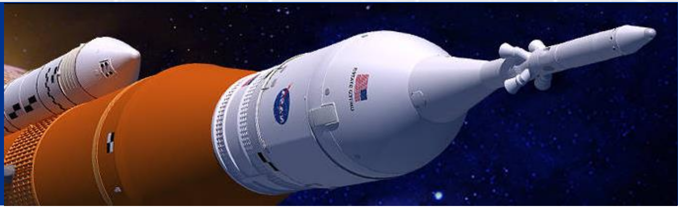
Analyses of Kennedy Space Center Tropospheric Doppler Radar Wind Profiler Data for Space Launch System Program Certification

Presentation to the Significant Role of Calibration/Validation and High Performance Computing for the Transition of Research to Operations Session: Part I, of the Ninth Conference on Transition of Research to Operations, as part of the 99th American Meteorological Society Annual Meeting



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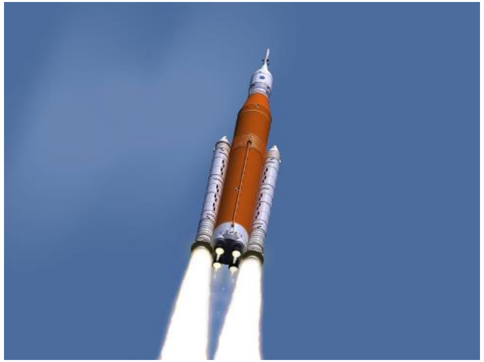
Agenda

1. Purpose
2. Certification Requirements
3. Data
4. Analyses
5. Summary

Purpose

- Explain the requirements and analyses performed to certify the Kennedy Space Center (KSC) Tropospheric Doppler Radar Wind Profiler (TDRWP) for use in Space Launch System Program (SLSP) day-of-launch (DOL) integrated vehicle performance assessments for commit to launch decision.

- Requirements are based on SLS vehicle response characteristics to the wind profile, consistency to previous databases used in vehicle design assessments, and DOL operational considerations.



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Certification Requirements

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

- For effective vertical resolution (EVR), the maximum wavelength of gust analyses is based on accounting for a 30-minute assessment.
  - EVR quantifies the vertical extent of the smallest feature that an instrument can resolve.
  - Boundary wavelength using Aerospace Corporation equation (Spiekermann et al. 1999) yields 768 m.
  - Set criterion to 700 m to add conservatism.

Data: Summary of Datasets

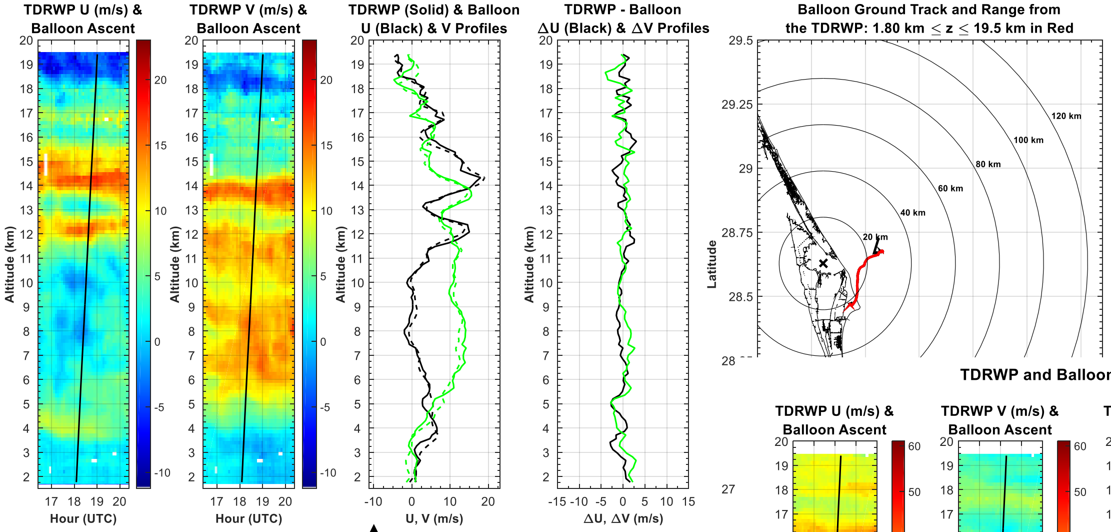
- Collected AMPS balloon and TDRWP data for the period of record (POR) 06/22/2016 – 06/22/2017.
- Implemented quality control (QC) algorithms on both datasets.
- Balloon
  - One-second AMPS high- and low-resolution profiles (1,159 profiles).
  - A total of 98 profiles failed altitude (50 kft) or shear (0.15 s^{-1} over 100 ft) check.
  - An additional 31 profiles failed duplicate profile (5-min) check, leaving 1,030 profiles available for analysis.
- TDRWP [no QC]: Data as archived by MSFC Natural Environments Branch (EV44).
- TDRWP [QC]:
  - QC based off Barbré (2012).
  - Automated checks for unrealistic values, possible convection, and parameters that exceeded shear, vertical velocity, temporal and vertical consistency, spectral width, and first-guess propagation (FGP) thresholds.
  - Manual checks to flag suspect or erroneous data that passed automated checks and to confirm convection.

