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Transition Marshall Space Flight Center Wind Profiler Splicing Algorithm to Launch Services Program Upper Winds Tool

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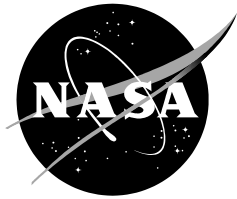
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Executive Summary

Customer: NASA's Launch Services Program (LSP) and Space Launch System (SLS) program

NASA's LSP customers and the future SLS program rely on observations of upper-level winds for steering, loads, and trajectory calculations for the launch vehicle's flight. On the day of launch, the 45th Weather Squadron (45 WS) Launch Weather Officers (LWOs) monitor the upper-level winds and provide forecasts to the launch team via the AMU-developed LSP Upper Winds tool for launches at Kennedy Space Center (KSC) and Cape Canaveral Air Force Station. This tool displays wind speed and direction profiles from rawinsondes released during launch operations, the 45th Space Wing 915-MHz Doppler Radar Wind Profilers (DRWPs) and KSC 50-MHz DRWP, and output from numerical weather prediction models.

The goal of this task was to splice the wind speed and direction profiles from the 45th Space Wing (45 SW) 915-MHz Doppler radar Wind Profilers (DRWPs) and KSC 50-MHz DRWP at altitudes where the wind profiles overlap to create a smooth profile. In the first version of the LSP Upper Winds tool, the top of the 915-MHz DRWP wind profile and the bottom of the 50-MHz DRWP were not spliced, sometimes creating a discontinuity in the profile. The Marshall Space Flight Center (MSFC) Natural Environments Branch (NE) created algorithms to splice the wind profiles from the two sensors to generate an archive of vertically complete wind profiles for the SLS program. The AMU worked with MSFC NE personnel to implement these algorithms in the LSP Upper Winds tool to provide a continuous spliced wind profile.

The AMU transitioned the MSFC NE algorithms to interpolate and fill data gaps in the data, implement a Gaussian weighting function to produce 50-m altitude intervals in each sensor, and splice the data together from both DRWPs. They did so by porting the MSFC NE code written with MATLAB® software into Microsoft® Excel® Visual Basic for Applications (VBA). After testing the new algorithms in stand-alone VBA modules, the AMU replaced the existing VBA code in the LSP Upper Winds tool with the new algorithms. They then tested the code in the LSP Upper Winds tool with archived data. The tool will be delivered to the 45 WS after the 50-MHz DRWP upgrade is complete and the tool is tested with real-time data. The 50-MHz DRWP upgrade is expected to be finished in October 2014.

Table of Contents

Executive Summary	2
List of Figures	4
1. Introduction	5
2. Data Analysis	5
2.1 Data Gap-filling.....	5
2.2 Interpolating to 50-m Altitudes	8
2.3 Weighting Scheme for Splicing	10
3. Updating the LSP Upper Winds Tool.....	13
4. Summary.....	14

List of Figures

Figure 1.	RMS component difference from the measured wind (ms^{-1}) as a function of data gap size (m) for the 50-MHz DRWP (green line) and the 915-MHz DRWP (blue line). The analysis uses the thresholds to determine how many consecutive gaps to tolerate when splicing 50- and 915-MHz DRWP profiles. Figure B2.3 from Barbré (2013). ..	6
Figure 2.	Excel spreadsheets showing observed (a) and gap-filled (b) data from 915-MHz DRWP data.	7
Figure 3.	Chart showing observed wind speed (red lines) and gap-filled interpolated wind speed (blue lines) from the 915-MHz DRWP for 1516 UTC 2 January 2014.	8
Figure 4.	Chart showing 145-m observed wind speed (red line) and 50-m interpolated wind speed (blue line) from the 50-MHz DRWP for 1515 UTC 2 January 2014.	9
Figure 5.	Chart showing 101-m observed wind speed (red line) and 50-m interpolated wind speed (blue line) from the 9150-MHz DRWP for 1516 UTC 2 January 2014.	10
Figure 6.	Results after applying the MATLAB Gaussian weighting function to the 31 overlapping altitudes from the 31 concurrent 915-MHz and 50-MHz DRWP profiles. The x- and y-axes denote the number of overlapping altitudes (L) and the weight (w ; dimensionless), respectively.....	11
Figure 7.	Normalized $w_n(z)$ values used to compute the spliced DRWP wind components for the overlapping altitude region extending from 2,666 to 4,117 m. The x- and y-axes denote the weight (w ; dimensionless) and altitude (m), respectively.....	11
Figure 8.	Example wind speed profile versus altitude (m) for 1515 UTC 2 January 2014. Red, green, and black lines stand for the concurrent 915-MHz, 50-MHz, and spliced DRWP profiles, respectively.....	12
Figure 9.	Example wind direction profile versus altitude (m) for 1515 UTC 2 January 2014. Red, green, and black lines stand for the concurrent 915-MHz, 50-MHz, and spliced DRWP profiles, respectively.....	12
Figure 10.	Spliced wind speed (left) and wind direction (right) from concurrent 915-MHz (orange line) and 50-MHz (red line) DRWPs as displayed in the LSP Upper Winds tool.....	13

1. Introduction

NASA's Launch Services Program (LSP) customers and the future Space Launch System (SLS) program rely on observations of upper-level winds for steering, loads, and trajectory calculations for the launch vehicle's flight. On the day-of-launch, the 45th Weather Squadron (45 WS) launch weather officers (LWOs) monitor the upper-level winds and provide forecasts to the launch team management via the AMU-developed LSP Upper Winds tool (Bauman and Wheeler 2012) for launches at Kennedy Space Center (KSC) and Cape Canaveral Air Force Station. This tool displays wind speed and direction profiles from rawinsondes released during launch operations, the 45th Space Wing 915-MHz Doppler Radar Wind Profilers (DRWPs) and KSC 50-MHz DRWP, and output from numerical weather prediction models.

