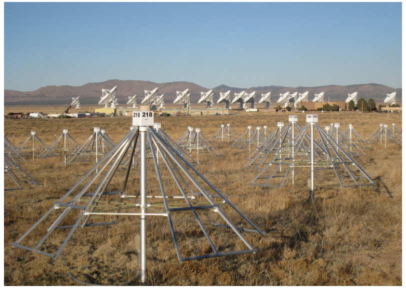
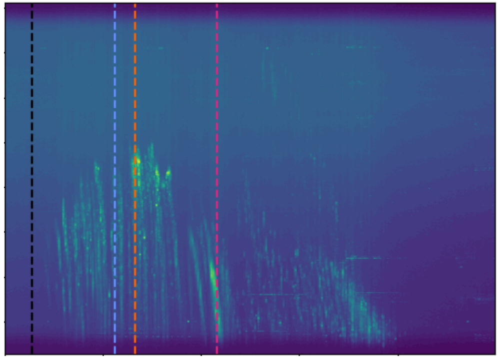
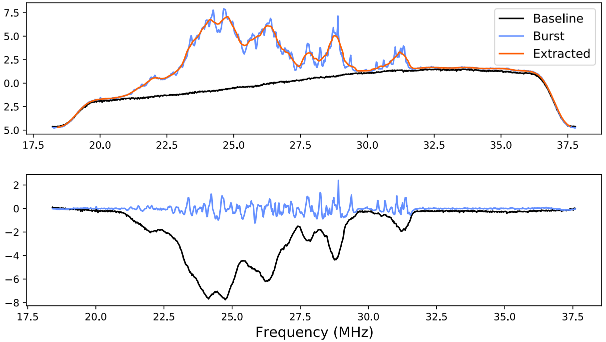
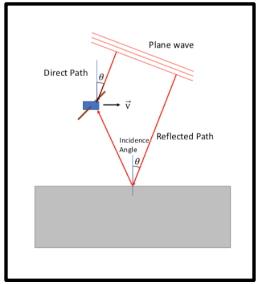








Conditioning Jovian Bursts for Passive Sounding

Prediction and Suppression of Artifact Formation due to Spectral Structure in Passive Sounding Applications Utilizing Jovian Noise

Principal Investigator: T. Maximillian Roberts 335F
Co-I: Andrew Romero-Wolf
Program: Innovative Spontaneous Concepts

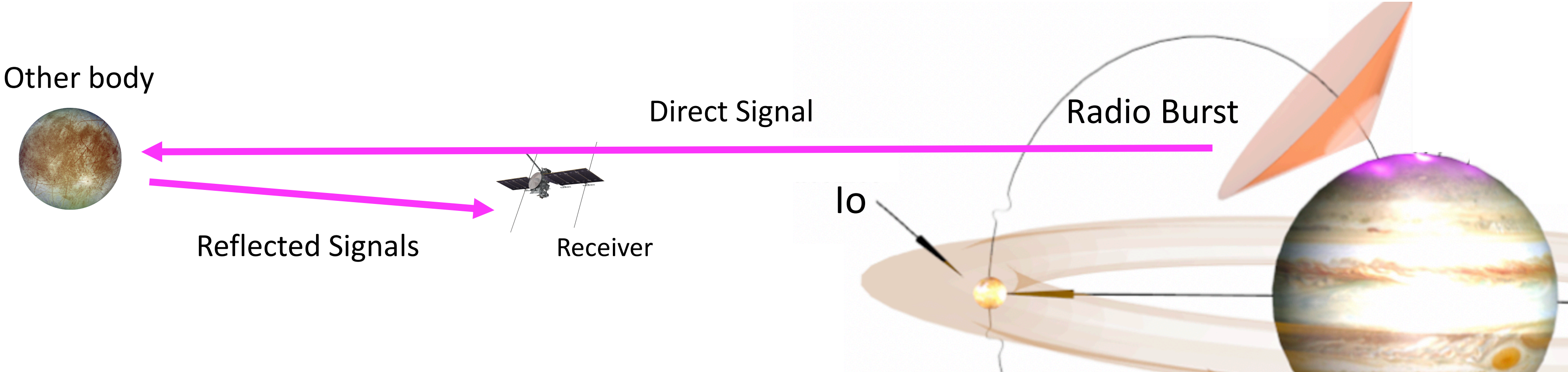
Assigned Presentation # RPC-069

Jet Propulsion Laboratory
California Institute of Technology

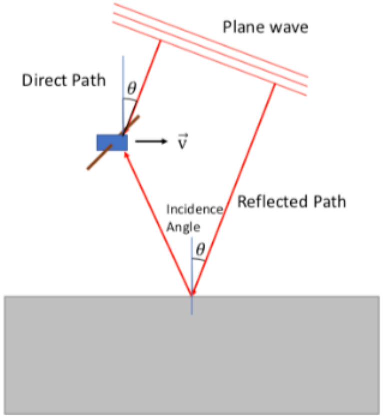
Tutorial Introduction

Abstract

Passively sounding icy and rocky bodies in our Solar System provides a way to observe the surface and subsurface of these objects without the need for costly transmitters. Jupiter's decametric radiation provides a suitable source of RF for sounding on geological scales of interest, but its spectral structure is non-ideal for sounding. We present conditioning processes that improve the echo detectability and sounding resolution for Jovian burst-like signals. More than 18 hours of Jovian burst recordings are used to simulate the consequences of the natural spectral variation, and the attainable improvement with these processes for noise conditions in the Jovian and Earth/Moon systems.

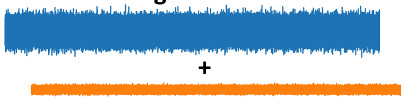


Passive Radio Sounding



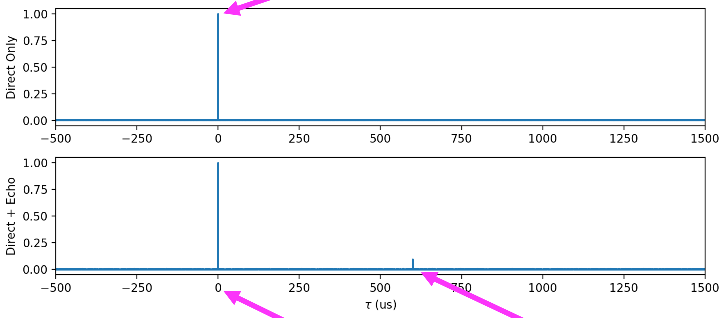
Autocorrelate
Direct Signal Only

Autocorrelate
Direct Signal with Echo



Echo signal delayed and attenuated

Noise only correlates with self at delay of 0

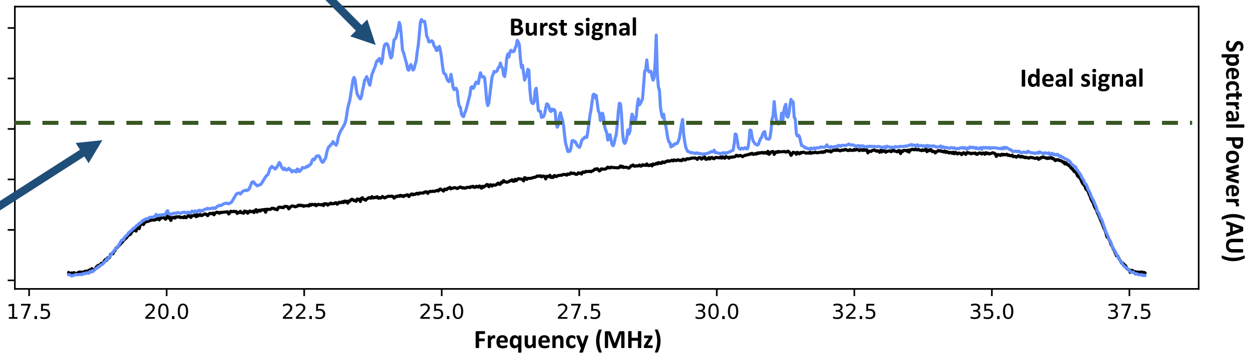


Noise correlates with self at delay of 0 AND echo delay!

