National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

Continuous Gust Functions for SLS Ascent Load Assessments

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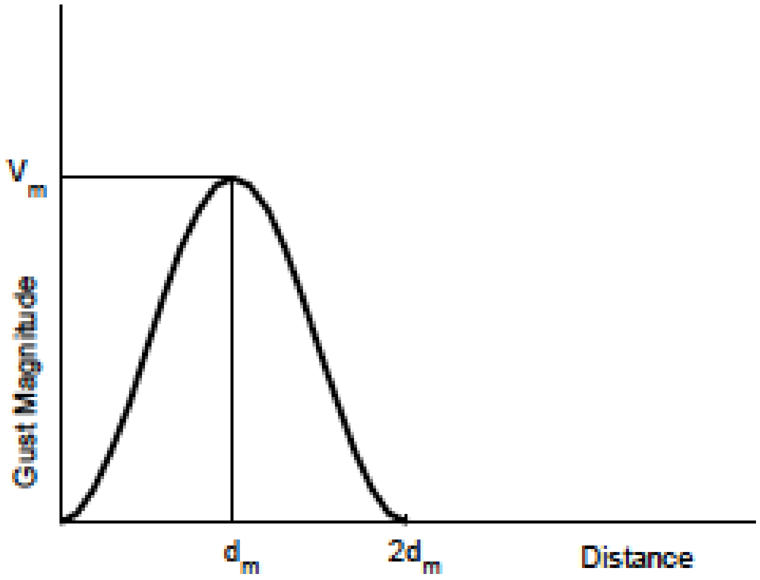
Outline

- Background
- Data
- SCARF Filter
- Continuous Gust Functions
- Summary

Background – Discrete Gust Model

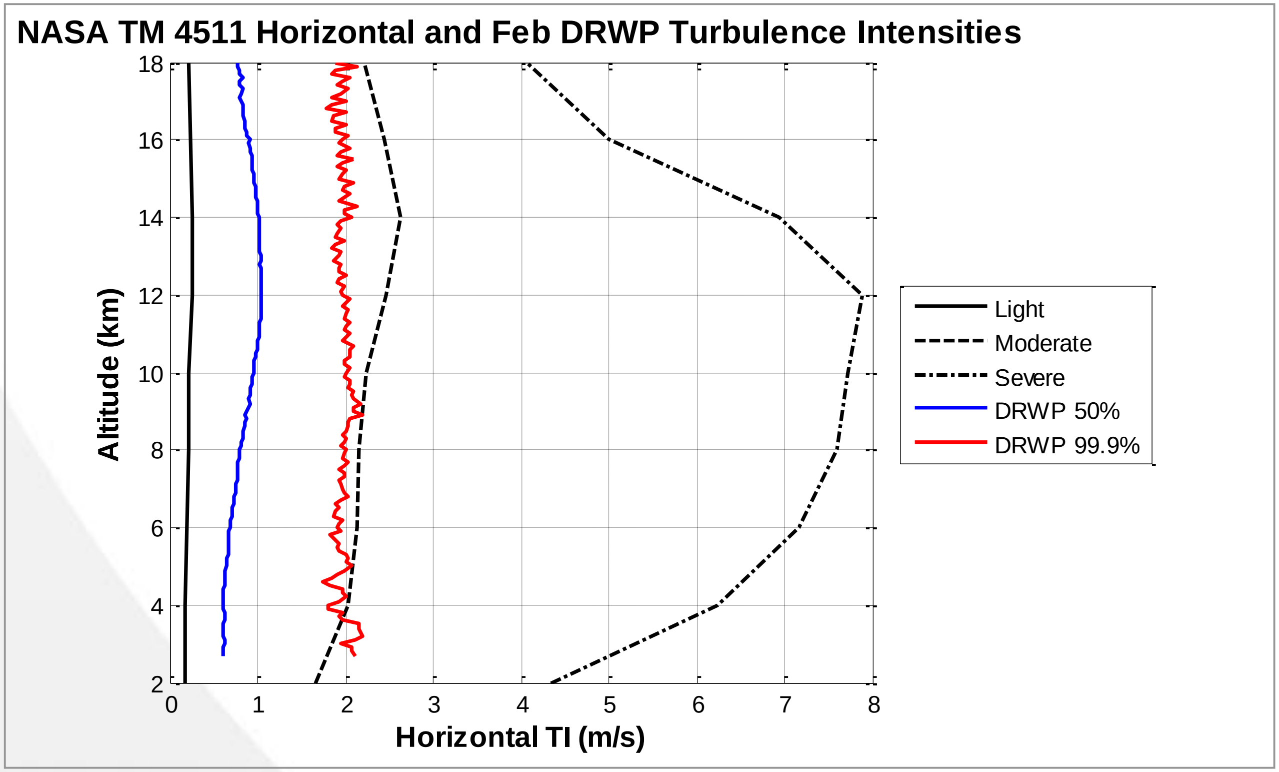
- **Vehicle structural loads during ascent have historically been assessed using discrete gust functions**
- **The gusts have a 1-cosine shape**
- **The magnitude is determined from climatology of worldwide aircraft turbulence intensity data**
  - Climatology provided for light, moderate, and severe turbulence
  - Magnitudes for both moderate and severe intensity provided for Space Launch System (SLS)



- **Magnitude is dependent on the width of the gust function, with longer widths having larger magnitude**
- **Magnitude is also a function of altitude, with higher values in the jet stream region (20 to 30 Kft)**
- **Magnitude chosen to sufficiently reduce risk of exceedance. For SLS, gust magnitudes chosen at the 99% level.**
- **Gusts are tuned (via width) to excite vehicle responses**

Background – Discrete Gust Model

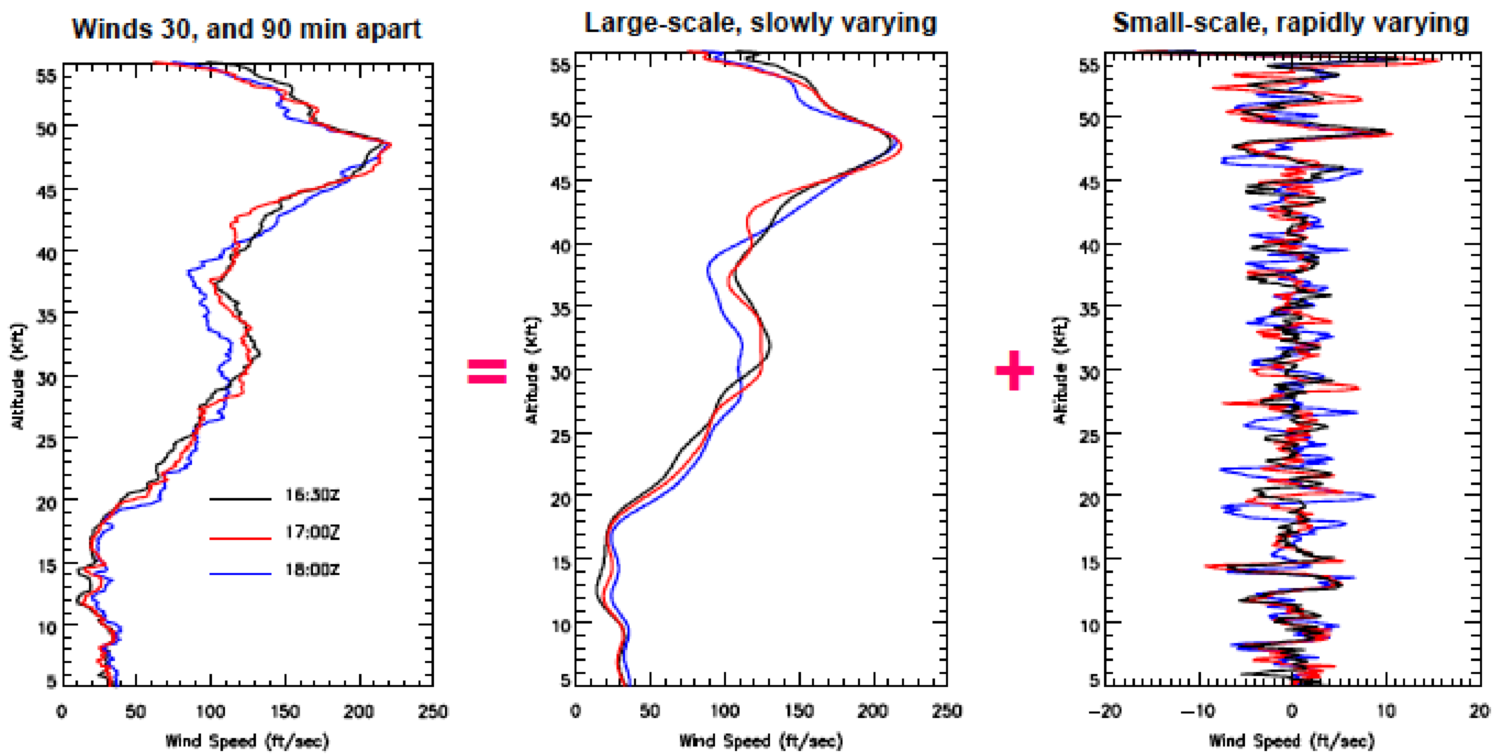
- SLS-SPEC-159 (DSNE) originally specified gust magnitudes based on severe turbulence
- SLS Loads Resolution Task Team was looking for load relief
- Turbulence intensities determined from KSC 50 MHz DRWP compared favorably with moderate turbulence climatology (From Barbre presentation to Joint Loads Task Team, September 2012)
- DSNE gust magnitudes changed from severe to moderate