The rawinsondes and models provide continuous profiles from the surface to over 60,000 ft, while the DRWPs do not. The 915-MHz DRWPs measure the winds at altitudes ranging from 285 to 14,560 ft (87–4,438 m) while the 50-MHz DRWP measures winds at altitudes ranging from 8,747 to 61,024 ft (2,700–18,600 m). Even though the nominal altitudes of these sensor's measurements overlap at the top of the 915-MHz DRWPs and bottom of the 50-MHz DRWP, the wind speeds and directions do not necessarily match at that interface. To compensate for this variation, the Marshall Space Flight Center (MSFC) Natural Environments Branch (NE) developed algorithms to splice concurrent measurements from both profilers.

The LSP Upper Winds tool uses both DRWP sources to create a continuous profile of winds from approximately 427 to 61,024 ft (130–18,600 m). In the original LSP Upper Winds tool, the 915-MHz DRWP wind profile was cut off to match the bottom altitude of the 50-MHz DRWP wind profile or the wind profiles were connected via a straight line interpolation from the top of the 915-MHz data to the bottom of the 50-MHz data. The straight line interpolation was implemented due to time constraints levied on the task but it does not provide the smoothed profile that can be realized by splicing the data together among overlapping altitudes from both sensors. This report describes how the AMU transitioned the MSFC NE algorithms for interpolating and splicing the data from the 915-MHz and 50-MHz DRWPs into the existing LSP Upper Winds Tool.

The MSFC NE splicing technique was developed using functions available in the MATLAB® software. Since the LSP Upper Winds tool was written in Microsoft® Excel® using Visual Basic for Applications (VBA), the AMU manually recreated the MATLAB functions in VBA.

2. Data Analysis

The preprocessing performed on individual 915- and 50-MHz DRWP profiles before splicing entails filling data gaps in the original profile and then interpolating the data from both sensors to 50-m altitudes. This section describes the processes needed to get to a complete spliced wind profile.

2.1 Data Gap-filling

MSFC NE performed an analysis that quantified the maximum tolerable data gap size from the 50- and 915-MHz DRWP profiles (Barbré 2013). Figure 1 shows the root mean square (RMS) of the maximum wind component differences versus gap size for each sensor. The analysis compared these results with a selected threshold of 1.0 ms^{-1} RMS, which is the 50-MHz DRWP acceptable measurement error (Pinter et al. 2006). No such quantification exists for the 915-MHz measurement error, but the NASA meteorological community considers the 915-MHz DRWP errors to resemble the 50-MHz DRWP errors (Barbré 2013). MSFC NE used the largest gap size that did not exceed the threshold as the criteria. Figure 1 depicts the gap sizes as 300 m for the 50-MHz DRWP analysis and 500 m for the 915-MHz DRWP analysis.

The 50-MHz DRWP reports observations at 145-m altitude intervals while the 915-MHz DRWP reports observations at 101-m altitude intervals. For the 50-MHz DRWP, the AMU wrote VBA code to fill data gaps ≤ 290 m by linearly interpolating the wind components through the gap. For the 915-MHz DRWP, they wrote VBA code to fill data gaps ≤ 505 m by linearly interpolating the wind components through the gap. The AMU chose these values instead of 300 and 500 m because they are multiples of the DRWP altitude intervals.

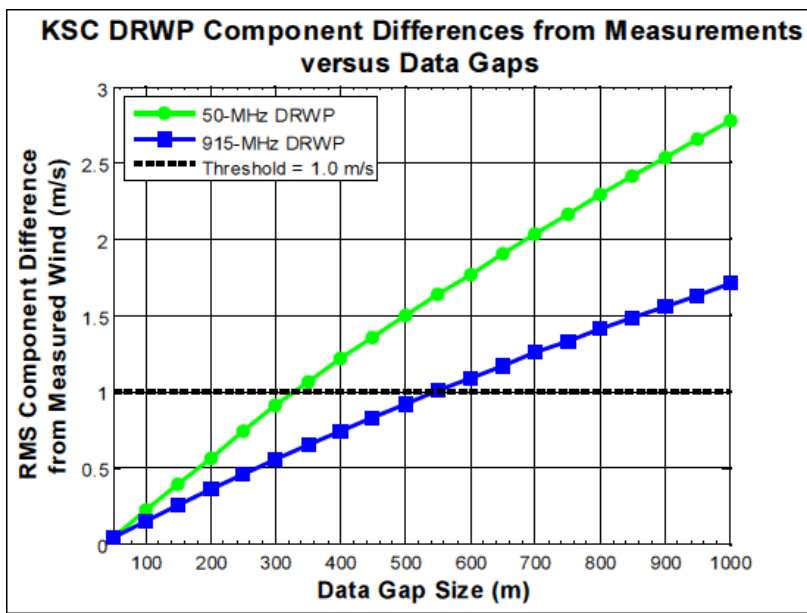


Figure 1. RMS component difference from the measured wind (ms^{-1}) as a function of data gap size (m) for the 50-MHz DRWP (green line) and the 915-MHz DRWP (blue line). The analysis uses the thresholds to determine how many consecutive gaps to tolerate when splicing 50- and 915-MHz DRWP profiles. Figure B2.3 from Barbré (2013).

