Interferometry for 21 cm Hydrogen Intensity Mapping

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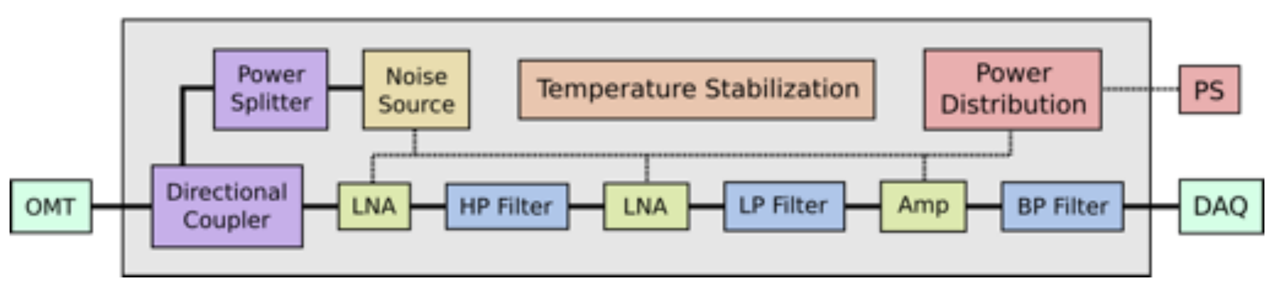
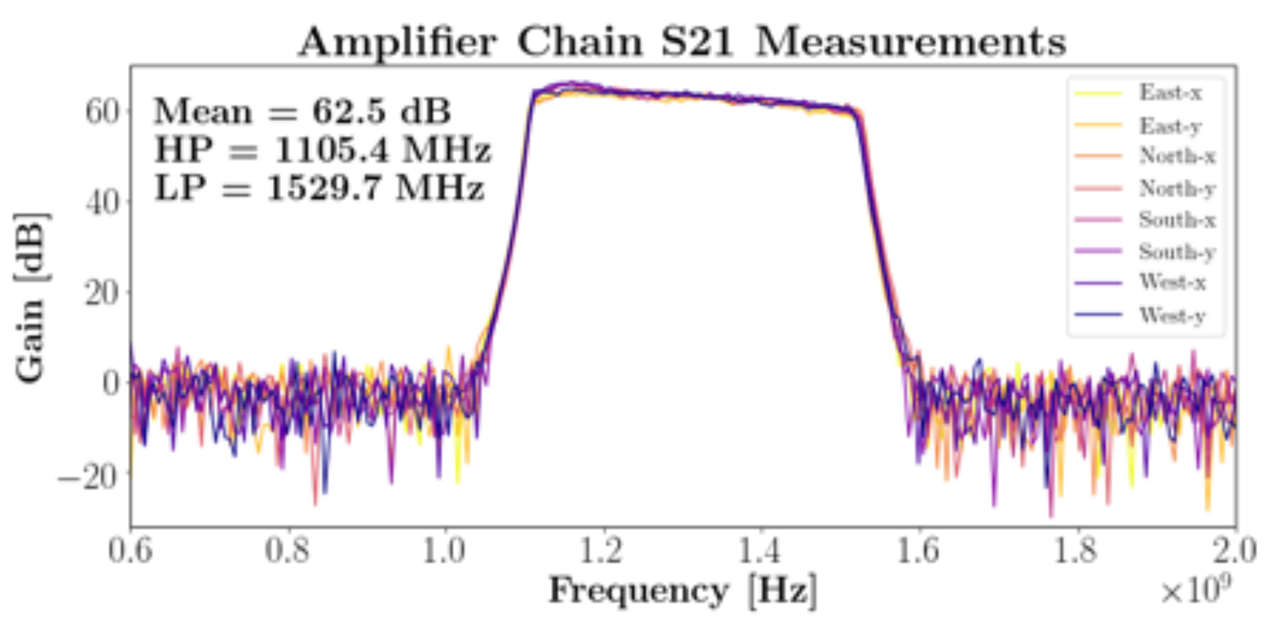
Abstract