- Something creates a strong noise-<u>like</u> signal for you (“passive”)
- Treat noisy signal like a unique code, similar to GPS (except you don’t know what it will be)
- Autocorrelation of random noise against itself will be low at non-zero delays
- If there is an echo of the noise in the signal, you will have a small peak off zero delay!
- Delay of peak is related to extra time (distance) travelled by echo ($\Delta x \approx c * \Delta t/2$)

Problem: Burst are Noise-like, NOT Noise

What we get

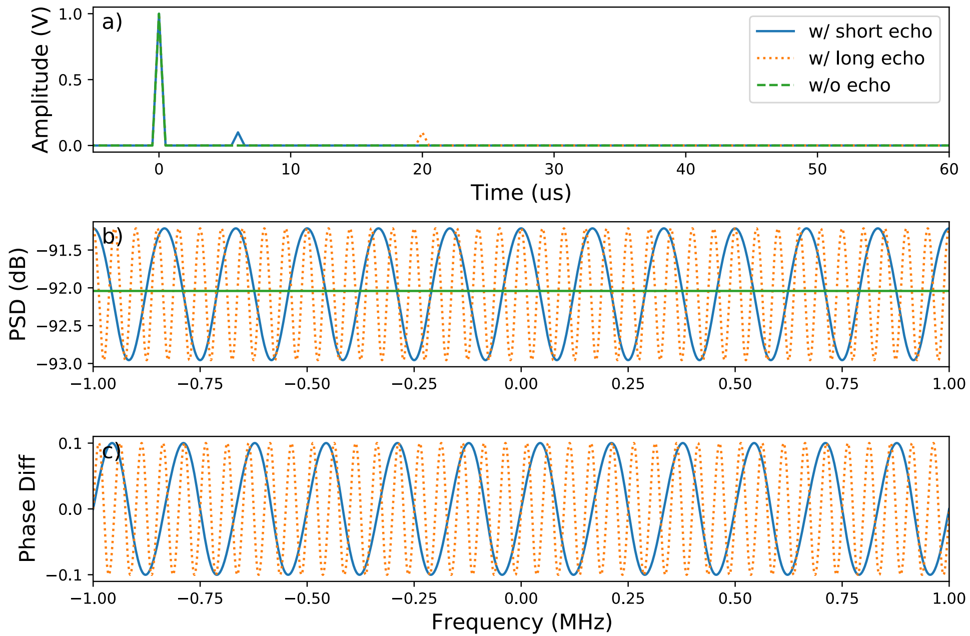


What we want

Correction to near spectral flatness is the goal!

Primer: Echoes and Spectra

Echoes in the time domain create ripples in frequency domain



Signal with Echo:

$$g(t) = \delta(t) + \rho\delta(t - t_d)$$

Echo scaled by rho, delayed

Example signal is delta function

FFT of Signal with Echo:

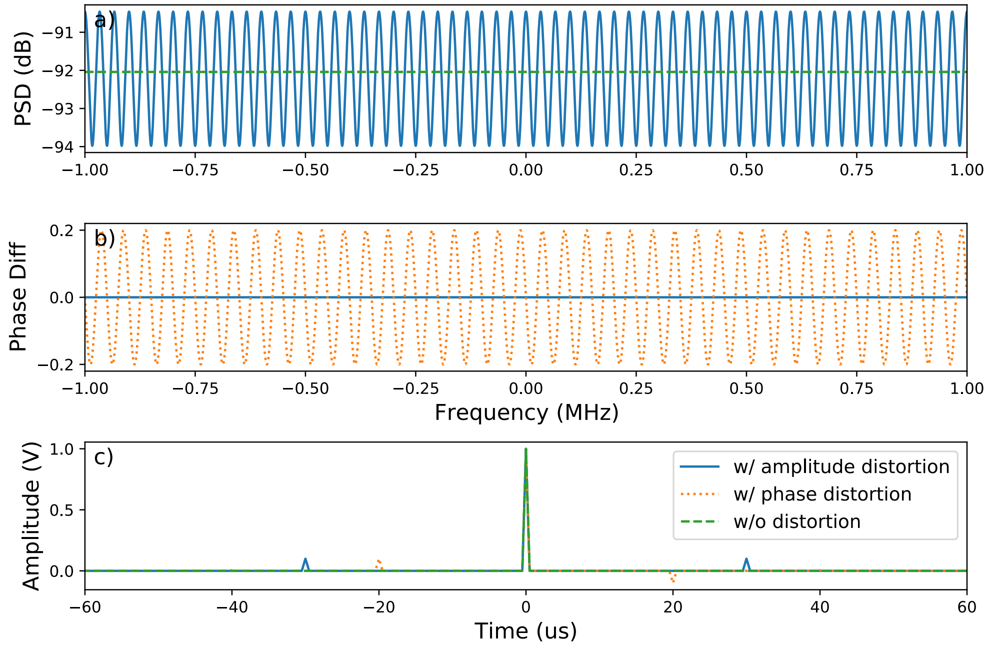
$$G(f) = \mathcal{F}[g(t)] = \int_{-\infty}^{\infty} (\delta(t) + \rho\delta(t - t_d))e^{-i2\pi ft}dt$$

$$= e^{-i2\pi f0} + \rho e^{-i2\pi ft_d} = 1 + \rho\big(\cos(2\pi ft_d) - i\sin(2\pi ft_d)\big)$$

Echo component varies with frequency!

Primer: Echoes and Spectra

Ripples in frequency domain create replicas in time domain



Representation of amplitude distortion:

$$A(f) = KH(f) = H(f) + H(f)b\cos(2\pi f t_c)$$

$$\mathcal{F}^{-1}[K] = \int_{-\infty}^{\infty}(1+a)e^{i2\pi ft}df = \int_{-\infty}^{\infty} e^{i2\pi ft}df + \int_{-\infty}^{\infty} b\cos(2\pi f t_c)e^{i2\pi ft}df$$

$$= \delta(t) + \frac{b}{2}(\delta(t+t_c) + \delta(t-t_c))$$

Replica pair!