Figure 2 demonstrates how the gap-filling algorithm works on a 915-MHz DRWP profile using data from 1516 UTC 2 January 2014. Figure 2a shows a portion of the Excel spreadsheet containing the observed data from a 915-MHz profile before gap-filling. The VBA code imports the raw data file in ASCII text format, reformats it into three columns containing altitude, wind direction, and wind speed, and then calculates u- and v-wind components in the fourth and fifth columns. The code flags missing data by changing the format of the altitude values to red, bold text and by changing missing values of “-9999” to empty cells. Once this is complete, another VBA macro looks for consecutive empty cells in the wind direction column to determine if and how the gap should be filled. If five or more consecutive empty cells are identified by the code, the profile is truncated at the highest altitude before reaching the first of the five empty cells. In Figure 2a, this condition was met above 4,177 m, so the profile was truncated at this altitude as shown in the resulting gap-filled data in Figure 2b. Missing data were also found at 2,558 m and between 2,761 m and 3,166 m. Since both of these gaps were ≤ 505 m, the code performed a linear interpolation of the observed data through the gap. The code interpolates the u- and v-wind components above and below the gap, inserts the interpolated results in the u-wind and v-wind columns at the appropriate altitudes as depicted in Figure 2b and then calculates wind direction and wind speed at each altitude resulting in a continuous vertical wind profile.

A chart of the observed and gap-filled data from the 1516 UTC 2 January 2014 915-MHz DRWP is shown in Figure 3. The red lines are plots of the observed wind speed derived from data

in the third column (Speed (kt)) in Figure 2a. The blue lines plots of the gap-filled interpolated wind speed derived from the data in third column (Speed (kt)) in Figure 2b. The gap-filling algorithm works in the same manner for the 50-MHz DRWP data. After the gap-filling process is complete for both sensors, the data are interpolated to 50-m altitudes.

<i>Observed</i>				
Altitude (m)	Direction (deg)	Speed (kt)	u-wind	v-wind
130	205	8.6	3.634517	7.794247
231	202	9.7	3.633684	8.993683
332	200	11.6	3.967433	10.900434
434	202	14.3	5.356874	13.258729
535	204	17.4	7.077217	15.895691
636	204	19.1	7.768670	17.448718
737	205	19.3	8.156532	17.491740
838	207	18.9	8.580420	16.840023
940	209	17.8	8.629611	15.568231
1041	211	16.4	8.446624	14.057544
1142	212	16.2	8.584692	13.738379
1243	214	16.0	8.947086	13.264601
1344	214	16.2	9.058925	13.430409
1445	215	16.8	9.636084	13.761754
1547	217	17.0	10.230855	13.576804
1648	226	15.1	10.862031	10.489342
1749	234	14.5	11.730746	8.522886
1850	235	14.8	12.123450	8.488931
1951	236	15.2	12.601371	8.499732
2053	240	15.7	13.596599	7.850000
2154	225	16.2	11.455130	11.455130
2255	223	17.0	11.593972	12.433013
2356	225	18.1	12.798633	12.798633
2457	222	19.6	13.114960	14.565639
2558				
2660	223	17.3	11.798571	12.652419
2761	231	16.9	13.133767	10.635515
2862				
2963				
3064				
3166	235	15.9	13.024517	9.119865
3267	238	15.3	12.975136	8.107765
3368	241	15.5	13.556605	7.514549
3469	243	16.1	14.345205	7.309247
3570	243	16.0	14.256104	7.263848
3671	241	16.0	13.993915	7.756954
3773	240	16.2	14.029611	8.100000
3874	241	17.0	14.868535	8.241764
3975	241	18.6	16.267926	9.017459
4076	241	20.5	17.929704	9.938597
4177	242	21.7	19.159963	10.187533
4279				
4380				
4481				
4582				
4683				
4784				

<i>Gap-Filled</i>				
Altitude (m)	Direction (deg)	Speed (kt)	u-wind	v-wind
130	205	8.6	3.634517	4.009707
231	202	9.7	3.633684	4.626750
332	200	11.6	3.967433	5.607668
434	202	14.3	5.356874	6.820880
535	204	17.4	7.077217	8.177450
636	204	19.1	7.768670	8.976396
737	205	19.3	8.156532	8.998529
838	207	18.9	8.580420	8.663256
940	209	17.8	8.629611	8.008990
1041	211	16.4	8.446624	7.231825
1142	212	16.2	8.584692	7.067633
1243	214	16.0	8.947086	6.823900
1344	214	16.2	9.058925	6.909199
1445	215	16.8	9.636084	7.079658
1547	217	17.0	10.230855	6.984511
1648	226	15.1	10.862031	5.396183
1749	234	14.5	11.730746	4.384551
1850	235	14.8	12.123450	4.367084
1951	236	15.2	12.601371	4.372640
2053	240	15.7	13.596599	4.038389
2154	225	16.2	11.455130	5.893028
2255	223	17.0	11.593972	6.396094
2356	225	18.1	12.798633	6.584186
2457	222	19.6	13.114960	7.493212
2558	222	18.4	12.456766	7.001089
2660	223	17.3	11.798571	6.508967
2761	231	16.9	13.133767	5.471381
2862	232	16.6	13.106454	5.276452
2963	233	16.4	13.079142	5.081523
3064	234	16.1	13.051830	4.886593
3166	235	15.9	13.024517	4.691664
3267	238	15.3	12.975136	4.170995
3368	241	15.5	13.556605	3.865818
3469	243	16.1	14.345205	3.760202
3570	243	16.0	14.256104	3.736846
3671	241	16.0	13.993915	3.990522
3773	240	16.2	14.029611	4.167000
3874	241	17.0	14.868535	4.239929
3975	241	18.6	16.267926	4.638982
4076	241	20.5	17.929704	5.112856
4177	242	21.7	19.159963	5.240920

