magnitude squared coherence, or ñcoherenceò as this paper denotes. Coherence describes the relationship between two signals at each wavelength, where incoherent noise dominates this relationship at values below 0.25 as this value corresponds to a signal-to-noise ratio of unity. The coherence was computed as

% B6 L Ã¼ Ì ½Ä· / ÃÉ Ì ½ÄÃÉ Ì ½Ä (7)

where brackets denote averages over the entire day at each wavelength, which must be performed in order to avoid the coherence resulting in unity.

The sample size (i.e., number of five-minute pairs) were tallied for each day, and the coherence was computed for each of the days containing at least 100 pairs. The composite coherence was then generated by computing a sample-size-weighted coherence at each wavelength. Figure 5 presents this result, which represents the composite wind component coherence for the entire TDRWP sample for two subsets. Each subset consisted of

valid data between altitude limits corresponding to



Kennedy Space Center 50-MHz Dopler Radar Wind Profiler Operational Acceptance Test. New Orleans, s.n.
Brenton, J. C., 2016. MSFC EV44 Natural Environments New Archive System, Huntsville, AL: s.n.
Carr, F. H., Spencer, P. L., Doswell, C. A. & Powell, J. D., 1995. A Comparison of Two Objective Analysis Techniques for Profiler Time-Height Data. Monthly Weather Review, Volume 123, pp. 2165-2180.
Curtis, N., Leahy, F. & Barbré, R., 2019. Analyzing Error in Wind Measurements due to Spatial Separation using the North American Regional Reanalysis. Phoenix, s.n.
DeTect, Inc. and Radiometrics, Inc., n.d. Email and verbal communication referencing TDRWP EVR and sampling characteristics. s.l.:s.n.
DeTect, Inc., 2014. Interface Control Document (ICD) for the Median Filter First Guess Server Computer (MSC) to the MIDDS, s.l.: s.n.
Detect, Inc., 2014. RAPTOR FBS-MST MFFG QC Operator's Manual, s.l.: s.n.
Leahy, F., 2007. Reliability Analysis of the AMPS High Resolution Flight Element. Huntsville(AL): s.n.
Leahy, F. B., 2014. Delivery of KSC Seasonal Atmospheric Profile Triplets Database, Huntsville: NASA MSFC.
Leahy, F. B. & Overbey, B. G., 2004. An Analysis of the Automated Meteorological Profiling System Low Resolution Flight Element. Reno, AIAA.
Lockheed Martin, n.d. Win9000 Processing and Display Software Operator's Manual., Marion, MA: s.n.
Marshall Space Flight Center Natural Environments, 2014. Operational Acceptance Test Plan for Qualification of Functional Peformance of the New NASA/KSC 50 Mhz Doppler Radar Wind Profiler (DRWP), Huntsville: s.n.
Merceret, F., 1997. Rapid Temporal Changes of Midtropospheric Winds. Journal of Applied Meteorology, Volume 36, pp. 1567-1575.
Merceret, F., 1999. The Vertical Resolution of the Kennedy Space Center 50 MHz Wind Profiler. Jounal of Atmospheric and Oceanic Technology, Volume 16, pp. 1273-1278.
Merceret, F. & Ward, J., 2006. Spatial Properties of Wind Differences in the Lowest Three Kilometres of the Atmosphere. Atlanta, GA, s.n.
Mesinger, F. et al., 2004. NORTH AMERICAN REGIONAL REANALYSIS. Bulletin of the American Meteorological Soceity, p. 42.
Pinter, D. J., Merceret, F. J. & Hatley, C. V., 2006. Performance Validation of the Upgraded Eastern Range 50 MHz Wind Profiler. Journal of Spacecraft and Rockets, Volume 43, pp. 693-695.
Schumann, R. S., Taylor, G. E., Merceret, F. J. & Wilfong, T. L., 1999. Performance Characteristics of the Kennedy Space Center 50-MHz Dopplar Radar Wind Profiler Using the Median Filter/First-Guess Data Reduction Algorithm. Journal of Atmospheric and Oceanic Technology, Volume 16, pp. 532-549.
Spiekermann, C. E., Sako, B. H. & Kabe, A. M., 2000. Identifying Slowly Varying and Turbulent Wind Features for Flight Loads Analysis. Journal of Spacecraft and Rockets, Volume 37, pp. 426-433.
Taylor, J. R., 1997. An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements. 2nd ed. Sausalito, CA: University Science Books.
Team Qinetiq North America, 2012. Performance Statement of Work (PSOW) for the KSC 50 Mhz Doppler Radar Wind Profiler, s.l.: s.n.
Wilfong, T., 2012. AMPS II Eastern Range Formal DT&E Analysis, Boulder, CO: s.n.
Wilfong, T. L., Smith, S. A. & Crosiar, C. L., 1997. Characteristics of High-Resolution Wind Profiles Derived from Radar-Tracked Jimspheres. Journal of Atmospheric and Oceanic Technology, Volume 29, pp. 318-325.

