354 BUILDING A QC DATABASE OF METEOROLOGICAL DATA FROM NASA KSC AND THE UNITED STATES AIR FORCE'S EASTERN RANGE

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1. INTRODUCTION

The National Aeronautics and Space Administration's (NASA) Marshall Space Flight Center (MSFC) Natural Environments Branch (EV44) has provided atmospheric databases and analysis in support of space vehicle design and day-of-launch operations for NASA and commercial launch vehicle programs launching from the NASA Kennedy Space Center (KSC), co-located on the United States Air Force's Eastern Range (ER) at the Cape Canaveral Air Force Station. The ER is one of the most heavily instrumented sites in the United States measuring various atmospheric parameters on a continuous basis. An inherent challenge with the large databases that EV44 receives from the ER consists of ensuring erroneous data are removed from the databases, and thus excluded from launch vehicle design analyses. EV44 has put forth great effort in developing quality control (QC) procedures for individual meteorological instruments; however, no standard QC procedures for all databases currently exist resulting in QC databases that have inconsistencies in variables, methodologies, and periods of record.

The goal of this activity is to use the previous efforts by EV44 to develop a standardized set of QC procedures from which to build flags within the meteorological databases from KSC and the ER, while maintaining open communication with end users from the launch community to develop ways to improve, adapt and grow the QC database. Details of the QC checks are described. The flagged data points will be plotted in a graphical user interface (GUI) as part of a manual confirmation that the flagged data do indeed need to be removed from the archive. As the rate of launches increases with additional launch vehicle programs, more emphasis is being placed to continually update and check weather databases for data quality before use in launch vehicle design and certification analyses.

2. SYSTEMS

Across the ER and KSC, EV44 archives data from numerous sources. Each source provides meteorological and atmospheric data from various heights and locations. Using these systems, data are recorded from the surface, through the troposphere, and deep into the stratosphere. The following provides a description of how each system operates, the location of each system, the altitudes at which data are provided, and the variables recorded from each system.

2.1 Systems: Wind Towers

The Weather Information Network Display System (WINDS) is a network of meteorological instruments located at towers across the ER and KSC. The WINDS has been in use since 1995 in support of numerous space vehicles. Instruments exist at various heights depending upon the tower, but the majority of towers have instruments at either two heights (6 feet and 54 feet above the surface), or at three heights (6 feet, 12 feet, and 54 feet above the surface) [WINDS, 2007]. Other towers are taller and have more instruments in order to support specific purposes. For example, the Lightning Protection System (LPS) towers are a network of three towers located at Launch Complex (LC)-39B with instruments at each tower at 132 feet, 257 feet, 382 feet, and 457 feet to provide meteorological data in support of the Space Launch System (SLS) while on the pad [Orcutt, et al. 2016].

The WINDS towers report several measured and derived meteorological parameters. The instruments collect wind speed, wind direction, temperature, and relative humidity every second.

Dew point is derived from the temperature and relative humidity measurements. One minute and five minute averages are calculated based on the one second data. In addition to the average wind speed and direction, the peak wind speed and corresponding wind direction for one minute and five minute intervals are recorded. In addition to temperature, dew point, relative humidity, mean wind speed, mean wind direction, peak wind speed, and peak wind direction, Tower 313 also has a barometer that records pressure at 6 feet above the surface [Brenton, 2017]. All of the values from the one-minute interval from 31 towers are archived by EV44 [Brenton 2017].