Representation of phase distortion: $\tilde{\phi}(f) = \phi(f) + p\sin(2\pi f t_c)$

$$A(f) = |H(f)|e^{i\tilde{\phi}(f)} = |H(f)|e^{i\phi(f)+ie\sin(2\pi f t_c)}$$

$$= H(f)e^{ip\sin(2\pi f t_c)}$$

p assumed small

$$\approx H(f)(1 + ip\sin(2\pi f t_c))$$

$$\mathcal{F}^{-1}[1 + ip\sin(2\pi f t_c)] = \int_{-\infty}^{\infty} e^{i2\pi ft}df + \int_{-\infty}^{\infty} ip\sin(2\pi f t_c)e^{i2\pi ft}df$$

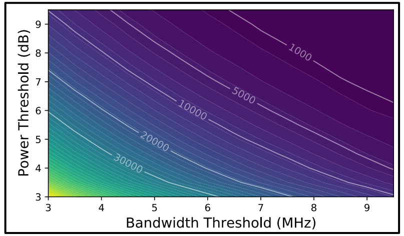
$$= \delta(t) + \frac{p}{2}(\delta(t+t_c) - \delta(t-t_c))$$

Replica pair!

Overview

1. Study and Characterize Jovian Bursts with LWA1 Data
2. Simulate “burst-like” signals using actual burst spectra
3. Develop corrective techniques to “flatten” the spectra
4. Apply techniques to simulated bursts, observe results

1.



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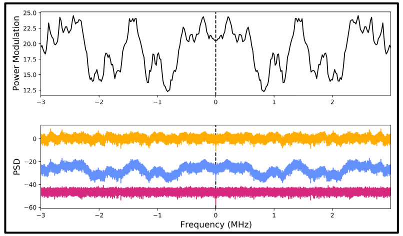

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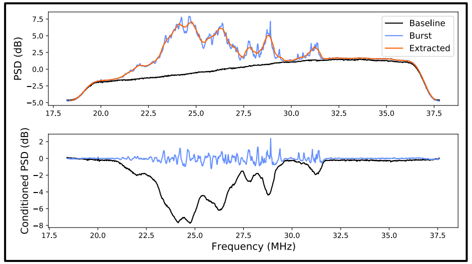

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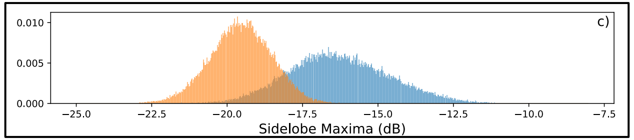
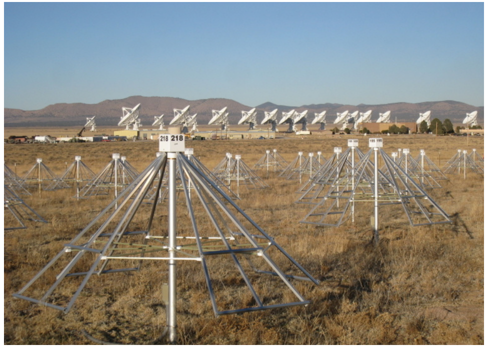
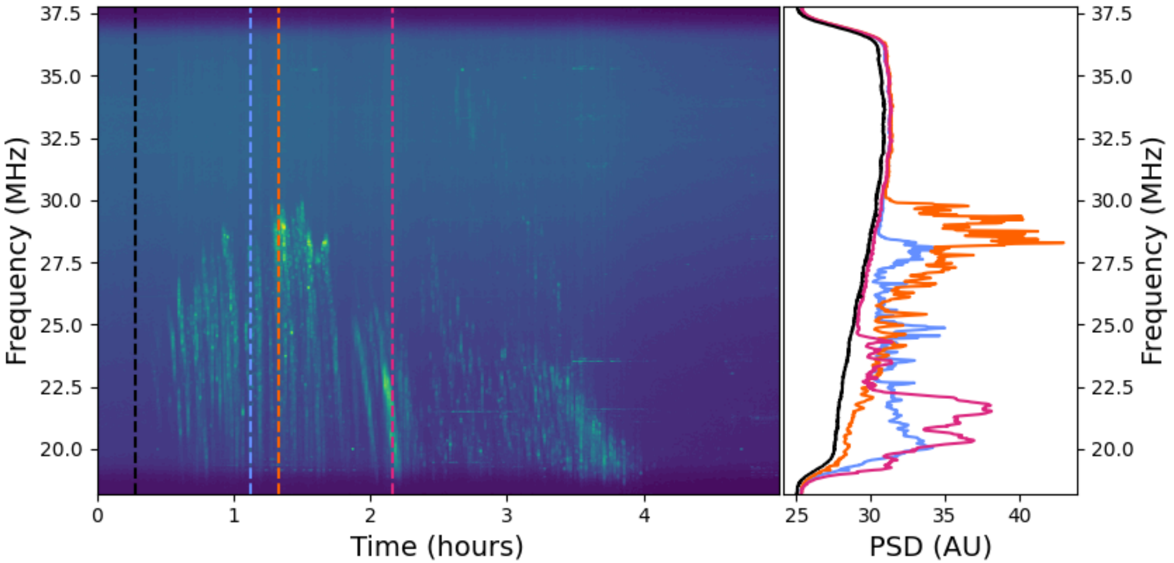


Jovian Bursts

Long Wavelength Array (LWA) observes Jovian bursts!



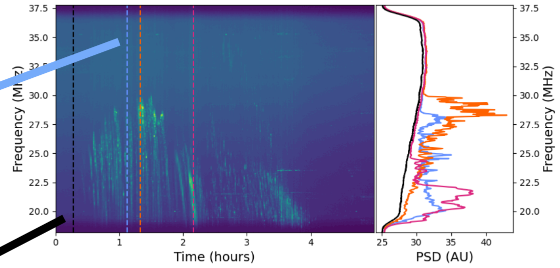
Spectrogram (and profiles) show activity in the 15-35 MHz range