8. APPENDIX: ANALYSIS AND IMPLEMENTATION OF NARR WIND COMPONENT DELTAS DUE TO SPATIAL SEPARATION

The TDRWP wind accuracy assessment incorporated tailored spatial separation estimates from the NARR utilizing the methodology in Curtis, et al. (2019). First, NARR data were extracted for the TDRWP certification POR (22 June 2016 through 22 June 2017) at all NARR altitudes from the gridpoints within 200 km of KSC. Next, deltas of wind components from each gridpoint and the gridpoint closest to KSC at each altitude were computed. Last, the RMS of each of these deltas were computed as a function of altitude and horizontal separation distance between each gridpoint and the KSC gridpoint.

Figure A1 presents the roughly RMS æU at 10 km altitude as an example of the data provided for the wind accuracy analysis. The provided RMS wind components at each separation, bearing, and altitude were then linearly interpolated to the TDRWP altitudes, of which an example is provided

915-MHz DRWP network. To obtain direct comparisons, Curtis, et al. (2019) extracted NARR output at the gridpoints closest to the 915-MHz DRWPs used in Merceret & Ward (2006), and from 12-21 UTC for JJAS 2000 and JJA 2001 to best match the POR and timestamps used in Merceret & Ward (2006).

Figure A7 shows a map of the NARR gridpoints overlaid with the 915-MHz DRWP network, and highlights the gridpoints and DRWPs used. Following the methodology presented in Curtis, et al. (2019), vector wind deltas were computed at each altitude and compared to the square root of the results presented in Merceret & Ward (2006) for the selected combination where the DRWPs being examined were roughly 30 km apart. The vector contribution to the small-scale features not resolved by the NARR were then computed (Figure A6). The total vector delta was then computed as

