Atmospheric Noise Removal for FYST: Current Methods and ML Prospects

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A novel sub-mm telescope: 2025

The Fred Young Submillimeter Telescope (FYST): wide-field, 6-m aperture sub-mm telescope.

Site location: at 5600 meters on Cerro Chajnantor in northern Chile.

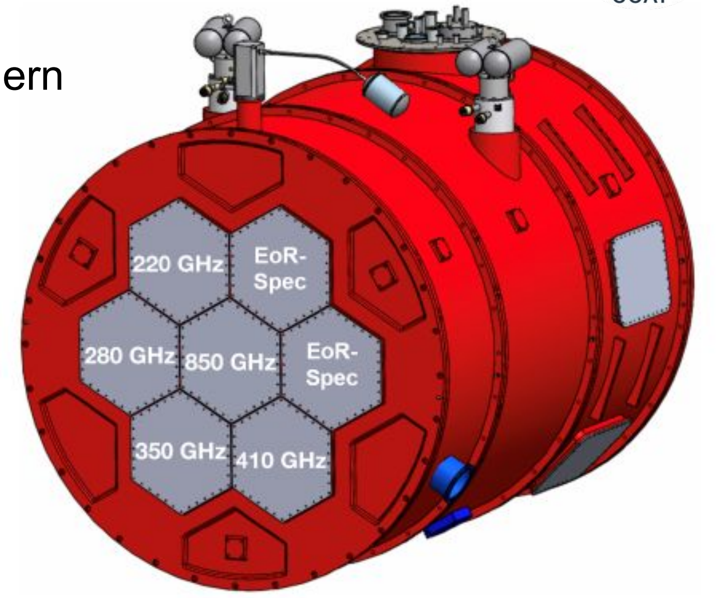
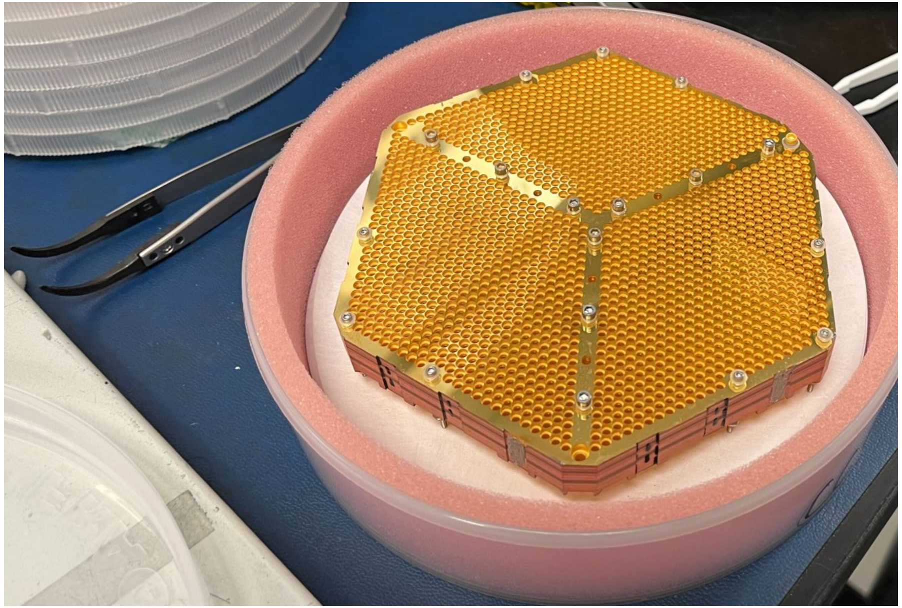
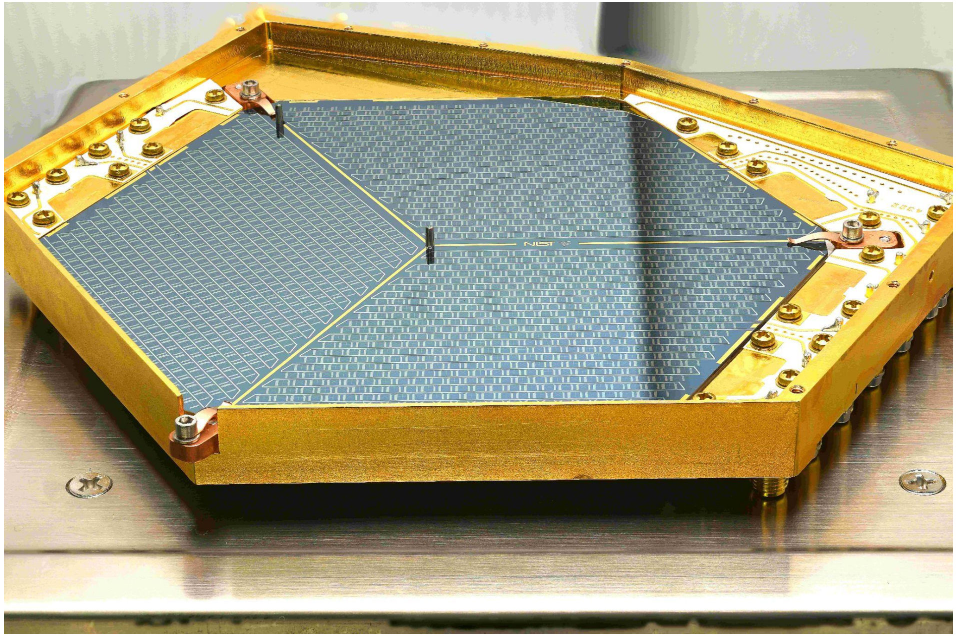


Fig above: FYST model at Cerro Chajnantor (www.ccatobservatory.org)
Fig below: Prime-Cam instrument design with the seven instrument modules (Vavagiakis+2018)

