Performance Assessment of a Western Range 915-MHz Doppler Radar Wind Profiler

BJ Barbré, Jacobs

Maggire Fielder, Linc

Jacobs Space Exploration Group / NASA MSFC Natural Environments

1. Introduction

The United States Space Force (USSF) is responsible for space vehicle launches at its Western Range (WR). Multiple systems are used to measure the atmosphere at the WR, including suites of Doppler Radar Wind Profilers (DRWPs) operating at 915 MHz. These DRWPs measure winds within the lowest few kilometers of the atmosphere. Observations of boundary layer winds can be used for multiple applications, including serving as input to toxic dispersion models and characterizing winds for low-level aborts. The USSF upgraded one of its DRWPs, which collected data during the winter of 2021. The USSF also requested NASA's Marshall Space Flight Center (MSFC) Natural Environments Branch (NE) to evaluate wind output from this DRWP system. This report describes the system and the analyses that MSFC NE conducted to demonstrate the system's wind accuracy relative to balloons from the Automated Meteorological Profiling System (AMPS), data availability, and effective vertical resolution (EVR).

2. Instrumentation Systems

The following subsections describe data from the different systems that were utilized during this study. WR personnel provided MSFC NE with WR balloon and DRWP data via a secured data server. DRWP and balloon data were provided for the period of record (POR) dating from January 25, 2021 to March 8, 2021. Figure 1 displays the locations of the DRWP and the weather station.

Figure 1: Locations of the WR weather station and the DRWP used for this study, denoted by the yellow pin and yellow circle, respectively.

2.1. 915-MHz DRWP

The DRWP measured boundary layer winds from 100 m (328 ft) to 4,500 m (14,764 ft) above ground level (AGL) in 50-m (164-ft) intervals. Although placeholders exist in the output data files for data records up to 4,500 m (14,764 ft), typical maximum altitudes were lower (see Section 3.2). The DRWP and weather station, from where balloons are typically released, are located 3.7 km (2.3 mi) from each other. MSFC NE and the USSF agreed the optimal configuration would be for balloon releases and the DRWP be co-located. However, due to logistics, configuration, and time constraints, not all balloon releases were from the DRWP site.

2.2. AMPS Balloons

The AMPS data used in this study were from balloons released during normal synoptic and launch operations during the POR, as well as balloons released at the 915-MHz DRWP site. The AMPS archive included both Low Resolution Flight Element (LR) balloons and High Resolution Flight Element (HR) balloons released during the POR. The LR balloons can reach over 30,000 m (98425 ft) altitude while the HRs typically reach approximately 16,000-18,000 m (52,493-59055 ft) altitude. Both LRs and HRs report data in one-second intervals, and MSFC NE extracted .gpx text files containing the Global Positioning System (GPS) one-second wind data from the binary .w9k files using the Win9000 processing software (Lockheed Martin, 2013). Variables extracted for this analysis consisted of launch date, as well as time, latitude, longitude, geometric height above mean sea level (MSL), wind speed, and wind direction at each one-second interval. During data processing, it was discovered that MSFC NE's version of Win9000 did not produce the custom text files that were utilized in previous DRWP studies. Appendix A presents a separate analysis that shows that the .gpx files contain the winds that are analogous to the balloon winds used in previous studies.

3. Analyses

This section describes the methodology and results of the three analyses that MSFC NE conducted to evaluate the DRWP. The first analysis entailed comparing DRWP wind profiles to concurrent AMPS balloon measurements to quantify the differences between the two systems. The second analysis consisted of assessing data availability versus altitude, which quantifies how often one should expect to obtain complete profiles to an altitude of interest. The third analysis comprised of examining the EVR of the DRWP, which quantifies the granularity of the wind features that the system resolves. Each subsection presents the analysis methodology and discusses results.

3.1. Comparison of Wind Profiles to Concurrent Balloon Measurements

MSFC NE compared wind profiles from the DRWP to concurrent wind profiles from the AMPS balloon. For this analysis, both LR and HR balloons were used. Balloon profiles were vertically matched to the 915-MHz DRWP profiles by block averaging the balloon westerly (U) and southerly (V) wind components in 100-m (328-ft) intervals. Additionally, DRWP altitudes were adjusted from height AGL to height above MSL for this analysis. In order to be compared to a balloon, the DRWP profile had to exist within ± 7.5 minutes of the first balloon observation. This procedure was performed without implementing any quality control.

Plots in this section show the sample size and statistical quantities of the differences between concurrent DRWP and balloon wind components, vector wind magnitude, and wind direction versus altitude (AGL). First, wind component deltas were generated as

$$\Delta U = U_{DRWP} - U_{Balloon}, \text{ and} \tag{1a}$$

$$\Delta V = V_{DRWP} - V_{Balloon} \tag{1b}$$

where subscripts "DRWP" and "Balloon" denote the source of the respective wind component. Next, the vector wind magnitude delta, $\Delta\vec{V}$, was computed as

$$\Delta\vec{V} = \sqrt{\Delta U^2 + \Delta V^2}. \tag{2}$$

Last, the wind direction delta, $\Delta\theta$, was computed as the smallest angle between the concurrent DRWP and balloon wind vectors. The cosine of this quantity is defined as the vectors' dot product divided by the product of their magnitudes, which equates to

$$\Delta\theta = cos^{-1}\left(\frac{U_{DRWP}*U_{Balloon}+V_{DRWP}*V_{Balloon}}{WS_{DRWP}*WS_{Balloon}}\right) \quad (3)$$

where WS_{DRWP} and $WS_{Balloon}$ denote the wind speed from the DRWP and balloon, respectively. Note that $WS_{Balloon}$ was computed as the root-sum-square of the block-averaged balloon wind components.

MSFC NE computed these quantities to statistically characterize the differences between balloon and DRWP observations, and thus quantify the error of the DRWP relative to balloon measurements. It is important to note that deltas from concurrent balloon measurements do not equate to the absolute error of the DRWP for two reasons. First, balloon observations contain their own measurement error. Second, valid measurements from multiple systems sampling different wind regimes (driven by the spatial separation between concurrent DRWP and balloon measurements) contribute to the calculated differences. No attempt was made to account for this attribute, but MSFC NE let it be known that that the separation between the balloon release point and the DRWP would impact this assessment. The USSF then agreed that results would represent an upper bound on DRWP measurement error. Sample size restrictions were implemented to ensure that statistical quantities were generated from a reasonable number of comparisons. At each altitude, the mean, root-mean-square (RMS), and 99% envelope were initially computed. Then, the mean, RMS, and 99% envelope were retained from at least 10, 30, and 100 comparisons, respectively. For reference, Pinter et al. (2004) found a mean delta of 0.85 m/s (2.79 ft/s) and an RMS delta of 1.51 m/s (4.95 ft/s) from 1-9 km (3,281-29,528 ft) for pairs of simultaneously released HR balloons at the ER.

Three sets of comparisons were performed against balloon measurements that were provided from the two sites. A total of 58 processed AMPS balloon profiles were from releases at the weather station and 27 profiles were from releases at the 915-MHz DRWP launch site. A third set of comparisons was performed using all 85 balloon releases to enhance sample size, given the relatively short distance between the DRWP site and balloon facility. This “composite” analysis is presented in the main body of the report, with Appendix B and Appendix C presenting the comparisons using balloon data at the weather station and DRWP site, respectively.

The balloon profiles were used to compute statistical quantities of wind component, vector wind magnitude, and wind direction deltas between concurrent DRWP and balloon measurements. Not every balloon was used, either because a DRWP profile was not reported within 7.5 minutes of the balloon profile or because the processed balloon profile contained corrupted data such as having no measurement altitudes. Additionally, sample size versus altitude varied because the DRWP did not contain data at all altitudes. Figure 2 displays the number of concurrent DRWP and balloon records available for comparison at each altitude for the composite analysis. Figure 2 shows that less than 60 comparisons were used to compute statistics at any given altitude. Therefore, the 99% deltas were not retained for this study. In addition, the RMS deltas were not retained below 500 m (1,640 ft), from 1,200-1,500 m (3,937-4,921 ft), at 2,000 m (6,562 ft), and above 2,900 m (9,514 ft) as fewer than 30 comparisons existed within these altitude regimes.

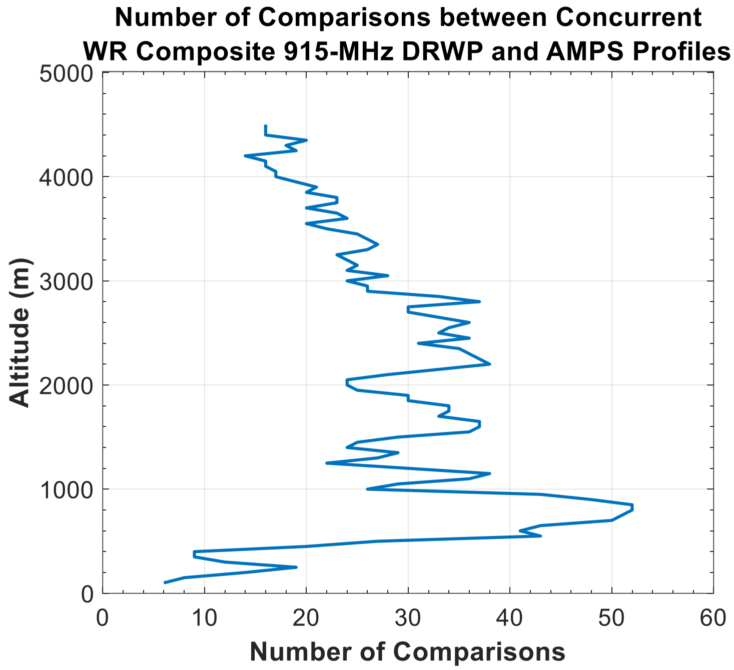

Figure 2: Number of comparisons to concurrent “composite” balloon data versus altitude (AGL) for the WR 915-MHz DRWP.