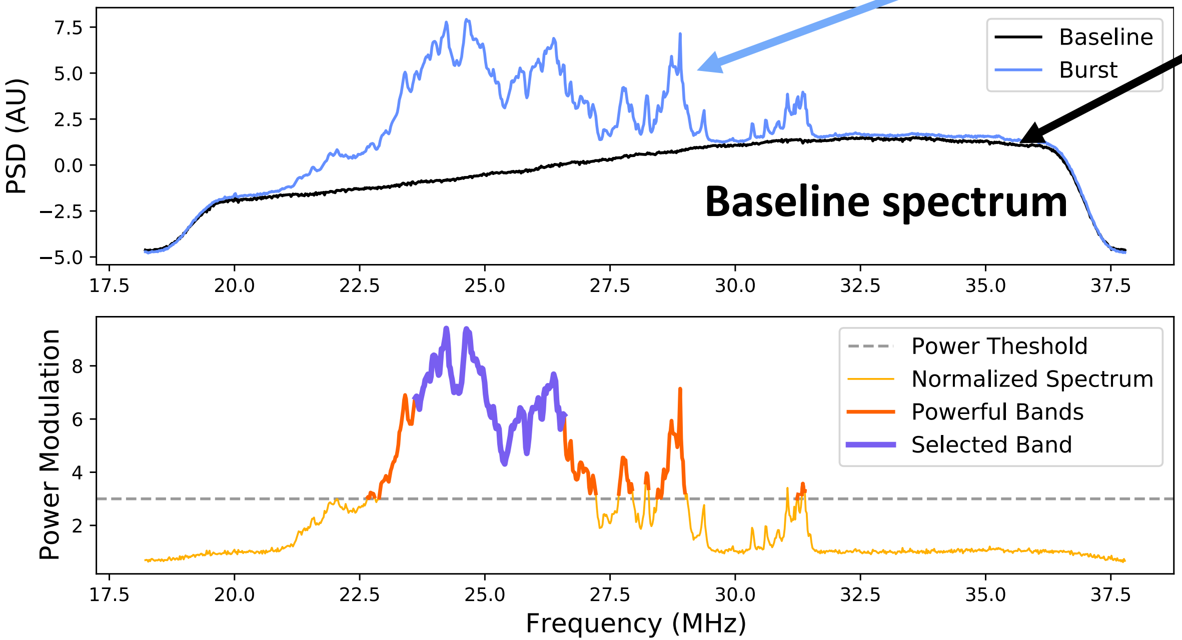
Identifying Useful Bursts

Detection and selection of useful bands in spectra

1s averaged profiles



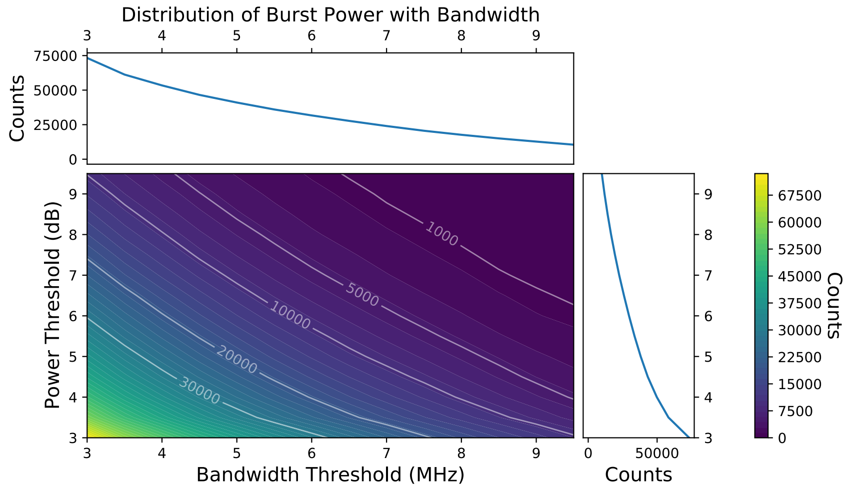
Spectrum during burst activity

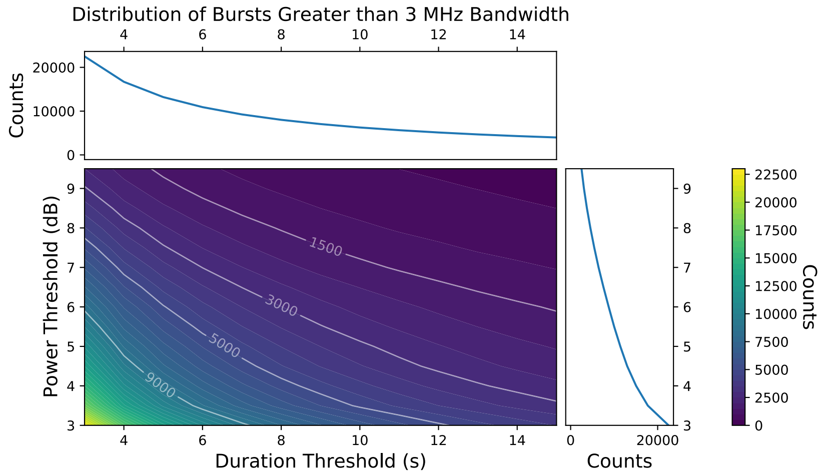


Bursting spectrum (blue) normalized by baseline (black) to yield the "Power Modulation" function

Jovian Bursts Statistics

- **400 hours of LWA data yielded 18 hours of burst signals usable for sounding**
- **Criteria for “useful” is a continuous bandwidth of 3 MHz at least 3 dB above baseline**
- **Plots show distributions of power with bandwidth and sustained duration**

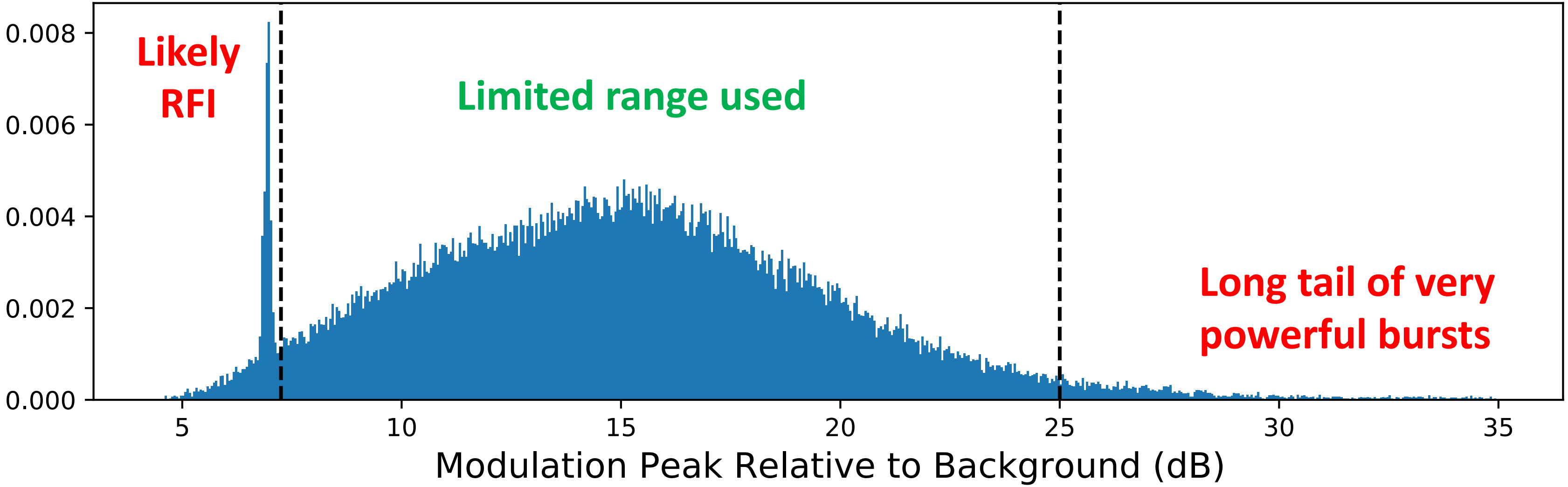




Duration metric useful for series of localized measurements

Excluding Powerful Spectra and RFI

- Analysis of these bursts revealed potential RFI
- Only bursts with peaks modulation 7-25 dB above back used
- Left with 65000 1-sec usable burst durations



Simulating Jovian Signals

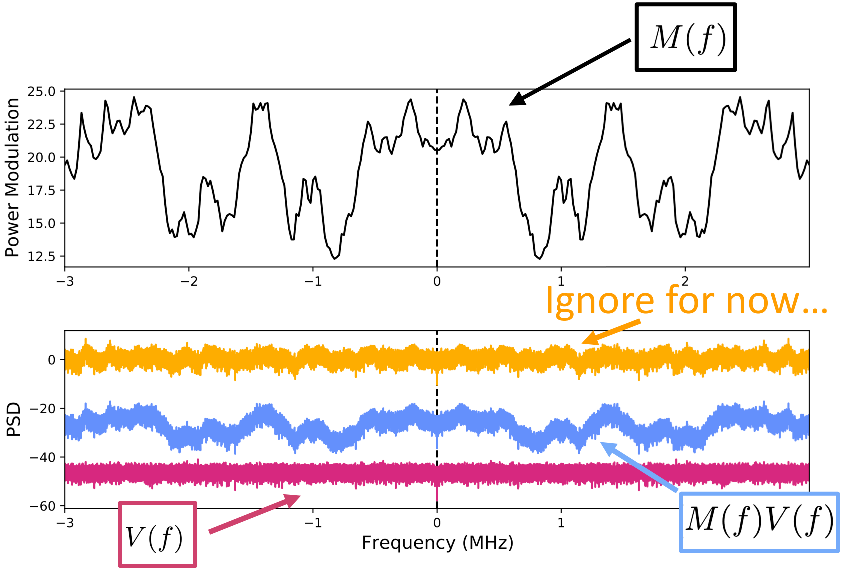
Simulation Process:

1. Extract profile from "useful" bands
2. Create "baseline" spectrum $M(f)$
3. Create baseline noise signal $v(t)$
4. Take FFT of signal $V(f) = \mathcal{F}[v(t)] = \int_{-\infty}^{\infty} v(t) e^{-i2\pi f t} dt$
5. Modulate the spectral amplitude $M(f)V(f)$
6. Take IFFT for the simulated signal

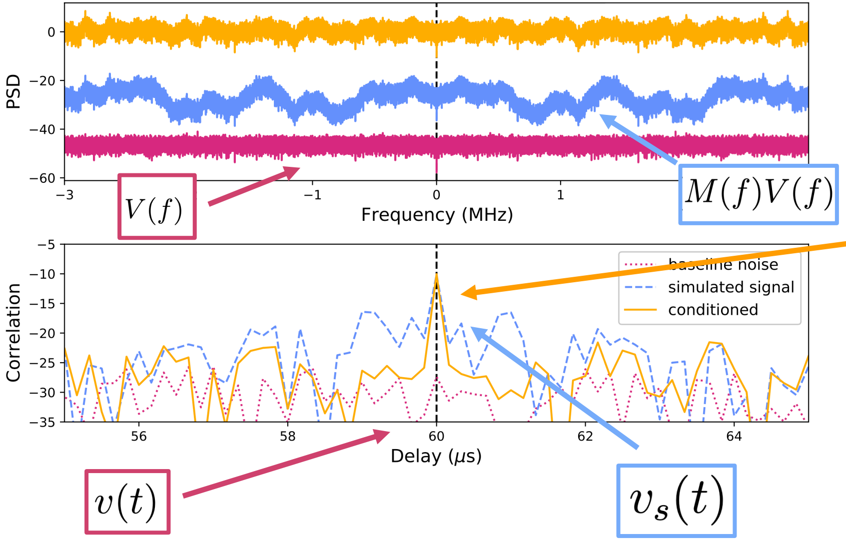
Direct Signal: $\mathcal{F}^{-1}[M(f)V(f)] = v_J(t)$

7. Create scaled, delayed "echo"

Total Signal: $v_s(t) = v_J(t) + \rho v_J(t - t_d)$



Autocorrelation (the Measurement)

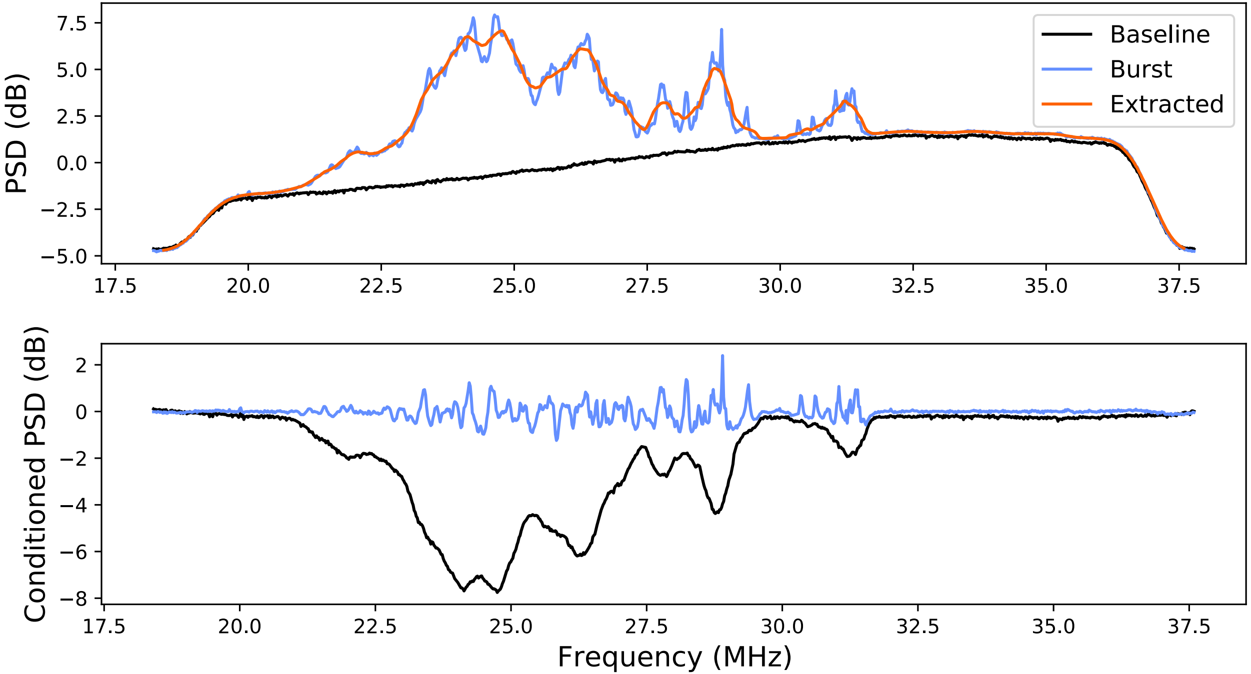


But this narrow peak would be a lot better!

Autocorrelation of original noisy signal shows no peak at echo delay

Autocorrelation of "simulated burst" signal shows broad peak w/ lobes at 60 us

Conditioning Process



Conditioning Process

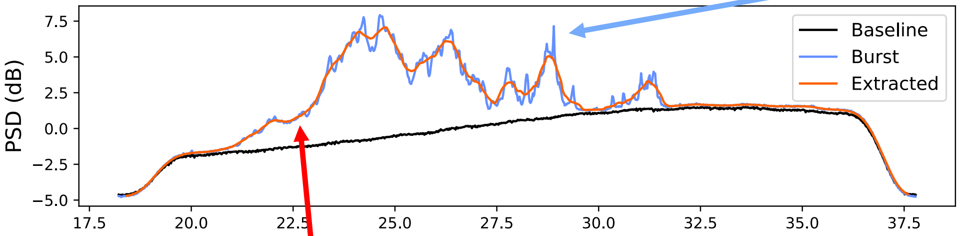
$$V_{tot,n}(f) = \int_{-\infty}^{\infty} v_{tot,n}(t) e^{-i2\pi f t} dt \quad v_{tot,n}(t) = v_{J,n}(t) + \rho v_{J,n}(t+t_d) + v_{G,n}(t)$$

$$= |V_{J,n}(f)| e^{-i2\pi f t_0} + \rho |V_{J,n}(f)| e^{-i2\pi f (t_0 + t_d)} dt + |V_{G,n}(f)| e^{i\phi_n(f)}$$

$$S_{tot,n} = V_{tot,n}(f) V^*_{tot,n}(f)$$

$$= |V_{J,n}|^2 (1 + 2\rho \cos(2\pi f t_d) + \rho^2) + \gamma_n + |V_{G,n}|^2$$

Noise term from Galactic Background Noise (GBN)

