Dust Devil Heartbeat Detection on Infrasound Sensors

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Abstract

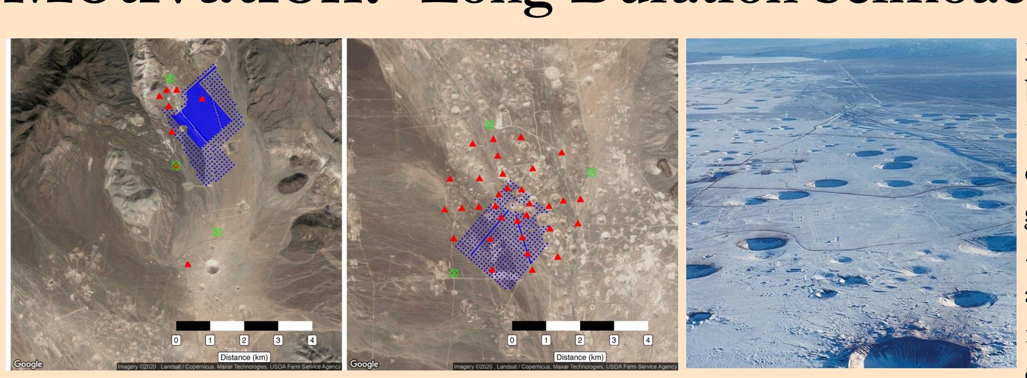
Particle-loaded convective vortices, or dust devils, are coherent, columnar shaped, fast rotating, dust-laden vortices at least one meter high and lasting for at least 10 seconds. These **vortices are created from heating of near-surface air by insolation and so are subject to boundary layer processes.** Dust devils consist of reduced pressure at their centers and are observed moving across pressure sensors as a pressure dip of varying duration (full-width at half maximum, FWHM) and amplitude, a function of dust devil radius and magnitude. These result in large, prominent signals on low frequency sound, or infrasound, stations.

However, **on raw infrasound data, this signal appears as a distinctly heartbeat shape due to convolution of the dust devil pressure dip and the instrument response.** We create a series of heartbeat templates spanning a variety of expected dust devil signals and, via **template-matching cross-correlation**, identify and characterize dust devils within infrasound time-series data. We statistically quantify the limitations and potential applications of this method to synthetic infrasound data and dust devils. Next, we apply this method to recorded infrasound data from multiple sensors in the Mojave desert in southern Nevada.

In addition, we develop an **empirical background noise model** for the Mojave desert infrasound sensors and test the capability of **wavelet transform-based methods** to differentiate dust devil signatures from background atmospheric variability.

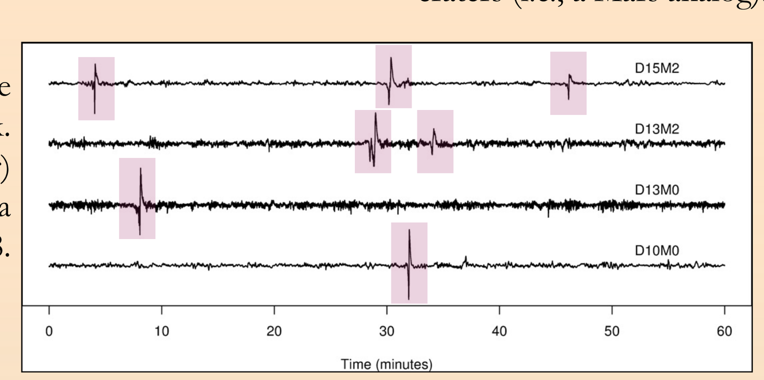
Not only is this of scientific interest in characterization of the planetary boundary layer, but it also has implications for the risk to life and property posed by these vortices. Furthermore, automatic dust devil detection may improve understanding of these signatures against instrument noise, and applicable to understanding the occurrence and variability of dust devils on Mars, which is answerable to several high-priority goals set forth by the Mars Exploration Program Analysis Group (MEPAG).

Motivation: Long Duration Seimoacoustic Record



32 microbarometers, 20 broadband seismometers, 100 geophones deployed over seven years (with some gaps), along with temporary 500-element geophone arrays. This site is one of the few places on Earth with craters (i.e., a Mars analog).