Plot courtesy of Barbre

Background - Aerospace Corp Recommendation

- Aerospace Corporation reviewed SLS ascent gust load process
- Concerned use of moderate gusts was under conservative
- Recommended to use continuous gust functions instead of discrete gusts
- Continuous functions more representative of the actual gust environment
- Wind content of continuous gusts are a function of time before launch
- MSFC Natural Environments tasked to develop functions created from archived high resolution balloon data



Plot from Brian Sako, Aerospace Corp

Background

- **Aerospace Corp recently developed continuous gust functions for an SLS sensitivity assessment**
- **MSFC NE to use Aerospace Corp methodology to develop official SLS gust functions**
- **Gust functions are intended to represent the wind features used in dynamic load assessments (pre-flight loads, not DOL loads)**
- **These wind features are the incoherent part on DOL (wavelengths less than $460\sqrt{T}$)**
- **Steps:**
  - 1) Obtain a set of high resolution balloon wind profiles
  - 2) Adjust each profile's noise floor to match it's spectral power law
    - Spectral Component Adaptive Reshaping Filter (SCARF)
    - SCARF filter is based on Principal Component Analysis (PCA)
  - 3) High pass filter data to obtain wind profiles consisting of incoherent wavelengths

Data

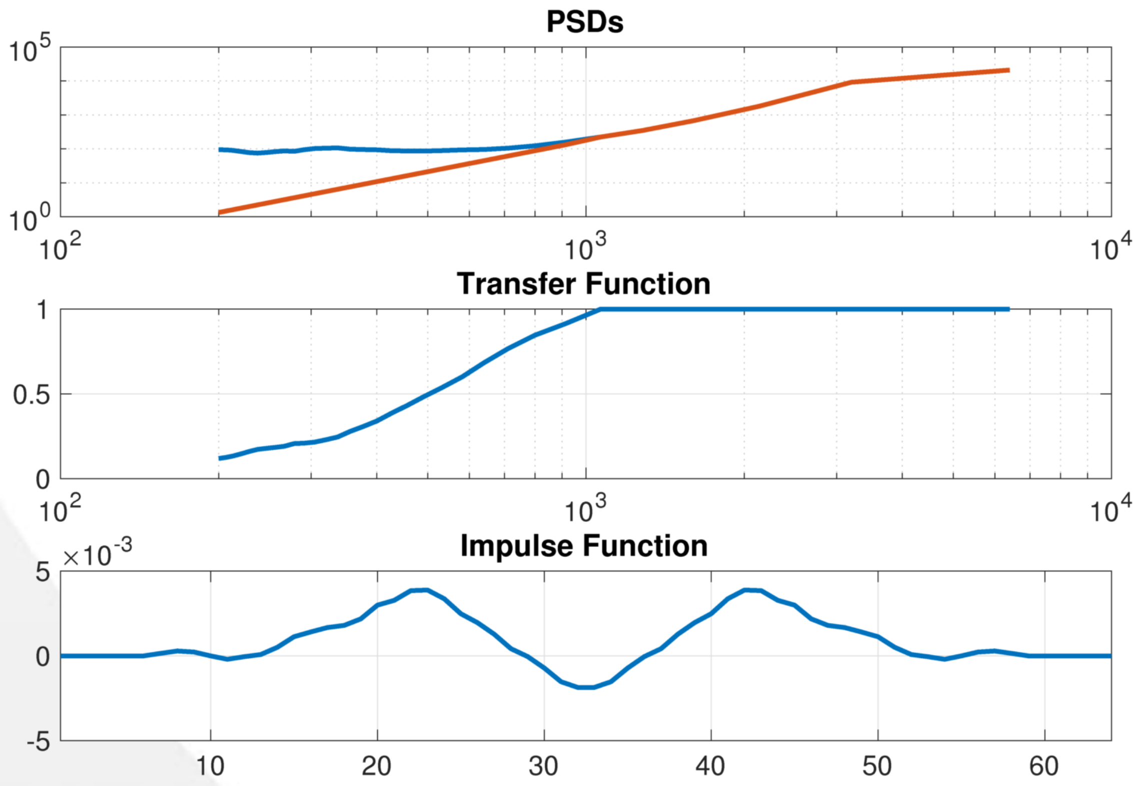
- Goal is to develop 2000 continuous gust functions for the following time periods: 30 minutes, 1 hour, 1.5 hours, 2 hours, 2.5 hours, 3 hours, 3.5 hours, 4 hours
- Gust functions developed from 2000 wind profiles of Jimsphere and Automated Meteorological Profiling System (AMPS) High Resolution (HR) balloons
- Previous studies have shown Jimspheres and HRs have comparable spectral characteristics
- Select profiles that reach at least 50 Kft

SCARF Filter

- Continuous gust functions cover the wavelengths typically containing signal noise in the wind measurements, so it is ideal to remove that noise
- Purpose of the SCARF filter is to reshape the power spectral density (PSD), via PCA, of individual wind profiles to remove the noise floor
- The PSDs are reshaped by reconstruction with a set of modified principal components
- Transfer functions (filters) are computed for each profile by taking the ratio of the raw PSD to the modified PSD