The mean deltas of each quantity, shown in Figure 3, provide an estimate of bias of the DRWP (relative to balloon measurements). The left panel displays the mean wind component deltas. Most of the mean deltas ranged from -1.0-2.0 m/s (-3.3-6.6 ft/s) of concurrent balloon wind components. The mean ∆U oscillated from 0.0-1.0 m/s (0.0-3.3 ft/s) from 500-1,000 m (1,640-3,281 ft), -1.0-0.0 m/s (-3.3-0.0 ft/s) from 1,000-1,500 m (3,281-4,921 ft), and 0.0-1.0 m/s (0.0-3.3 ft/s) from 1,500-3,500 m (4,921-11,483 ft) before remaining between -1.0 m/s (-3.3 ft/s) and 0.0 m/s (0.0 ft/s) from 3,500-4,500 m (11,483-14,764 ft). The mean ∆V was positive over much of the profile, ranging from 0.0-1.0 m/s (0.0-3.3 ft/s) from 500-2,250 m (1,640-7,382 ft) and remaining between 1.5-2.5 m/s (4.9-8.2 ft/s) above 2,250 m (7,382 ft). The mean wind component deltas indicated slight systematic bias in V between the two systems, with the DRWP tending to measure greater V (i.e., more southerly winds) than the balloon above roughly 2,000 m. The center panel shows the mean vector delta. This quantity started near 3.0 m/s (9.8 ft/s) at the lowest altitudes, reached a minimum of 1.7 m/s (5.6 ft/s) at 700 m (2,297 ft), ranged from 2.0-3.1 m/s (6.6-10.2 ft/s) up to 3,500 m (11,843 ft), and ranged from 3.0-4.0 m/s (9.8-13.1 ft/s) at the higher altitudes. The right panel presents the mean ∆θ versus altitude, which peaked at 28° at 300 m (984 ft). Then, the mean ∆θ decreased with increasing altitude, fluctuating between 10° and 20° over much of the profile, and ranging from 7-10° above 3,500 m (11,483 ft). This analysis of ∆θ was performed ignoring the relationship between wind direction and wind speed. Further investigation found that many high wind direction deltas were concurrent with low wind speeds, where wind direction is expected to vary more significantly. Appendix D contains a sensitivity study that showed the mean ∆θ fluctuating around 10° when only considering wind speeds exceeding 4.0 m/s (13.1 ft/s).

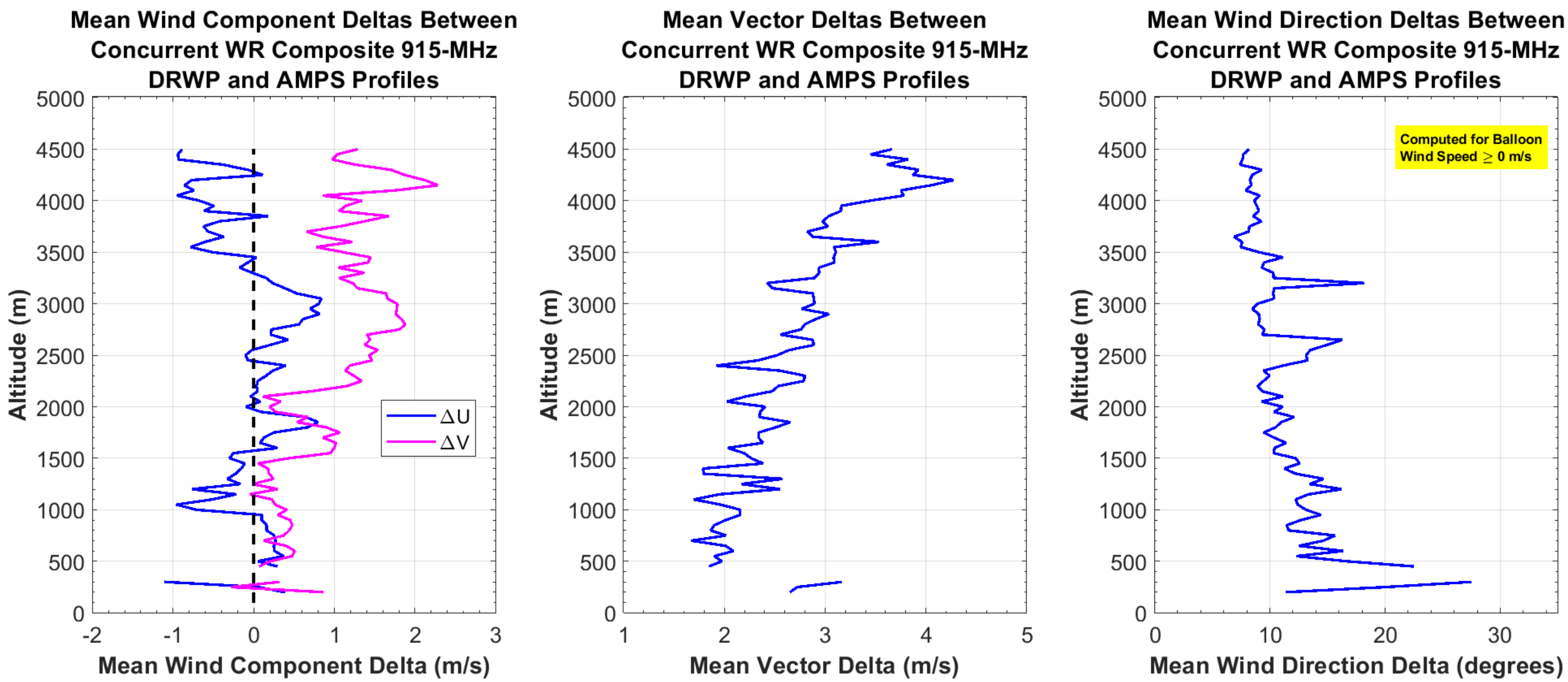

Figure 3: Mean deltas of wind components (m/s, left), vector magnitude (m/s, center), and wind direction (degrees, right) versus altitude (AGL) between concurrent data from the WR 915-MHz DRWP and the composite balloon data.

The RMS deltas of each quantity from the composite analysis, shown in Figure 4, provided an estimate of the error of the DRWP (relative to balloon measurements), including the system's bias. The left panel displays the RMS wind component deltas. Most of the RMS deltas of both wind components ranged from 1.0-2.3 m/s (3.3-7.5 ft/s) with the RMS delta of both components exhibiting similar attributes. The minimum RMS wind component delta existed from roughly 2,100-2,300 m (6,890-7,546 ft), and an anomalous increase in the RMS ΔU to 3.4 m/s (11.2 ft/s) at 1,200 m (3,937 ft) was noted. The center panel shows the RMS vector delta. This quantity started near 2.5 m/s (8.2 ft/s) below 1,000 m (3,281 ft) and gradually increased to roughly 3.3 m/s (10.8 ft/s) from 2,000-3,000 m (6,562-9,843 ft). An anomalous increase of the RMS vector delta to near 4.0 m/s (13.1 ft/s) at 1,200 m (3,937 ft) was also present. The right panel presents the RMS $\Delta\theta$ versus altitude, which ranged from 15-30° from 500-1,200 m (1,640-3,937 ft). Then, the RMS $\Delta\theta$ decreased to roughly 15° from 1,500-2,000 m (1,640-3,937 ft) and increased to 34° at 2,650 m (8,694 ft) before decreasing to near 10° at 2,800 m (9,186 ft). As with the analysis of mean $\Delta\theta$, this analysis of $\Delta\theta$ was performed ignoring the relationship between wind direction and wind speed. Appendix D contains a sensitivity study that showed the RMS $\Delta\theta$ ranging from roughly 10-20° when only considering wind speeds exceeding 4.0 m/s (13.1 ft/s).