2.2 Systems: Balloons

The ER utilizes the Automated Meteorological Profiling System (AMPS) to launch and record data from weather balloons. AMPS uses two different types of balloon systems: Low Resolution Flight Elements (LRFE) and the High Resolution Flight Elements (HRFE). The LRFE uses a standard latex balloon and is tracked by a Global Positioning System (GPS), which derives wind speed and direction and measures altitude directly. Because the volume of the latex balloon changes with changes in pressure, the maximum altitude of the balloon can vary depending on the atmospheric conditions. Typically, the LRFE has a maximum height of at least 100,000 feet. The LRFE also measures temperature and relative humidity, and derives dew point, pressure, and density [Leahy, et al. 2003]. AMPS can collect and process the LRFE data in two different file formats: Low Resolution AMPS (LRAM) and Low Resolution Winds Only AMPS (LWAM). The LRAM format includes altitude, wind speed, wind direction, and thermodynamic data; as well as data from altitudes pertinent to weather forecasting. The LWAM format includes altitude, wind speed, wind direction, and rise rate, and is used to support loads and trajectory calculations for launches [Brenton 2017].

The HRFE is lofted with a clear, plastic balloon with small cone-like protrusions on the surface. The protrusions dampen vibrations and oscillations during balloon ascent. Like the LRFE, the HRFE is tracked by GPS. The balloon maintains a constant volume throughout the ascent so the maximum altitude a HRFE balloon can reach is approximately 60,000 feet. The HRFE does not contain any thermodynamic instrumentation so only wind and altitude data are recorded. The HRFE is based on the heritage Jimsphere balloon [Adelfang 2003]. The Jimsphere pioneered the protrusions over the surface of the balloon during the 1960s, but unlike the HRFE, was coated in a reflective surface to be tracked via radar. Today, Jimspheres are rarely used at the ER, but a substantial database of Jimsphere data from 1989 to 2017 is included in the EV44 archive for climatological studies [Brenton 2017]. When Jimsphere data are received by EV44, the data will have the same QC checks as a HRFE.

2.3 Systems: 915 MHz Doppler Radar Wind Profilers

The ER maintains and operates five 915 MHz Doppler Radar Wind Profilers (DRWPs). The 915 MHz DRWPs operate in a three beam configuration. Each DRWP has a vertical beam and two oblique beams at an elevation of 75^{o}. But, the azimuth of the two oblique beams is unique to each profiler, and can be altered due to local beam interference (Table 1). The 915 MHz DRWP measures wind speed from 426 feet to 20,013 feet at approximately 328 feet intervals.

DRWP ID. #	DRWP Location	DRWP Obl. Beam 1 Azi.	DRWP Obl. Beam 2 Azi.
1	South Cape	91	1
2	False Cape	2	272
3	Merritt Island	17	287
4	Mosquito Lagoon	34	304
5	Titusville	36	306

Table 1: DRWP Locations and Oblique Beam Azimuths [Lambert, et al. 1998]

Each beam transmits an electromagnetic pulse, and based on the return from the three beams, a three-dimensional wind vector can be determined. To prevent returns from non-atmospheric targets, coherent integration is implemented to boost the signal-to-noise ratio. A single Doppler velocity spectrum is produced by performing a Fast Fourier Transformation over a set of coherent integrations. The strongest peak from the spectrum is assumed to be the peak from the “actual” atmospheric backscatter. The spectral peak is used to find the signal power, radial velocity, and spectral width. Finally, a wind speed and direction is derived by converting the

radial velocities into the meteorological coordinate system. This process is repeated across each range gate. The consensus average from 13 to 14 minutes of observations is calculated to produce a profile once every 15 minutes [ESRL 2005]. The locations of the DRWPs allow users to analyze the boundary layer winds of differing environments and still support launches from KSC and the ER.