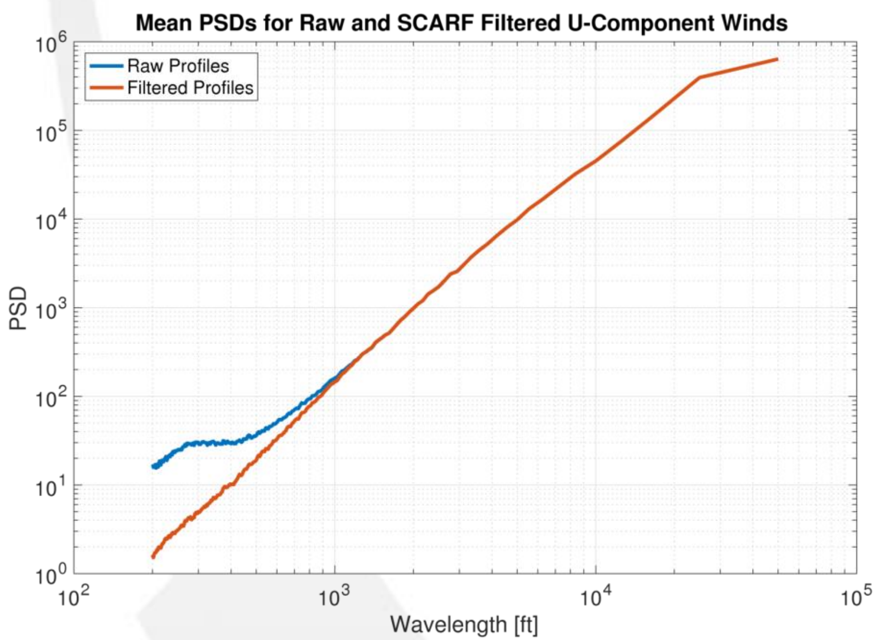
SCARF Filter

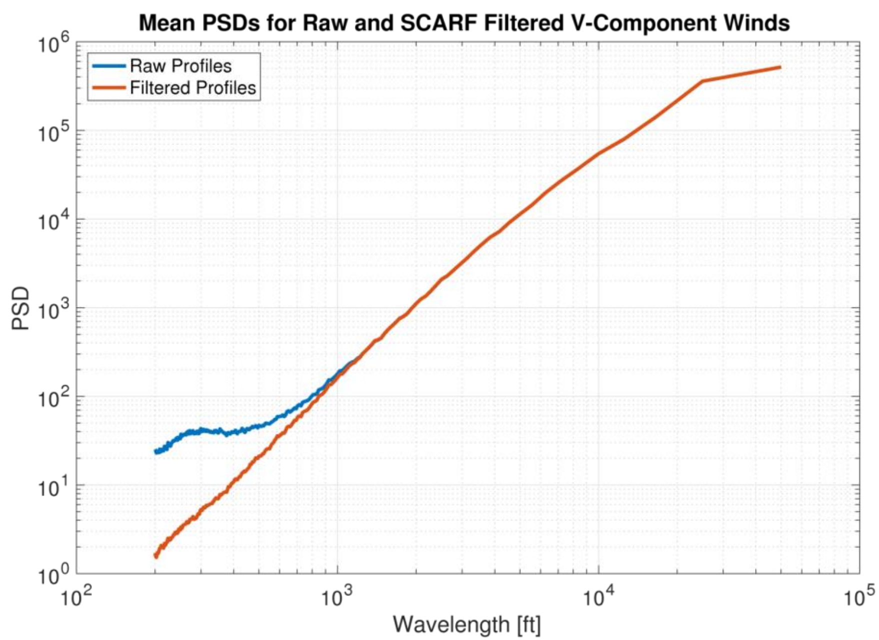
- Construct unique transfer function for each profile, by taking the ratio of the modified PSD to the raw PSD
- Compute the filter impulse function by taking the inverse Fourier transform of the transfer function



SCARF Filter

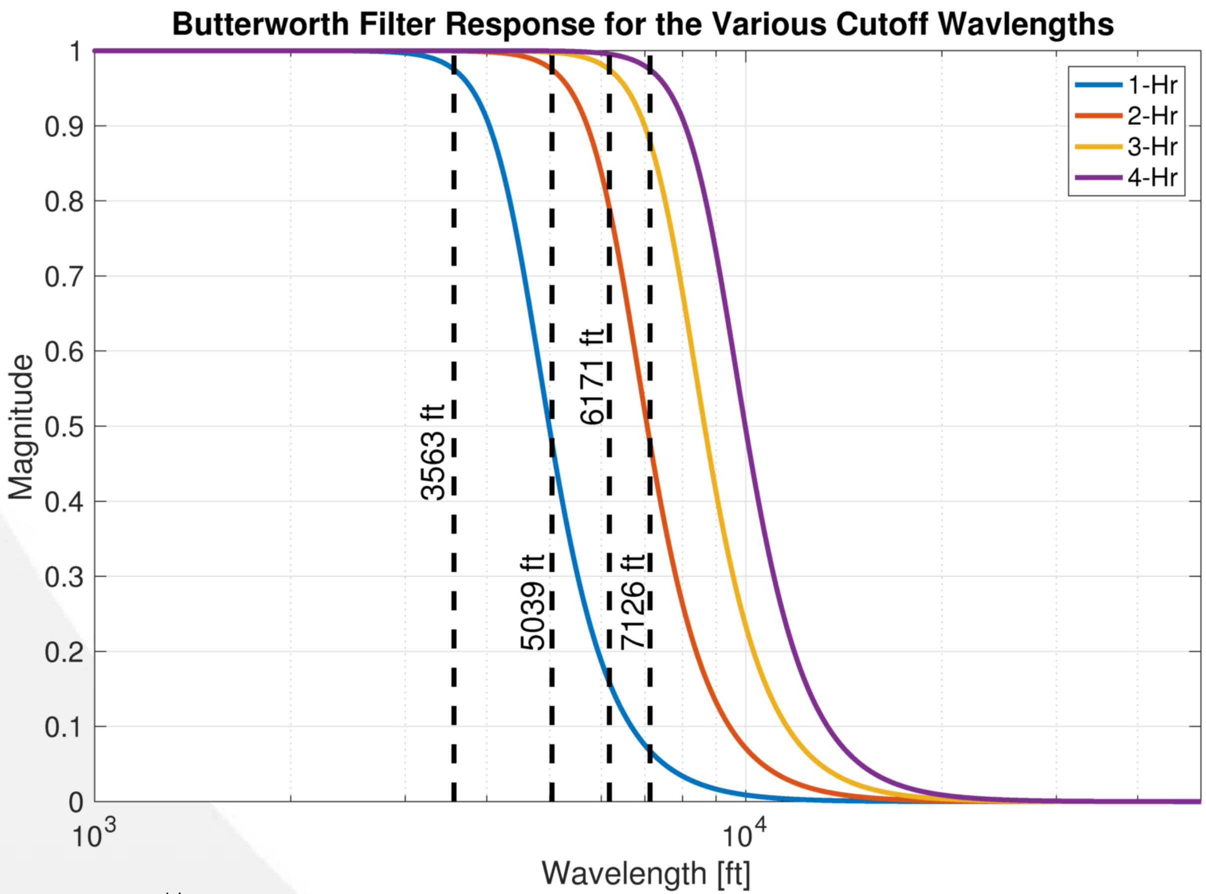
- **SCARF filter successfully removes the noise floor**