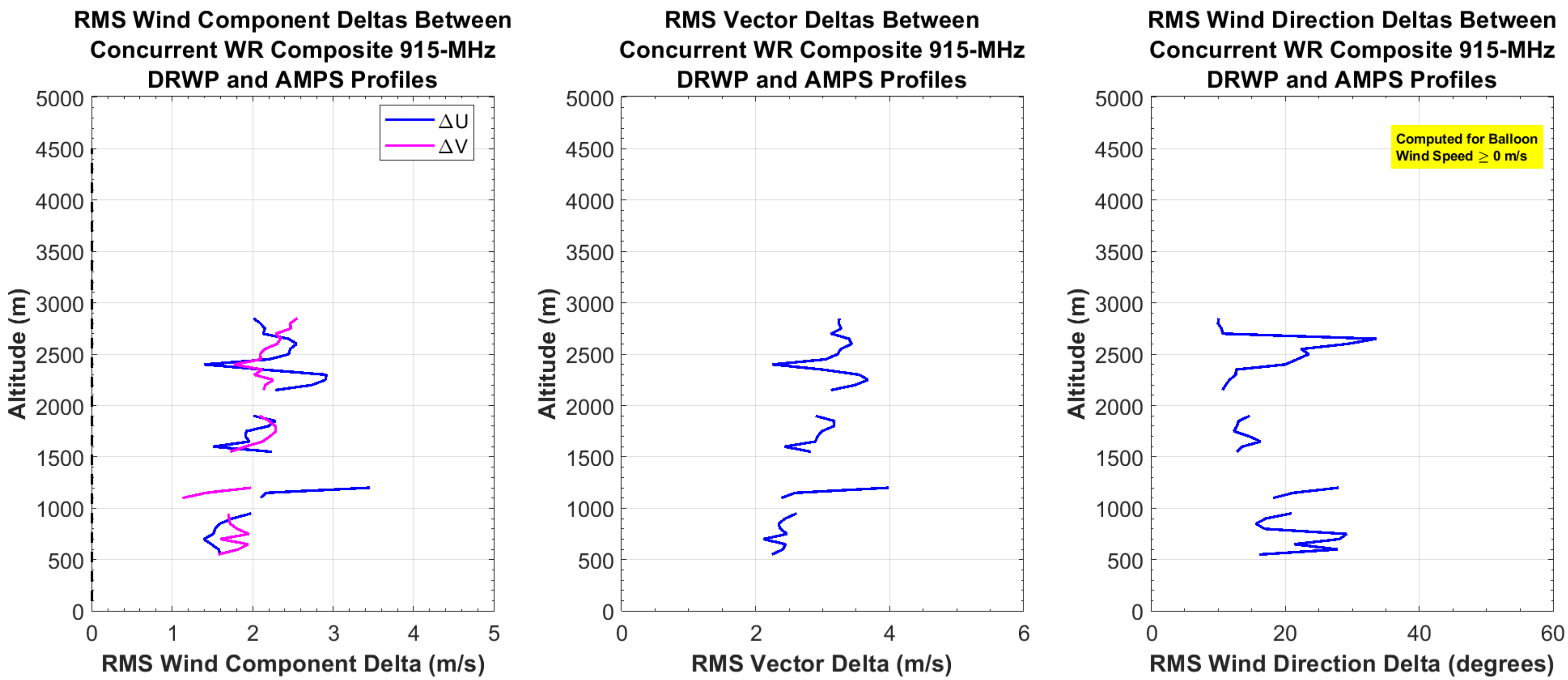

Figure 4: RMS deltas of wind components (m/s, left), vector magnitude (m/s, center), and wind direction (degrees, right) versus altitude (AGL) between concurrent data from the WR 915-MHz DRWP and “composite” balloon data.

3.2. Data Availability

An analysis of data availability versus altitude was conducted for the DRWP to show the probability of receiving vertically complete profiles within a specified altitude range. For this analysis, data availability was defined as 100% times the ratio of the number of profiles that contained data at all altitudes between the bottom of the profile and a given altitude to the total number of profiles collected. A profile was collected at 50.8% of the total number of 15-minute timestamps in the POR. This attribute largely stems from data being provided over 23 days within the 43-day POR.

Figure 5 shows the probability of a profile extending without gaps from the bottom altitude of 100 m (328 ft) to the selected altitude on the ordinate. Data availability at 100 m (328 ft) was near 18%, and the percent of available profiles decreased with increasing altitude range. One should interpret this figure as the percent of complete profiles from 100 m (328 ft) to the altitude specified on the ordinate, given that a profile existed. For example, 3% of the DRWP profiles were complete from 100-1,000 m (328-3,281 ft).

Additional examination of data availability versus altitude was also performed. Figure 6 displays the percent of valid data records at discrete altitudes, and shows that data availability oscillated from 17-50% below 350 m (1,148 ft), increased to near 75% at 600 m (1,969 ft) and near 94% at 800 m (2,625 ft), oscillated between roughly 45% and 75% from 1,000-2,200 m (3,281-6,562 ft), and decreased from roughly 65% to near 30% from 2,200-4,500 m (6,562-14,764 ft). The percent data availability at discrete altitudes (Figure 6) also provides insight to any applications that do not require complete profiles, such as assessments at discrete altitudes or within specified altitude ranges.

Figure 7 was created to show the percent of complete profiles extending from 600 m (1,969 ft) to specified altitudes to quantify data availability ignoring the relatively low data availability below 600 m (1,969 ft). Results display a similar trend to Figure 5, with a slightly higher percent availability of profiles. For example, 33% of the DRWP profiles were complete from 600-1,000 m (1,969-3,281 ft), and 4% of the DRWP profiles were complete from 600-3,000 m (1,969-9,843 ft).

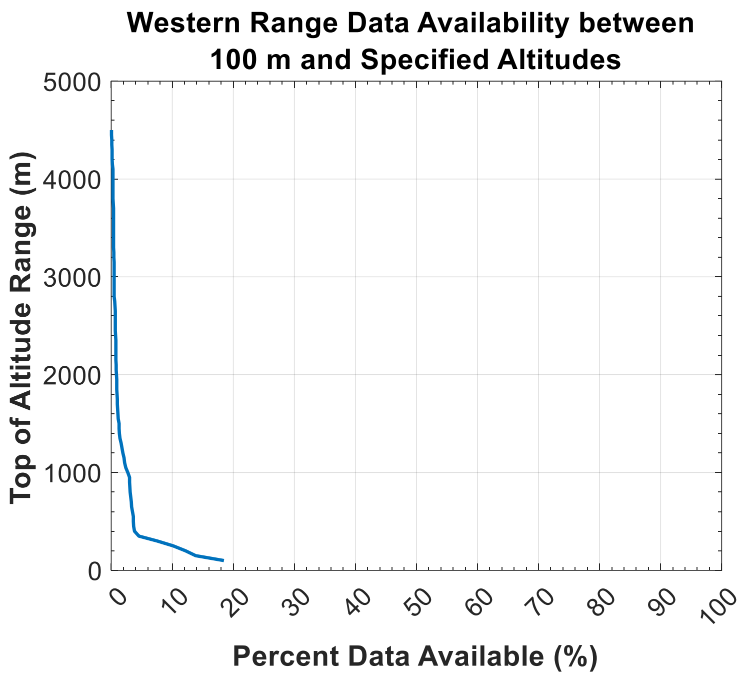

Figure 5: Percent of profiles containing no missing data from 100 m (328 ft) to the altitude specified on the ordinate.

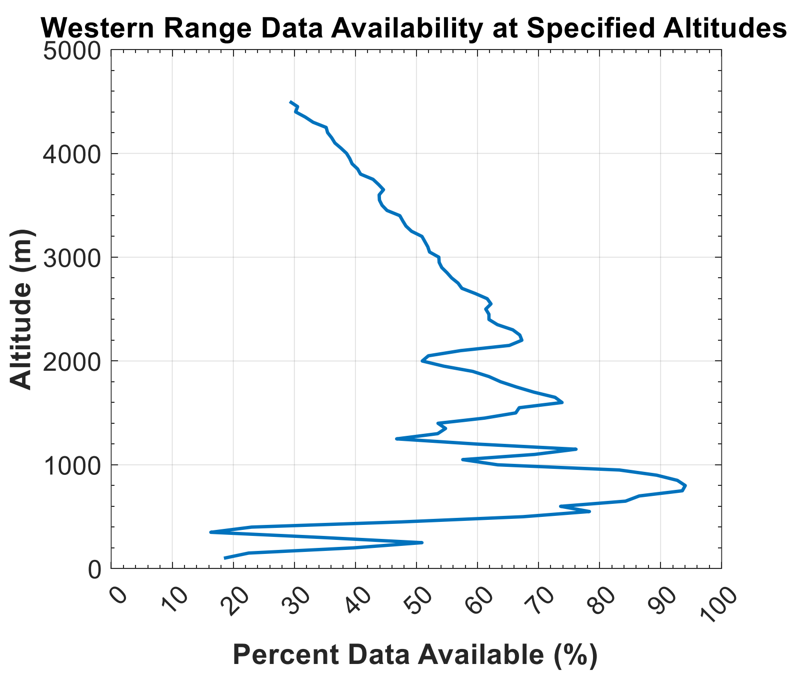

Figure 6: Percent of the DRWP archive that contains data records at discrete altitudes.

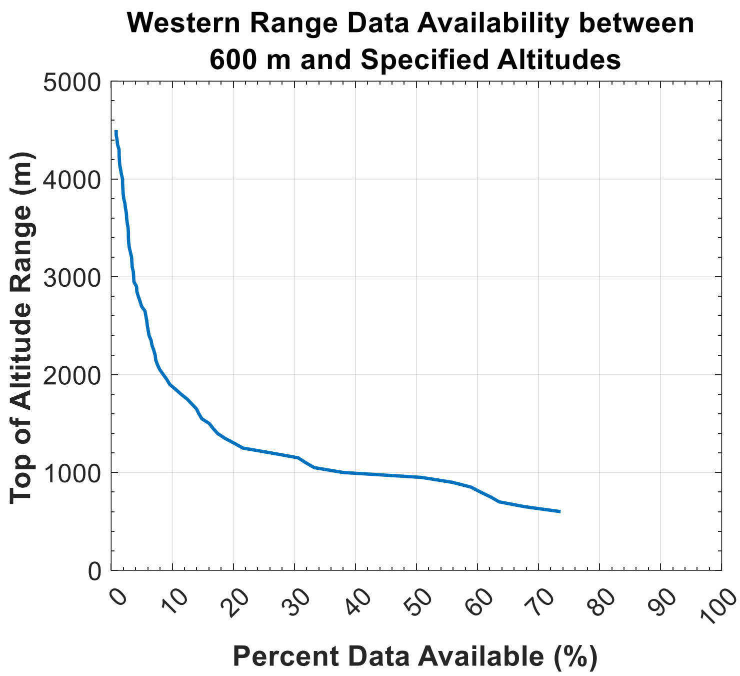

Figure 7: Percent of profiles containing no missing data from 600 m (1,969 ft) to the altitude specified on the ordinate.