Figure 2. Excel spreadsheets showing observed (a) and gap-filled (b) data from 915-MHz DRWP data.

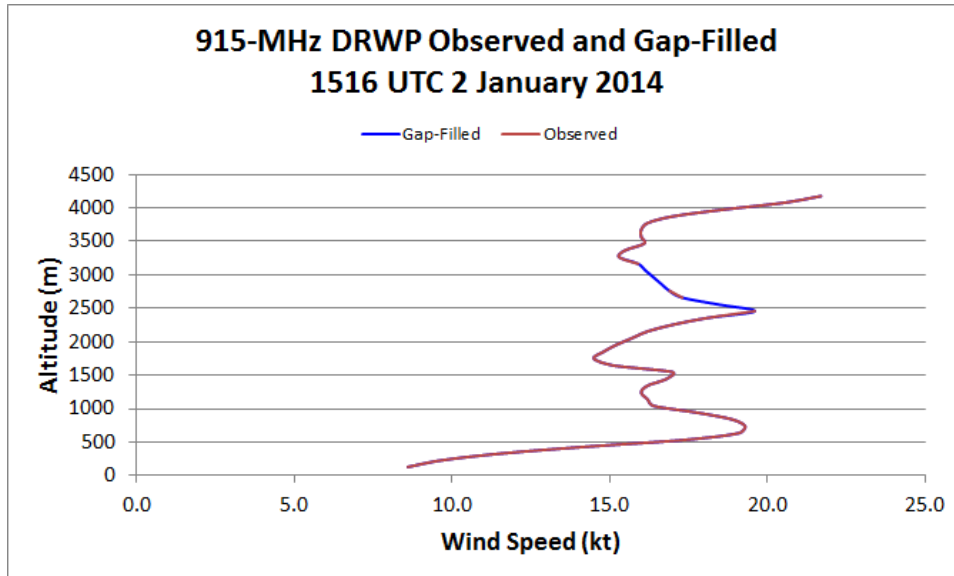


Figure 3. Chart showing observed wind speed (red lines) and gap-filled interpolated wind speed (blue lines) from the 915-MHz DRWP for 1516 UTC 2 January 2014.

2.2 Interpolating to 50-m Altitudes

MSFC NE used a MATLAB function called *interp1* to interpolate the 915-MHz and 50-MHz observations from 101 m and 145 m, respectively, to 50-m altitude intervals. Since the AMU did not have a copy of MATLAB and the LSP Upper Winds tool was developed in Excel, Mr. Barbré from MSFC NE outlined how the function worked so the AMU could write the code in VBA. Creating the algorithm required computing a weighted value, w , for each observed and interpolated altitude, and applying w to the u - and v -wind components at each interpolated 50-m altitude. The VBA code computes w by finding the highest altitude (z_{blw}) that is below the altitude of interest, z_i , and the lowest altitude (z_{abv}) that is above the altitude of interest, z_i , using all the observed 101-m (915-MHz DRWP) and 145-m (50-MHz DRWP) interval altitudes, z . The equations for these quantities are

$$z_{blw} = \max (z (z \leq z_i))$$

$$z_{abv} = \min (z (z \geq z_i))$$

$$w = (z_i - z_{blw}) / (z_{abv} - z_{blw}). \text{ If } z_{abv} = z_{blw} \text{ then } w = 1.$$

For example, for the 50-MHz DRWP, given altitudes at $z = 2,666$ m and 2,811 m, z_i would include altitudes at 2,666 m, 2,716 m, and 2,766 m, resulting in three values for w at each z_i .

w at $z_i = 2,666$:

$$z_{blw} = \max ([2,666 \leq 2,666]) = 2,666$$

$$z_{abv} = \min ([2,666 \geq 2,666, 2,811, 2,956, 3,101 \dots]) = 2,666$$

$$w = 1 \text{ since } z_{abv} = z_{blw}$$

w at $z_i = 2,716$:

$$z_{blw} = \max ([2,666, 2,811, 2,956 \dots \leq 2,716]) = 2,666$$

$$z_{abv} = \min ([2,666, 2,811, 2,956 \dots \geq 2,716]) = 2,811$$

$$w = (2,716 - 2,666) / (2,811 - 2,666) = 0.34483$$

w at $z_i = 2,766$:

$$z_{blw} = \max ([2,666, 2,811, 2,956 \dots \leq 2,766]) = 2,666$$

$$z_{abv} = \min ([2,666, 2,811, 2,956 \dots \geq 2,766]) = 2,811$$

$$w = (2,766 - 2,666) / (2,811 - 2,666) = 0.68966$$

To compute the u-component at each interpolated altitude, u_i , use the equation:

$$u_i = (1 - w) * u(z_{blw}) + w * u(z_{abv})$$

Therefore, if $u = 6.8$ kt at 2,666 m and $u = 7.9$ kt at 2,811 m, the u-components at the interpolated altitudes are:

At 2,666 m:

$$u_{2666} = (1 - 1) * 6.8 + 1 * 6.8 = 6.8 \text{ kt}$$

At 2,716 m:

$$u_{2716} = (1 - 0.34483) * 6.8 + 0.34483 * 7.9 = 7.2 \text{ kt}$$

At 2,766 m:

$$u_{2766} = (1 - 0.68966) * 6.8 + 0.68966 * 7.9 = 7.6 \text{ kt}$$

The interpolation algorithm was applied to 50-MHz DRWP and 915-MHz DRWP profiles as shown in Figure 4 and Figure 5. Figure 4 shows a 50-MHz wind speed profile from 1515 UTC 2 January 2014 with data plotted at 145-m (observed) and 50-m (interpolated) altitude intervals and Figure 5 shows a 915-MHz wind speed profile from 1516 UTC 2 January 2014 with data plotted at 101-m (observed) and 50-m (interpolated) altitude intervals.

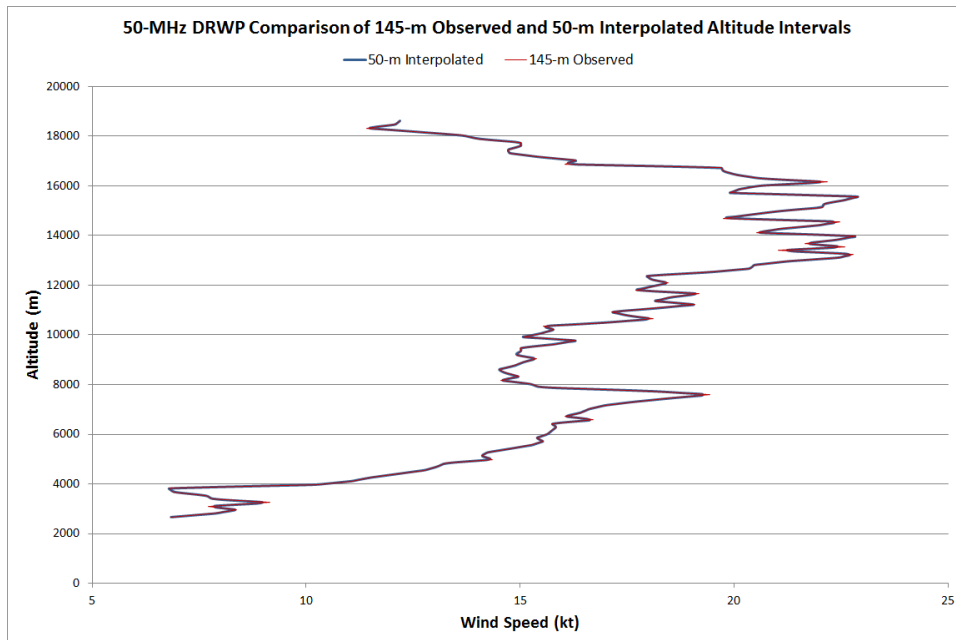


Figure 4. Chart showing 145-m observed wind speed (red line) and 50-m interpolated wind speed (blue line) from the 50-MHz DRWP for 1515 UTC 2 January 2014.

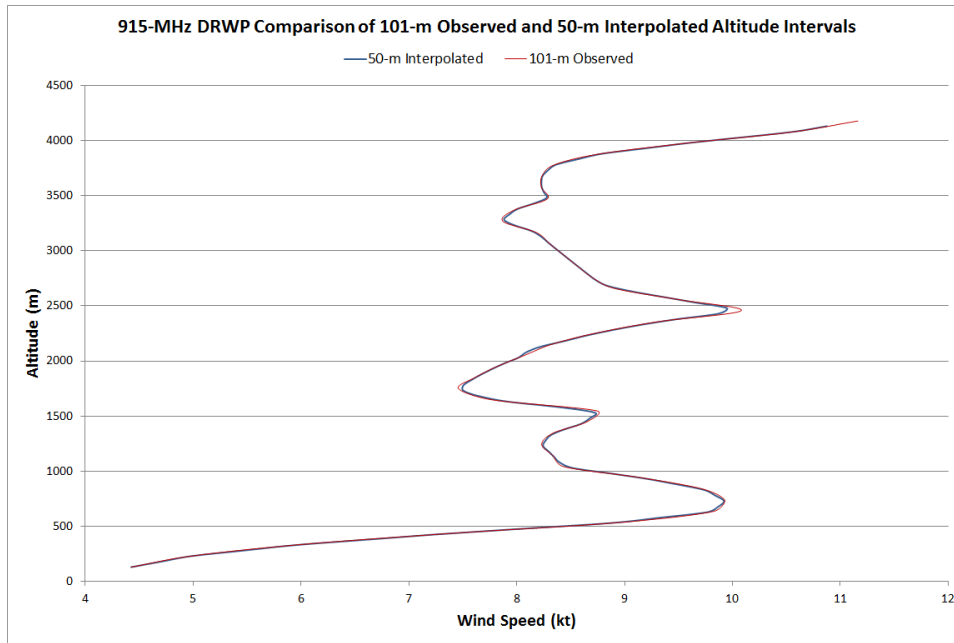


Figure 5. Chart showing 101-m observed wind speed (red line) and 50-m interpolated wind speed (blue line) from the 9150-MHz DRWP for 1516 UTC 2 January 2014.