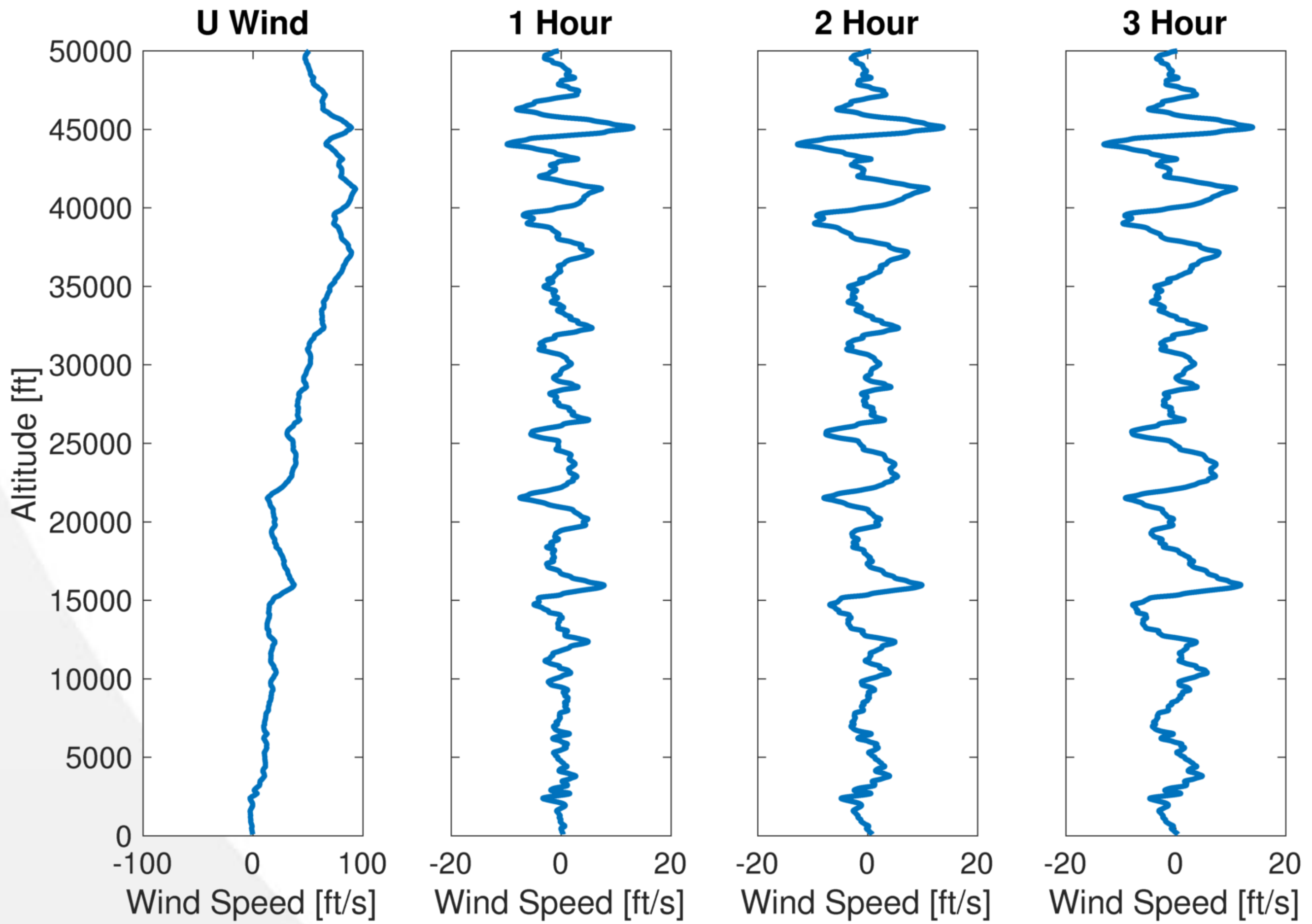
Continuous Gust Functions

- Use the SCARF filtered wind profiles to build the continuous gust functions
- High-pass filter each component profile using a 6 pole Butterworth filter
- Filter cutoff wavelength is chosen by the Aerospace Corporation persistence equation ($460\sqrt{T}$)
- Butterworth will have 5% attenuation at the cutoff wavelength



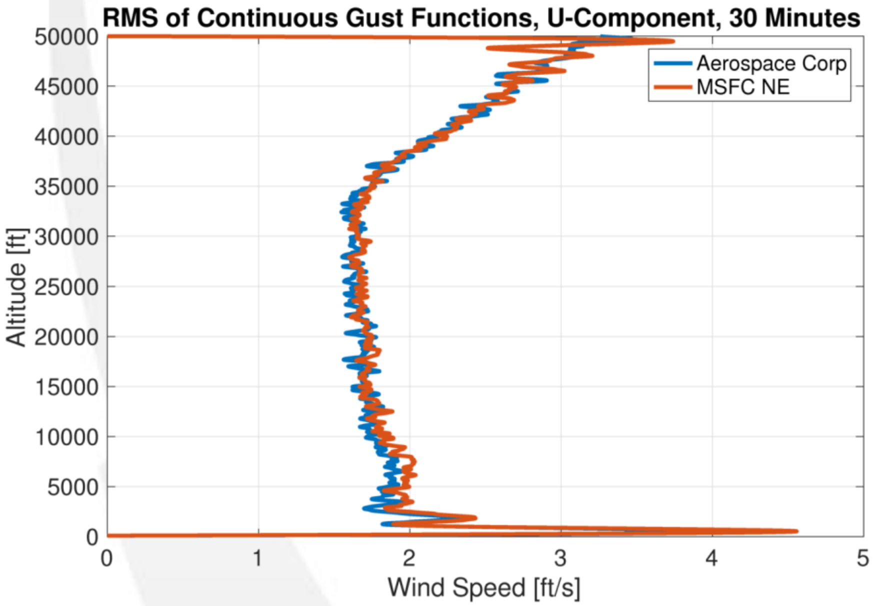
Continuous Gust Functions

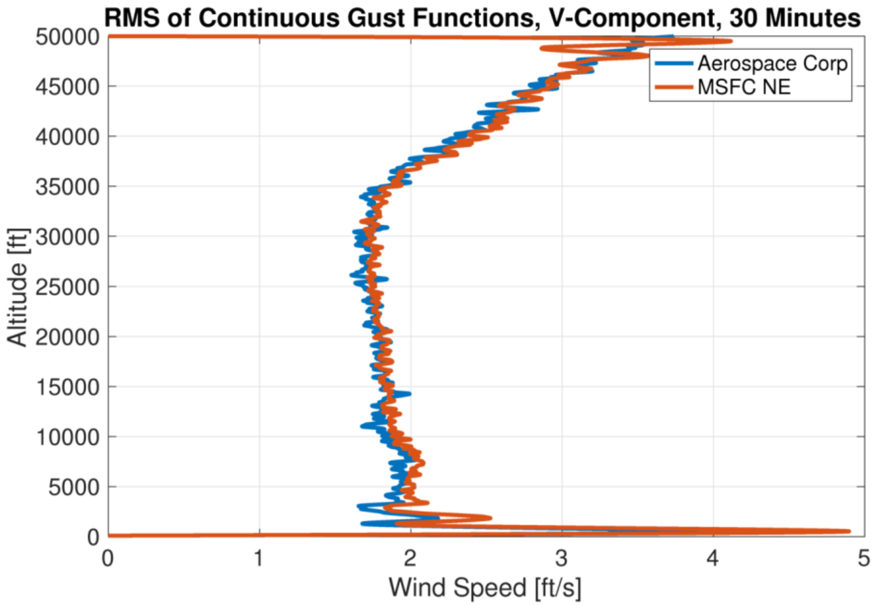
- Example continuous gust functions for a single U component profile
- Note as time delta increases, size of gusts increase
- Functions contain several discrete type gust features



Continuous Gust Functions

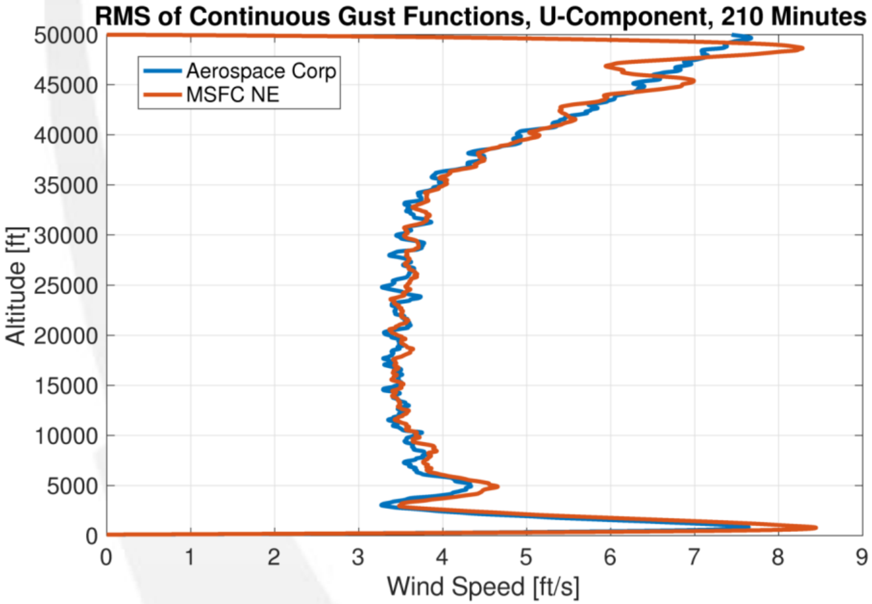
- **Comparison of Aerospace Corp and MSFC NE gust functions, 30 minutes**