Dust devils create some the largest amplitude signals on the microbarometer network. Several are visible (highlighted in lavender) per station over this one hour snippet of data from Summer 2018.



Project Plan

Phase I: Develop Database of Vortex Detections across the study period
Process data from multiple years of microbarometer recordings
Develop & apply detection algorithms

Phase II: Quantify vortex occurrence patterns
Station variability, seasonal / diurnal cycles & topography

Phase III: Track discrete vortices
If dust devils emit detectable acoustic waves, can they be tracked across infrasound subarrays?
If dust devils emit detectable seismic waves, can they be tracked with a 'Large N' array of geophones?

Correlation Heartbeat Detector

Goal: Build a detector of the characteristic vortex heartbeat signal observed on Hyperion pressure sensors

Steps:
1. Build templates of synthetic vortex pressure signals as expected for Hyperion pressure sensors
2. Create algorithm and methodology to efficiently calculate the correlation coefficient between templates and data streams
3. Test robustness of correlation method on synthetics
4. Apply to a 6 hour period of recorded data across multiple sensors

Correlation Coefficient

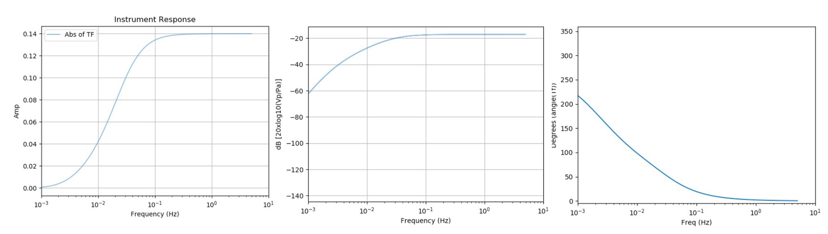
$$C_i(t) = \frac{x_i(t_0).y_i(t)}{\sqrt{x_i(t_0).x_i(t_0)}\sqrt{y_i(t).y_i(t)}}$$

Gibbons & Ringdal (2006)

1. Build templates of expected vortex pressure signals

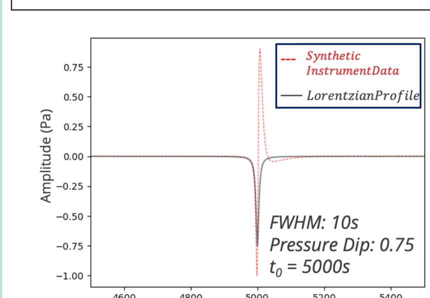
Hyperion Instrument Transfer Function — *Merchant (2015)*

$$H(f) = \frac{(f^3)}{(f-0.001483i)(f-0.003387i)(f-.02949i)}$$



Synthetic Dust Devil Vortex for Hyperion Sensors

$$SyntheticInstrumentData(f) = LorentzianProfile(f)\ H(f)$$



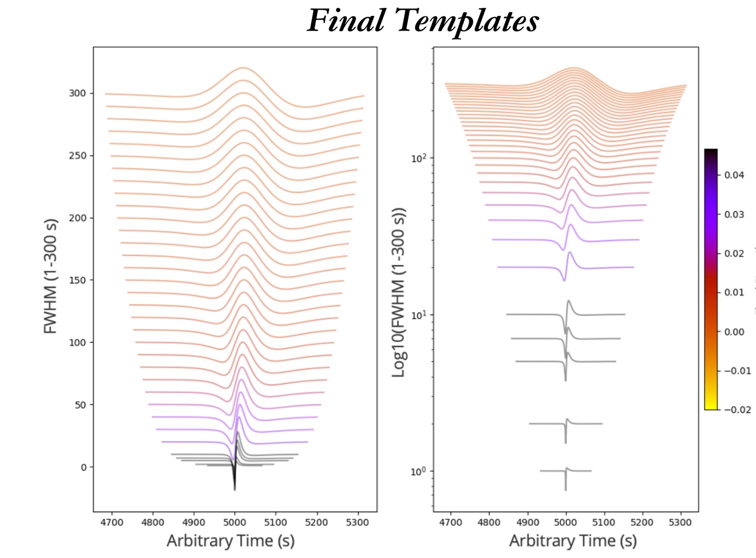
Example of a dust devil as calculated to be observed by a Hyperion sensor, using the above formula. The synthetic dust devil has a pressure dip of 0.75 Pa, FWHM of 10 s, and is centered at 5000s. The predicted signal on the Hyperion sensor has the characteristic heartbeat shape.