2.3 Weighting Scheme for Splicing

Once the 915-MHz and 50-MHz DRWPs winds were interpolated to 50-m intervals, MSFC NE used the MATLAB function *gausswin* as a Gaussian weighting function to determine which profiler had more influence on the resulting wind component values at each height. This function, $w(z)$, is defined by the equation:

$$w(z) = e^{-\frac{1}{2}\left(\alpha\frac{n}{N/2}\right)^2}$$

Where:

$$\alpha = 2.5 \text{ (MathWorks 2014)}$$

$N = L-1$ where L is the number of overlapping altitudes from both DRWPs

$$n = (0:N)-N/2$$

The AMU ported this equation to Excel and tested it with the 31 overlapping altitudes from 2,666 m to 4,117 m from both DRWPs on 2 January 2014 at 1515 UTC and 1516 UTC. The resulting Gaussian distribution of $w(z)$ is shown in Figure 6. The cumulative sum of w is normalized by its maximum to produce the chart in Figure 7, which is a plot of the weights used to compute the spliced wind components at the 31 altitudes where the 915-MHz DRWP profile overlaps the 50-MHz DRWP profile. In this case, w starts at 0.0 at 2,666 m, transitions from 0.0-1.0 from 2,666 to 4,117 m, and remains at 1.0 above 4,117 m.

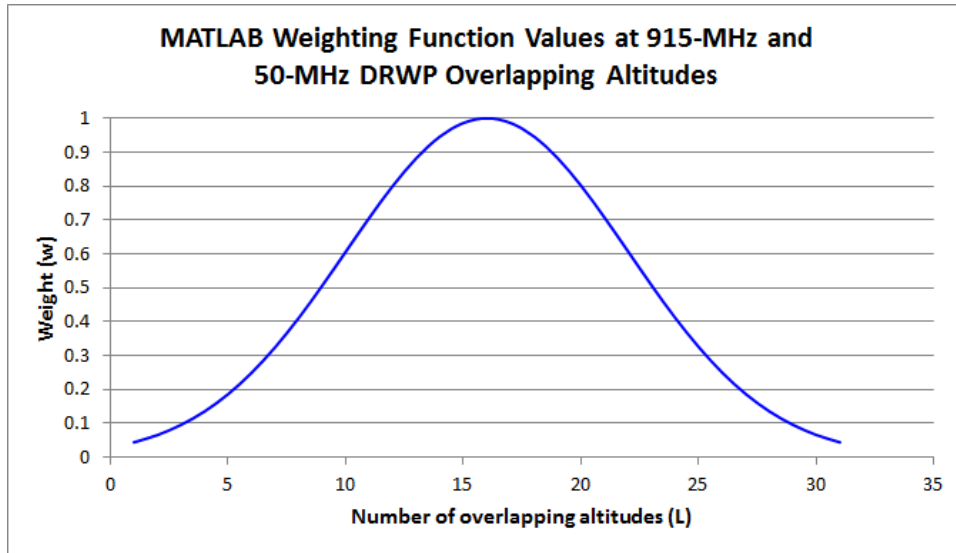


Figure 6. Results after applying the MATLAB Gaussian weighting function to the 31 overlapping altitudes from 915-MHz and 50-MHz DRWP profiles. The x- and y-axes denote the number of overlapping altitudes (L) and the weight (w; dimensionless), respectively.

To compute the spliced DRWP wind components, the AMU used Equation (12) from Barbré (2013) for the u- and v-components, where $w_n(z)$ is the normalized weight shown in Figure 7:

$$u(z) = w_n(z) * u_{50}(z) + [1 - w_n(z)] * u_{915}(z)$$

$$v(z) = w_n(z) * v_{50}(z) + [1 - w_n(z)] * v_{915}(z)$$

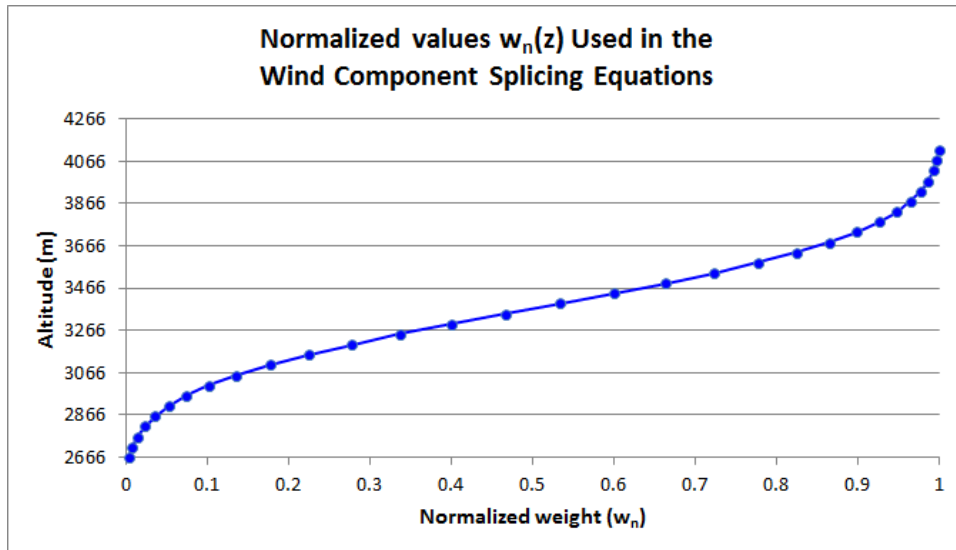


Figure 7. Normalized $w_n(z)$ values used to compute the spliced DRWP wind components for the overlapping altitude region extending from 2,666 to 4,117 m. The x- and y-axes denote the weight (w; dimensionless) and altitude (m), respectively.