2.4 Systems: Tropospheric Doppler Radar Wind Profiler

KSC operates and maintains the Tropospheric Doppler Radar Wind Profiler (TDRWP). The TDRWP is located east of the Shuttle Landing Facility and is comprised of a network of transmitting and receiving nodes laid out over 200,000 square feet. The TDRWP is located at the site of the heritage 50 MHz DRWP system and uses the same methodology to collect data, but has had the frequency altered from 50 MHz to 48.25 MHz, and now operates in a four beam configuration rather than a three beam configuration. [Barbré 2017].The system utilizes a four beam configuration at 48.25 MHz where each beam is an oblique beam with an azimuth 45° off of the cardinal directions (45°, 135°, 225°, 315°) at an elevation angle of 75.7°. Unlike the 915 MHz, the TDRWP uses the Median Filter/First-Guess (MFFG) algorithm to provide continuous wind data. The MFFG algorithm uses three steps to produce a wind profile. First, the MFFG applies a running temporal median three-point filter to successive spectra from the oblique beams. Next, the MFFG algorithm computes the noise, interpolates over the zero Doppler shift, and then identifies the wind signal from within the power spectrum. Finally, the velocity of the wind is computed from the signal. Wind data is produced every five minutes from 5,899 feet to 63,861 feet at 492 feet intervals [Shumann, R. S. et al. 1999].

3. QC CHECKS: USAGE AND PURPOSE

The following automated checks are purposed and may be altered as the checks are implemented. Each check creates a flag for further QC work or analysis, and ignores previous or subsequent checks. Implementing the checks in this manner thus enables multiple flags to apply to a given data point. These flags are developed with the intent of notifying the user of potentially erroneous data within the archive. The user would then manually exclude data from their analysis based largely on the flags generated by the automated process described herein. A GUI is currently being developed to allow users to perform this manual screening in the most efficient manner possible.

3.1 QC Checks: Wind Tower

For wind towers, there are four different types of checks: thermodynamic checks for individual sensors, wind speed and direction checks for individual sensors, multiple sensor/tower checks, and upwind sensor/tower check. These checks are largely based upon the previous work of Barbré (2008) and Orcutt, et al. (2015).

The first thermodynamic check determines if temperature and relative humidity data is available but dew point is not available. Since temperature and relative humidity are directly measured, dew point can be calculated. This dew point value is flagged and will be calculated at a later time using the following equation from Alduchov (1996):

$$T_d = 243.04 \ * \ \frac{\ln\left(\frac{RH}{100}\right)+\left(\frac{17.625+T}{243.04+T}\right)}{17.625 - \ln\frac{RH}{100} - \frac{17.625 \ * T}{243.04+T}} \qquad (1)$$

The next thermodynamic check is for realistic values of temperature, dew point, and relative humidity. Cumulative distribution functions (CDFs) for temperature and dew point for the entire period of record (January 2017 to October 2017) were plotted and thresholds were determined to separate data from obvious outliers. For relative humidity, the realistic value check ensures that all values are within 0 to 100. The next check is to flag all temperatures that are less than the dew point reported. The next check compares each value to its respective daily median. All of the differences from the daily medians are plotted in a CDF to determine a threshold separating data from outliers. The final thermodynamic check is an hourly consistency check on temperature, dew point, and relative humidity. This check compares each value to mean from the surrounding hour. If the difference from the hourly mean exceeds a specific threshold, the data is flagged. The threshold is determined by examining CDFs of the difference

from the mean of the surrounding hour. Figures 1-3 illustrate how CDFs are used to determine thresholds for QC checks for realistic data, daily median differences, and hourly mean differences.

