

826 RESULTS OF THE UPDATED KENNEDY SPACE CENTER 50-MHZ DOPPLER RADAR WIND PROFILER OPERATIONAL ACCEPTANCE TEST

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1. INTRODUCTION

We present here the methodology and results of the Operational Acceptance Test (OAT) performed on the new Kennedy Space Center (KSC) 50-MHz Doppler Radar Wind Profiler (DRWP). On day-of-launch (DOL), space launch vehicle operators have used data from the DRWP to invalidate winds in prelaunch loads and trajectory assessments due to the DRWP's capability to quickly identify changes in the wind profile within a rapidly-changing wind environment. The previous DRWP has been replaced with a completely new system, which needs to undergo certification testing before being accepted for use in range operations.

The new DRWP 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 new system contains updated user interface software while maintaining the same general capability as the previous system. The new DRWP continues to use the Median Filter First Guess (MFFG) algorithm to generate a wind profile from Doppler spectra at each range gate. DeTect (2015) contains further details on the upgrade.

The OAT is a short-term test designed so that end users can utilize the new DRWP in a similar manner to the previous DRWP during mission operations at the Eastern Range in the midst of a long-term certification process. This paper describes the Marshall Space Flight Center Natural Environments Branch's (MSFC NE's) analyses to verify the quality and accuracy of the DRWP's meteorological data output as compared to the previous DRWP. Ultimately, each launch vehicle program has the responsibility to certify the system for their own use.

2. DRWP VERIFICATION SPECIFICATIONS

MSFC NE (2014, hereafter the OAT Test Plan) outlines the OAT's intentions and verification criteria, which are presented in Table 1. Criteria for required data, time interval, and vertical data interval parallel the data reporting characteristics of the previous DRWP, and MSFC NE examined data records to ensure that all of these variables passed their respective criterion. MSFC

NE performed spectral analysis of DRWP wind data to assess the effective vertical resolution (EVR) criteria. To address wind accuracy, MSFC NE compared concurrent DRWP and Automated Meteorological Profiling System (AMPS, Leahy and Overbey 2004) balloon profiles. The OAT Test Plan quoted a desire to have at least 30 concurrent profiles in conditions where the balloon would not drift far (e.g., 100 km) downrange. AMPS Low-Resolution Flight Element (LRFE) and High-Resolution Flight Element (HRFE) profiles were released during operations at the Cape Canaveral Weather Station (CCWS) during normal synoptic or mission support.

The OAT's wind accuracy and EVR criteria shown in Table 1 are based on previous test results. A comparison of DRWP and AMPS data (Pinter et. al 2006) provided the basis for the OAT's 1.5 m/s root-mean-square (RMS) wind component difference criteria. This study generated RMS westerly (u) and southerly (v) wind component differences of 1.57 m/s and 1.56 m/s, respectively, given that the balloon was less than 50 km downrange or not within a large horizontal wind gradient. However, using all balloons produced RMS u - and v -component differences of 1.70 and 1.65 m/s, respectively. This characteristic highlighted the influence of the balloon's downrange distance on wind component differences, and MSFC NE addressed this criterion with the understanding that the OAT's results could be easily higher than 1.50 m/s yet still be acceptable. Similarly, the OAT used the results from a spectral analysis performed on the previous DRWP (Merceret 1999) as a basis for the 500-m wind component EVR. Thus, MSFC NE's intention consisted of assessing results of the new DRWP data against the criteria in Table 1, documenting possible reasons for any discrepancy, and determining if these reasons are valid. The paper herein describes in detail the OAT's data, analyses, results, and recommendation.

Table 1: NASA 50-MHz DRWP OAT Criteria.