Analyses: Time Interval, Vertical Data Interval, Data Collection Period

- Examined TDRWP [no QC].
- Time interval passes criteria under nominal operations.
- Vertical data interval passes criteria.
- Data were collected over a calendar year (348 days available).

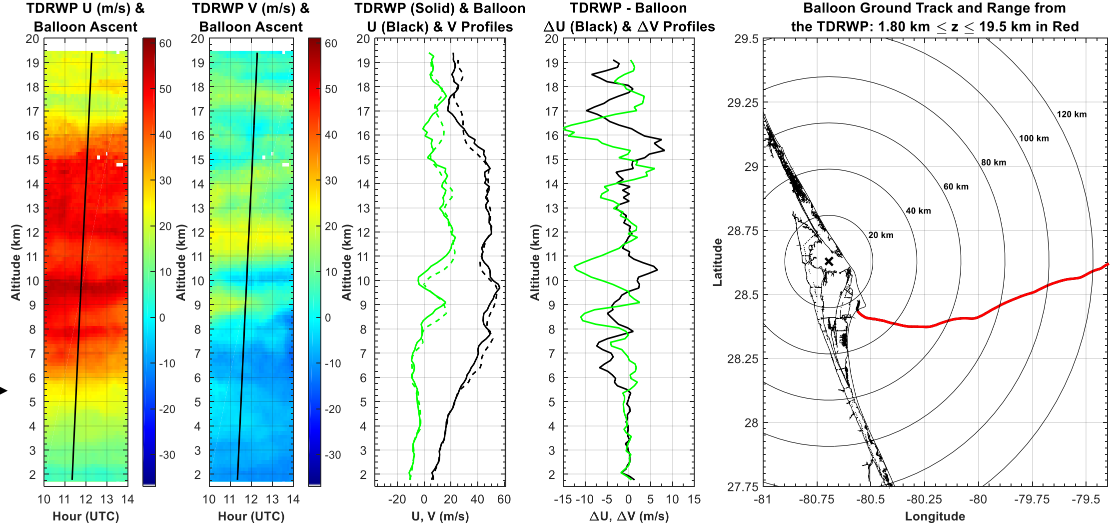
Analyses: Wind Accuracy and Altitude Methodology

TDRWP and Balloon Comparison, Case 275: Balloon Release at 10/03/2016 18:00 UTC



- Averaged all 1-s balloon data within 75 m of each TDRWP altitude.
- Temporally matched balloon and TDRWP data throughout balloon ascent.
- Utilized 287 comparisons spaced by at least 24 hours to maintain sampling independence.
- Examined five-panel plots of each comparison.

TDRWP and Balloon Comparison, Case 471: Balloon Release at 01/08/2017 11:15 UTC



Small delta between TDRWP and balloon winds

Large delta between TDRWP and balloon winds

Analyses: Wind Accuracy and Altitude Methodology, Isolating TDRWP Error

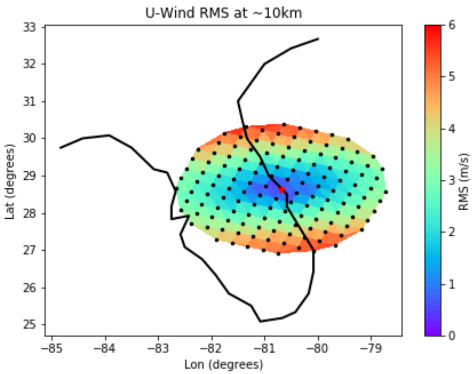
- Delta between concurrent balloon and TDRWP measurements includes measurement errors from both systems, as well as the deltas due to spatial separation. Reference Eq. (1).
- Quantified RMS deltas due to spatial separation using the North American Regional Reanalysis (NARR) (Curtis et al. 2019).
- NARR profiles are coarse and do not capture small scale wind features. Therefore, a small scale component must be added to the spatial separation determined from the NARR.
- Utilizing the calculated estimate of small scale features accounts for balloon errors. Reference Eq. (2).
- Solve for the TDRWP error. Reference Eq. (3).