Under development : FYST Detector Arrays

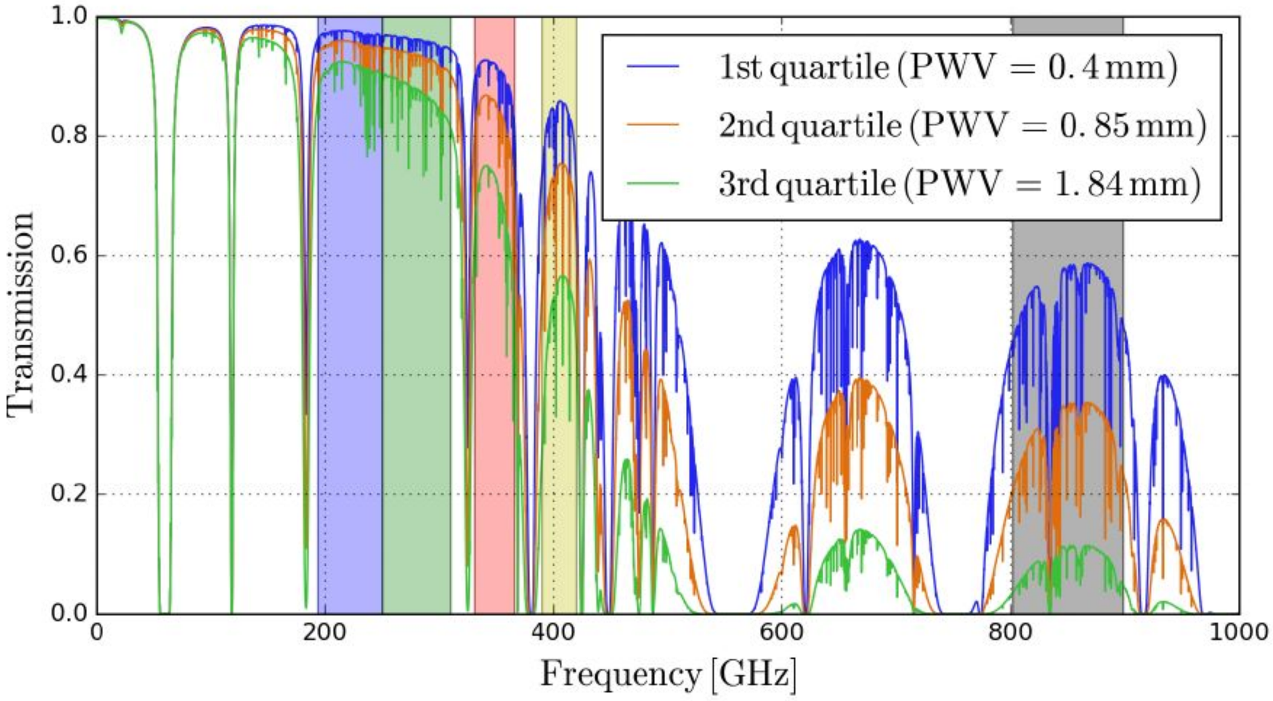




~ 3500 detectors per array times x3 ;
400Hz sampling rate
⇒ Big data volume

Fig Credit: Silicon feedhorn package, and 280GHz aluminum array (Cody Duell, Jordan Wheeler)

Correlated Atmospheric Noise is a Challenge



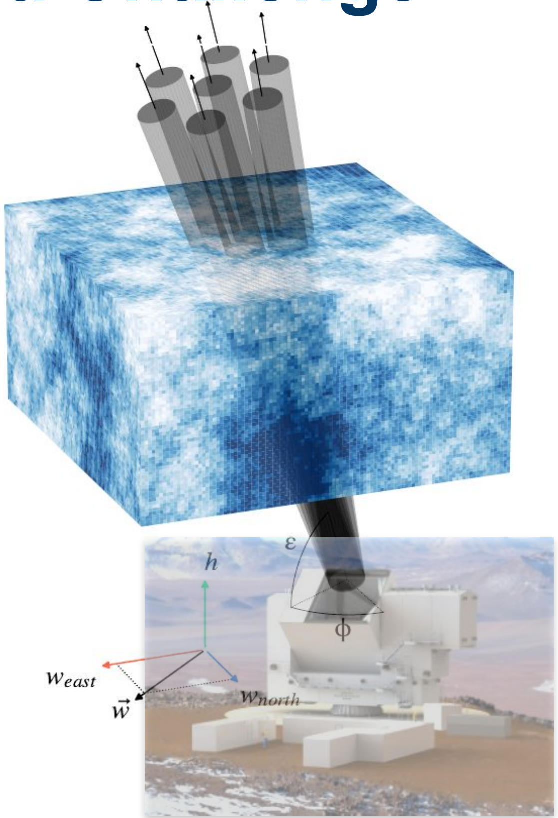


Fig left: Atmospheric transmission spectra for FYST Site (Choi et al 2020)

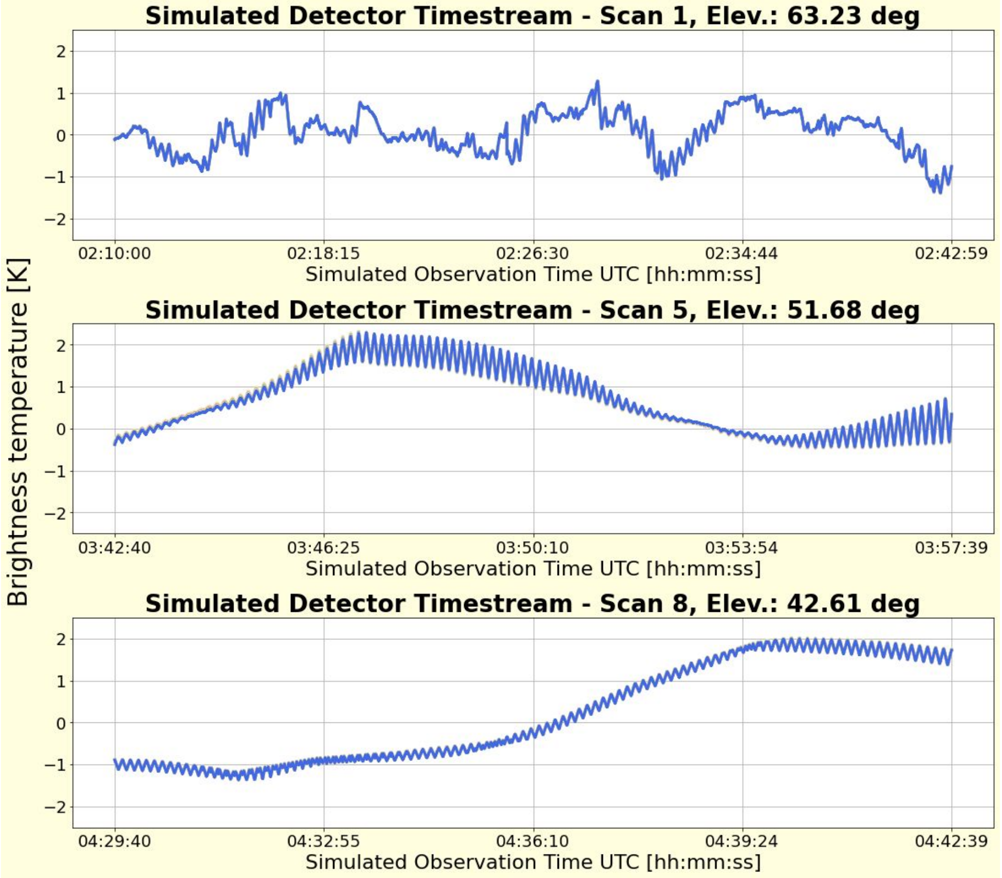
Fig right: Array of detectors observing through inhomogeneous atmosphere (Morris+2022) ; Adapted with FYST model