Applying this equation with the appropriate w_n at each z produces the spliced profile, which fares the 915-MHz DRWP winds into the 50-MHz DRWP winds within the transition region. Figure 8 shows the spliced wind speed profile and Figure 9 shows the spliced wind direction profile for

1515 UTC 2 January 2014. Note the spliced profile (black line) significantly resembles the 915-MHz DRWP profile (red line) below approximately 3,400 m and the 50-MHz DRWP profile (green line) above 3,400m, which shows the weighting scheme's effect.

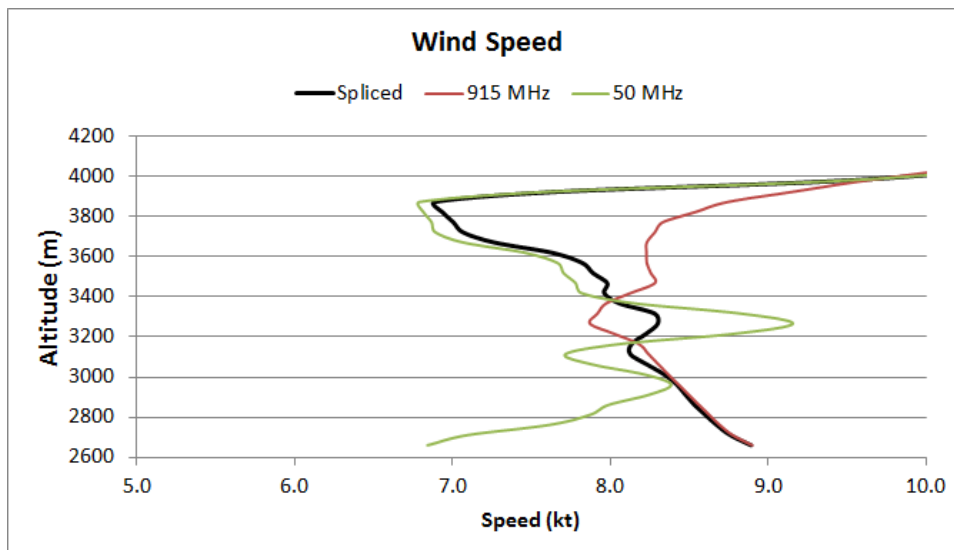


Figure 8. Example wind speed profile versus altitude (m) for 1515 UTC 2 January 2014. Red, green, and black lines represent the concurrent 915-MHz, 50-MHz, and spliced DRWP profiles, respectively.

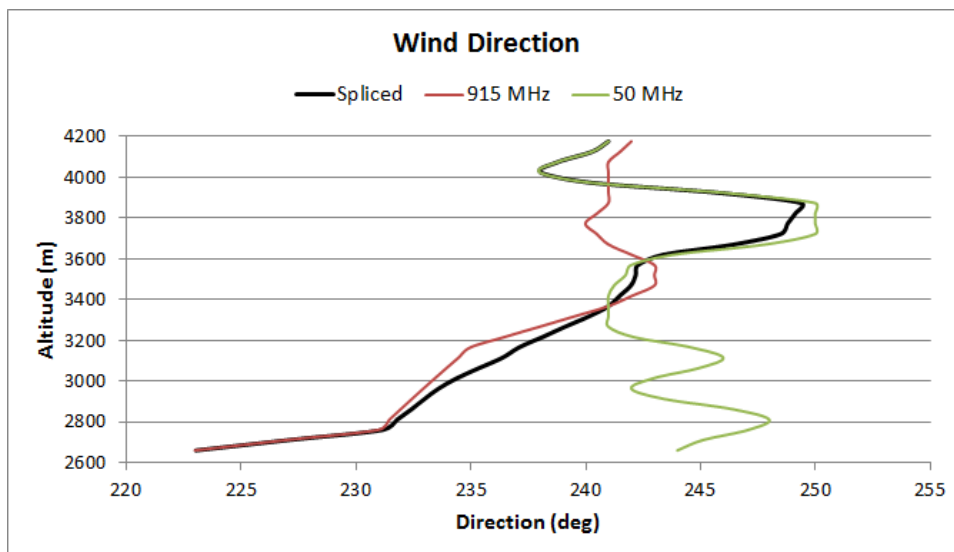


Figure 9. Example wind direction profile versus altitude (m) for 1515 UTC 2 January 2014. Red, green, and black lines represent the concurrent 915-MHz, 50-MHz, and spliced DRWP profiles, respectively.

3. Updating the LSP Upper Winds Tool

The final part of this work required porting the new VBA code into the existing LSP Upper Winds tool. There are 12 modules in the tool that use data from both wind profilers. Each concurrent file from the 50-MHz DRWP and 915-MHz DRWP accessed by the LSP Upper Winds tool will need to be checked for missing data using the data gap filling algorithm, interpolated to 50-m altitude intervals using the interpolation algorithm, and then spliced together using the weighting scheme. The AMU copied the VBA code that was developed and tested independent of the LSP Upper Winds tool and inserted it in the appropriate modules in the tool. The code was modified to work within the framework of the existing code in the tool and then tested on archived data. An example of final spliced profiles of wind speed and wind direction from concurrent 915-MHz and 50-MHz DRWPs are shown in Figure 10.