Current radio telescopes have reached technical limitations such that increased resolution can only be obtained through larger collection geometries. Interferometry between many small dishes offers this resolution without the exponential cost of large dish telescopes. Here we review the upgrade of Brookhaven's Stage I radio telescope to a four-dish interferometer. Correlated signals from the radio galaxy Cygnus A are modeled and collected data is analyzed for calibration and precise determination of dish position, time delay, pointing, and beam shape. This Stage I design development shall inform the planned Stage II 256 x 256 dish array designed to map the intensity of the redshifted 21 cm emission line from neutral hydrogen.

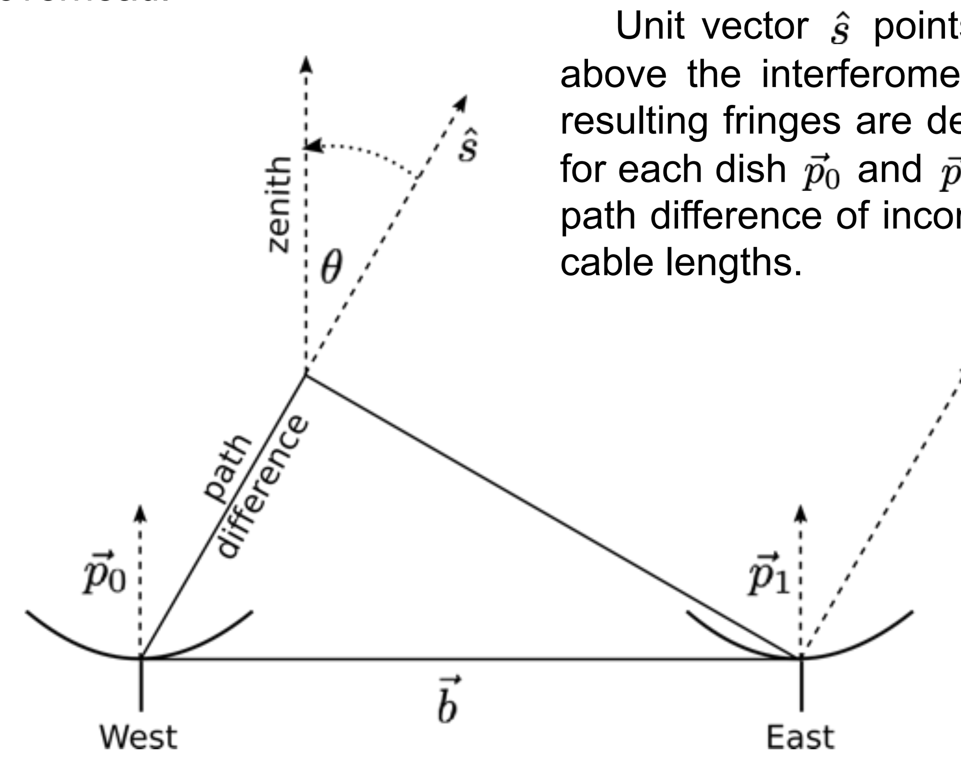
Amplifier Chain





Methods

The BMX Stage I telescope has been upgraded to a four-dish interferometer. Radiation from the sky is reflected off the parabolic aluminum dishes and collected via an orthomode transducer (OMT) which separate the electromagnetic radiation into x and y polarizations. The signals are sent into an amplifier chain with a mean gain of 62.5 dB in the radio band between 1105.4 to 1529.7 MHz before digitization and FFT. Signals from each dish are multiplied and time averaged with every other dish resulting in distinct fringes as a source passes overhead.