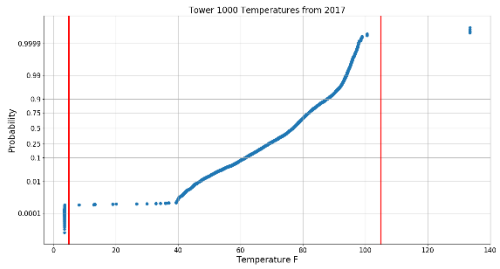

Figure 1: CDF with Thresholds for Tower 1000 Realistic Value QC Check

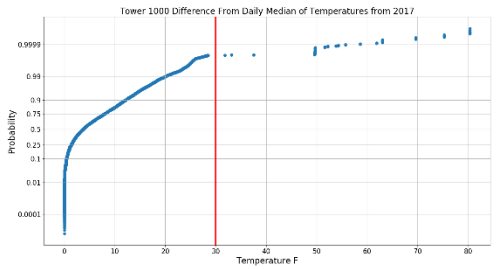

Figure 2: CDF with Thresholds for Tower 1000 Daily Median QC Check

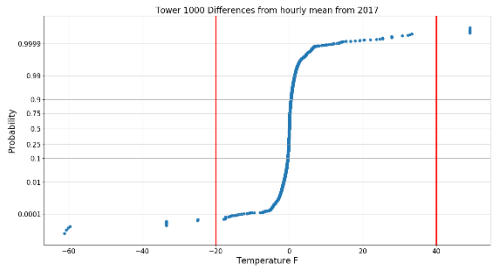

Figure 3: CDF with Thresholds for Tower 1000 Hourly Consistency QC Check

The first wind speed and direction check is a realistic data check of the mean and peak wind speed and the mean and peak wind direction. Thresholds for the realistic data check for the mean and peak wind speeds were determined through CDFs. Mean and peak wind direction realistic data check thresholds were set at 0 – 360º. The next wind speed and direction check flags mean wind speed data that is greater than the peak wind speed. The next wind speed check flags light winds instances where the mean and peak wind speeds are equal and are greater than 10 knots. Given the variable nature of wind speed, having equal mean and peak wind speeds for any conditions more than a light wind is likely due to instrument error. The next check is an hourly consistency check on mean and peak wind speeds. This check uses the same methodology as the thermodynamic hourly consistency check and helps to identify spontaneous data. The final wind speed and direction check if a mean wind speed exceeds a vector difference consistency threshold. First, the vector component (u,v) differences from the adjacent data values are calculated using:

$$\Delta u_i = {}^{1}/_{2}\,(u_{i-1} + u_{i+1}) - u_i \qquad (2)$$

$$\Delta v_i = {}^{1}/_{2}\,(v_{i-1} + v_{i+1}) - v_i \qquad (3)$$

Then, the vector component differences are used to calculate the vector difference using:

$$\Delta V_i = [(\Delta u_i)^2 + (\Delta v_i)^2]^{\frac{1}{2}} \qquad (4)$$

The threshold of vector differences was determined by plotting a CDF of all vector differences.

3.2 QC Checks: Balloon

There are two different types of QC checks for balloons; checks that apply to both LRFE and HRFE systems, and checks that apply to only a specific system (either LRFE or HRFE). The first balloon QC check applies to both systems and checks if any gaps exist in the profile. If gaps do exist, the check determines if at least 50% of the profile is available. Furthermore, this gap will flag any gaps that are larger than 16,400 feet. Also, both types of balloons have an altitude check that flags any altitudes that are not in ascending order. Both types of balloons will have wind speed check that flags any wind speeds of zero knots above the surface.

The next two QC checks apply to both systems, but are unique to the available data variables. The first check flags any data that exceed a realistic data threshold. The second of these QC checks flags any values that exceed six standard deviations from the annual mean for each system's unique variables. These two checks would be applied to temperature, dew point, relative humidity, wind speed, wind direction, pressure, and density from the LRAM

files. Meanwhile, LWAM, HRFE, and Jimsphere files will have realistic and six sigma data checks for wind speed, wind direction, and rise rate.

The remaining balloon system QC checks apply to specific systems. The first check flags temperature values that exceed a lapse rate of 8^{o} F per 100 feet. This check protects against spurious temperature readings in the LRFE data. The last QC check identifies data points from an LRFE that provide pressure, temperature, altitude, dew point, but not density. Density is flagged to be calculated at a later time during archiving.