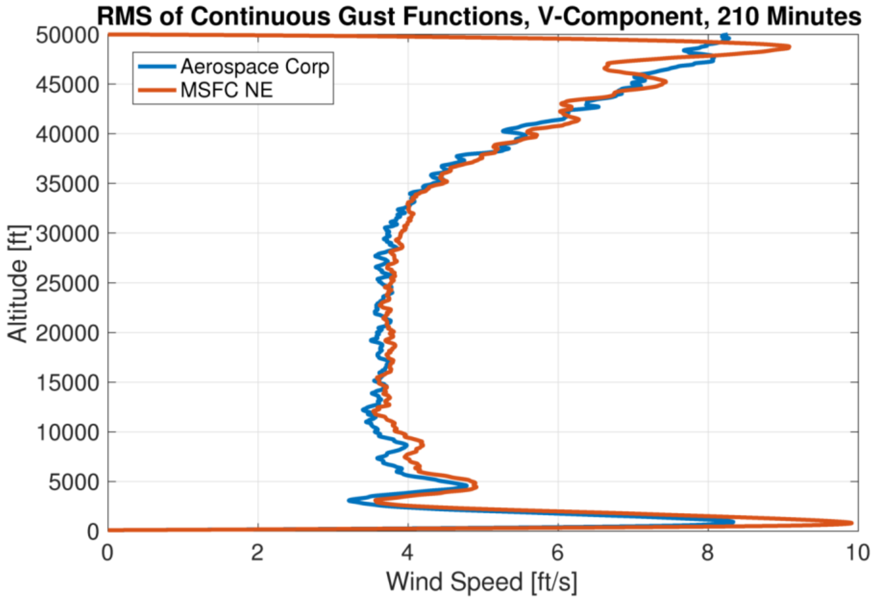




Continuous Gust Functions

- **Comparison of Aerospace Corp and MSFC NE gust functions, 210 minutes**





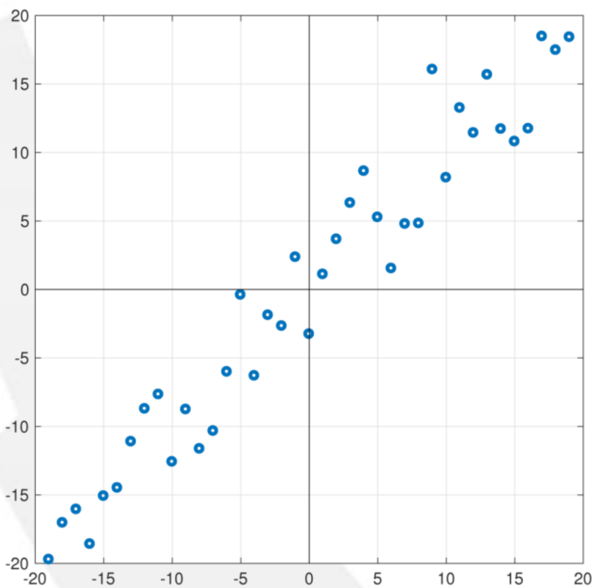
Summary

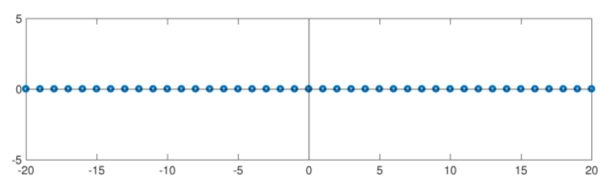
- **Vehicle structural loads during ascent have historically been assessed using discrete gust functions**
  - DSNE discrete gust magnitudes originally based on severe turbulence
  - SLS Loads Resolution Task Team needed load relief
  - KSC 50 MHz DRWP derived turbulence intensity matched favorably with moderate intensity, providing justification for changing the DSNE to moderate gusts to help with load relief
- **Aerospace Corp reviewed SLS ascent load methodology, and had concerns using moderate gusts was under conservative**
  - Recommended SLS ascent load assessments use continuous gust functions
  - Continuous gust functions provide a better representation of the gust environment
  - Using Aerospace Corp methodology, MSFC Natural Environments was tasked to provide continuous gust functions developed from NASA database of high resolution balloon wind profiles
- **Developed 8 sets of continuous gust functions (2000 in each set), at 30 minute intervals ranging from 30 minutes to 4 hours**
- **SLS will use continuous gust functions for Block 1 verification assessments, and for Block 1B design assessments**

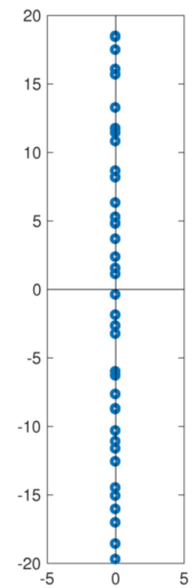
Backup

Principal Component Analysis

- Principal component analysis (PCA) is a method used to show variation and strong patterns in data
- If the data has many dimensions or variables (components), PCA can be used to remove those components which have little variation
- During PCA, the components are ordered from the strongest (most variable) to the weakest
- Typically, the first few components contribute to the majority of variability
- Simple example: The below data has equal variability in both the X and Y direction

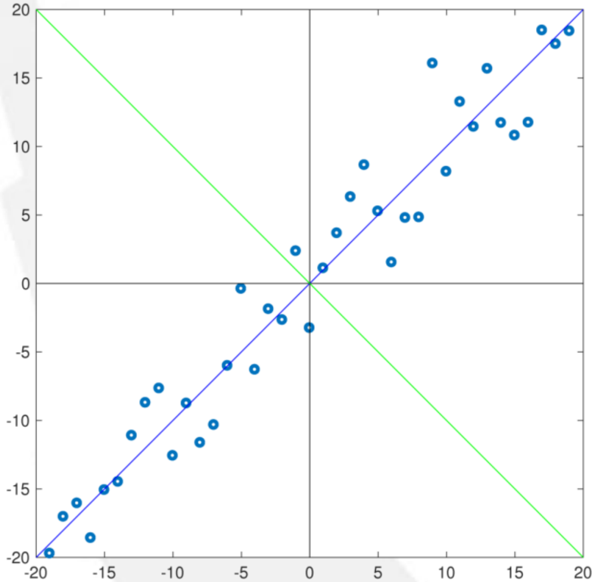


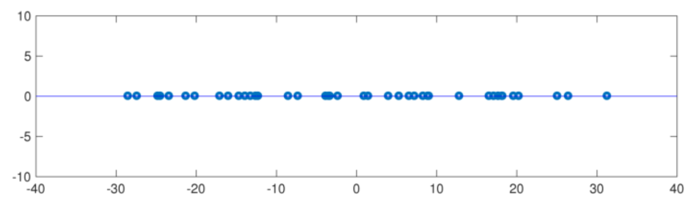


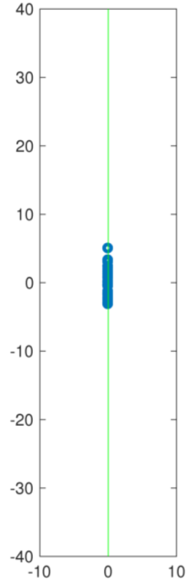


Principal Component Analysis

- Compute principal components for the data on the previous page
- First principal component will be along axis of most variability (blue axis)
- Second principal component will be orthogonal to the first component (green axis)
- Note that majority of variability is now in the first component
- Components with insignificant variance can be removed
- Reconstruction using only the strongest principal components is similar to filtering/smoothing (shown later)