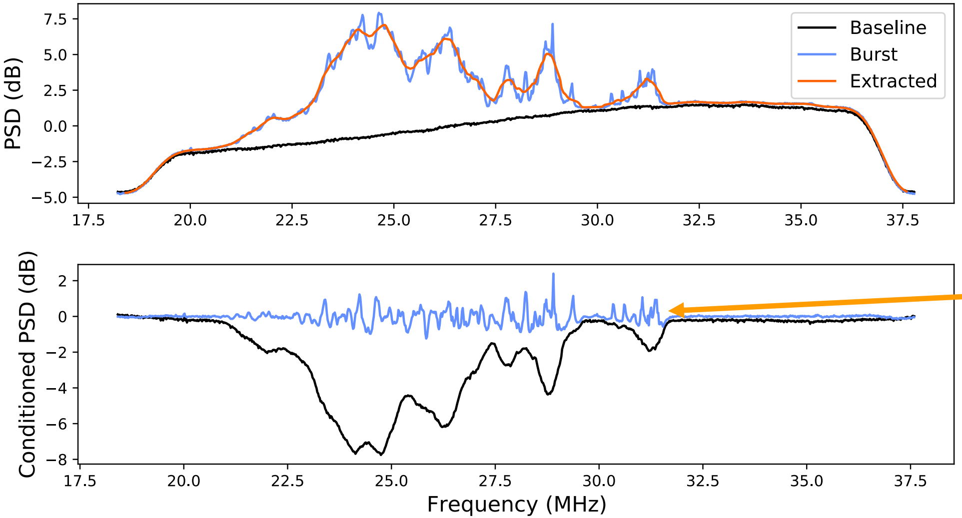


$$S_{SRR,n} = \int_{-\infty}^{\infty} \left[< |V_G|^2 > \alpha^2 M_n^2(f')(1 + 2\rho \cos(2\pi f t_d) + \rho^2) + \gamma_n + |V_{G,n}|^2 \right] B(f - f') df'$$

Using…

$$|V_{J,n}| = \alpha M_n(f) \sqrt{< |V_G|^2 >}$$

Conditioning Process: Low Noise Case



Assuming low noise (large alpha):

$$S_{SRR,n} \approx <|V_G|^2> \alpha^2 M'^2(f), \quad M'^2(f) \equiv \int_{-\infty}^{\infty} M^2(f')B(f-f')df'$$

$$\hat{S}_{tot,n}(f) = \frac{S_{tot,n}(f)}{S_{SRR,n}(f)}$$

(Blue)
(Red)

For case when we can ignore background noise:

$$\hat{S}_{tot,n}(f) = \frac{S_{tot,n}(f)}{S_{SRR,n}} \approx \frac{<|V_G|^2> \alpha^2 M_n^2(f)(1+2\rho\cos(2\pi f t_d)+\rho^2)+\gamma_n+|V_{G,n}|^2}{<|V_G|^2> \alpha^2 M'^2(f)}$$