3.3. Effective Vertical Resolution

Analyses of mean power spectral density (PSD) were conducted to estimate the EVR of the DRWP. The analysis utilized complete profiles over two specified altitude regimes. First, complete wind component profiles from 600-4,500 m (1,969-14,764 ft) corresponding to the entire DRWP altitude range and complete profiles from 600-2,100 m (1,969-6,890 ft) were extracted to optimize the altitude range versus data availability. The lower bound of 600 m (1,969 ft) was chosen to mitigate any effects due to the relatively low data availability described in Section 3.2. This segregation resulted in 17 complete profiles from 600-4,500 m (1,969-14,764 ft), with 79 points per profile, and 159 complete profiles from 600-2,100 m (1,969-6,890 ft), with 31 points per profile. Next, the mean and linear trend were removed from each wind component profile and a Hanning window with zero overlap was applied to the profile. Then, the Fast Fourier Transform of each profile was computed as a function of wavelength and used to generate each profile's PSD. Last, mean PSD at each wavelength was computed and displayed on a log-log plot. Results are shown in Figure 8, which also includes a reference line derived from the linear fit to the linear portion of the mean U component PSD (in log space).

The EVR was estimated by determining the wavelength at which the PSD begins to deviate from a linear trend when reading the plot from right-to-left. The PSDs were found to be quasi-parallel to the reference line down to the smallest wavelengths. By utilizing the zoomed-in plots on the bottom panel, the PSD of wind profiles from 600-4,500 m (1,969-14,674 ft) and from 600-2,100 m (1,969-6890 ft) appear to deviate from a linear trend around 200 m (656 ft) and 300 m (984 ft), respectively. This result indicates that wind features smaller than approximately 250 m (820 ft) are not distinguishable from instrument noise, which is consistent with similar DRWP systems at the ER (MSFC NE 2021). Thus, the WR DRWP was found to be “noise-limited” below approximately 250 m (820 ft), and it is surmised that this boundary wavelength would be solidified if more data were analyzed. Iterations of this analysis performed using a Parzen window produced similar results that are not shown here. For reference, Wilfong (2017) found the EVR of AMPS one-second HR and LR profiles to approximate 160 m (525 ft) and 270 m (886 ft), respectively.

This study did not utilize coherence to determine EVR as in previous studies. The coherence analysis relies on an assumption that the profiles in the pair used represent a static atmosphere. The mean coherence versus wavelength was computed, but results showed extremely large boundary wavelengths and did not align with the spectral signatures shown in the PSDs. It was determined that the discrepant results in the coherence analysis stemmed from the time separation of 15 minutes between temporally adjacent profiles not meeting the assumption that the atmosphere remains static over the sampling period.

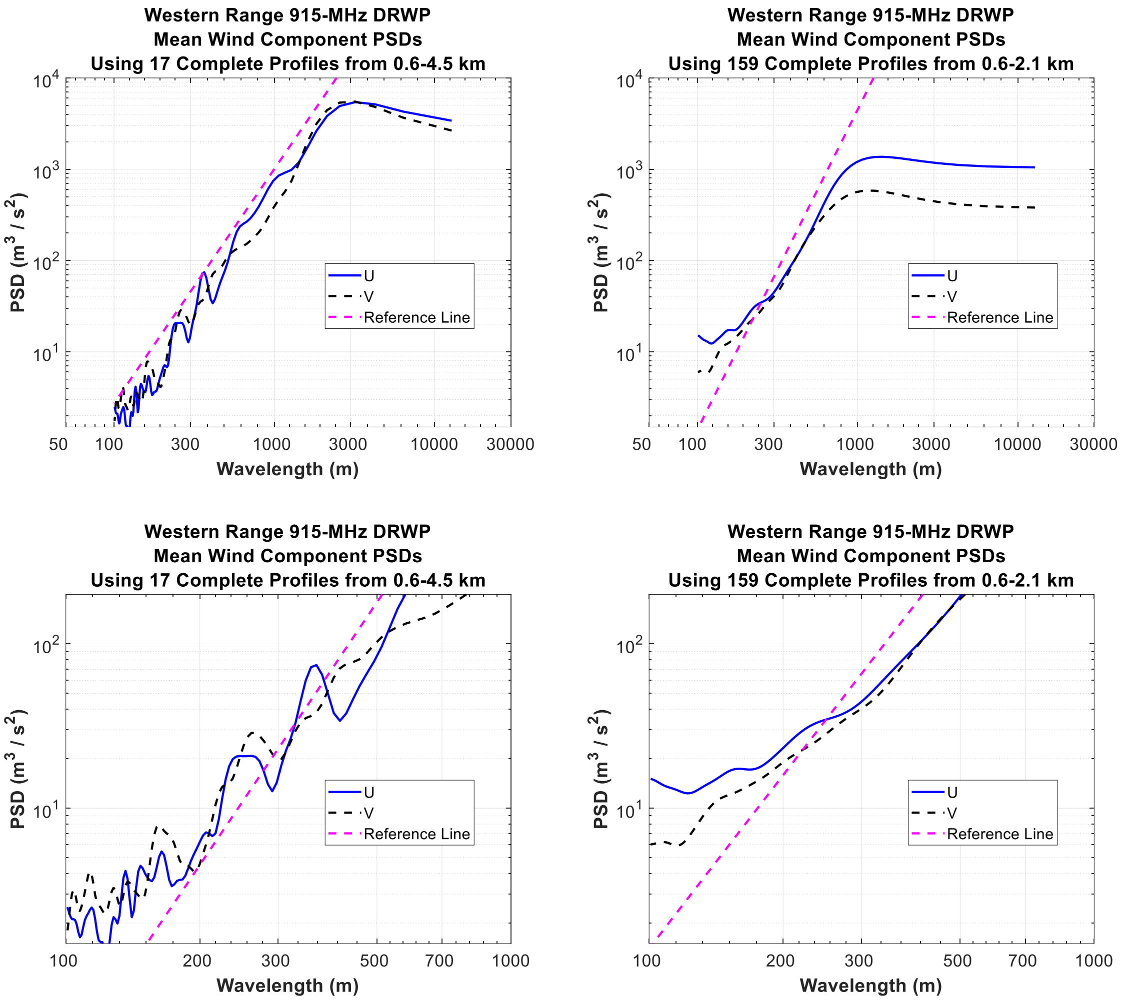

Figure 8: Mean PSDs (m^3s^{-2}) versus wavelength (m) using complete DRWP profiles from 600-4,500 m (1,969-14,764 ft) altitude (left) and 600-2,100 m (1,969-6,890 ft) altitude (right) at all wavelengths (top) and from 100-1,000 m (656-3,281 ft) wavelength (bottom). Blue, solid lines and dashed, black lines denote the PSD for U and V, respectively. The dashed, magenta line shows a linear approximation for reference.

4. Summary

This report documents analyses conducted to evaluate wind profile output from the WR 915-MHz DRWP using wind profile measurements from January 25, 2021 to March 8, 2021. Analyses included comparing wind components from the DRWP to concurrent AMPS balloon wind profiles, examining the percent of complete profiles, and quantifying the DRWP's EVR. While some exceptions existed, at a given altitude the RMS wind component delta was approximately 1.5-3.0 m/s (4.9-9.8 ft/s), the RMS vector delta was roughly 2.0-3.5 m/s (6.6-11.5 ft/s), and the RMS wind direction delta ranged from 10-35°. Appendix A shows the use of applicable winds from the GPS data files, Appendix B and Appendix C document the balloon data comparison segregating balloon releases from the weather station and 915-DRWP site, and Appendix D presents the susceptibility of wind direction comparisons to low wind speeds.

The percent of available profiles from the DRWP tended to decrease with increasing altitude and showed a sensitivity to the minimum altitude selected. Data availability at 100 m (328 ft) was found to be 18%, but data availability at 600 m (1,969 ft) was approximately 75%. This attribute led to slightly higher probability of obtaining a complete profile from 600 m (1,969 ft) versus 100 m (328 ft). For example, 0% of the profiles contained no missing data from 100-3,000 m (328-9,843 ft) and 4% of the profiles contained no missing data from 600-3,000 m (1,969-9,843 ft).

The DRWP was found to be noise-limited, resolving wind features with wavelengths larger than approximately 250 m (820 ft). Results for wind comparisons and EVR are consistent with previously documented studies of AMPS balloon measurements. One should note that the DRWP produces wind profiles more frequently than typical balloon releases, but DRWP profiles tend to have a smaller vertical domain and a larger sampling interval.