Unit vector $\hat{s}$ points towards a source with frequency ω transiting directly above the interferometer with an angle $\theta = \dot{\theta} t$ with respect to zenith. The resulting fringes are defined by the vector between dishes $\vec{b}$, the pointing error for each dish $\vec{p}_0$ and $\vec{p}_1$, the dish beam width σ, and the time delay τ due to the path difference of incoming wavefronts and additional delays τ_0 due to differing cable lengths.

$$V_0 = V\exp[i(\omega t + \phi)]$$

$$V_1 = V\exp[i(\omega(t+\tau) + \phi)]$$

Time delay $\tau = \tau_0 + (\vec{b}\cdot\hat{s})/c$

Correlated Signal

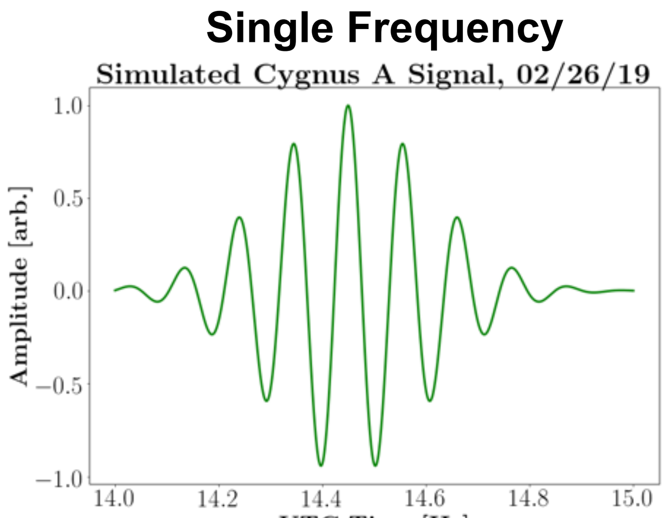
$$\langle V_0 | V_1^* \rangle_t = V^2 \exp(i\omega\tau)$$

Received Signal $$R(\hat{s}) = V^2 \exp\left[-\frac{(\hat{s}-\hat{p}_0)^2}{2\sigma_0^2} - \frac{(\hat{s}-\hat{p}_1)^2}{2\sigma_1^2} + i\omega\left(\tau_0 + \frac{\vec{b}\cdot\hat{s}}{c}\right)\right]$$

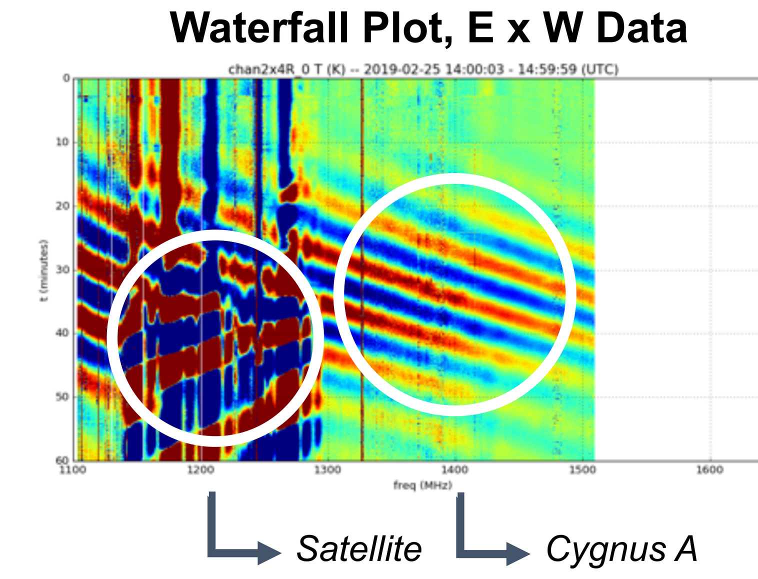
Gaussian Beam Shape

The galaxy Cygnus A, a bright radio source, happens to transit once per day nearly perfectly east to west above the BMX telescope. By generating waterfall plots of the correlated signals in time and frequency, we can observe the transit of Cygnus A. Individual objects can be discerned by their distinct fringes due to their unique transits.