$$\approx \frac{M_n^2(f)}{M'^2(f)}(1+2\rho\cos(2\pi f t_d)+\rho^2)$$

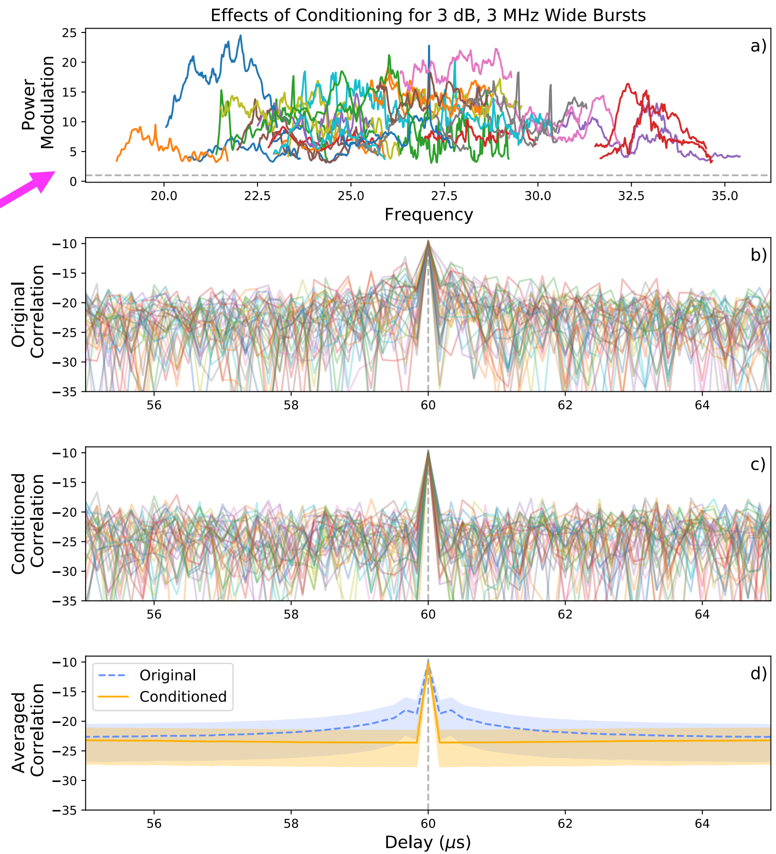
Conditioning Ratio

Echo Component

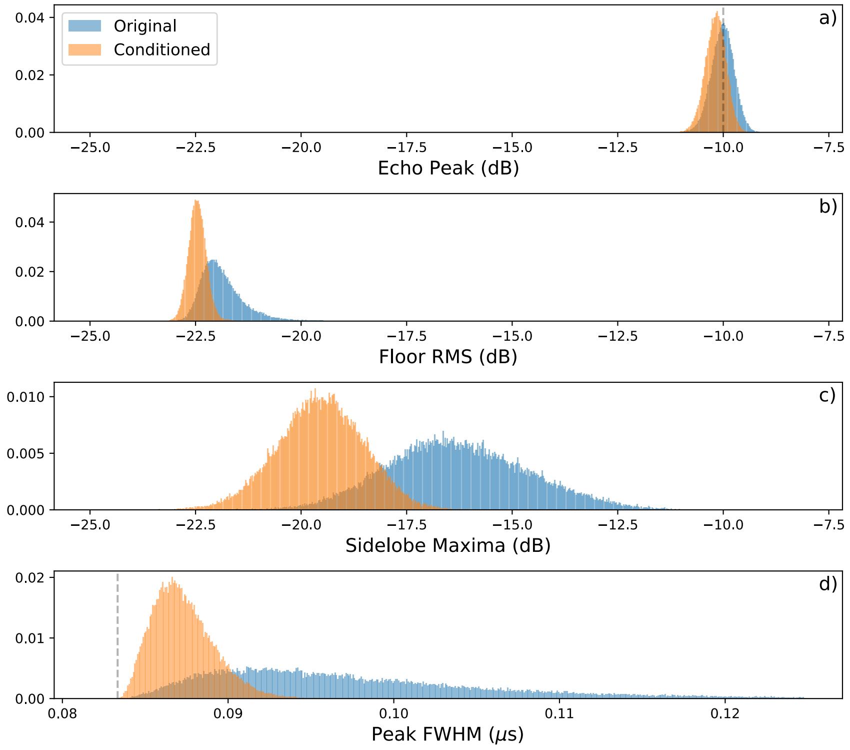
Effects of Conditioning

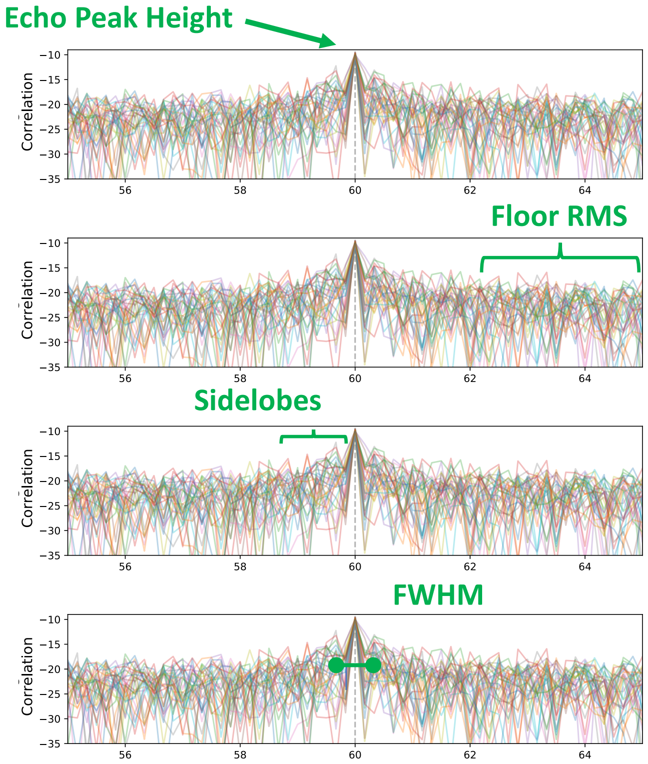
To observe the effects of condition we:

1. Use LWA to simulate 65000 burst signals
2. Autocorrelate, look at the echo delay
3. Apply conditioning process to all signals
4. Autocorrelate, look at the echo delay
5. Compare!



Effects of Conditioning





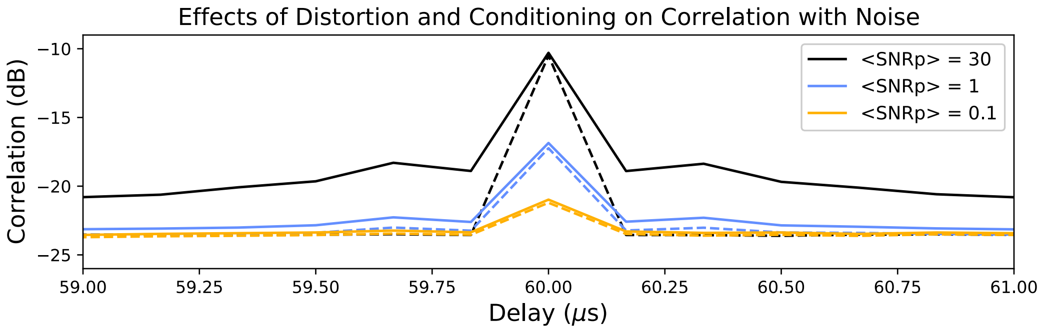
Adding Noise to the Signal

So far only considered terms from direct signal and echo

$$S_{tot,n} = |V_{J,n}|^2(1 + 2\rho\cos(2\pi f t_d) + \rho^2) + \gamma_n + |V_{G,n}|^2$$

But what about these noise terms?

Looking at cases where the Galactic Background Noise (GBN) is increasingly large,

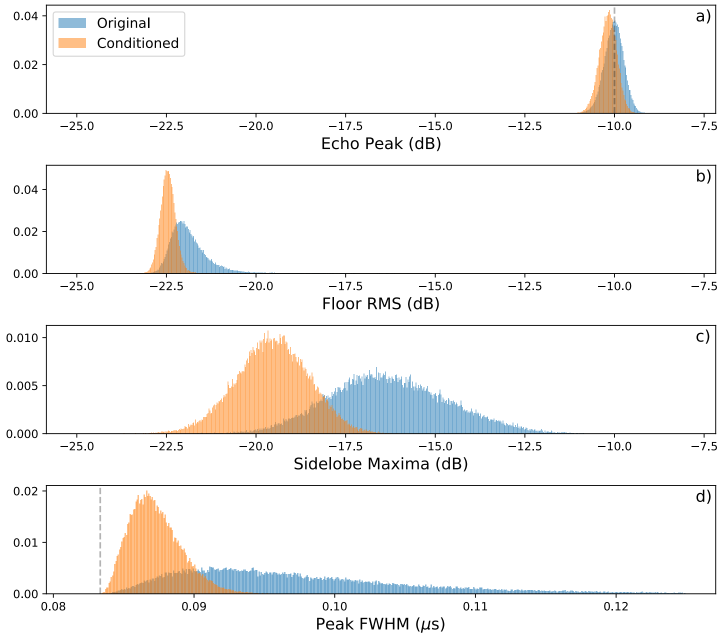


$$\mathrm{SNRp} = \frac{<|V_J|^2>}{<|V_G|^2>} \propto \alpha^2$$

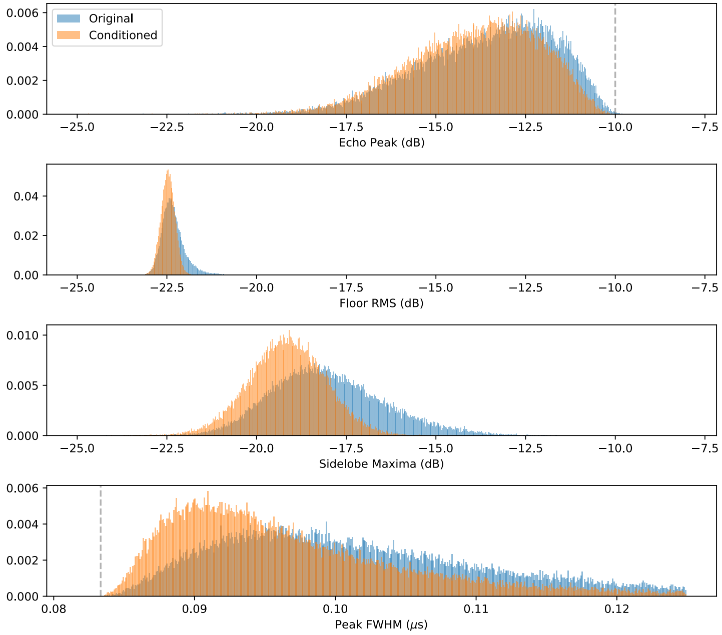
Not only is the correlation reduced, but so are the improvements from conditioning