Goal: Removing low-frequency Correlated Noise

We want to remove the correlated noise component, while retaining the underlying cosmological signal

$$d_v(t) = \langle d_v \rangle P_{cel}\, \Delta s^v_{science} + n_{white}(t) + n_{corr}(t)$$

Detector Timestreams / Time-ordered Data (TOD)



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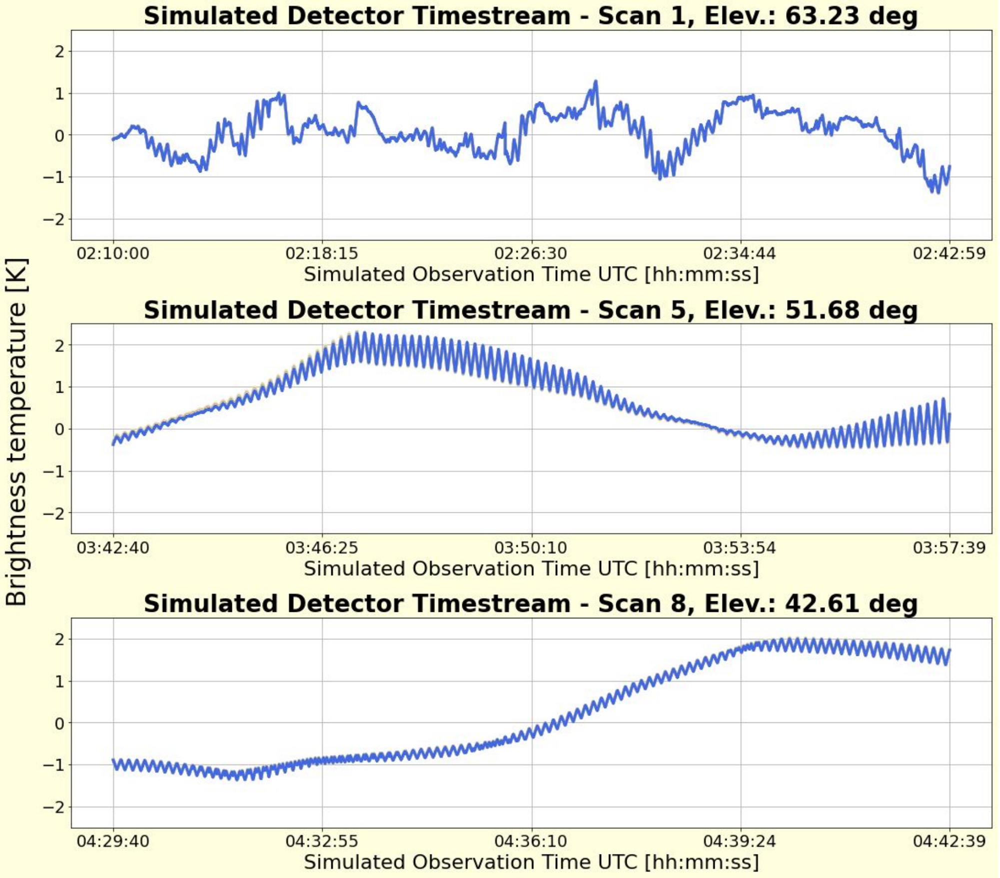

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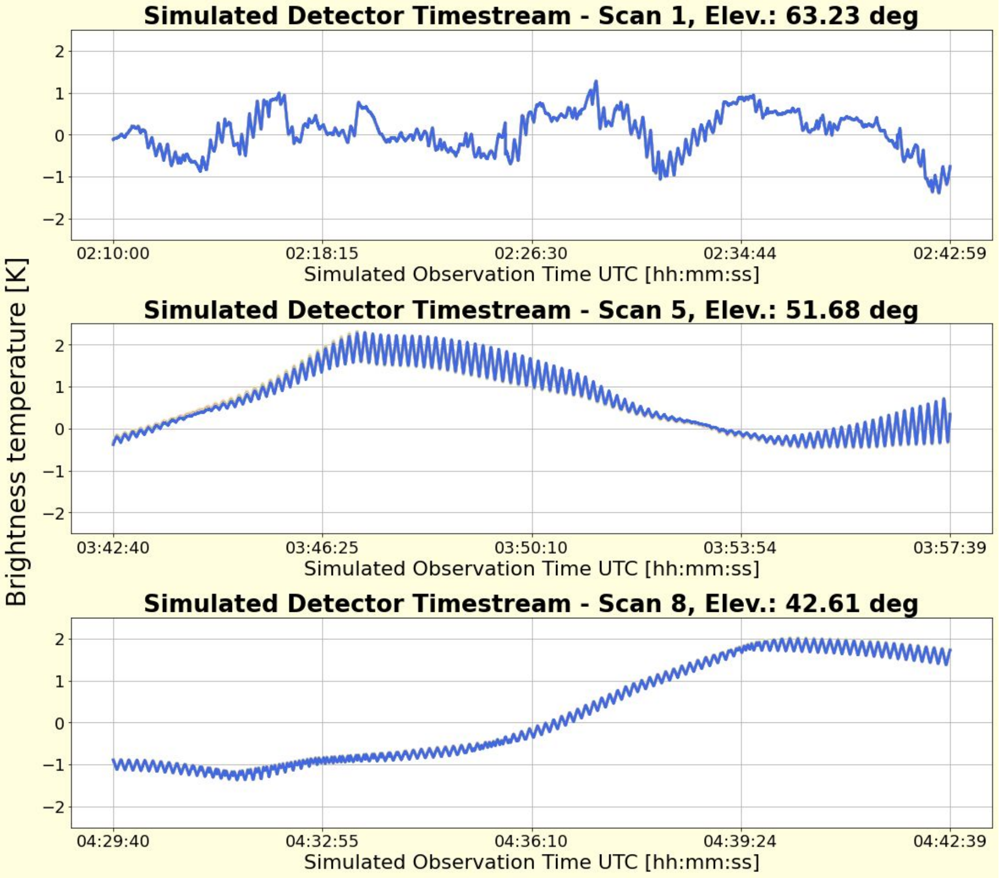
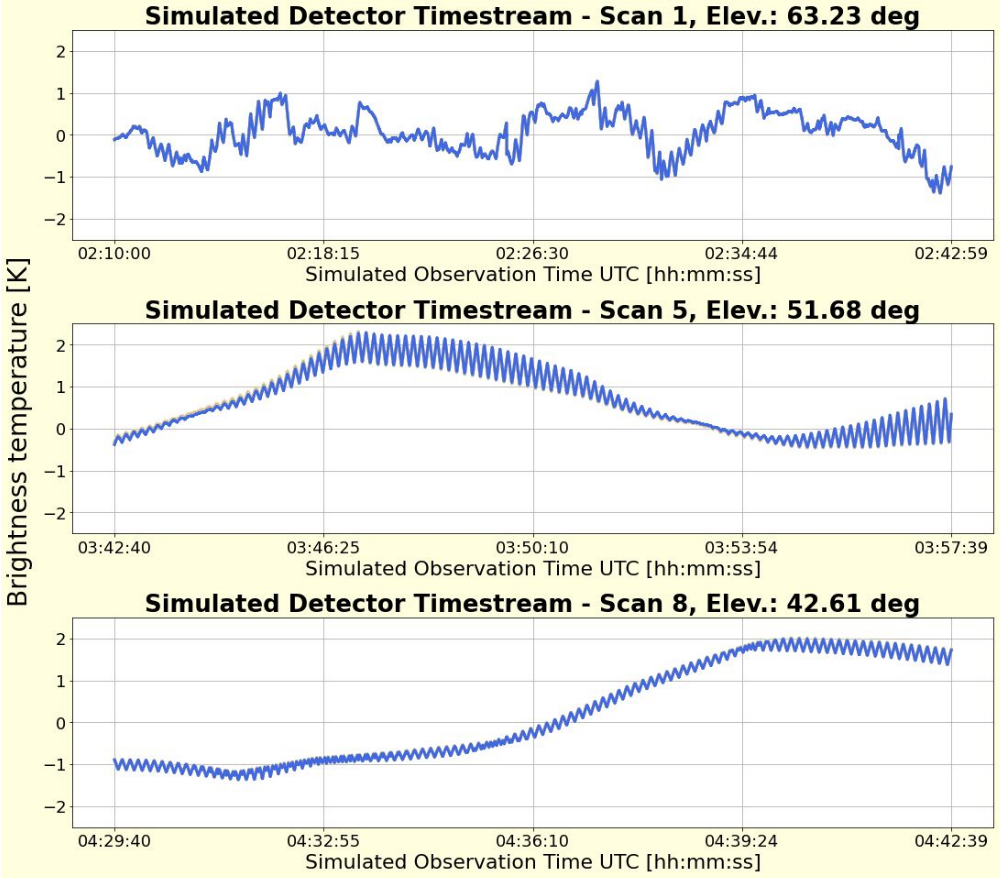