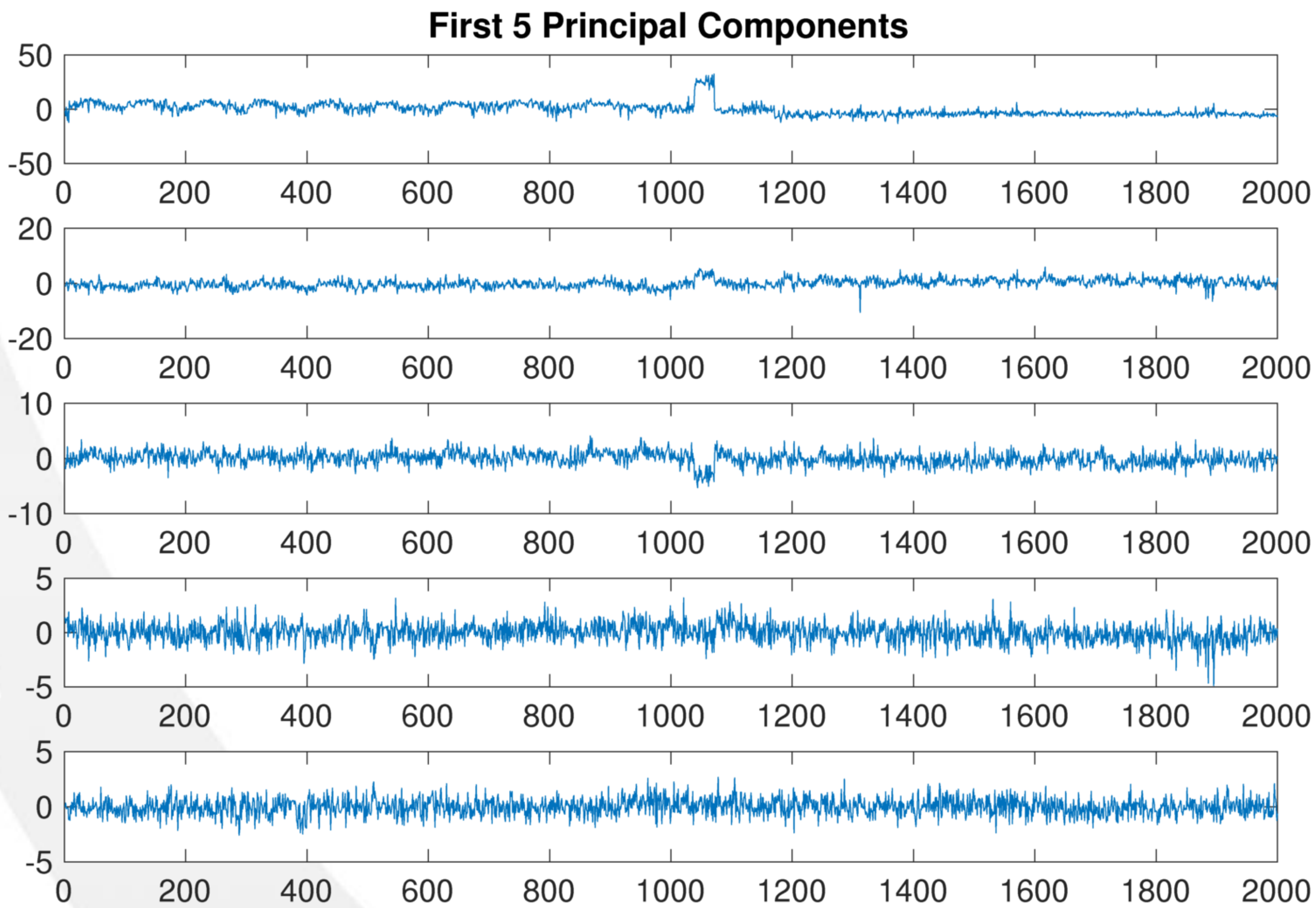






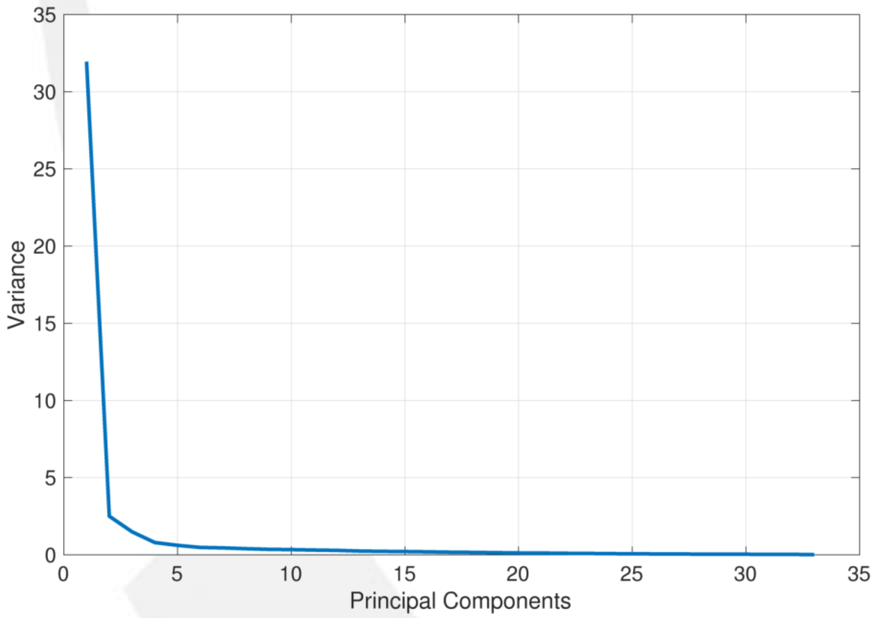
SCARF Filter

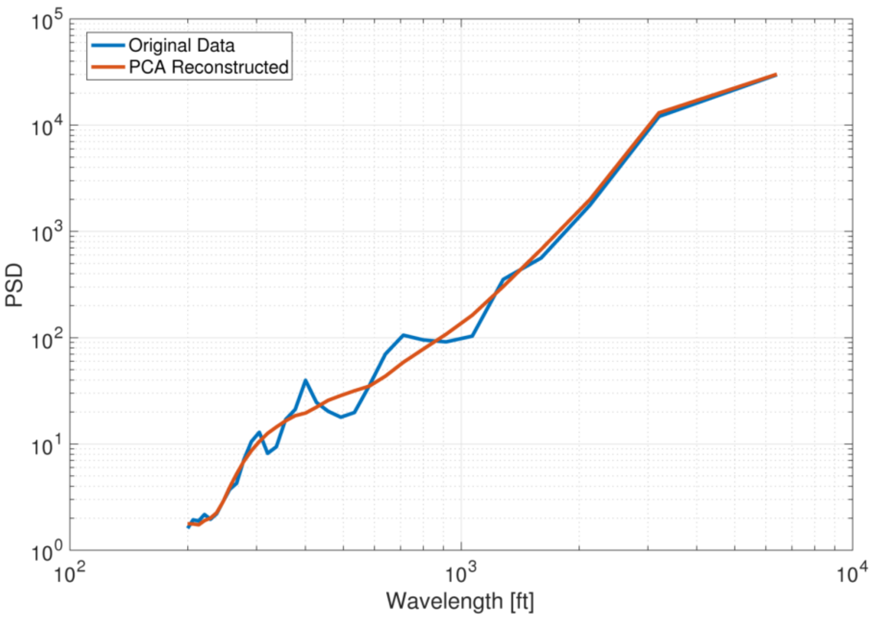
- Compute Singular Value Decomposition (SVD) of the centered data
- SVD determines the principal components and component directions