5. Acknowledgements

Much appreciation goes to numerous personnel at multiple organizations who helped with this project. Alexander Hibbs / USSF supplied the data from all the DRWP and balloon systems at the WR. Nathan Curtis / MSFC NE and Frank Leahy / MSFC NE obtained much of the data used for this study and coordinated scope and schedules with RGNext. Suzanne Siverling / RGNext served as the Technical Point of Contact during this study, and graciously addressed several questions about the data. Many thanks go to the reviewers of this report. This work was performed under contract 80MSFC18C0011.

6. References

F. Merceret, "The Vertical Resolution of the Kennedy Space Center 50 MHz Wind Profiler," *Jounal of Atmospheric and Oceanic Technology,* vol. 16, pp. 1273-1278, 1999.

D. J. Pinter, F. J. Merceret and C. V. Hatley, "Performance Validation of the Upgraded Eastern Range 50 MHz Wind Profiler," *Journal of Spacecraft and Rockets,* vol. 43, pp. 693-695, 2006.

MSFC Natural Environments. “Performance assessment of the Eastern Range Titusville-Cocoa 915-MHz Doppler Radar Wind Profiler.” NASA Memo EV44 (21-001).

Lockheed Martin, “Win9000 Processing and Display Software Operator’s Manual,” Contractor report P/N 9017-248, Rev. K, 2013.

T. Wilfong, "AMPS II Eastern Range Formal DT&E Analysis," Boulder, CO, 2012.

Appendix A: Utilizing wind data from the GPS text file produced by Win9000

MSFC NE utilized winds from the .gpx file produced by Win9000, which consisted of extracting winds from different files than those utilized in previous studies. MSFC NE's process had entailed generating custom text files that contained the balloon's geometric height and "unsmoothed" wind components that had undergone a low-pass filter to remove balloon motion. However, it was found during data processing that MSFC NE's version of Win9000 (version 6.2.1) did not produce any text files from the binary .w9k files, including these custom text files. The WR provided text files that have a predetermined format from Win9000, which include the one-second GPS winds in the files that have a .gpx suffix. This appendix describes the analyses that demonstrated the validity of using winds from these .gpx files.

MSFC NE conducted a comparison using data from the ER that could be analyzed through processing both the custom text file and the .gpx file. For this analysis, MSFC NE generated a .gpx file and a custom text file from an arbitrary profile at the ER. The custom text file contains the "unsmoothed" wind speed and wind direction used in previous DRWP analyses. The .gpx file contains "wind speed", "wind direction", "E/W wind", and "N/S wind." Both files contain geometric height. The U wind component profile from three data sources was generated and examined. The first source consisted of the "E/W wind" field directly from the .gpx file, the second source entailed U calculated from the "wind speed" and "wind direction" fields in the .gpx file, and the third source entailed U calculated from the "wind speed" and "wind direction" fields in the custom text file.

This analysis demonstrated that the .gpx files contain the needed winds. Figure A1 shows an overlay of U from each source. One can discern that U calculated from the wind speed and wind direction fields in the .gpx file matches the U calculated from the wind speed and wind direction in the custom file. Much more small-scale variation exists in U taken directly from the .gpx file. The PSD of this profile, shown in Figure A2, highlights the increased energy content at periods below roughly 30 seconds, with a spectral peak near 10 seconds. This attribute reflects the reported winds being affected by the periodic motion of the sonde under the balloon. Figure A2 also displays nearly identical spectral signatures in U calculated from the wind speed and wind direction fields in custom file and in the .gpx file. These profiles contain winds that result from applying a filter that removes the sonde motion under the balloon. Therefore, the wind components calculated from the wind speed and wind direction fields in the .gpx files were shown to match the winds used in previous analyses, and thus were utilized for the WR DRWP study as the custom files could not be created using the MSFC NE's version of Win9000.

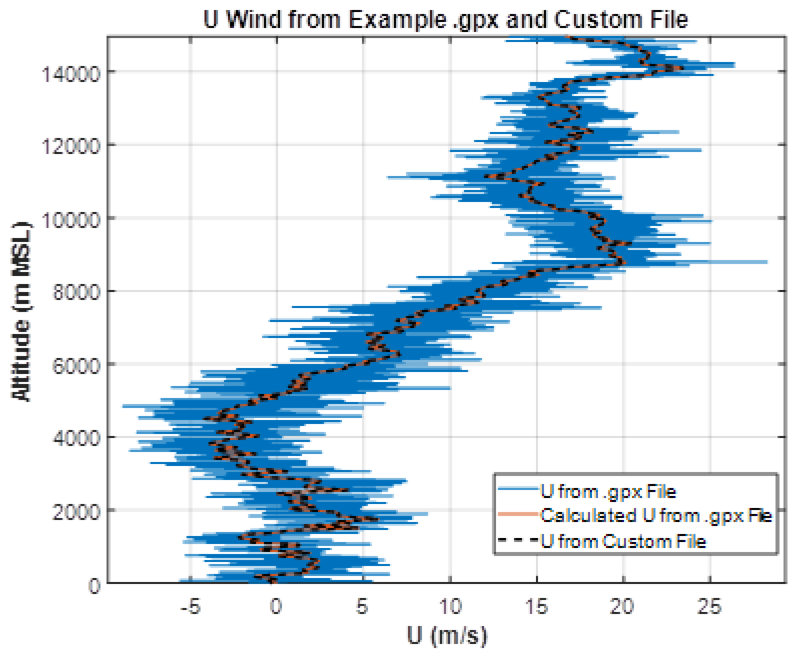

Figure A1: U wind component (m/s) versus altitude (m MSL) from an arbitrary balloon release. The solid, blue line denotes U taken directly from the .gpx file. The solid, red line shows U calculated from the wind speed and wind direction in the .gpx file. The dashed, black line shows U calculated from the wind speed and wind direction in the custom file used in previous DRWP analyses.

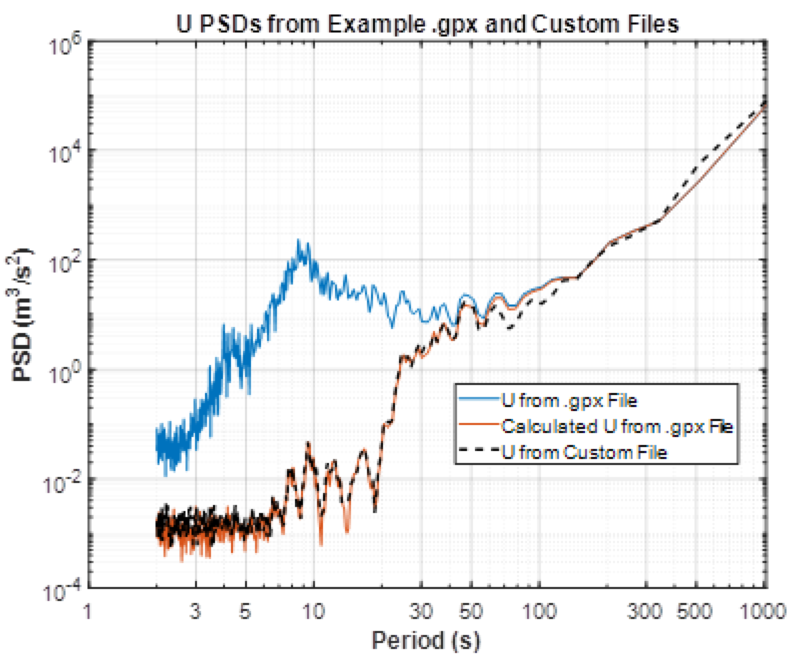

Figure A2: U wind component PSDs (m^3/s^2) versus period (s) from an arbitrary balloon release. The solid, blue line denotes U taken directly from the .gpx file. The solid, red line shows U calculated from the wind speed and wind direction in the .gpx file. The dashed, black line shows U calculated from the wind speed and wind direction in the custom file used in previous DRWP analyses.

Appendix B: Comparisons between concurrent DRWP and balloon measurements at the weather station

This appendix presents the analysis of comparisons performed against 58 AMPS balloon measurements that were from releases at the weather station. The balloon profiles were used to compute statistical quantities of wind component, vector wind magnitude, and wind direction deltas between concurrent DRWP and balloon measurements. Not every balloon was used, either because a DRWP profile was not reported within 7.5 minutes of the balloon profile or because the processed balloon profile contained corrupted data. Additionally, sample size versus altitude varied because the DRWP did not contain data at all altitudes. Figure B1 displays the number of concurrent DRWP and balloon records available for comparison at each altitude for this analysis. Figure B1 shows that less than 35 comparisons were used to compute statistics at any given altitude. Therefore, the 99% deltas were not retained for this study. In addition, the RMS deltas were only retained from 700-900 m (2,297-2,953 ft), as fewer than 30 comparisons existed at all other altitudes.