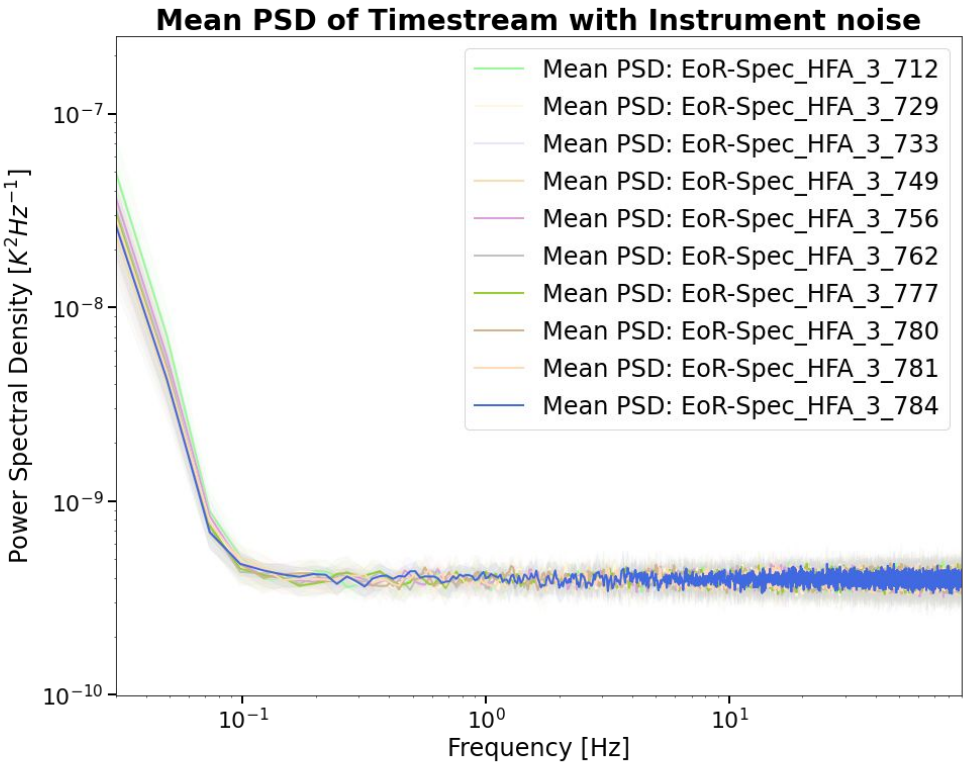
Goal: Removing low-frequency Correlated Noise

We want to remove the correlated noise component, while retaining the underlying cosmological signal

Data reduction includes:

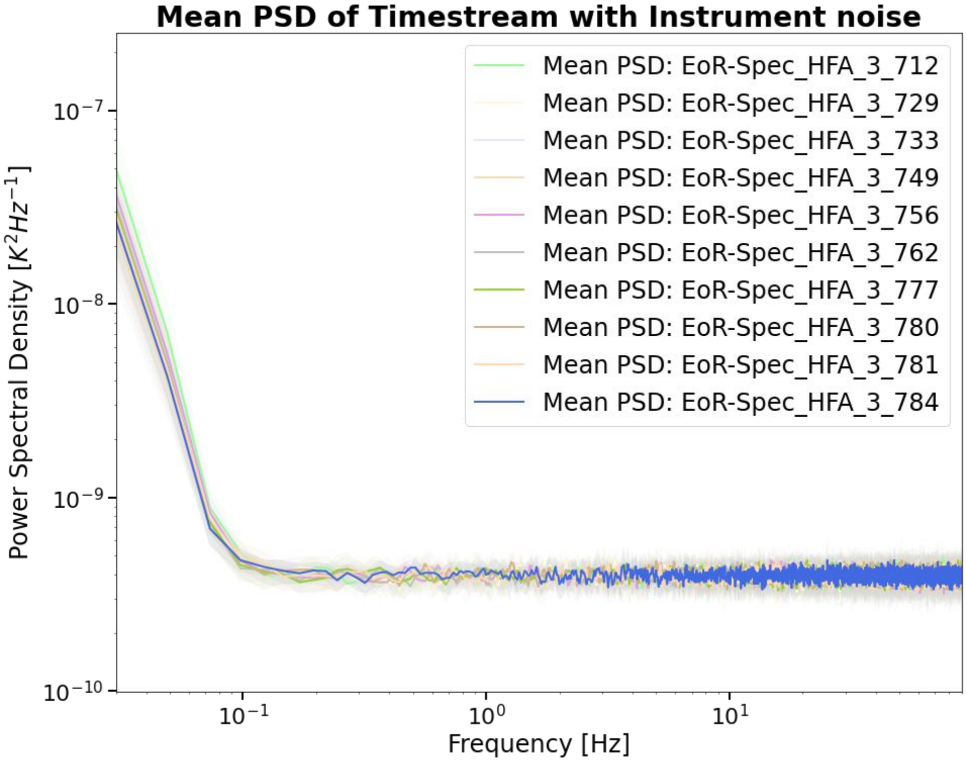
- Data selection
- Detrending
- Filtering : Polynomial and Fourier space
- Principal Component Analysis (PCA)
- Flagging operations
- Map-making from Timestream