SCARF Filter

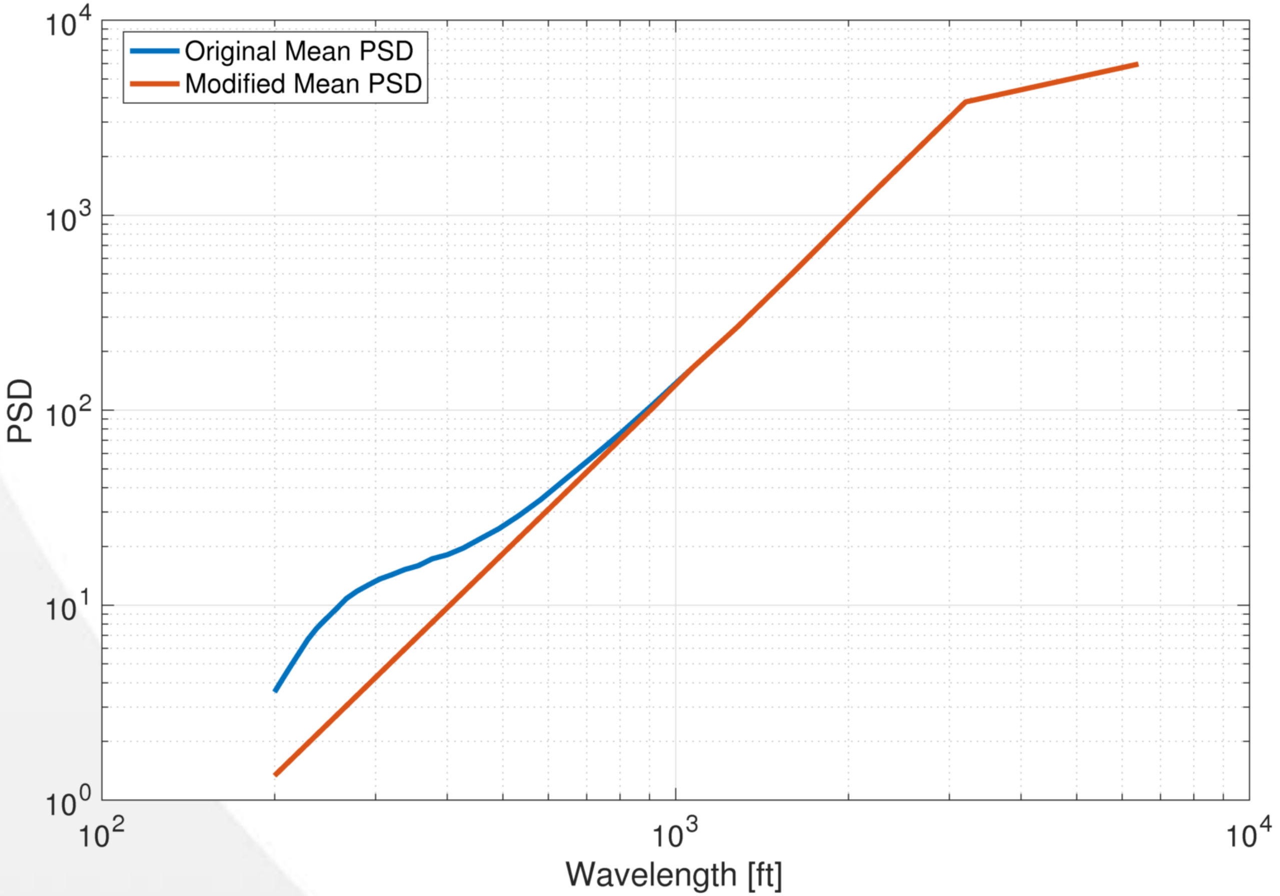
- Reconstruct the centered PSDs by using the first 7 principal components, and add back the mean PSD
- Note the reconstructed PSD is a smoother version of the original PSD
- This will be needed for developing transfer functions





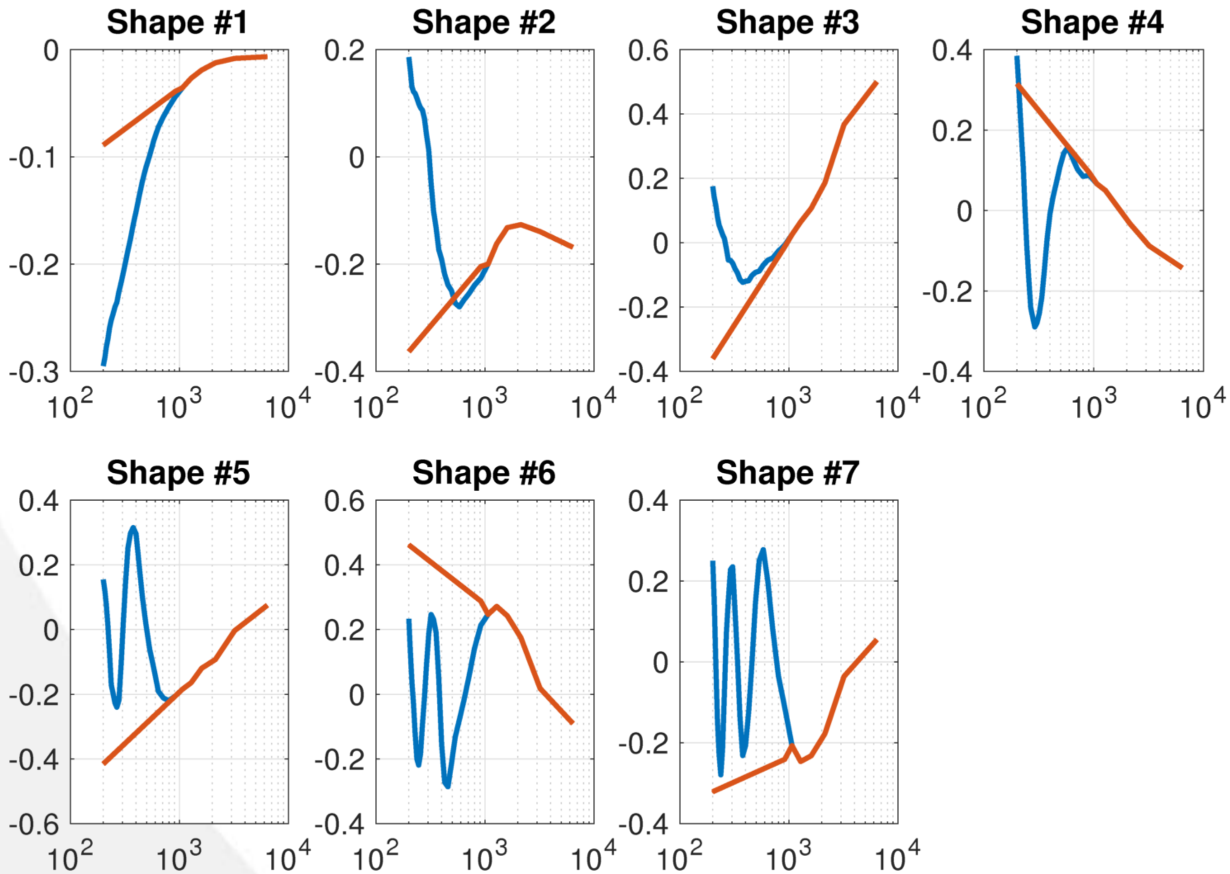
SCARF Filter

- **Modify the mean PSD between 200 and 1000 ft wavelengths, by extending the power law fit to the mean PSD for wavelengths between 1000 and 2500 ft**