Required Data	Wind Speed and Direction, Altitude, Shear, Radial velocities, Signal Power, Noise Power, Spectral Width
Time Interval	5 min
Vertical Data Interval	150 m
Altitude	2.0-18.6 km
Wind Accuracy	1.5 m/s RMS component difference
EVR	500 m

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3. DATA OBTAINED FOR ANALYSIS

MSFC NE acquired DRWP data from 6 January 2015 through 19 February 2015 for the OAT. Data files contain altitude, wind speed, wind direction, radial shear, vertical velocity, signal power, noise level, number of first-guess propagations (FGPs), and quality control (QC) flags for each profile. The new DRWP is a four-beam system and the 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 FGP. Approximately five minutes exist between successive profiles, and altitude coverage ranges from 1,798-19,645 m, at 150 m intervals.

Additionally, MSFC NE acquired AMPS balloon data for the DRWP and balloon comparison. The CCWS released all balloons under normal synoptic and mission support operations. All collected data were examined for wind profiles reporting winds at 30.48 m altitude intervals. LRFEs typically reach roughly 30 km altitude and consist of wind speed, wind direction, and thermodynamic data. The HRFEs typically reach 16-17 km altitude. HRFE output does not contain thermodynamic data, but does contain rise rate. Thus, the OAT used the rise rate directly from the HRFE profiles and assumed a constant rise rate of 5.1816 m/s, or 17.0 ft/s to assess LRFE profiles. The CCWS also provided MSFC NE with weather observer logs for each balloon release.

MSFC NE implemented specific QC procedures for each analysis, with the general philosophy that the OAT should evaluate the functionality of the DRWP system as the system was designed. Therefore, an extensive QC effort (e.g., Merceret 1997, Lambert et al. 2003, and Barbré 2012) was not applied to the OAT DRWP database before analysis. Sections describing individual analyses provide the respective QC procedures used.

4. SUPPORTING ANALYSES

4.1 Comparison of Concurrent Balloon and DRWP Wind Components

The balloon / DRWP comparison utilized concurrent winds from both sources that met specified criteria. First, the analysis extracted candidate AMPS LRFE and HRFE profiles. These profiles contained wind reports at 30.48 m intervals to at least 15.24 km and at least five minutes existed between temporally adjacent releases. From these profiles, a shear QC check removed 0.2% of individual balloon winds that exceeded a vector wind shear of 0.15 s^{-1} over 30.48 m. Balloon data preprocessing derived wind components, as well as two displacement variables, for the DRWP comparison:

- The timestamp at each altitude, which utilized the balloon's release time, rise rate, and altitude.
- Horizontal distance from the DRWP's vertical plane at each altitude.

Next, the balloon / DRWP comparison extracted DRWP profiles during days that contained candidate balloon data. The analysis implemented vector shear and convection checks on DRWP data to parallel the QC performed on the balloons and to remove cases where the environment was known to contaminate output from both DRWP and balloon systems. All DRWP measurements on these days contained vector shear at or below 0.15 s^{-1} over 150 m. The analysis addressed convection through examining the CCWS weather log and time-height sections of output from the algorithm used in Barbré (2012).

The analysis then extracted balloon data at each DRWP altitude to mitigate the discrepancies inherited from each source sampling at different altitude intervals. First, the candidate balloon profile's wind components, timestamps, and horizontal displacement were interpolated at 0.3048 m, or 1.0 ft intervals. Next, the process averaged each quantity existing within 75.0 m of each DRWP altitude. As an illustration, Figure 1 shows all 0.3048 m values of u within 75.0 m of the DRWP's altitude (3,898 m) that were averaged to obtain u representing the balloon's output at that altitude.

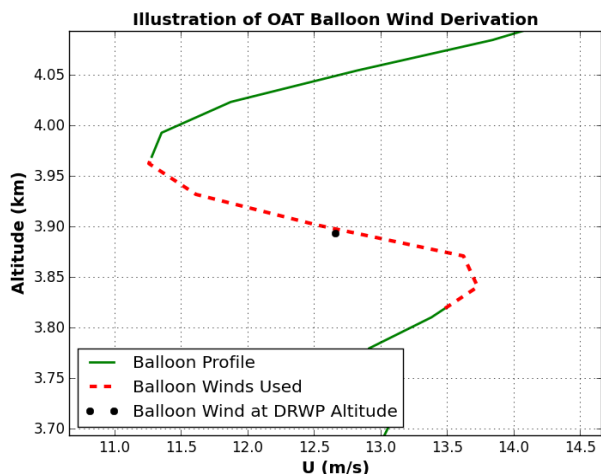


Figure 1: Example of balloon u -component derived at an individual DRWP altitude.