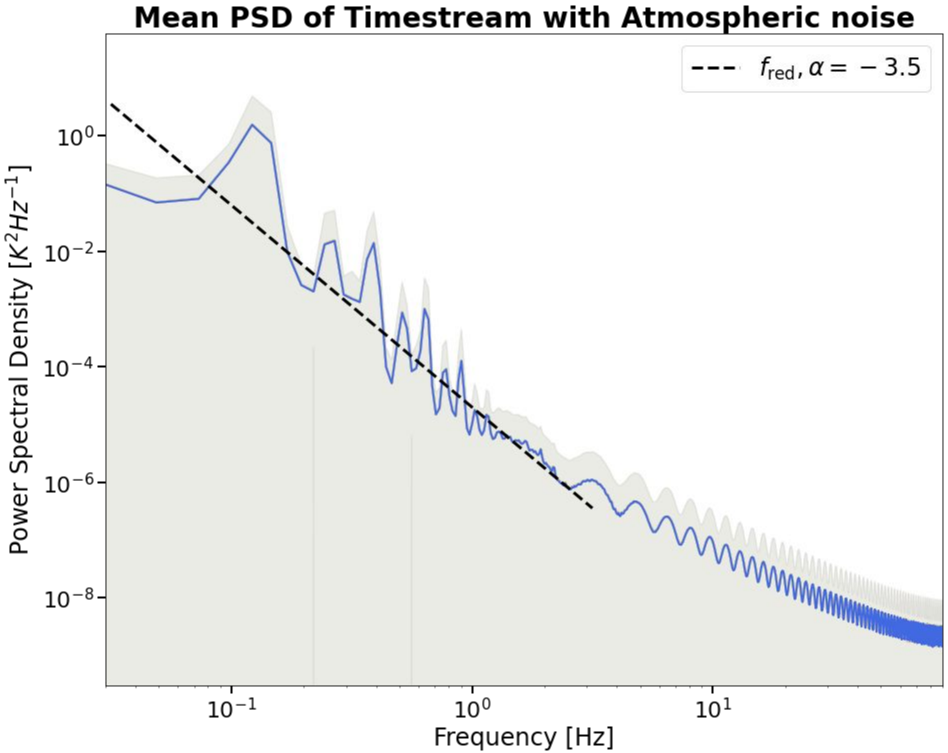



Mean PSD of Timestream with Instrument noise
Mean PSD: EoR-Spec_HFA_3_712
Mean PSD: EoR-Spec_HFA_3_729
Mean PSD: EoR-Spec_HFA_3_733
Mean PSD: EoR-Spec_HFA_3_749
Mean PSD: EoR-Spec_HFA_3_756
Mean PSD: EoR-Spec_HFA_3_762
Mean PSD: EoR-Spec_HFA_3_777
Mean PSD: EoR-Spec_HFA_3_780
Mean PSD: EoR-Spec_HFA_3_781
Mean PSD: EoR-Spec_HFA_3_784
Power Spectral Density [$K^2 Hz^{-1}$]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-1}
10^{0}
10^{1}
Frequency [Hz]

Power Spectral Density: Atmosphere introduces 1/f Noise

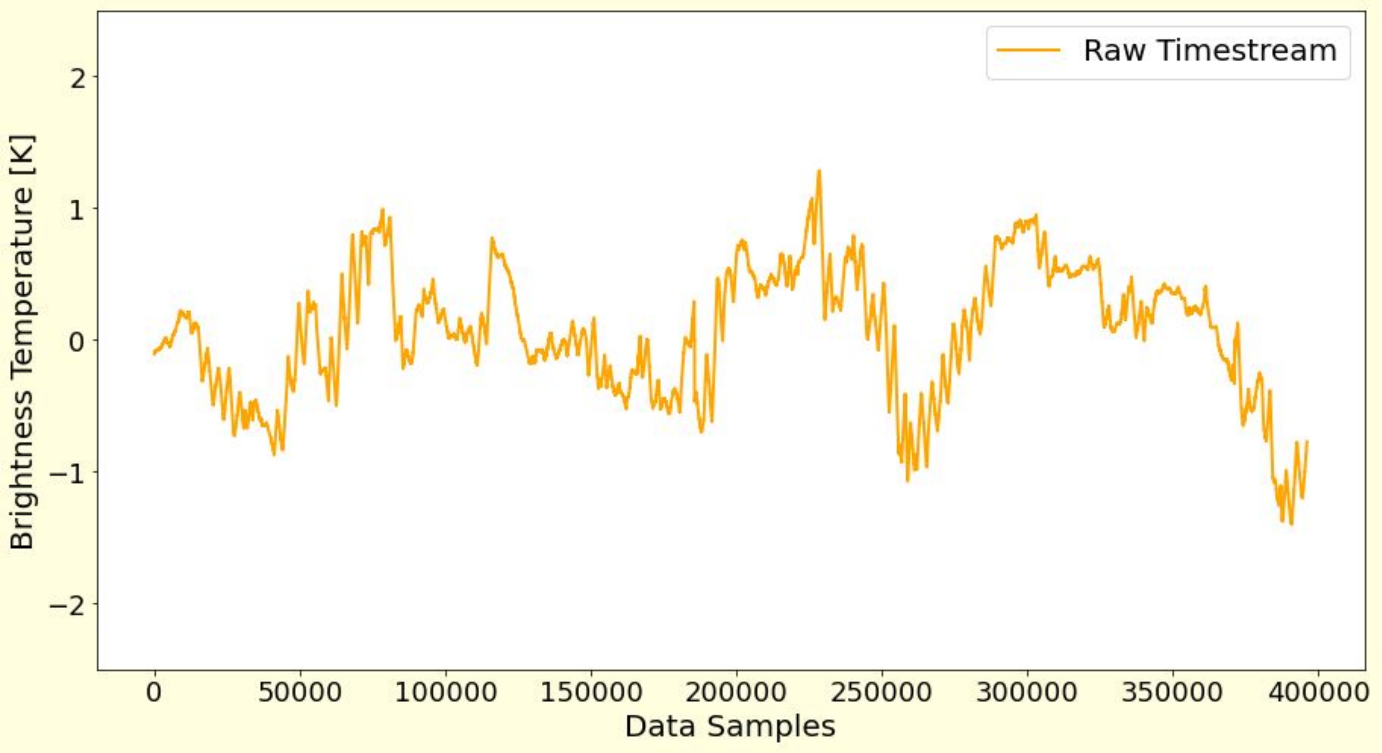
$$N(f) = \sigma_0^2 \left(1 + \left(\frac{f}{f_{\text{knee}}}\right)^{\alpha}\right)$$

