Extracting the Global 21-cm Signal

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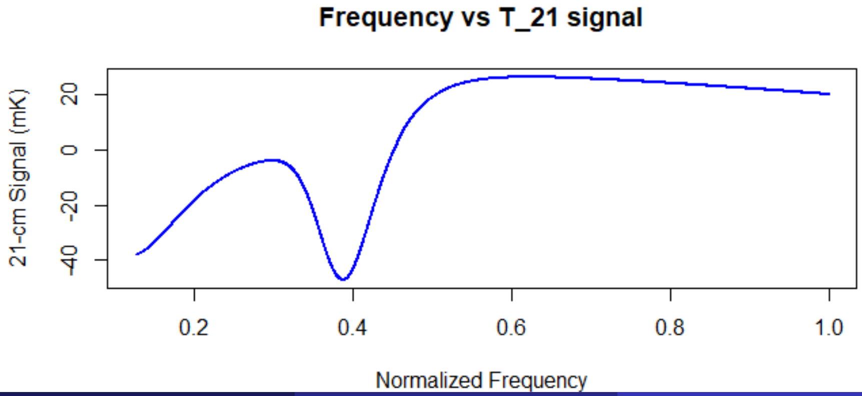
Motivation

- Detecting the redshifted H_I 21-cm emission during the Cosmic Dawn and Epoch of Reionization.
- Major challenge: Separating the faint 21-cm signal from strong foregrounds and ionospheric noise.
- Objective: Exploring nonparametric methods like GP and trendfiltering to extract the 21-cm signal from simulated sky average data.
- Just for comparison: Average SNR (signal against noise) $= 17.890$, while Average SNR (signal against T_{fg}) $= -107.73$ (in logarithmic scale).

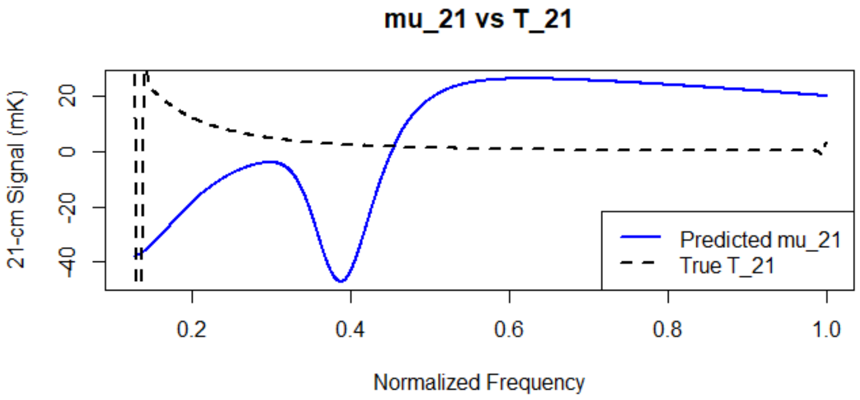
Simulation Setup

- Based on [Tripathi et al., 2024], using tanh parameterization and ARES algorithm.
- Generated 1000 samples: T_{21} (signal), T_{fg} (foreground), and noise over 1024 frequency channels.
- Assumed perfect instrument.



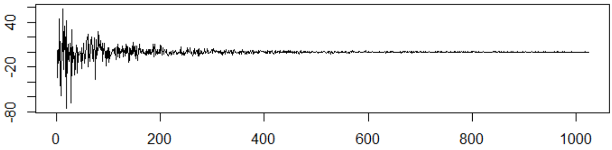
Gaussian Process Regression (Homoscedastic Noise)

- Used Matern kernels for both foreground and signal:
  - $\nu_{fg} = 1.5$, $\ell_{fg} = 0.03$
  - $\nu_{21} = 0.5$, $\ell_{21} = 0.0024$
- Posterior mean for T_{21} estimated via marginal likelihood optimization.