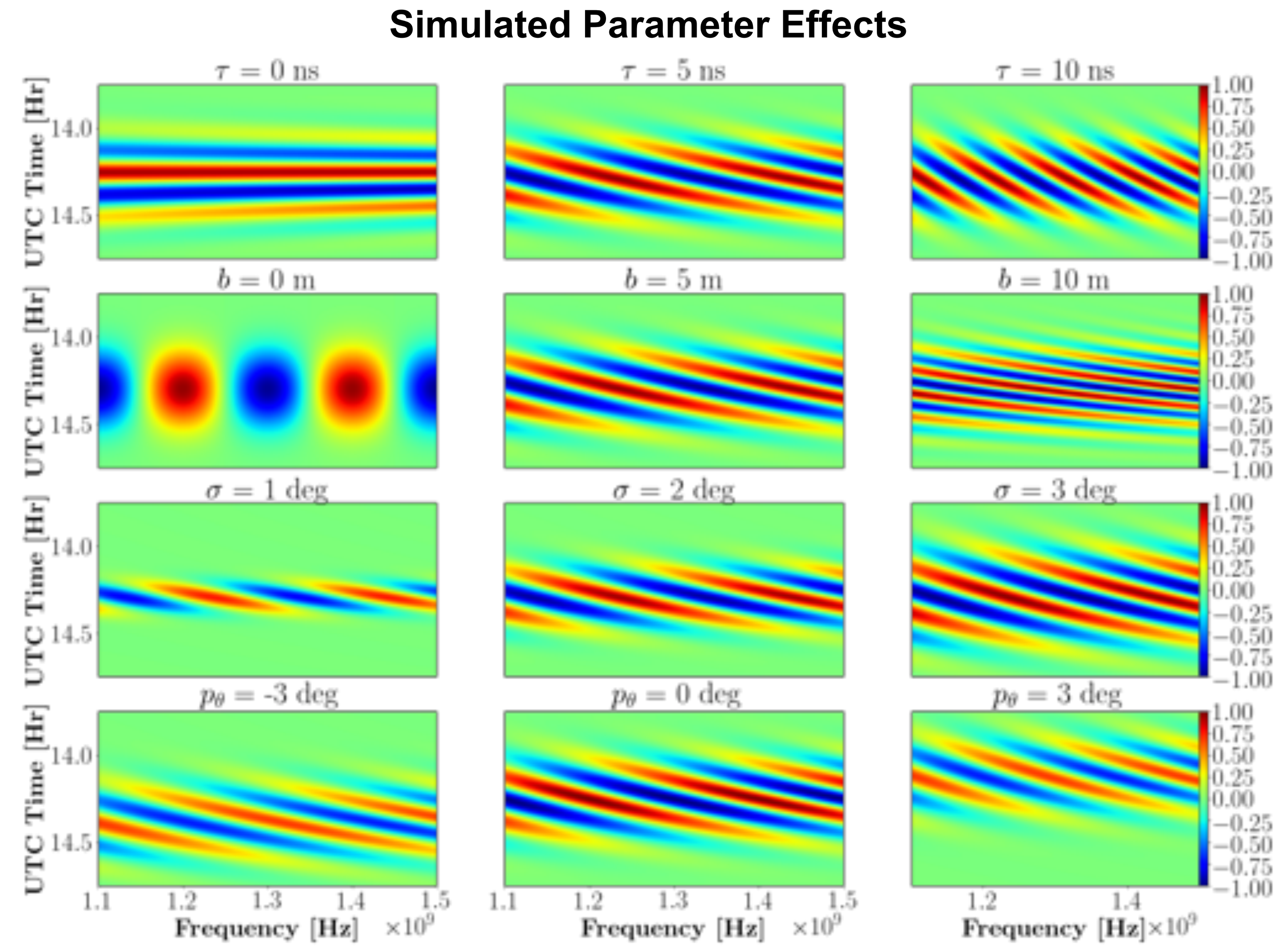
Single Frequency



Waterfall Plot, E x W Data



Simulated Parameter Effects



The **time delay** varies the shear of the fringes.