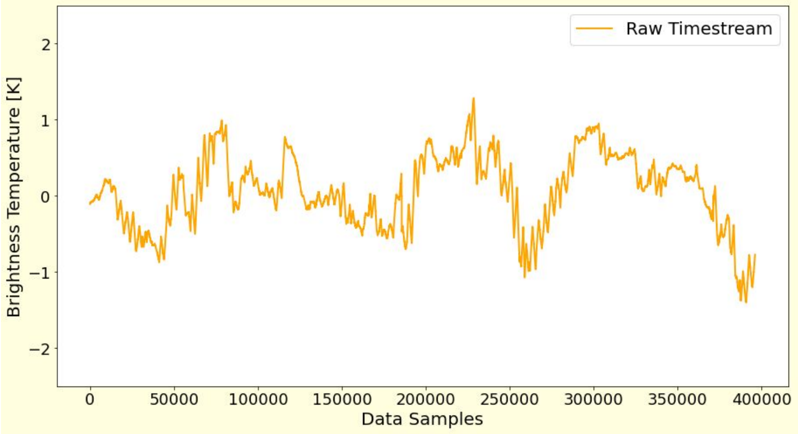




Data-processing for removing Atmospheric Noise

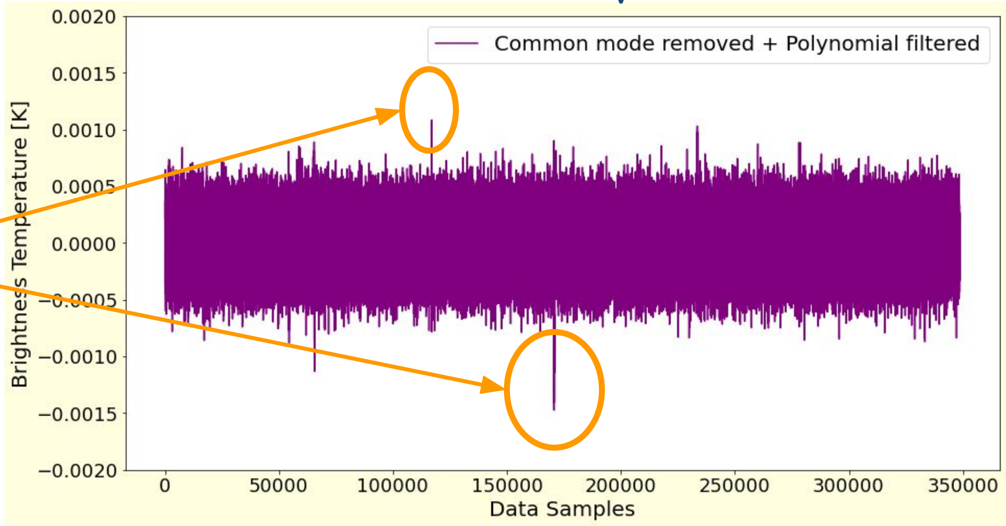
Data:
Detector timestream to be processed for removing trends





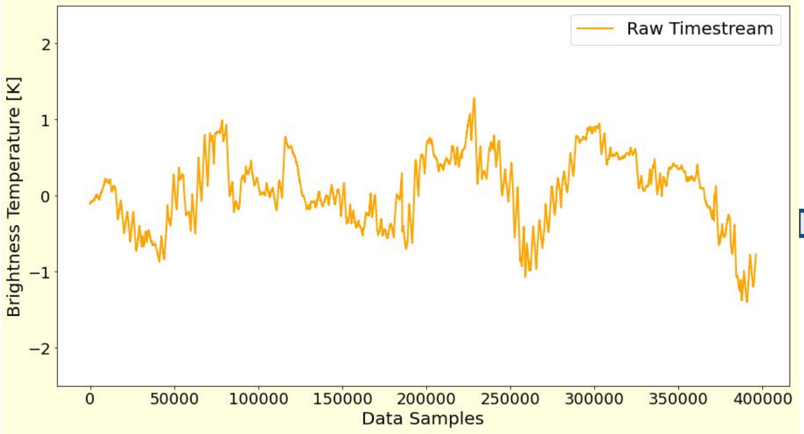
Step 1: Common mode removed from all detectors