Synthetic Dust Devil Vortex — *Jackson & Lorenz (2015)*

$$LorentzianProfile(t) = -\frac{PressureDip}{1+(2(t-t_0)/FWHM)^2} + B$$

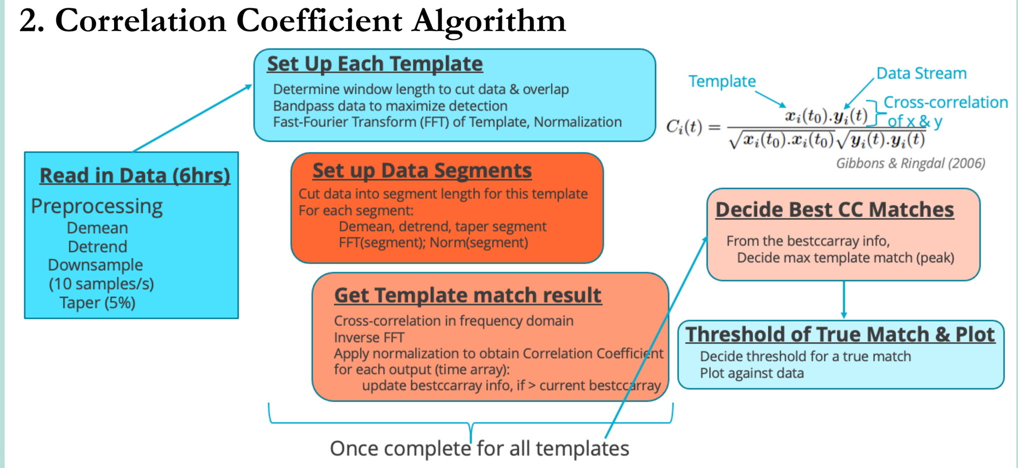
FWHM: Full-Width Half Maximum; t_0 = Time of max dip

Final Templates



As the correlation coefficient is sensitive to the phase (not amplitude) of the signal, our templates are created via a range of FWHM, which alters the shape.
We note that the signal strength is much lower for FWHM > approximately 100 s.