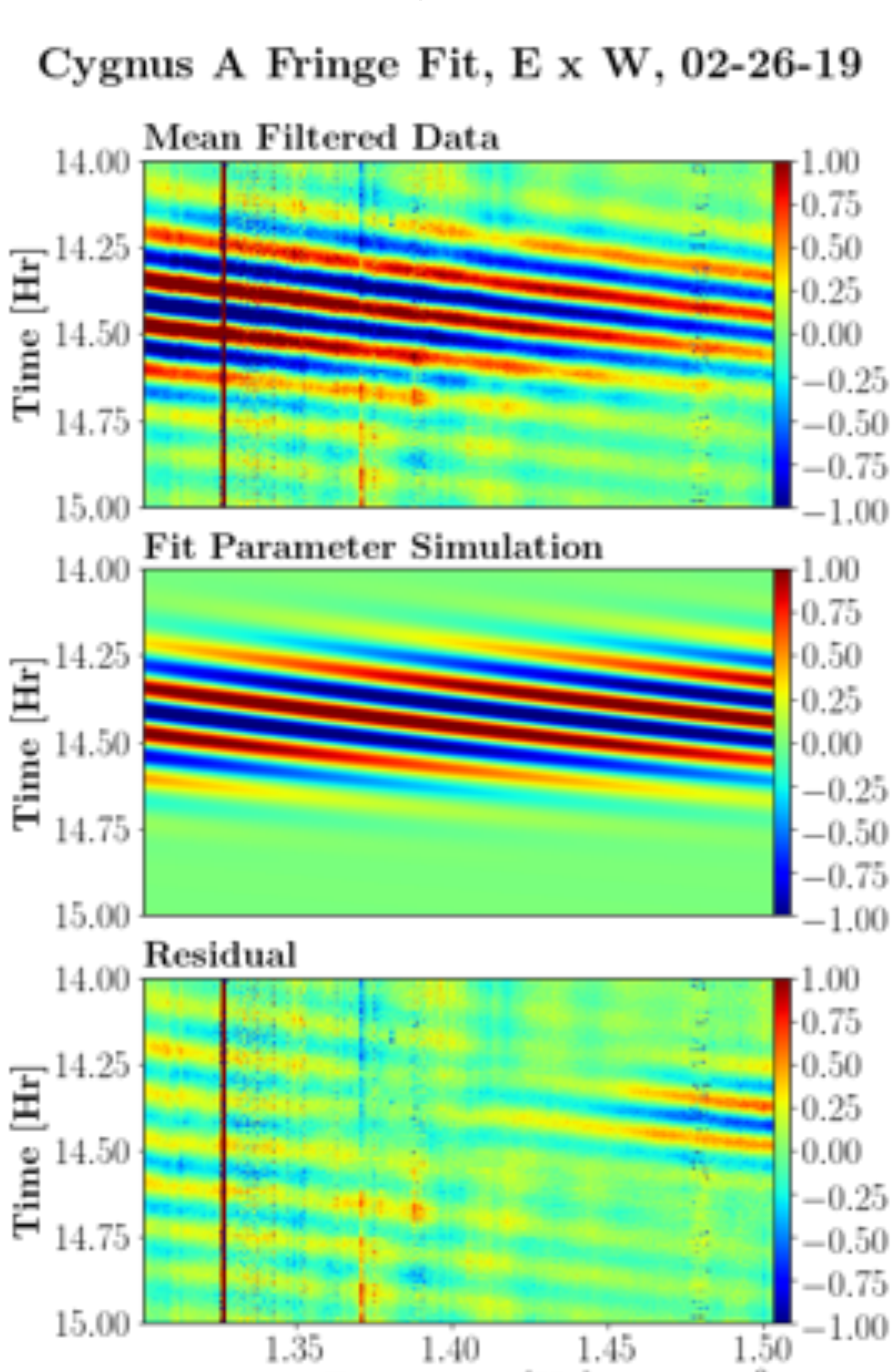
The **baseline** varies the number of fringes in time.