Adding Noise to the Signal

Earlier case with no added noise

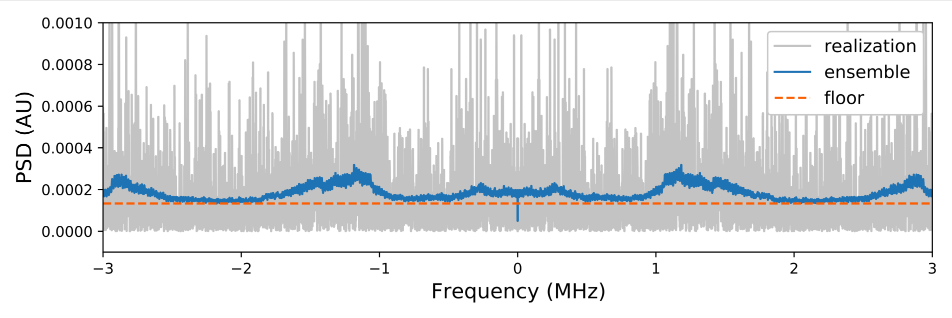


Reduced improvement for noisy signals



Treating Noisy Signals: Ensemble Averaging

$$
\begin{aligned}
< S_{tot} > &= \frac{1}{N}\Sigma_{n=1}^{N} S_{tot,n} \\
&= \frac{1}{N}\Sigma_{n=1}^{N} |V_{J,n}|^2 (1 + 2\rho\cos(2\pi f t_D) + \rho^2) + \gamma_n + |V_{G,n}|^2 \\
&= \frac{1}{N}\Sigma_{n=1}^{N} \alpha^2 M_n^2(f) < |V_G|^2 > (1 + 2\rho\cos(2\pi f t_D) + \rho^2) \\
&\qquad + \frac{1}{N}\Sigma_{n=1}^{N} |V_{G,n}|^2 + \frac{1}{N}\Sigma_{n=1}^{N}\gamma_n \\
&\approx \alpha^2 < M^2(f) >< |V_G|^2 > (1 + 2\rho\cos(2\pi f t_D) + \rho^2) + < |V_G|^2 >
\end{aligned}
$$



Ensemble (incoherent) averaging yields a noise floor to PSD

$$
\begin{aligned}
< S_{SRR,n} > &= < |V_G|^2 > \alpha^2 M'^2(f) + \frac{1}{N}\Sigma_{n=1}^{N}\gamma_n + \frac{1}{N}\Sigma_{n=1}^{N}|V'_{G,n}|^2 \\
&\approx < |V_G|^2 > \alpha^2 M'^2(f) + < |V_G|^2 > \qquad \text{(For sufficiently large N)}
\end{aligned}
$$

Measure modulation from ensemble spectrum, which <u>includes an offset</u>

Treating Noisy Signals: Redefine Conditioning

Subtract the offsets

Divide by *ensemble*

$$\hat{S}_{tot,n}(f) = \frac{S_{tot,n} - <|V_G|^2>}{<S_{SRR}> - <|V_G|^2>}$$

$$= \frac{<|V_G|^2> \alpha^2 M_n^2(f)(1 + 2\rho\cos(2\pi f t_d) + \rho^2) + \gamma_n + |V_{G,n}|^2 - <|V_G|^2>}{<|V_G|^2> \alpha^2 M'^2(f)}$$

$$= \frac{M_n^2(f)}{M'^2(f)}(1 + 2\rho\cos(2\pi f t_d) + \rho^2) + \frac{\gamma_n}{<|V_G|^2> \alpha^2 M'^2(f)} + \frac{<|V_G|^2> (\psi_{G,n} - 1)}{<|V_G|^2> \alpha^2 M'^2(f)}$$

$$= \frac{M_n^2(f)}{M'^2(f)}(1 + 2\rho\cos(2\pi f t_d) + \rho^2) + \frac{\gamma_n}{<|V_G|^2> \alpha^2 M'^2(f)} + \frac{\psi_{G,n} - 1}{\alpha^2 M'^2(f)}$$

Conditioning Ratio

Vary realization to realization

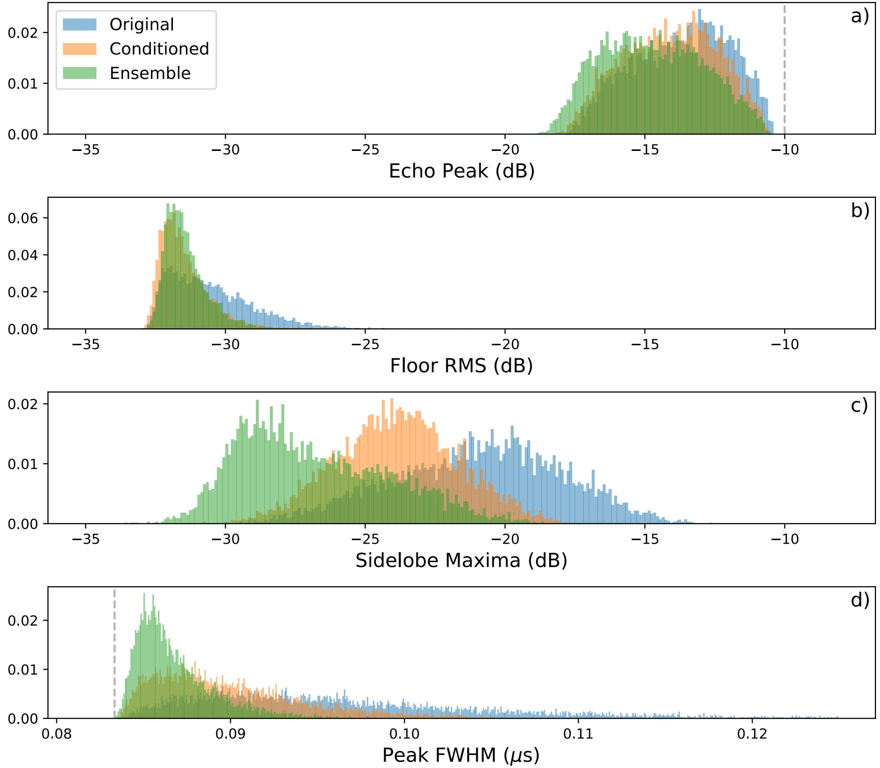
Average many spectra/correlations to achieve conditioning:

$$<\hat{S}_{tot,n}(f)> \approx \frac{<M^2(f)>}{M'^2(f)}(1 + 2\rho\cos(2\pi f t_d) + \rho^2)$$

$$\hat{C}_{v_J,\rho v_J}(t) = \int_{-\infty}^{\infty} \frac{<M^2(f)>}{M'^2(f)} 2\rho\cos(2\pi f t_d) e^{i2\pi f t} df$$

Correlation at echo

Improved Conditioning for Noisy Signals



Conclusions and Next Steps

These results are important in that:

- Applicability of Jovian bursts for sounding has been characterized statistically
- Problematic features of these bursts were demonstrated
- Techniques were developed for Jovian-system and Earth/Moon-system noise levels
- These analyses should be considered for missions passively sounding with Jovian bursts

Continuation of this work would include:

- A study of the presence of phase stability (nonrandomness) in the bursts
- Develop conditioning for amplitude <u>and</u> phase issues
- Understanding applicability of differing burst types (location, Io/non-Io driven)

References and Publication

[1] M. S. Marques, P. Zarka, E. Echer, V. R. Astronomy & Astrophysics, "Statistical analysis of 26 yr of observations of decametric radio emissions from Jupiter," 2017.

[2] H. A. Wheeler, "The interpretation of amplitude and phase distortion in terms of paired echoes," *Proceedings of the I. R. E.* , 1939

[3] S W Ellingson and G B Taylor. The LWA1 radio telescope. *IEEE Transactions on Geoscience and Remote Sensing*, 2013.

This work is in the final stages of preparation for publication.