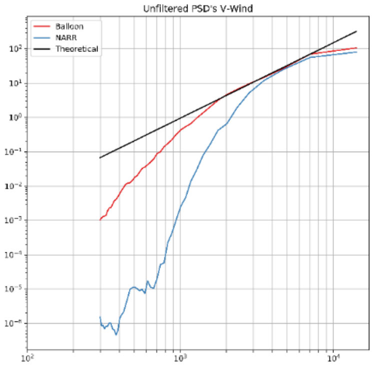
$$\Delta^2_{TDRWP-balloon} = E^2_{TDRWP} + E^2_{balloon} + \Delta^2_{spatial,NARR} + \Delta^2_{small} \qquad \text{Eq. (1)}$$

$$\Delta^2_{small,calc} = \Delta^2_{small} + E^2_{balloon} \qquad \text{Eq. (2)}$$

Substitute Eq. (2) into Eq. (1) and solve for E_{TDRWP} to obtain:

$$E_{TDRWP} = \sqrt{\Delta^2_{TDRWP-balloon} - \Delta^2_{spatial,NARR} - \Delta^2_{small,calc}} \qquad \text{Eq. (3)}$$





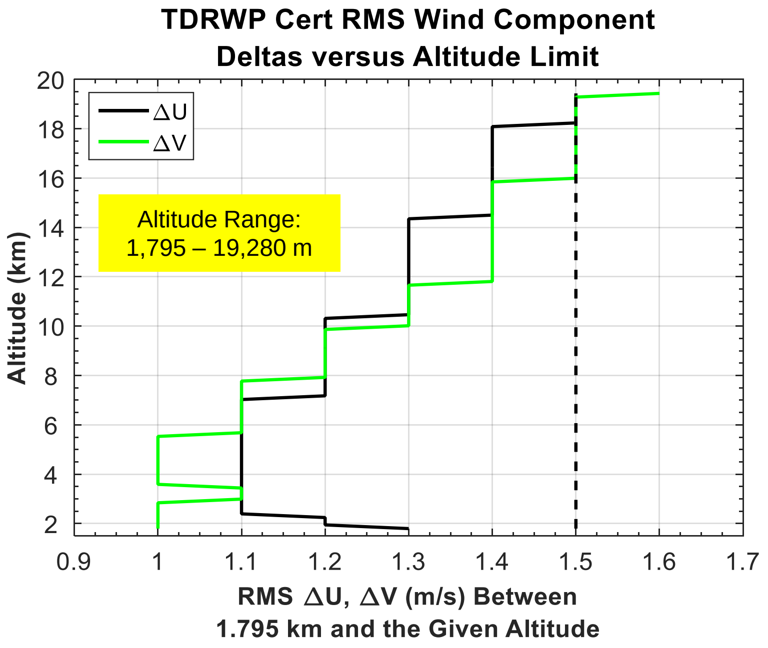
Plots provided by N. Curtis / EV44

Variable list

$\Delta_{TDRWP\text{-}balloon}$	difference between a concurrent TDRWP and balloon report
E_{TDRWP}	difference attributed to TDRWP measurement errors
$E_{balloon}$	difference attributed to balloon measurement errors
$\Delta_{spatial}$	estimate of expected differences due to spatial separation
$\Delta_{spatial,NARR}$	estimate of expected differences due to spatial separation from NARR
Δ_{small}	estimate of expected differences due to small-scale features for which the NARR does not account
$\Delta_{small,calc}$	calculated estimate of expected differences due to small-scale features for which the NARR does not account