2. Correlation Coefficient Algorithm

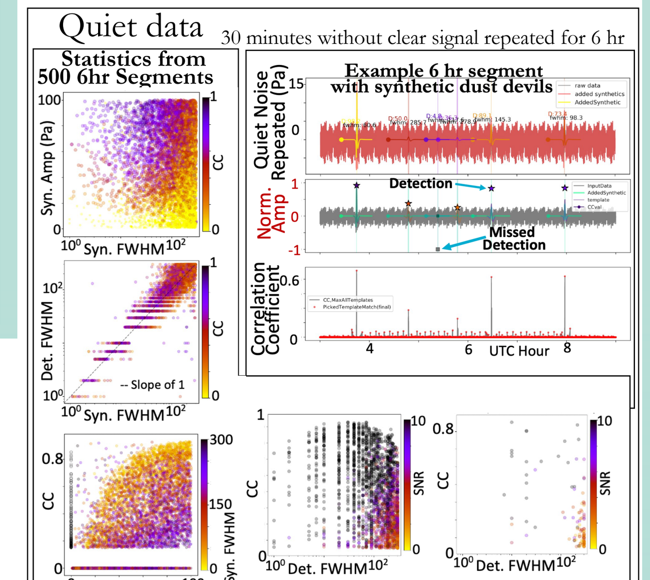


3. Synthetic Tests

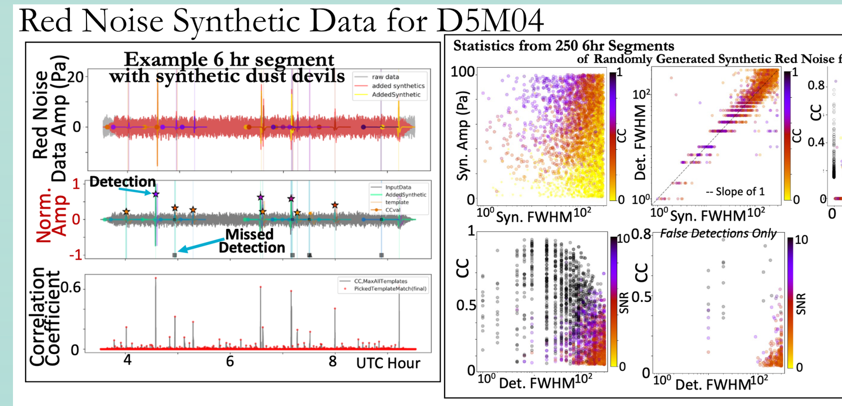
Set up Empty 'Data'
'Quiet' data (500 6 hr Segments)
Red Noise (250 6 hr Segments)

Statistics for Seeding
6-25 Dust Devil Events per 6 hr segment
For each event, randomly determine:
Dip (1-100 Pa)
FWHM (1-300 s)
Time inserted into 6hr segment

Quiet data — 30 minutes without clear signal repeated for 6 hr

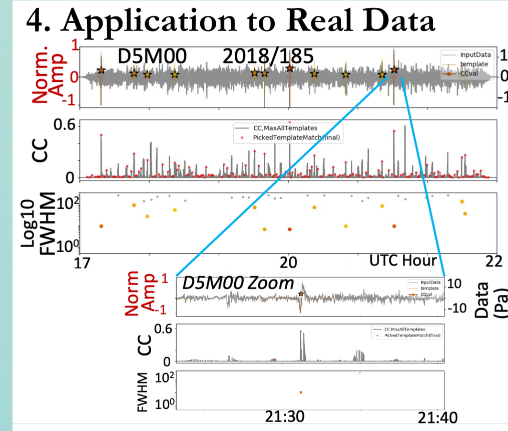


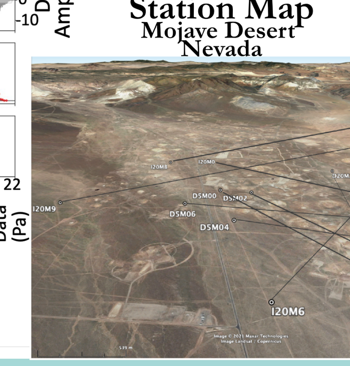
Red Noise Synthetic Data for D5M04

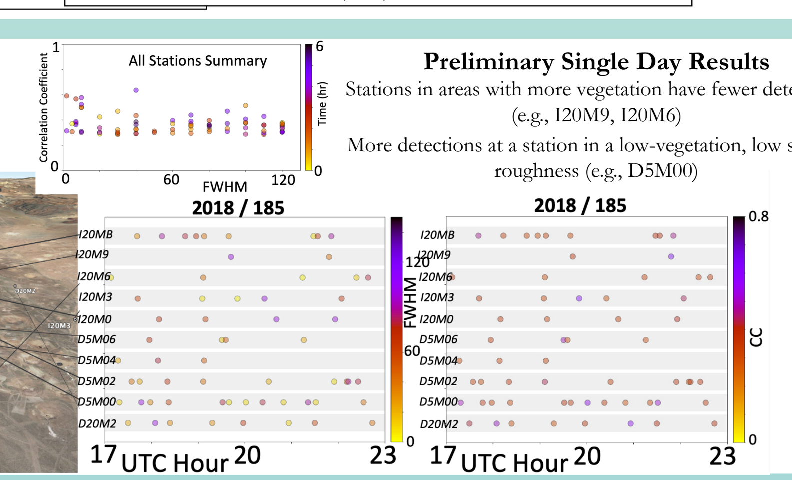


Quiet Data & Red Noise Synthetic Test Findings
Synthetic Matches Detected FWHM
Higher CC for larger amplitude, lower FWHM (<100 s)
Few false detections, majority clustered > 100 s FWHM