Transformed Model

- Noise variance assumed proportional to foreground: $\mathrm{Var}(\epsilon(\nu)) \propto T_{fg}(\nu)^2$



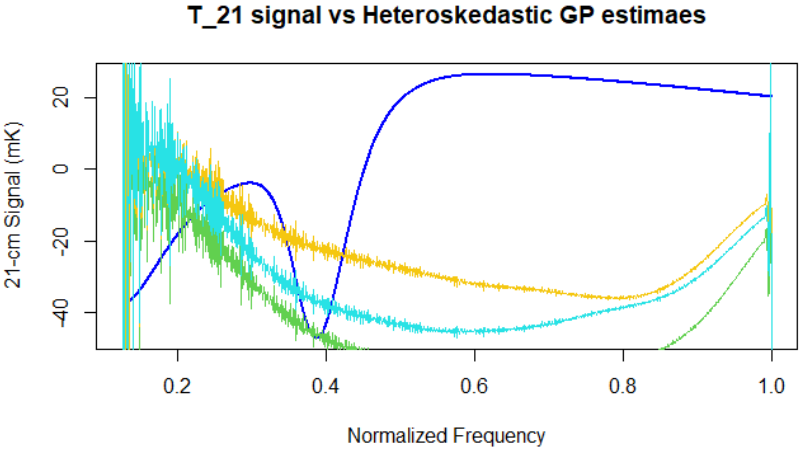
- Transforming data:

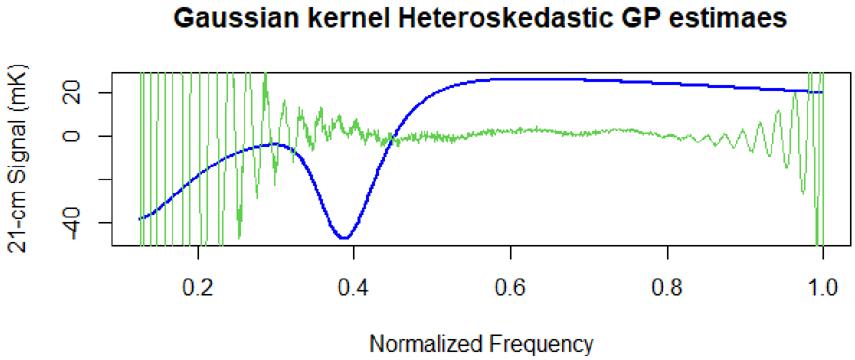
$$r(\nu) = \frac{T_{sky}(\nu)}{\hat{T}_{fg}(\nu)} - 1$$

- Performed GP on residual $r(\nu)$ with homogeneous noise.
- Recover the T_{21} by multiplying with $\hat{T}_{fg}$.

Gaussian Process with Heteroscedastic Noise

- Used mleHetGP to estimate the foreground.
- Experimented with different kernels, hyperparameters and bounds.




Gaussian kernel Heteroskedastic GP estimaes
21-cm Signal (mK)
20
0
-40
0.2
0.4
0.6
0.8
1.0
Normalized Frequency

Trend Filtering

- Applied trendfiltering for foreground modeling.
- It over-smoothed the signal and removed structure in 21-cm absorption dip.
- Residuals were flat, so was the estimate.

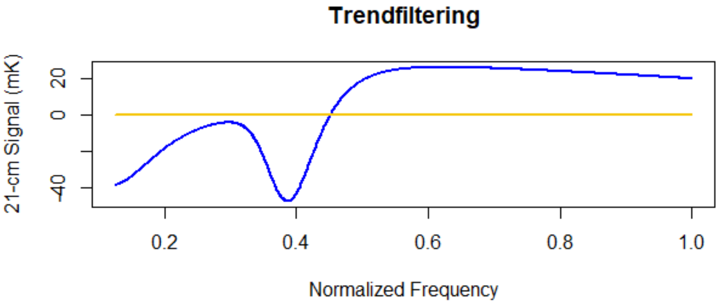


Figure: The yellow line denotes the 21-cm estimate after trendfiltering the foreground

What Next

- Hierarchical GP in Stan.
- Trend filtering ?.
- Potential solutions: Nonparametric kernel-learning methods.

Tripathi, A., Datta, A., Choudhury, M., and Majumdar, S. (2024).
Extracting the global 21-cm signal from cosmic dawn and epoch of reionization in the presence of foreground and ionosphere.
Monthly Notices of the Royal Astronomical Society, 528(2):1945–1964.