3.3 QC Checks: 915 MHz DRWP

The QC checks for the 915 MHz DRWP are largely based upon the work of Orcutt, et al. (2017), where DRWP data were flagged for failing the following QC checks. The first 915 MHz DRWP QC check flags data where the vertical beams do not provide an adequate number of consensus records. This check ensures that enough profiles are sampled in the processing of these data. The next check flags data where the signal-to-noise ratio (SNR) of the vertical and oblique beams are less than -20 dB. The next check flags a profile where the consensus averaging time period is less than 6 minutes. This check flags a profile where there hasn't been enough time to collect data and generate a representative consensus average. The next QC check flags profiles where there are not enough consensus records to meet the number of required records. This check flags profiles that under-sample the consensus average. The next QC check flags instances where the radial velocity from the oblique beams exceeds the Nyquist Doppler velocity. This check makes sure that the radial velocity is Nyquist limited. The remaining checks examine the quality of the reported winds. The next QC check flags unrealistic wind direction by identifying wind directions outside of a range between 0^{o} and 360^{o}. The next QC check flags vertical wind velocity that exceeds 19 knots. The climatology of Atlantic coastal Florida vertical wind speeds are typically very small and this flag will identify either an extreme convective event or an erroneous data point. The next QC check identifies data points where the shear exceeds 0.1 s^{-1}. This is an important QC flag as shears of this magnitude can exist, but need the manual confirmation provided with the GUI to determine if these flagged shears are real or indeed spurious. The final check for the 915 MHz DRWP is to flag profiles where less than 50% of the data up to 3,300 feet are available. This check flags profiles that do not provide enough data to be useful in day-of-launch (DOL) activities. In addition to flags, the data will be plotted in a time height section in a GUI for visual examination of flags and the surrounding atmospheric features. This visual examination via a GUI is also used in the QC process of TDRWP data. An example of the GUI and a time height graph is available in Figure 4.

3.4 QC Checks: TDRWP

The TDRWP QC process relies heavily upon manual QC through the GUI as seen in Barbré (2013). The GUI will plot TDRWP in a time-height plot so that wind features can be identified by the user.

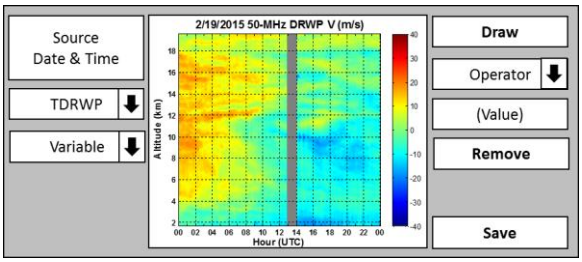

Figure 4: Concept of GUI editing TDRWP data

However, there are still a few QC checks that can flag data to assist with the removal of data. The output files from the TDRWP include QC flags from the system's own internal QC procedures. The internal QC flags from the TDRWP that are saved for the EV44 archive include flags for failing SNR, shear, and first guess propagations. In addition to recording the internal QC flags, there are three other QC checks that EV44 performs. The first is a check for convection based on vertical velocity and spectral width. This check can identify periods of intense convection that could affect the returns of the signal, such as a thunderstorm. The next check identifies and flags vertical wind speeds exceeding 4 knots. These flags can be used to help identify spurious data points. Finally, a QC check calculates the median based on the surrounding heights and times from each point, and if the difference between the median and the

data point exceeds a certain threshold, the data are flagged. This QC check helps especially with the manual QC via the GUI by identifying individual data points that are discontinuous.

4. FUTURE WORK

The procedures outlined in this paper are still in work, and are subject to change as more work is done. Continued work by EV44 will further mature these checks and the software that will apply these checks to the databases. The GUI is still being developed, but EV44 intends to leverage on previous efforts implemented to develop a QC database for the heritage 50-MHz DRWP system [Barbré 2013].

As the SLS program continues to progress and commercial launches become more frequent, more instrumentation will be installed to replace aging hardware installed during the Shuttle Program. The QC checks and procedures will need to be revisited as new instruments are installed. Furthermore, as current instrumentation is updated, the data formats will need to be updated; thus necessitating an update to the QC software.

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