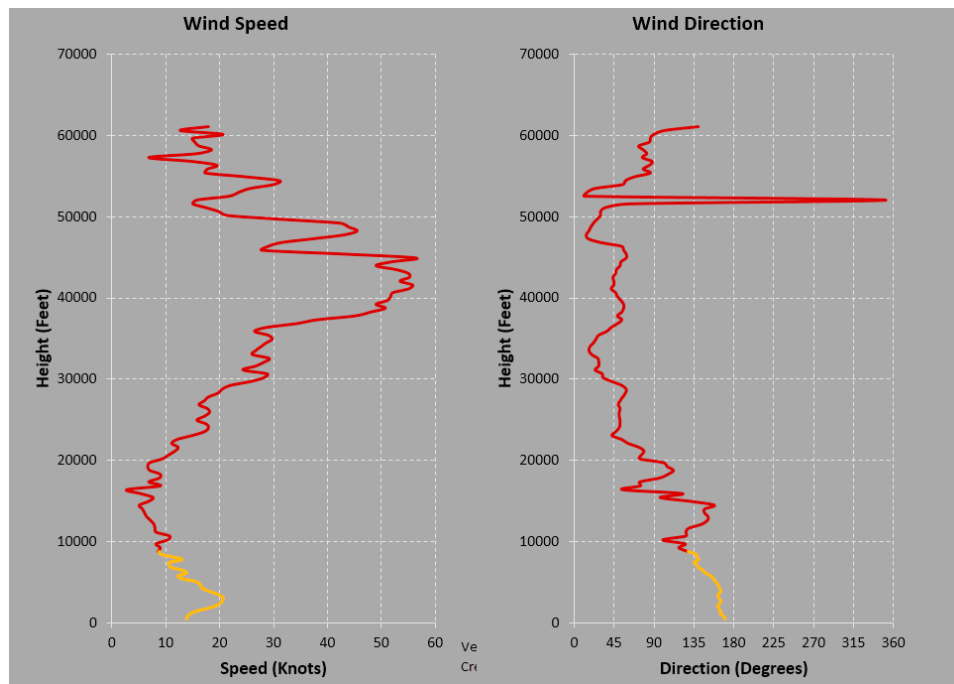


Figure 10. Spliced wind speed (left) and wind direction (right) from concurrent 915-MHz (orange line) and 50-MHz (red line) DRWPs as displayed in the LSP Upper Winds tool.

During this task, the KSC 50-MHz DRWP was undergoing a complete replacement. Therefore, it was not possible to test the LSP Upper Winds Tool with real-time data from the profiler. Once the replacement project is completed in late 2014, the AMU will test the LSP Upper Winds tool with the real-time data to ensure the newly developed code is working correctly before releasing the tool for operational support.

4. Summary

NASA's LSP customers and the future SLS program rely on observations of upper-level winds for steering, loads, and trajectory calculations for the launch vehicle's flight. On the day of launch, the 45 WS LWOs monitor the upper-level winds and provide forecasts to the launch team via the AMU-developed LSP Upper Winds tool for launches at KSC and CCAFS. This tool displays wind speed and direction profiles from rawinsondes released during launch operations, the 45 SW 915-MHz DRWPs and KSC 50-MHz DRWP, and output from numerical weather prediction models.

The rawinsondes and models provide continuous profiles from the surface to over 60,000 ft, while the DRWPs do not. The 915-MHz DRWPs measure the winds at altitudes ranging from 285 to 14,560 ft (87–4,438 m) while the 50-MHz DRWP measures winds at altitudes ranging from 8,747 to 61,024 ft (2,700–18,600 m). Even though the nominal altitudes of these sensor's measurements overlap at the top of the 915-MHz DRWPs and bottom of the 50-MHz DRWP, the wind speeds and directions do not necessarily match at that interface. To compensate for this variation, MSFC NE developed algorithms to splice concurrent measurements from both profilers, which the AMU transitioned into the LSP Upper Winds tool to create a smooth profile.

The AMU transitioned the MSFC NE algorithms to interpolate and fill data gaps in the data, implement a Gaussian weighting function to produce 50-m altitude intervals in each sensor, and splice the data together from both DRWPs. They did so by porting the MSFC NE code written with MATLAB software into Microsoft Excel VBA. After testing the new algorithms in stand-alone VBA modules, the AMU replaced the existing VBA code in the LSP Upper Winds tool with the new algorithms. They then tested the code in the tool with archived data. The tool will be delivered to the 45 WS after the 50-MHz DRWP upgrade is complete and the tool is tested with real-time data. The 50-MHz DRWP upgrade is expected to be finished in October 2014.

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List of Acronyms

45 WS	45th Weather Squadron	LWO	Launch Weather Officer
45 SW	45th Space Wing	MSFC	Marshall Space Flight Center
AMU	Applied Meteorology Unit	NE	Natural Environments Branch
DRWP	Doppler Radar Wind Profiler	SLS	Space Launch System
KSC	Kennedy Space Center	VBA	Visual Basic for Applications
LSP	Launch Services Program		

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