In addition, the algorithm addressed the fact that the DRWP generates multiple profiles during the balloon's ascent, with higher portions of the DRWP profile representing the altitude regime later in the balloon's flight (Figure 2). First, the algorithm subtracted 7.5 minutes from the DRWP's timestamp as the DRWP profile represents an average wind profile over the previous 15 minutes (DeTect 2015). Next, the algorithm found DRWP winds that existed within 10 minutes of the balloon's timestamp at the DRWP's altitude to avoid the closest DRWP timestamp being too far removed from the balloon's timestamp at a given altitude. In Figure 2, the DRWP profile used for comparison consists of ~2.0 km altitude segments from 12 individual DRWP profiles. Last, the process accepted concurrent DRWP and balloon profiles if at least 75% of concurrent data existed below 15.24 km altitude.

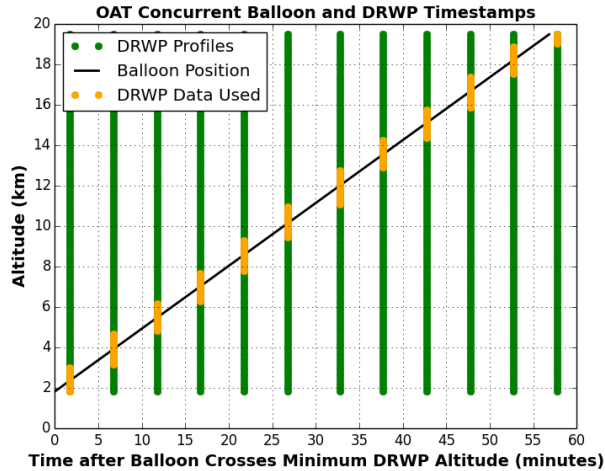
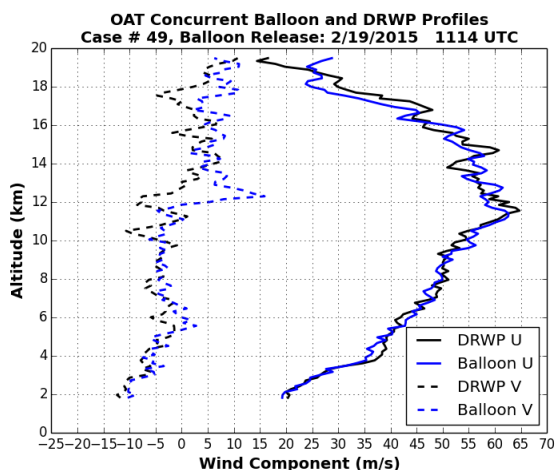


Figure 2: Illustration of temporally matching balloon and DRWP profiles. Orange segments of each DRWP profile indicate the segments of the DRWP profile used for comparison

The process then implemented a manual QC check on each set of concurrent profiles to ensure that one or both systems do not contain artificial, non-meteorological reports that could contaminate the wind component comparison. This process included examining DRWP time-height sections during days with concurrent profiles (Figure 3). The manual QC removed concurrent data where one or both systems seemed to report a suspect non-meteorological feature, but retained large differences produced by different environments. Figure 3 shows an example of the latter near 12-13 km altitude. Large gradients in v existed and the balloon and DRWP sampled different wind environments at the same altitude. Specifically, one could discern that the balloon sampled the wind regime that existed over the DRWP just before 1000 UTC – and that this regime had migrated downrange (via $u \sim 65$ m/s) into the balloon’s ascent path by the time the balloon reached 12 km altitude at approximately 1145 UTC. The manual process removed four individual reports from all concurrent balloon and DRWP profiles.