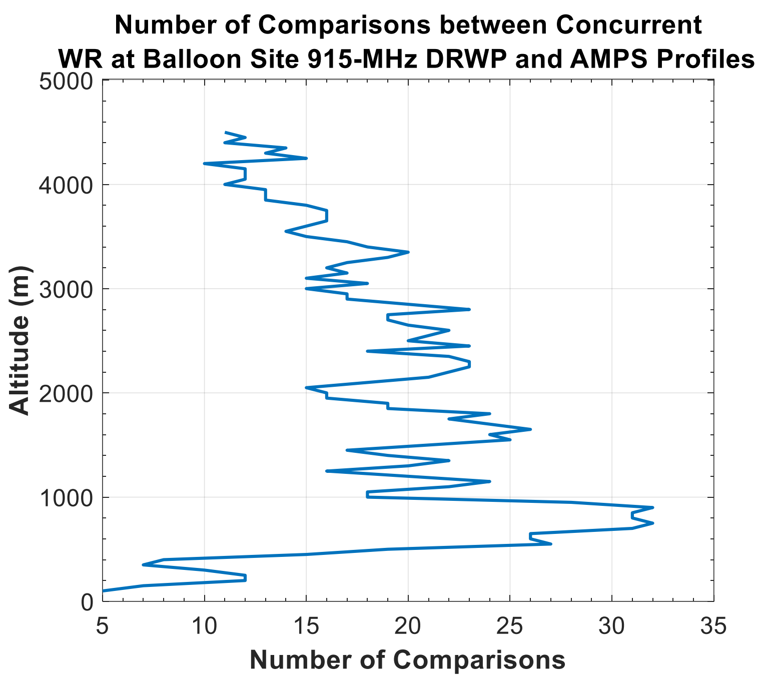

Figure B1: Number of comparisons to concurrent balloon data from the weather station versus altitude (AGL) for the WR 915-MHz DRWP.

The mean deltas of each quantity, shown in Figure B2, provide an estimate of bias of the DRWP (relative to balloon measurements). Results in Figure B2 are like those presented in Figure 3, as this sample comprises most of the composite dataset. The left panel displays the mean wind component deltas. Most of the mean deltas ranged from -1.0-2.0 m/s (-3.3-6.6 ft/s) of concurrent balloon wind components. The mean ΔU oscillated from -1.2-0.0 m/s (-3.9-0.0 ft/s) from 500-1,000 m (1,640-3,281 ft), ranged from -1.2-0.0 m/s (-3.9-0.0 ft/s) from 1,000-1,500 m (3,281-4,921 ft), and ranged from 1.2-1.0 m/s (-3.9-3.3 ft/s) from 1,500-3,500 m (4,921-11,483 ft) before remaining between -2.0 m/s (-

6.6 ft/s) and 0.0 m/s (0.0 ft/s) from 3,500-4,500 m (11,483-14,764 ft). The mean ∆V was positive over much of the profile, ranging from -0.3-1.0 m/s (-1.0-3.3 ft/s) from 500-2,250 m (1,640-7,382 ft) and remaining between 0.5-2.2 m/s (1.6-7.2 ft/s) from 2,250 m (7,382 ft) to the top of the profile. The mean wind component deltas indicated slight systematic bias in V between the two measurement systems, with the DRWP tending to measure greater V (i.e., more southerly winds) than the balloon above roughly 2,500 m (8,202 ft). The center panel shows the mean vector delta. This quantity started near 3.0 m/s (9.8 ft/s) at the lowest altitudes, reached a minimum of 1.9 m/s (6.2 ft/s) at 700 m (2,297 ft), ranged from 1.9-3.2 m/s (6.2-10.5 ft/s) up to 3,000 m (9,842 ft), and ranged from 2.5-4.8 m/s (8.2-15.7 ft/s) at the higher altitudes. The right panel presents the mean ∆θ versus altitude, which ranged from 10-22° below 500 m (1,640 ft). Then, the mean ∆θ gradually decreased with increasing altitude, fluctuating between 7° and 21° over much of the profile, with an outlier of 24° at 3,200 m (10,499 ft). This analysis of ∆θ was performed ignoring the relationship between wind direction and wind speed.

The RMS deltas of each quantity using balloons released at the weather station, shown in Figure B3, provided an estimate of the error of the DRWP (relative to balloon measurements), including the system's bias. RMS statistics are only presented from 700-900 m (2,297-2,953 ft), as the sample size criteria were only met between these altitudes. Wind component RMS deltas were between 1.5 m/s (4.9 ft/s) and 2.1 m/s (6.9 ft/s), vector wind deltas ranged from 2.3-2.8 m/s (7.5-9.2 ft/s), and RMS wind direction deltas were between 18° and 35°. As with the analysis of mean ∆θ, this analysis of ∆θ was performed ignoring the relationship between wind direction and wind speed.

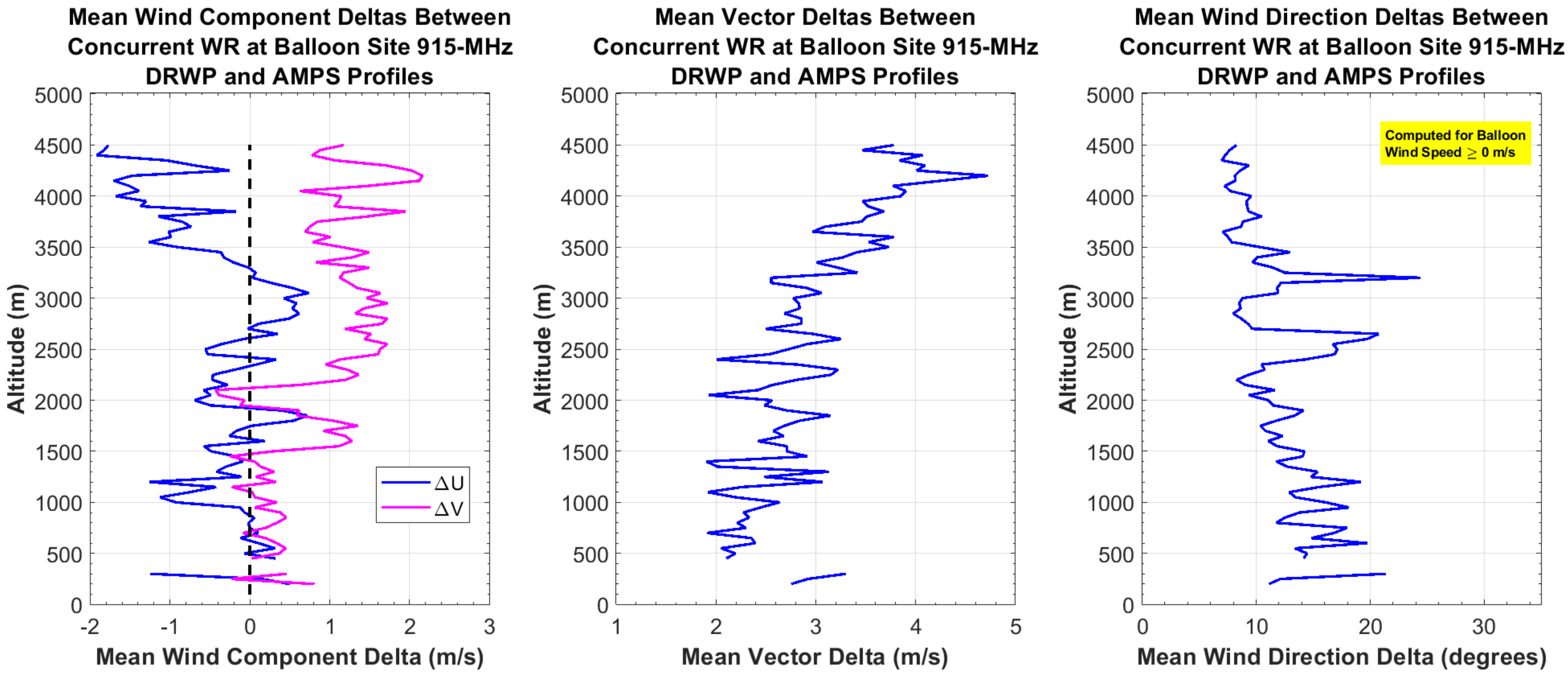

Figure B2: Mean deltas of wind components (m/s, left), vector magnitude (m/s, center), and wind direction (degrees, right) versus altitude (AGL) between concurrent data from the WR 915-MHz DRWP and data from balloons released at the weather station.