Step 2: 0th Order Polynomial subtracted



Few data-samples are poorly behaved

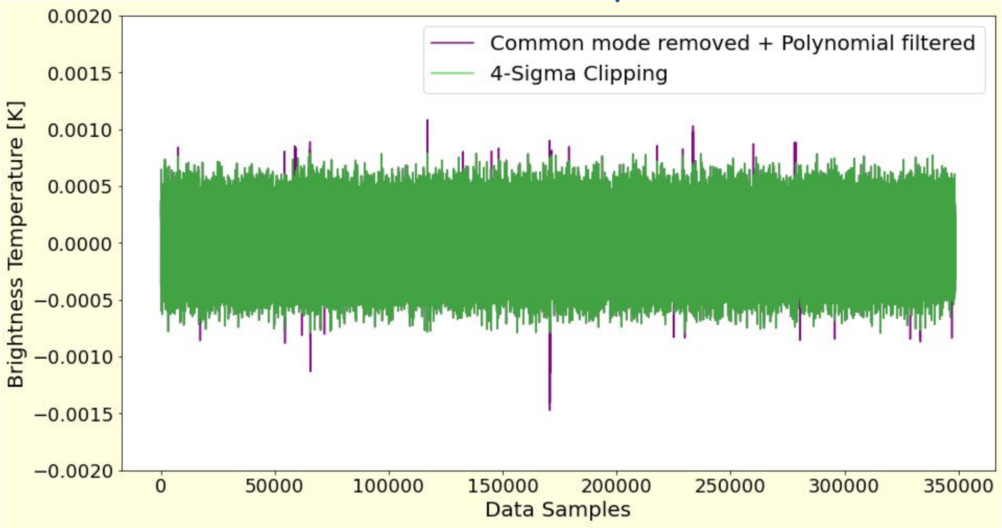
Time-domain analysis



Step 1: Common mode removed from all detectors

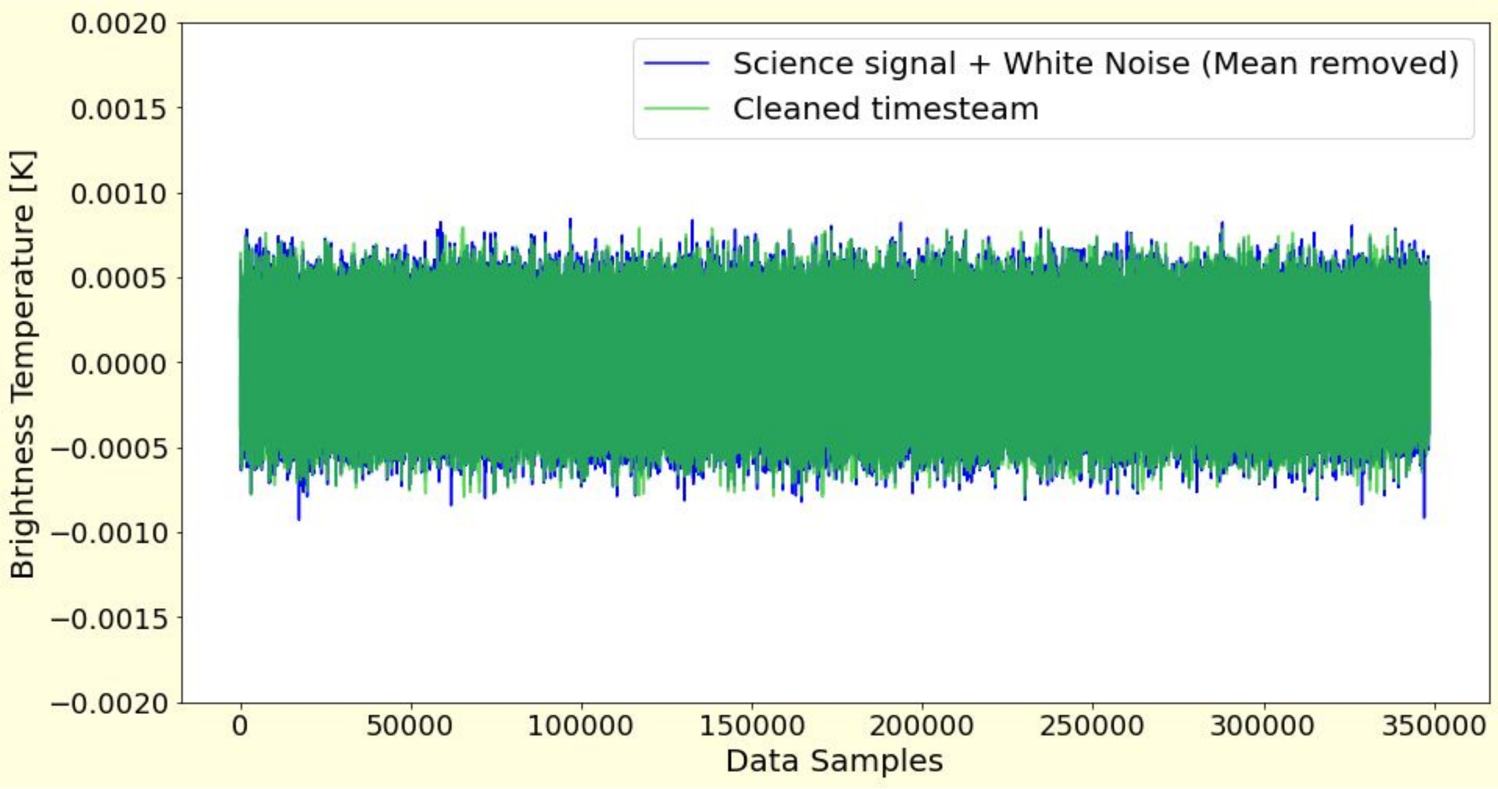
Step 2: 0^{th} Order Polynomial subtracted

Step 3: Excluding extreme statistical outliers (4-sigma clip)