The resulting dataset consisted of 5,426 reports from 49 concurrent DRWP and balloon profiles (one HRFE and 48 LRFE). Multiple profiles existed on 6 January, 10 January, 20 January, 21 January, 8 February, and 11 February. Few HRFEs existed because they either did not reach 15.24 km altitude and/or were released on days where DRWP data were not available. Because data were collected during winter, many of the balloon profiles were released in strong and / or dynamic wind environments. At 11 km, median u reached 35-40 m/s, and maximum u approached 70 m/s. Envelopes of v ranged from -15 to +15 m/s, varying slightly with altitude.

After data QC, statistical analysis was performed on the differences between concurrent DRWP and balloon wind components at the same altitude. Using all reports, mean u and v differences (DRWP-balloon) were found to be -0.03 m/s and -0.14 m/s, respectively. RMS u and v differences were 2.02 m/s and 2.14 m/s, respectively. These RMS differences exceeded the 1.5 m/s criterion in Table 1, which promoted further investigation.

The first of two sensitivity studies of the DRWP / balloon comparison addressed the characteristics of each system. Recall, other than a shear and convection check, the analysis did not implement any QC procedures for the DRWP data. In addition, no effort was made to address system noise. The comparison computed the same mean and RMS statistics after adjusting the input data in three additional ways.

- (1) Implement a low-pass, six-pole, Butterworth filter on the LRFE profile to remove any LRFE artifacts that would not exist in the DRWP output.
- (2) Item (1) and remove DRWP data where any beam’s FGP exceeded four as DRWP data processing interpolates radial velocities for these FGPs.
- (3) Item (1), item (2), and remove DRWP data if the DRWP QC flag exceeded three but was not exactly 64. This operation retained DRWP data only if no QC criteria were flagged, but ignored manual QC indicators and communication establishment between the DRWP site and the CCWS.

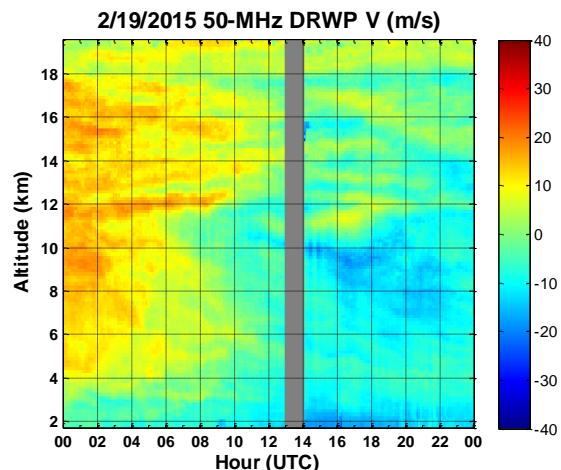


Figure 3: Example of concurrent DRWP and balloon profiles (left) and the corresponding t-z section of DRWP v (right).

Scrutinizing the quality of the output data from each system provided a negligible effect on the comparison of wind component differences. Table 2 shows the sample size, as well as wind component RMS and bias differences after each adjustment compared to the initial analysis. Neither the bias nor RMS quantity changed by more than 0.03 m/s, which is two orders of magnitude less than the quantity being evaluated and the accepted error of the previous DRWP. In addition, implementing QC item (3) actually increased the negative bias in v .

Table 2: OAT DRWP / balloon comparison results after implementing a low-pass filter on the LRFE and additional QC checks on DRWP profiles. All bias and RMS results are in m/s.

	Initial Analysis	LRFE Filter	LRFE Filter + FGP QC	LRFE Filter + FGP QC + DRWP QC Flag
N	5426	5426	5345	4989
RMS du	2.02	2.01	2.01	1.99
RMS dv	2.14	2.14	2.14	2.13
Bias du	-0.03	-0.03	-0.04	-0.03
Bias dv	-0.14	-0.14	-0.15	-0.16