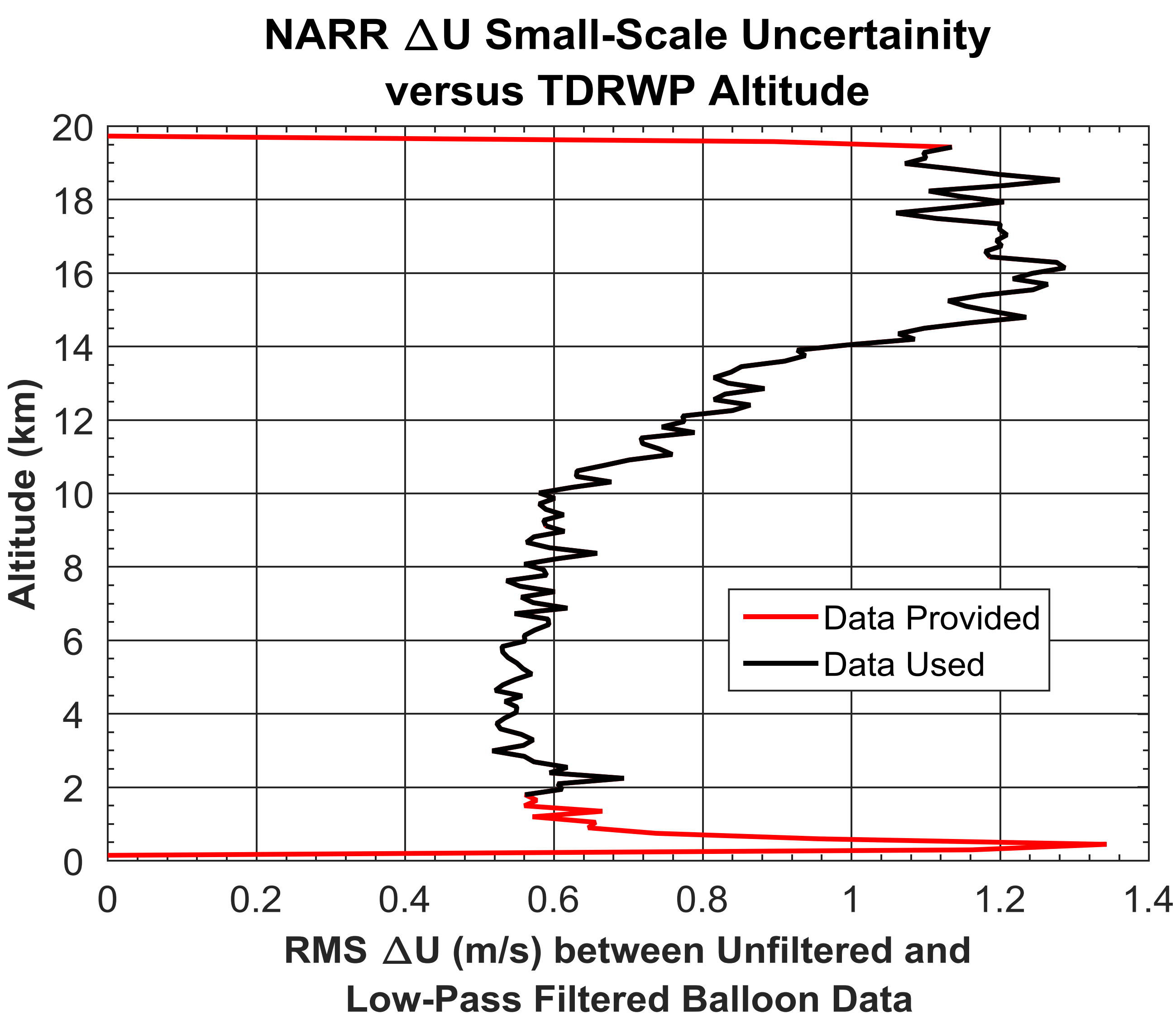
$$\sigma_{spatial,vec}(\Delta x, \Delta z) = \left[\sigma^2_{spatial,NARR,vec}(\Delta x, \Delta z) + \sigma^2_{small,calc}(\Delta z)\right]^{1/2}. \quad \text{(A1)}$$

Figure A5: Mean PSD (m^3/s^2) of unfiltered NARR (blue) and filtered balloon (red) V, overlaid with a theoretical PSD slope (black) versus wavelength (m) (Curtis, et al., 2019).

Figure A6: RMS σ_V (m/s) used to estimate $\sigma_{small,calc}$ versus altitude (km). The red line denotes the data provided, and the black line presents the data used in the wind accuracy analysis.

Figure A7: Domain used for the NARR separation analysis (Curtis, et al., 2019). Blue dots represent the NARR gridpoints, red stars display the NARR gridpoints used in the comparison to Merceret & Ward (2006), black dots show the 915-MHz DRWP locations, and green stars show the locations of the 915-MHz DRWPs used for the comparison.

The result $\sigma_{spatial,vec}$ was then plotted against applicable results from Merceret & Ward (2006). Figure A8 shows that the RMS vector wind deltas from data used analogous to data used in the wind accuracy analysis are roughly 0.1-0.5 m/s smaller than such deltas computed from 915-MHz DRWP. Note that Figure A8 differs from the analogous figure in Curtis, et al.(2019) as the latter does not incorporate the small-scale features that the NARR does not contain. Rather, Figure A8 results from applying the methodology described in Curtis, et al.(2019) (and in this Appendix) to add


NARR ΔU Small-Scale Uncertainity
versus TDRWP Altitude
Altitude (km)
RMS ΔU (m/s) between Unfiltered and
Low-Pass Filtered Balloon Data
Data Provided
Data Used
0
2
4
6
8
10
12
14
16
18
20
0
0.2
0.4
0.6
0.8
1
1.2
1.4