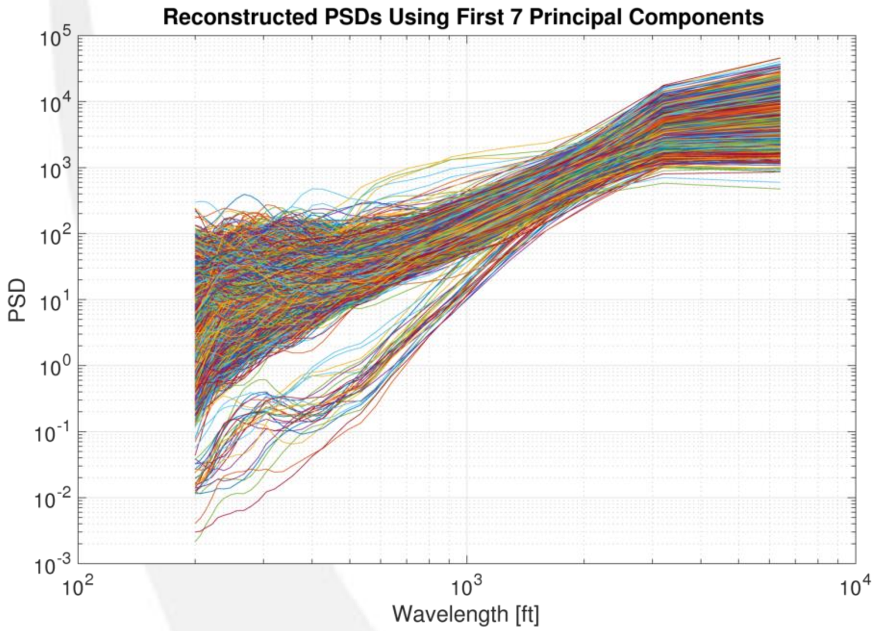
SCARF Filter

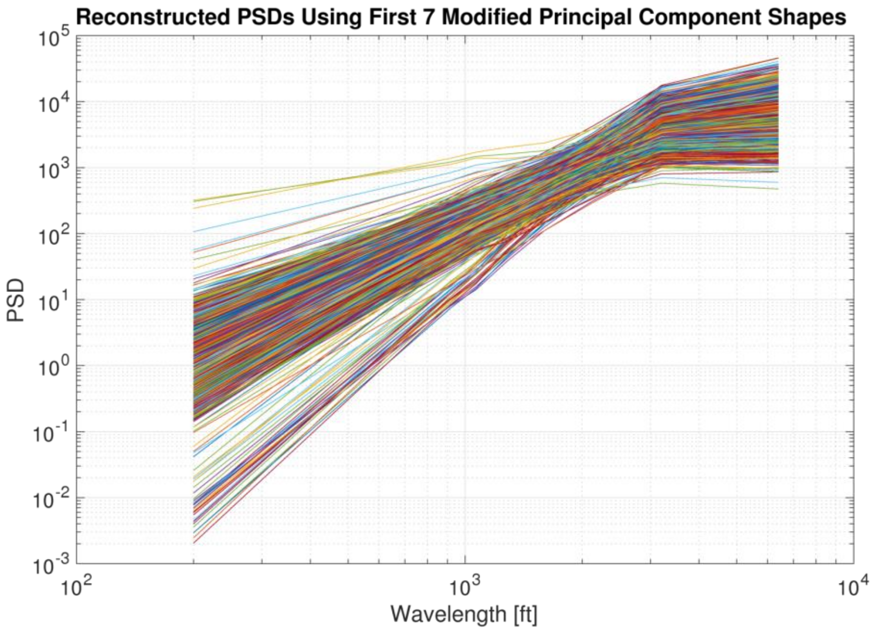
- **Modify the first 7 principal component shapes (directions) between 200 and 1000 ft wavelengths, by extending the best line fit to the component shape for wavelengths between 1000 and 2500 ft**



SCARF Filter

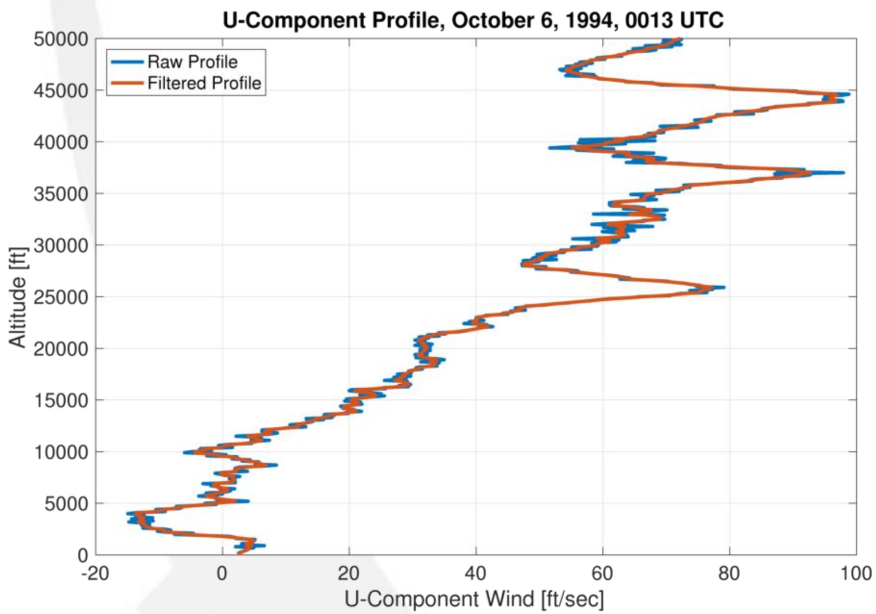
- **Reconstruct the centered PSDs using the modified component shapes, and add back the modified mean PSD**

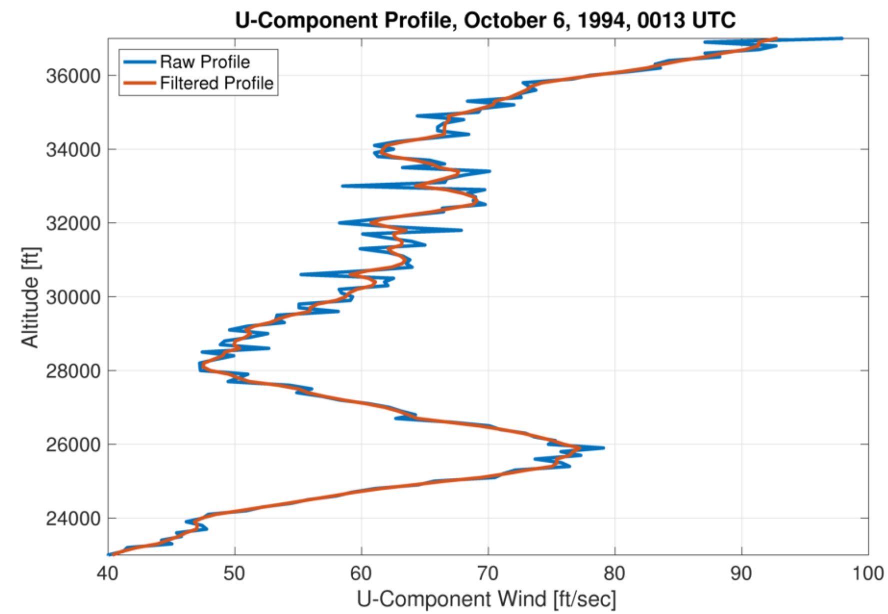




SCARF Filter

- Filter by convolving the impulse function with the wind profile
- Combine the lower and upper altitude blocks by using a cosine taper over the transition region (24.5 to 35.5 Kft)





Continuous Gust Functions

- U-component PSDs for continuous gust functions corresponding to 1, 2, 3, and 4 hour time deltas
- Vertical dashed lines represent Aerospace Corp persistence wavelengths
- Gust functions contain wavelengths between 200 ft (original Nyquist) and persistence wavelength