The second sensitivity study of the DRWP / balloon comparison found that balloon drift negatively impacted the analysis results. Figure 4 shows an example of a balloon's zonal and meridional displacement relative to the DRWP's vertical axis throughout the balloon's ascent. The balloons follow the wind after release from the CCWS, which is located roughly 21 km south-southeast of the DRWP. In Figure 4, the balloon drifted to near 100 km due east of the DRWP by the time the balloon reached 18 km in altitude. The sensitivity study computed the RMS wind component difference for all the reports given that the balloon's total displacement did not exceed a specified threshold at a given altitude (Figure 5). At displacements greater than 30 km, nearly all RMS wind component differences increased monotonically, with

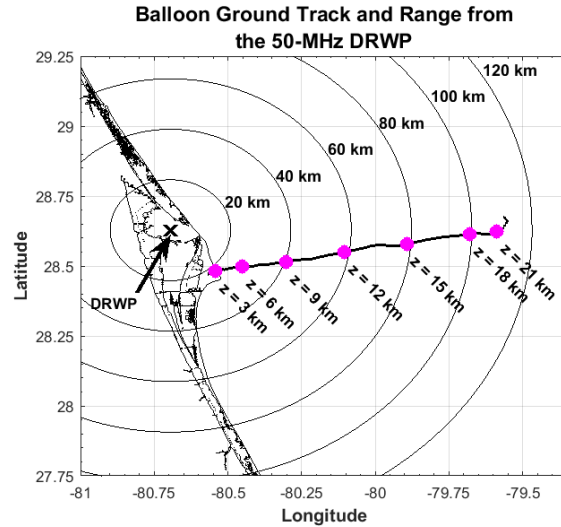


Figure 4: Example of the balloon's ground track from the CCWS. Range rings are placed every 20 km from the DRWP and magenta circles denote the balloon position every 3 km in altitude from 3-21 km.

minimum RMS wind component differences of approximately 1.55 m/s. Sample size could attribute to the higher RMS wind component differences at displacements less than 30 km as the dataset of concurrent reports contained less than 1,000 differences that meet this displacement criterion.

4.2 DRWP EVR Assessment

The EVR analysis utilized all available DRWP data during the OAT collection period, and followed the methodology of an analysis of the previous DRWP's EVR (Merceret 1999) and Jimsphere balloons (Wilfong et al. 1997). For an individual day, the analysis first removed profiles during convective periods and extracted five-minute wind component pairs. Next, the analysis computed the Fast Fourier Transform (FFT) as a function of wavelength on

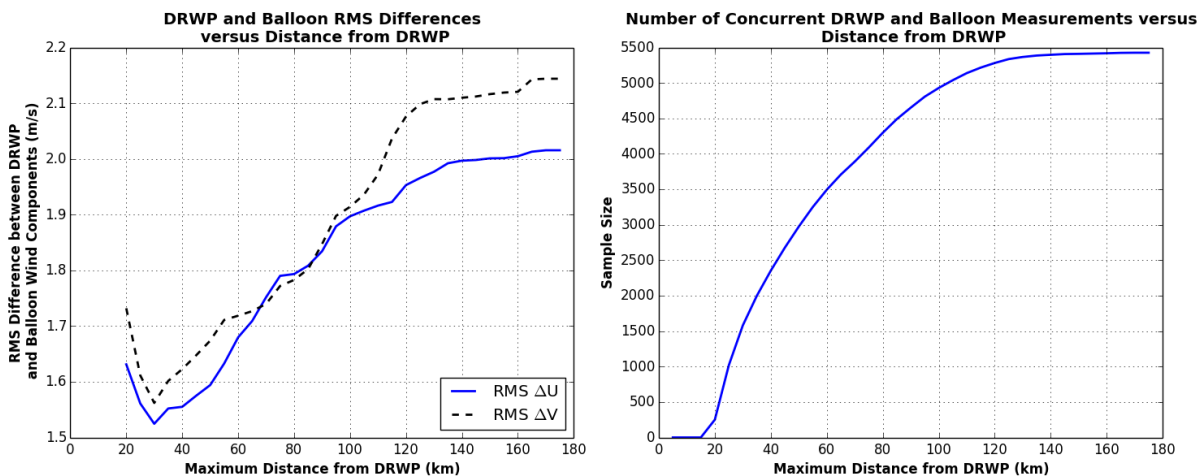


Figure 5: RMS (left) and sample size (right) of wind component differences that are limited by a specified distance from the DRWP.