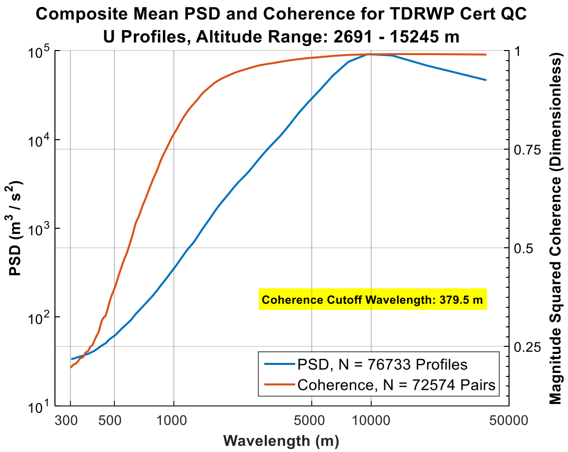
Analyses: Wind Accuracy Results

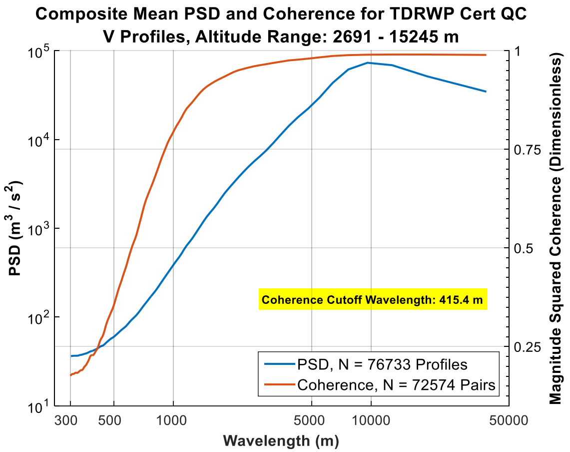
- Subtracted the RMS delta due to large-scale spatial separation and the RMS delta due to accounting for small-scale wind features (which include balloon error) from the initial TDRWP-balloon computation.
- Rounded E_{TDRWP} to the nearest 0.1 m/s to account for instrument precision. Wind speed is provided to the nearest 0.1 m/s.
- Plot shows RMS wind component delta = X for profiles between 1.795 km and Y km.
- Results yield an altitude range of 1,795 – 19,280 m where the wind accuracy meets the criteria of 1.5 m/s RMS wind component delta.

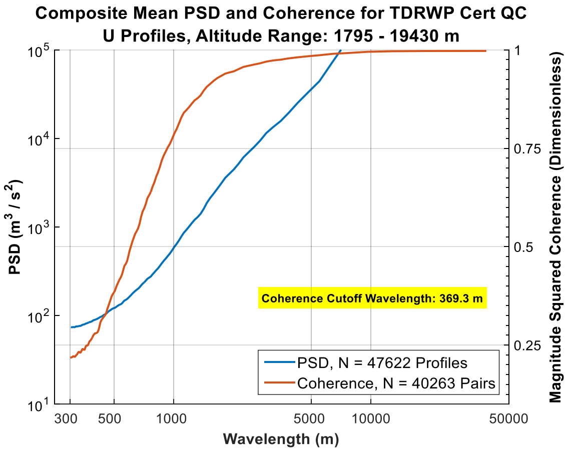


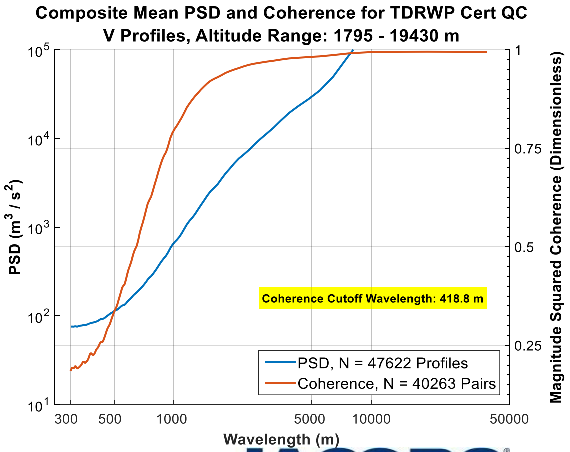
Analyses: EVR

- Methodology (Merceret 1999)
  - Used data from 2.70-15.25 km from days containing at least 100 five-minute pairs.
  - Preprocessing
    - Removed linear trend.
    - Applied Parzen window on entire profile.
  - Computed the daily mean coherence.
    - Power spectral density (PSD) of each profile within pair.
    - Cross-spectral density (CSD) of each pair.
  - Computed sample-weighted mean coherence and PSD.
- Results: estimated EVR of the TDRWP is 450 m.
  - Coherence crosses 0.25 at 379.5 m and 415.4 m for U and V, respectively.
  - Slope of mean PSDs appear to flatten (going from right to left) around 400-500 m.
  - Similar results noted when assessing the entire altitude range.









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Summary

Requirement	Criteria	Pass / Fail w/Remarks
Time Interval	5 min	Pass
Vertical Data Interval	150 m	Pass
Data Collection Period	One year	Pass
Wind Accuracy	1.5 m/s root-mean-square component difference	Root-mean-square differences pass criterion from 1,795-19,280 m.
Altitude	2,700 - 15,250 m	Pass, altitude range within which wind accuracy passes envelopes the criteria.
Reliability	No criterion. Will report the percent of usable profiles.	Probability of obtaining a usable profile per requirement is 86.5%. Probability of obtaining any profile is 93.8%.
Effective Vertical Resolution	700 m	Pass, EVR estimated at 450 m.

- The TDRWP passes criteria for SLSP certification.

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