4. Application to Real Data







Preliminary Single Day Results
Stations in areas with more vegetation have fewer detections (e.g., I20M9, I20M6)
More detections at a station in a low-vegetation, low surface roughness (e.g., D5M00)

Wavelet Detector

Goal: Distinguish peaks due to dust devils from background noise via wavelets

Methodology

χ^2 statistical significance testing of wavelet power at time index n and scaling s, $|W_n(s)|^2$ to detect dust devils:

$$\frac{|W_n(s)|^2}{\sigma^2 P_k} \rightarrow \frac{\chi_2^2}{2}$$

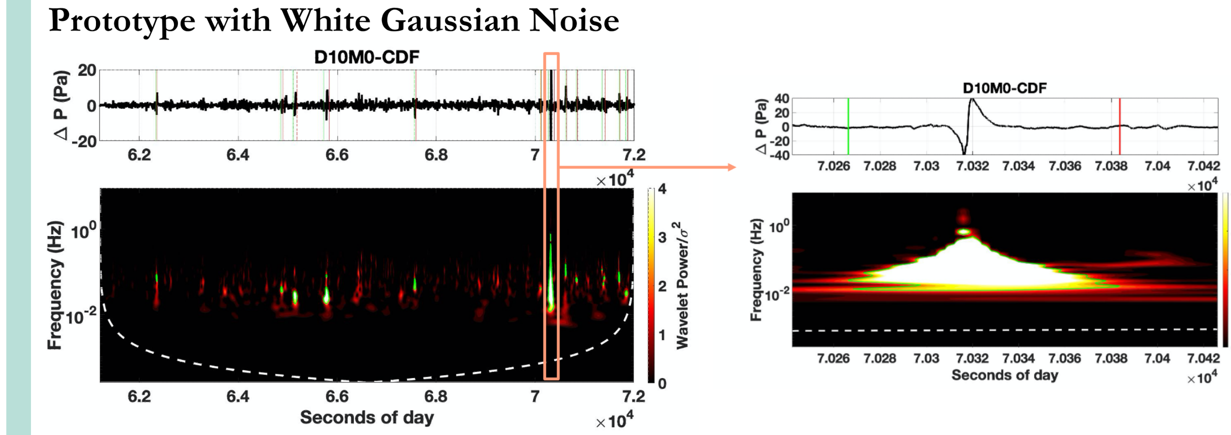
Torrence and Compo (1997)

where P_k is noise power in the k^{th} frequency bin and σ^2 is the signal variance

Processing

1. Decimate time series from 1000 Hz to 25 Hz sampling rate through a 2-stage decimation process. Final filter cutoff is 10 Hz.
2. Window the signal into chunks (~ few hours)
3. Generate wavelet coefficients using continuous wavelet transform with Morlet wavelets
4. Compute outlier-removed variance of the signal and noise power spectrum for normalization of wavelet power
5. Compare normalized wavelet power with values of $\chi_2^2(1-\alpha)$, with α as the required confidence interval.
6. Mark start and end times of regions that have normalized wavelet power greater than $\frac{1}{2}\chi_2^2(1-\alpha)$

Prototype with White Gaussian Noise



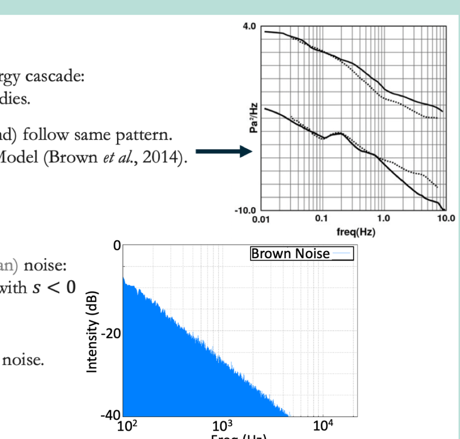
- GWN has flat frequency spectrum $\Longrightarrow P_k = 1\ \forall k$
- Sample 3-hour window (takes a few seconds on a laptop)
- Type-I and Type-II error rate needs to be characterized
- More representative background noise model is needed