each wind component profile on all 119 range gates assuming a 150 m sampling interval. Implementing these inputs results in output at wavelengths ranging from 300-17,850 m. Before computing the FFT, the algorithm removed the mean and linear trend of the profile and used a Parzen window with zero overlap to align with the previous EVR studies. From the FFTs, the analysis computed each profile's power spectral density (PSD) and each pair's cross-spectral density (CSD). These quantities were then used to compute the magnitude squared coherence, hereafter referred to as the "coherence." Coherence describes the correlation between two signals versus wavelength, where incoherent noise dominates at values below 0.25 as this value corresponds to a signal-to-noise ratio (SNR) of unity when examining data from the same system (Wilfong et al. 2000). The coherence was computed as

$$Coh^2 = \frac{|(CSD)|^2}{(PSD_1)(PSD_2)}, \quad (1)$$

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

The analysis computed and stored the coherence for each day with at least 100 5-minute pairs. The composite coherence was then generated by computing a sample-size-weighted coherence at each wavelength. Figure 6 presents this computation's result, which represents the composite wind component coherence for the entire OAT DRWP sample. The composite dataset's coherence remained above 0.25 for all wavelengths above 300 m, which is the DRWP's Nyquist limit for both u and v . Thus, the DRWP's EVR is limited by the system's sampling interval.

4.3 Vertical Data Coverage Analysis

The vertical data coverage analysis addressed the DRWP's altitude extent of data that contains a signal strong enough so as not to introduce any errors from utilizing previously recorded winds. The MFFG processing algorithm, which was developed for the previous DRWP (Wilfong et al. 1993) and implemented on the new DRWP, enables the DRWP to generate a wind record at every altitude using a first-guess velocity. This attribute meets the altitude and vertical interval specifications in Table 1. However, like all profilers, certain atmospheric conditions and / or instrument settings can limit the DRWP's signal return, especially at higher altitudes. The MFFG algorithm uses the previous first-guess velocity in situations when the updated DRWP's SNR falls below -30 dB (compared to -15 dB with the previous system). This process of first guess "propagating" essentially uses a wind that is an additional five minutes old as input to the current radial velocity computation. Thus, adding an FGP could introduce errors in the radial velocity estimate, especially in dynamic wind environments and / or if a non-atmospheric signal exists near the signal associated with the real wind (Wilfong et al. 1993). In addition, these errors could compound over time and the algorithm smoothes the radial velocity

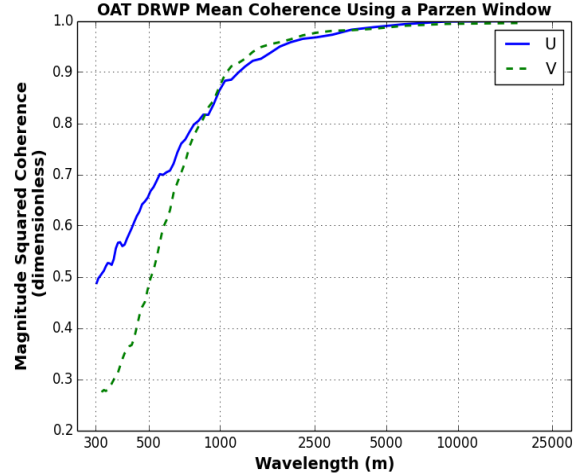


Figure 6: DRWP composite coherence for u (solid blue line) and v (dashed green line) as a function of wavelength using a Parzen window.

estimate if greater than four FGPs exist. Both of these characteristics provide evidence for addressing the DRWP output associated with a large number of FGPs for situational awareness (and possibly removal) of possibly erroneous data, and thus warrant an assessment of how often specified FGP thresholds were exceeded.