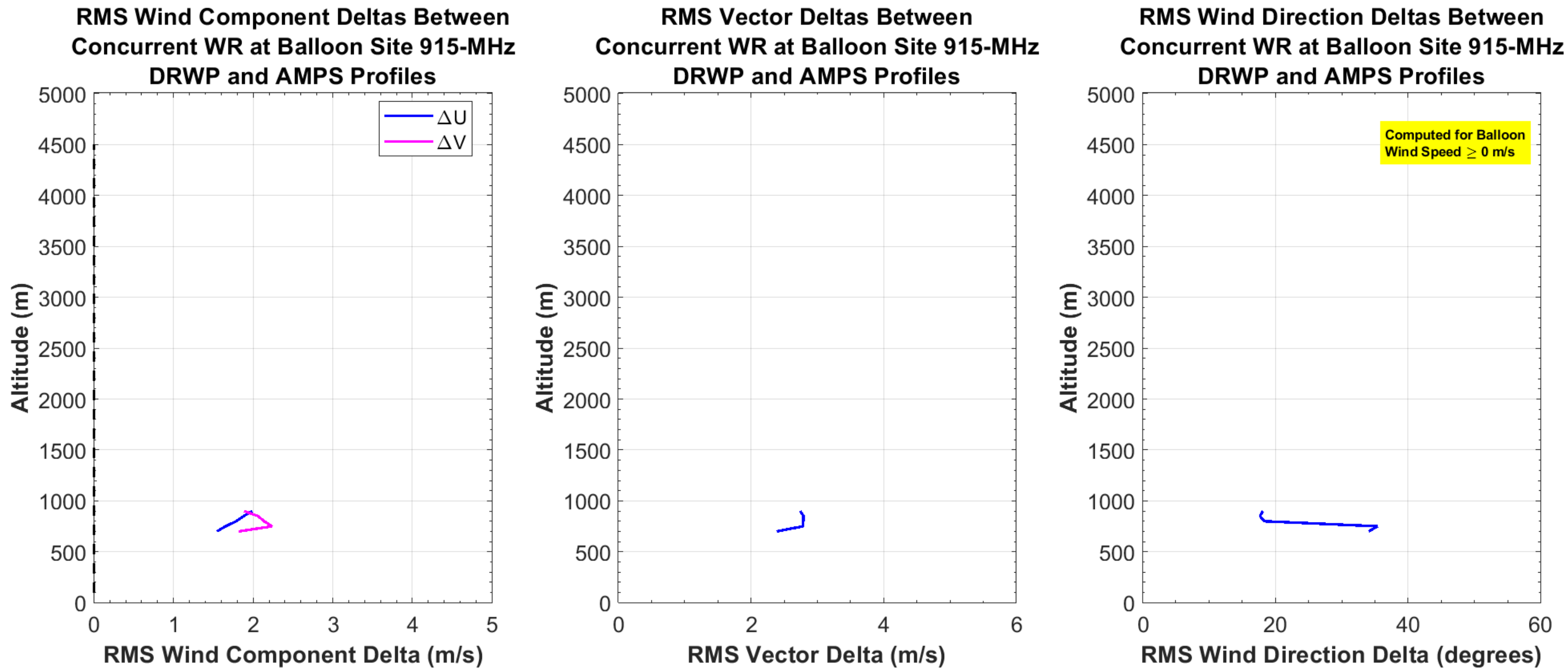

Figure B3: RMS deltas of wind components (m/s, left), vector magnitude (m/s, center), and wind direction (degrees, right) versus altitude (AGL) between concurrent data from the WR 915-MHz DRWP and data from balloons released at the weather station.

Appendix C: Comparisons between concurrent DRWP and Balloon Measurements at the DRWP Site

This appendix presents the analysis of comparisons performed against 27 AMPS balloon measurements that were from releases at the DRWP site. The balloon profiles were used to compute statistical quantities of wind component, vector wind magnitude, and wind direction deltas between concurrent DRWP and balloon measurements. Not every balloon was used, either because a DRWP profile was not reported within 7.5 minutes of the balloon profile or because the processed balloon profile contained corrupted data. Additionally, sample size versus altitude varied because the DRWP did not contain data at all altitudes. Figure C1 displays the number of concurrent DRWP and balloon records available for comparison at each altitude for the composite analysis. Figure C1 shows that less than 25 comparisons were used to compute statistics at any given altitude. Therefore, the RMS and 99% deltas were not retained for this study.

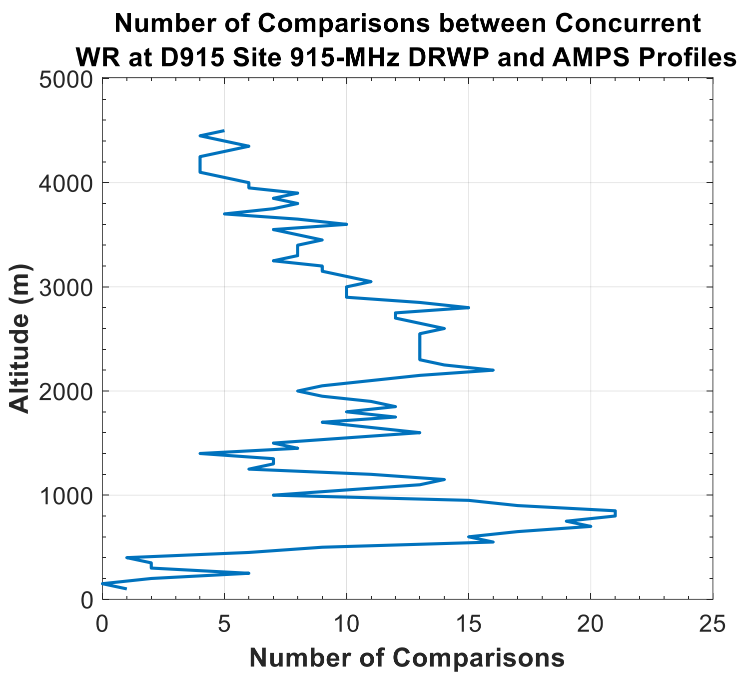

Figure C1: Number of comparisons to concurrent balloon data from the DRWP site versus altitude (AGL) for the WR 915-MHz DRWP.

The mean deltas of each quantity, shown in Figure C2, provide an estimate of bias of the DRWP (relative to balloon measurements). The left panel displays the mean wind component deltas. The mean ∆U oscillated from 0.0-1.0 m/s (0.0-3.3 ft/s) throughout the entire, sans a delta of -1.3 m/s (-4.3 ft/s) at 1,050 m (3,445 ft). The mean ∆V was positive over all of the profile, ranging from 0.5-1.0 m/s (1.6-3.3 ft/s) from 500-2,000 m (1,640-6562 ft) and gradually increasing to a maximum of 2.7 m/s (8.9 ft/s) at 2,850 m (9,350 ft). The mean wind component deltas indicated slight systematic bias in U and V between the two measurement systems, with the DRWP tending to measure greater U (i.e., more westerly winds) and greater V (i.e., more southerly winds) than the balloon. This analysis of ∆θ was performed ignoring the relationship between wind direction and wind speed.

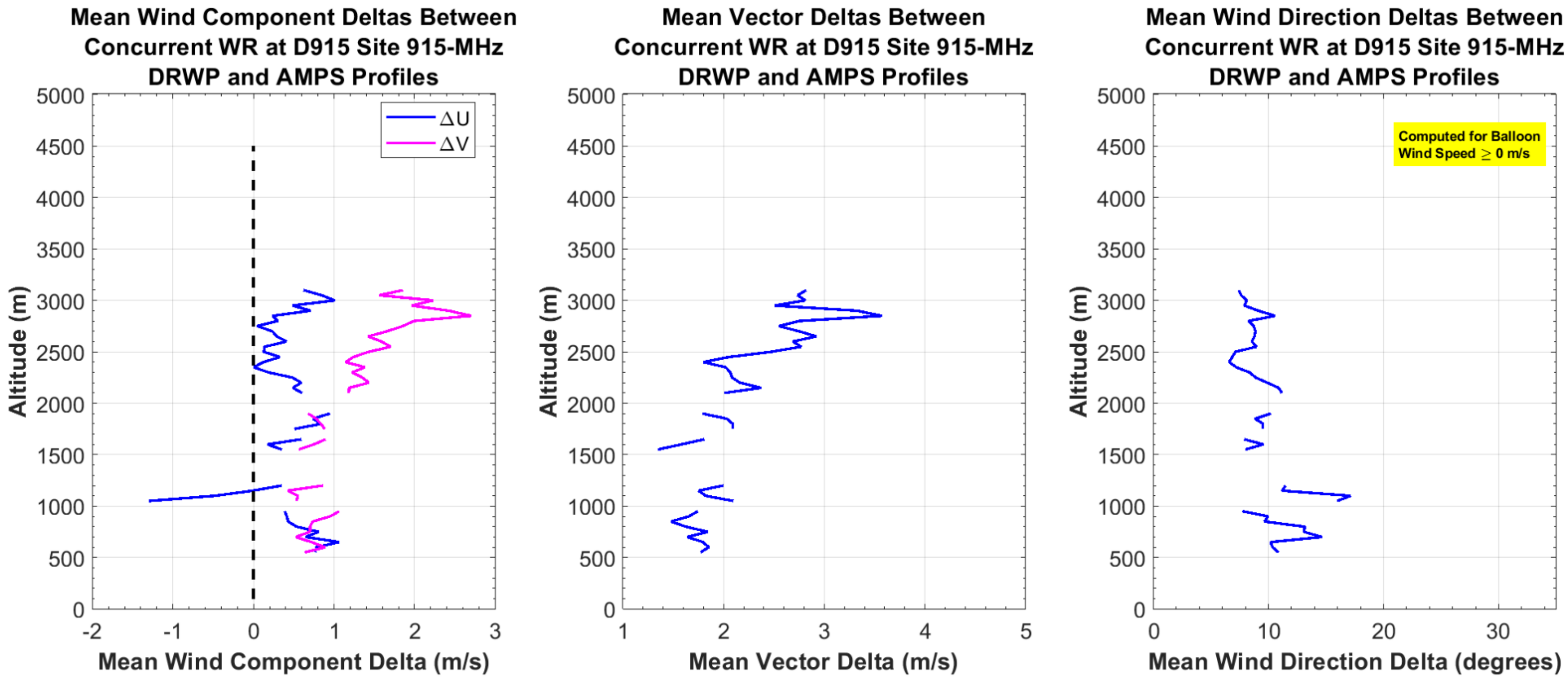

Figure C2: Mean deltas of wind components (m/s, left), vector magnitude (m/s, center), and wind direction (degrees, right) versus altitude (AGL) between concurrent data from the WR 915-MHz DRWP and data from balloons released at the DRWP site.