Red Noise Empirical Modeling

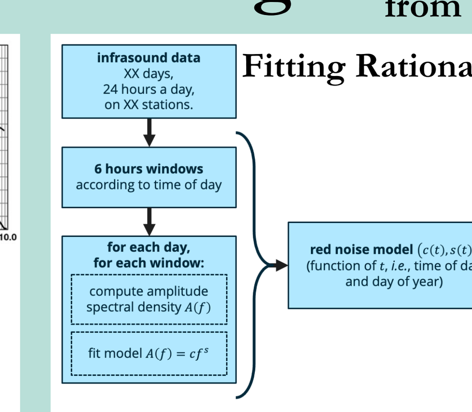
Goal: Determine background noise model from stations spanning multiple years

Methodology

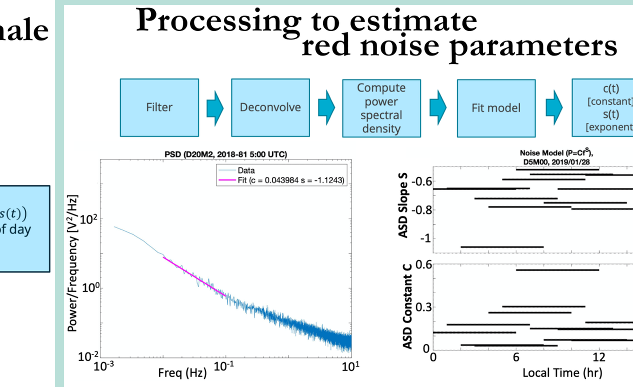
- Atmospheric dynamics follows energy cascade: larger eddies dissipate to smaller eddies.
- Pressure fluctuations (*e.g.*, infrasound) follow same pattern. See IDC Global Infrasonic Noise Model (Brown *et al.*, 2014).
- Red (AKA pink, brown, or Brownian) noise: power spectral density $P(f) \propto f^s$ with $s < 0$
- $\Rightarrow$ model experimental noise as red noise.



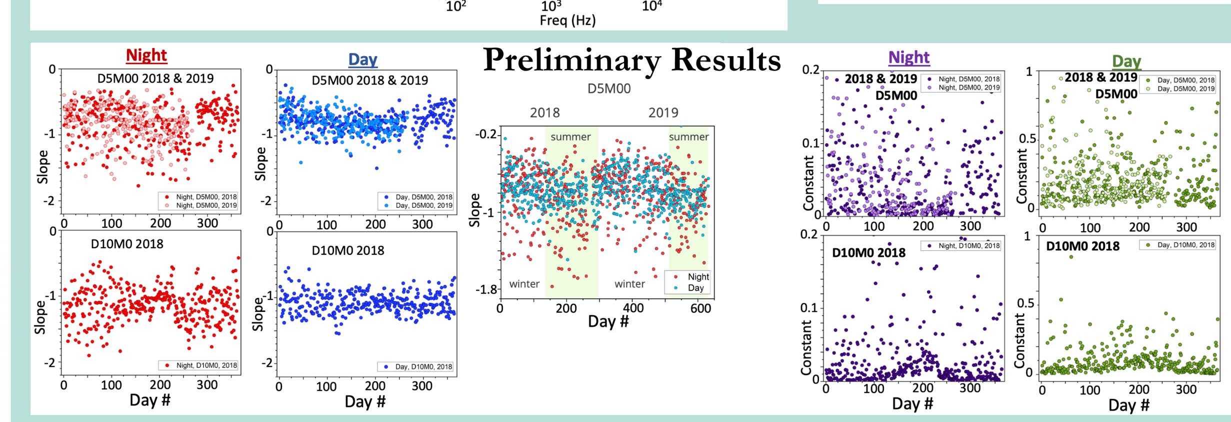
Fitting Rationale



Processing to estimate red noise parameters



Preliminary Results



Key Findings

Larger variation of slope values during night hours in comparison to day

Lower absolute slope values a winter, although strong distribution, than summer

Constant at night lower values than during the day

Constant also sees range of values that will be investigated moving forward

Conclusions

Promising results from the correlation detector, will be extended to more stations across greater number of days
Wavelet detector also shows potential from initial white Gaussian noise application
Red noise empirical modeling suggests atmospheric complexities that will be investigated

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