This analysis computed the percentage of data records at each altitude that did not exceed a given FGP threshold using all 9,300 profiles from the available DRWP data during the OAT collection period. No QC procedures were implemented in order to characterize the amount of data availability and to avoid removing output associated with an incremented FGP. The analysis selected FGP thresholds corresponding to 30-minute increments over which the first-guess velocity would be propagated. The percentage of reports containing an FGP from all beams that did not exceed thresholds of 0-24 FGPs at 6-FGP intervals are computed and plotted at each altitude. The result thus represents the percentage of the data from which the MFFG algorithm used first-guess velocities, which were generated from winds that occur 0-120 minutes, at 30-minute intervals, before the time of interest.

Figure 7 shows that the FGP check primarily affects data above 7 km, where weak signal return dominates. Below 7 km, isolated instances of other events that propagate the first guess velocity (e.g., excessive radial shear) likely caused FGP increases. If one does not tolerate incrementing the FGP, then the amount of available data at a given altitude decreases from near 100% at roughly 7 km to about 58% at the DRWP's maximum altitude, with a general decrease in the amount of available data as altitude increases above 7 km. Increasing the FGP threshold to six and 12 produces data availability of at least 90% and at least 95%, respectively. A sensitivity study examining data availability for all FGPs found that implementing an FGP threshold of at least 44 retained all data at all altitudes.

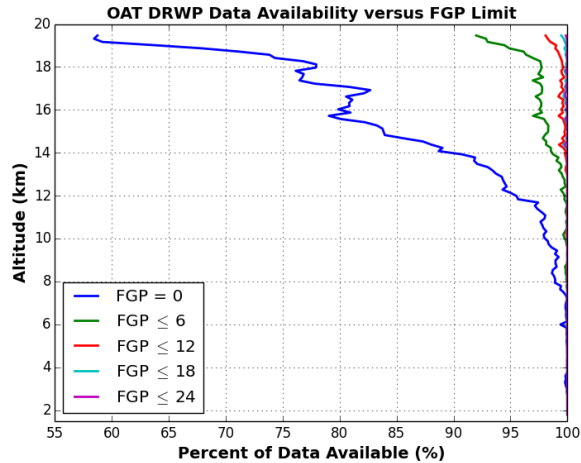


Figure 7: Percent of DRWP data available at each altitude after implementing different FGP thresholds.

DRWP users must determine how or if to implement FGP criteria. Examples could consist of determining the measurement errors associated with incrementing each beam's first-guess velocity (Barbré 2012) for this system, rejecting a first-guess velocity generated from a wind before a pre-determined time before assessment (Merceret 1997, Schumann et al. 1999), or comparing suspect DRWP output to output from other sources.

5. Conclusion

The OAT results passed all criteria outlined in the OAT Test Plan except for wind accuracy; however, DRWP data are acceptable to use for its short-term purpose based on the OAT's intent and through experience in analyzing DRWP and balloon wind data. Complete profiles exist every five minutes from 1,798-19,645 m every 150 m, which address the "time interval", "vertical data interval", and "altitude" specifications in Table 1. Analysis of the DRWP's EVR showed that the DRWP can resolve atmospheric features above approximately 300 m for u and v using all available data. A sensitivity of the DRWP's vertical data coverage to signal return is also presented for situational awareness. Analysis of "wind accuracy" found RMS differences between concurrent DRWP and AMPS balloon wind components of near 2.0 m/s. RMS differences decreased to around 1.5 m/s if the balloon measurement existed within 30 km downrange of the DRWP. These results are consistent with Pinter et al. (2006), which showed that the RMS wind component differences were near 1.55 m/s for winds that did not exist within a significant horizontal wind gradient. Experience of monitoring DRWP and balloon profiles during vehicle launches and studying climatologies of each system have revealed that large differences in concurrent measurements likely owe to each system sampling a different environment – with the DRWP's time and altitude domain closely matching that of an ascending space vehicle. In addition, the OAT methodology is intended to be used for the DRWP full certification, which will include balloon releases during all seasons.

6. Acknowledgements

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