Appendix D: Comparisons of Wind Direction versus Wind Speed Using the Composite Balloon Data

A study was performed to show the sensitivity of Δθ to wind speed following the intuition that larger Δθ comparisons could stem from the large wind direction variability that is common in light wind environments. Figure D1 displays individual computations of Δθ versus balloon wind speed, along with the mean Δθ within 1.0 m/s (3.3 ft/s) wind speed bins using the "composite" balloon dataset described in Section 3.1. Examining Figure D1 confirmed that a significant number of large Δθ values corresponded to low wind speeds. As such, Δθ and the associated statistics would decrease if Δθ were to be performed only corresponding to wind speeds above a specified threshold. A wind speed of 4.0 m/s (13.1 ft/s) was selected as the threshold for this sensitivity study, as the slope of the mean Δθ versus wind speed began to decrease to a lesser extent at higher wind speeds when examining the plot from left-to-right. Thus, a modified analysis was conducted, which computed the mean and RMS of Δθ corresponding to wind speeds exceeding 4.0 m/s (13.1 ft/s).

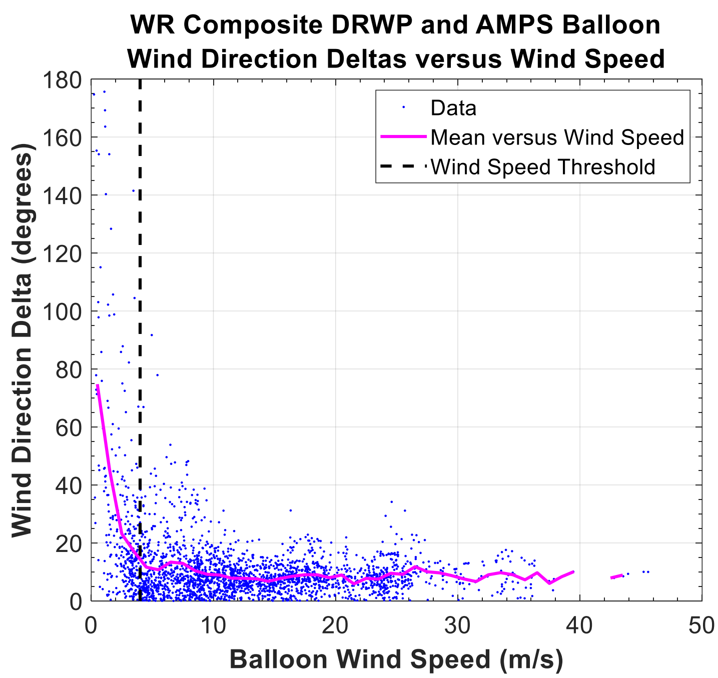

Figure D1: Wind direction deltas (degrees) between concurrent WR DRWP and composite balloon measurements versus balloon wind speed (m/s). The solid, magenta line denotes the mean wind direction delta versus wind speed, and the dashed, black line shows the wind speed threshold selected for this sensitivity study.

The mean and RMS Δθ were found to decrease significantly with the modified analysis. Figure D2 shows the mean Δθ from the original and modified analysis. The modified analysis reduced the maximum mean Δθ versus altitude from roughly 28° to near 14°. Mean Δθ from the modified analysis fluctuated around 10° throughout the profile. Figure D3 presents analogous results for the RMS Δθ. The modified analysis reduced the maximum RMS ∆θ from roughly 35° to near 20°. The RMS ∆θ from the modified analysis varied from roughly 10-20° throughout the profile.

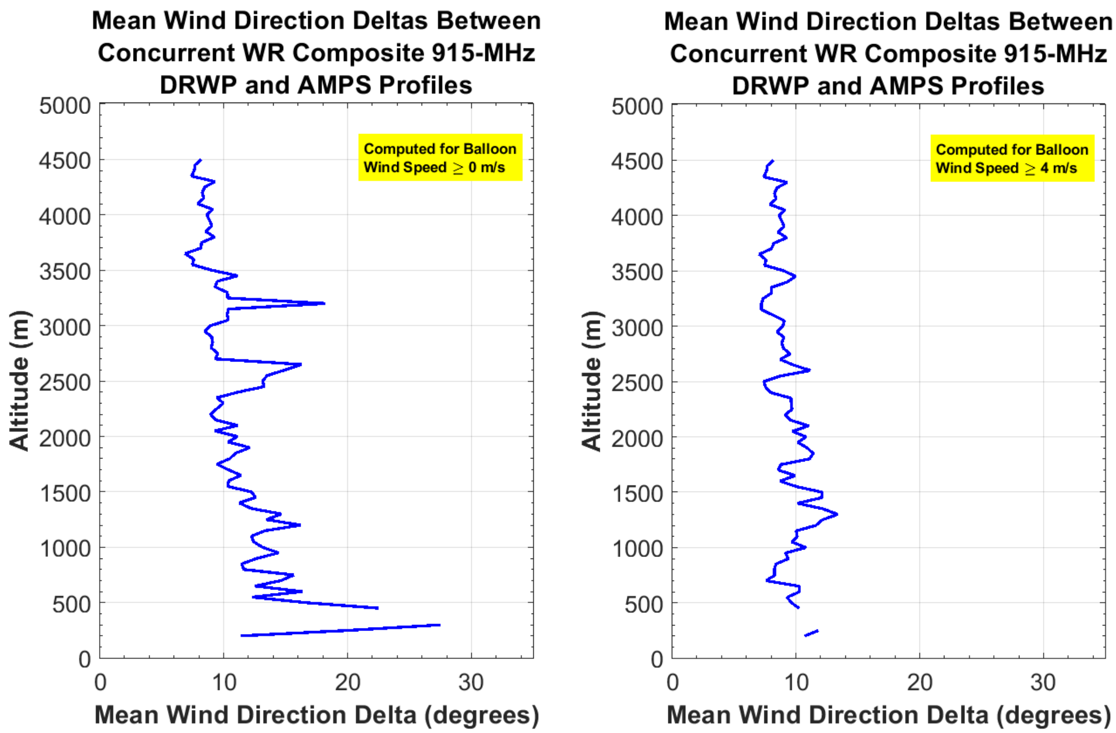

Figure D2: Mean wind direction deltas (degrees) versus altitude (AGL) between concurrent WR DRWP and composite balloon measurements corresponding to balloon wind speeds exceeding 0.0 m/s (0.0 ft/s) (left) and 4.0 m/s (13.1 ft/s) (right).

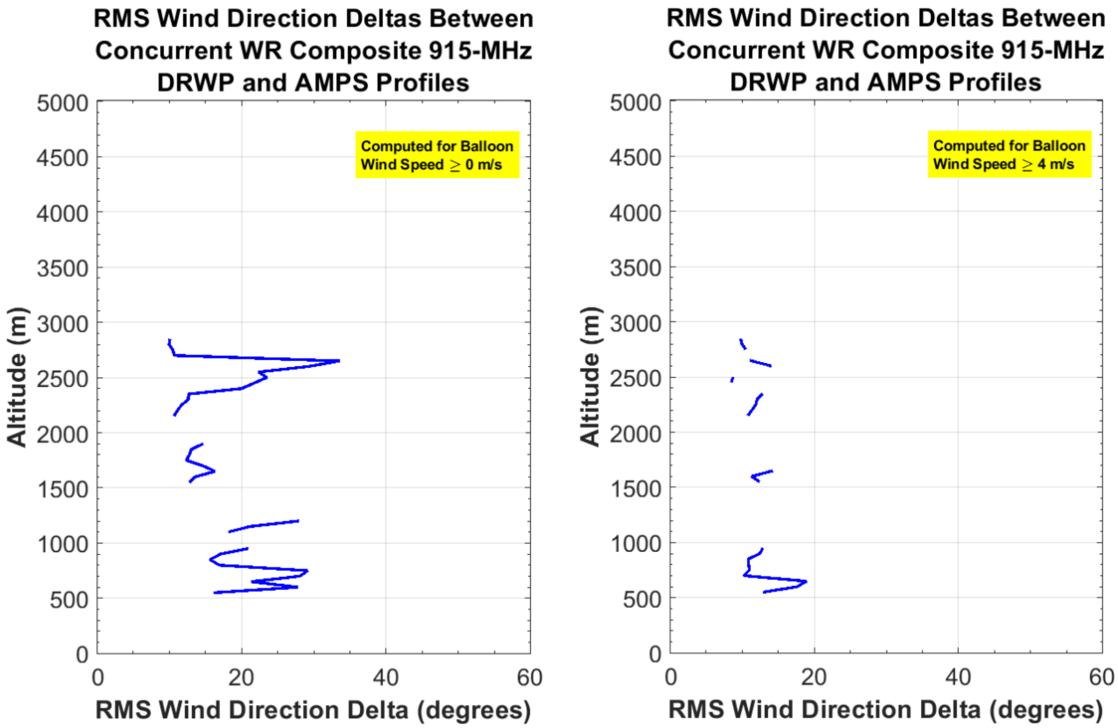

Figure D3: RMS wind direction deltas (degrees) versus altitude (AGL) between concurrent WR DRWP and composite balloon measurements corresponding to balloon wind speeds exceeding 0.0 m/s (0.0 ft/s) (left) and 4.0 m/s (13.1 ft/s) (right).