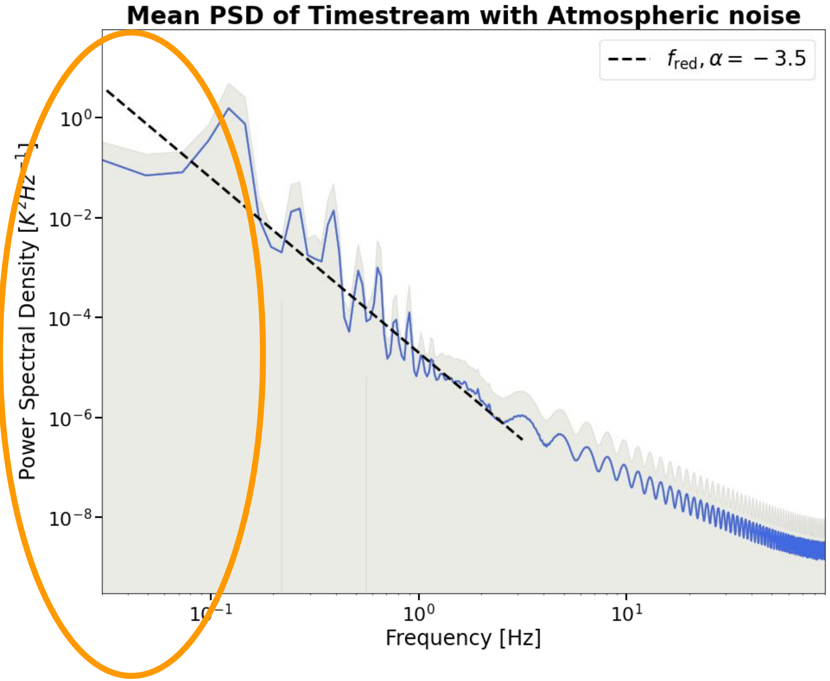


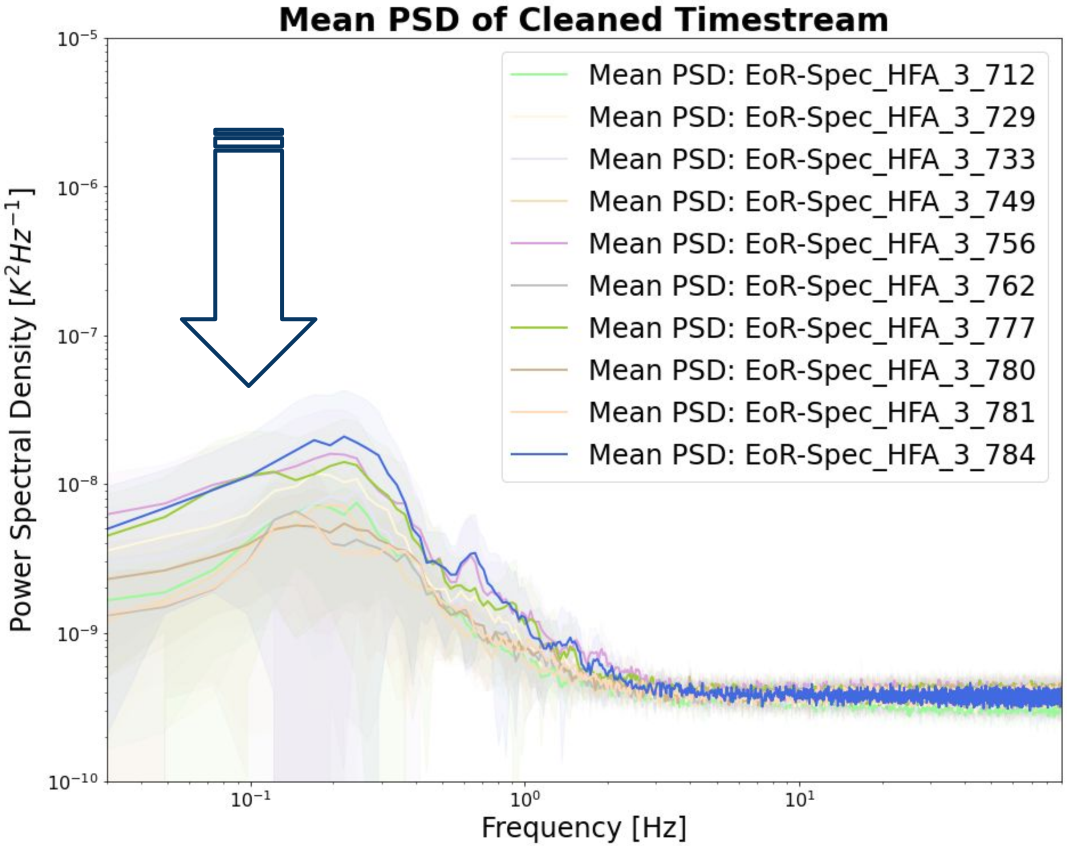
Time-domain analysis

Timestream Cleaned to White Noise Level



Power Spectral Density Comparison of Cleaned Timestream





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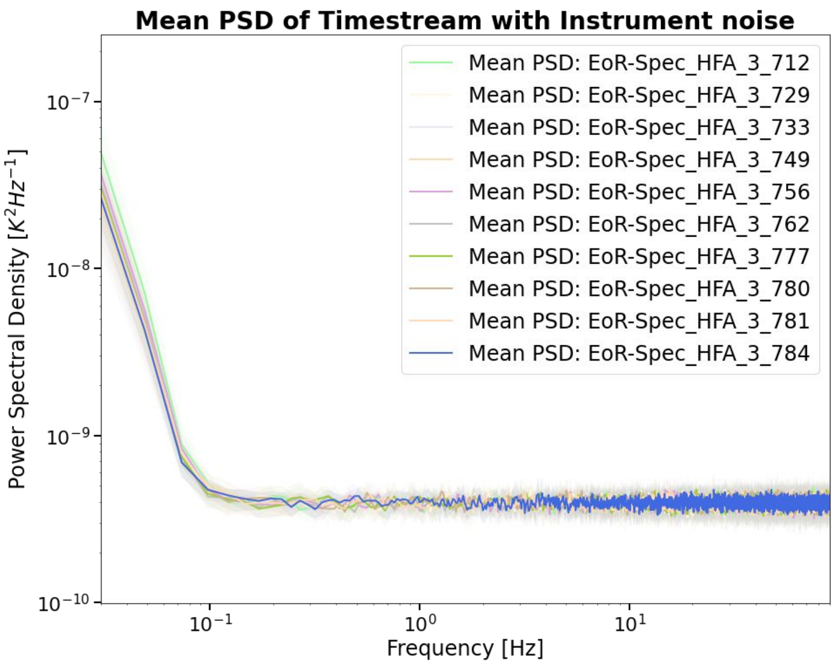

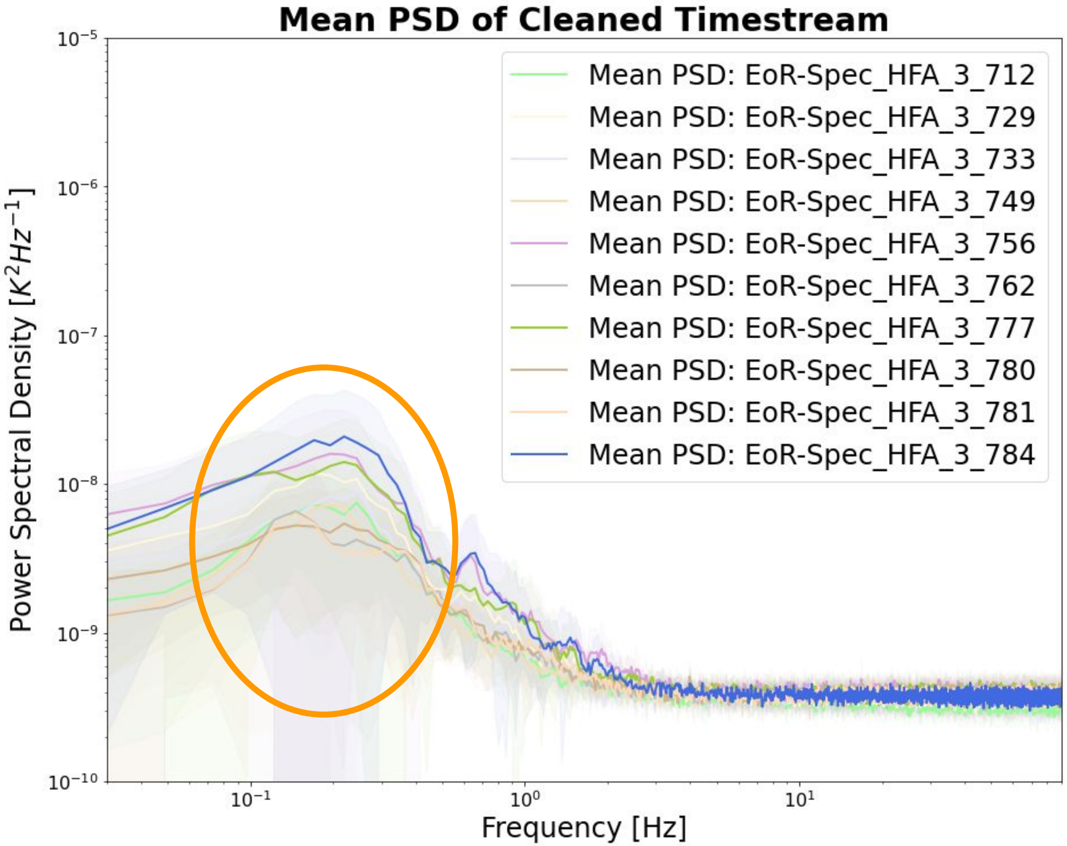

Can ML methods contribute to current data reduction techniques?

- Convolutional Neural Networks (CNNs)
  - Layered, hierarchical architectures for spatial/temporal pattern recognition.
  - Adaptability in identifying and reducing diverse noise components through encoding-decoding structures.
- Gaussian Process Regression (GPR)
  - non-parametric, Bayesian approach to model and predict time-series data.
  - modeling complex noise structures
- Monitoring Data Quality
  - Outlier Detection: Leveraging ML for identification of anomalies in detector timestreams.
  - Data Selection and Cuts

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