The **beam width** varies the amount of time we see the source.

The **pointing error** varies when we see the source in time.

Results

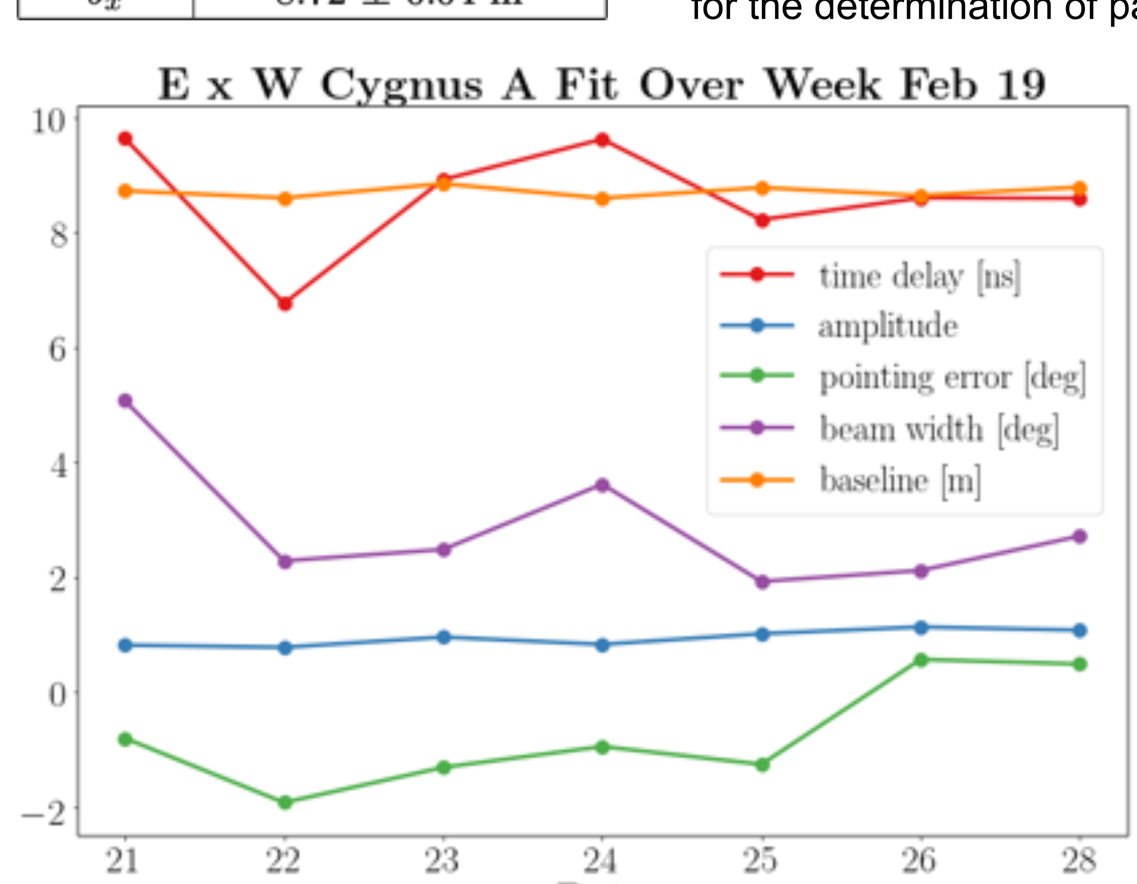
Through performing a least-squares fit of Cygnus A transits to this model, we can precisely determine the dish parameters. For a single pair of dishes, these parameters are necessarily resolved as the difference between dishes $\tau = \tau_0 - \tau_1$, $p = p_0 - p_1$, $b = b_0 - b_1$, etc. Therefore, to solve for the parameters of individual dishes we must utilize the results from every combination of dishes. Since Cygnus A transits east to west above the telescope, variations in the north to south parameters do not significantly effect the appearance of the the fringes and thus we only have enough resolution to resolve the parameters in the east to west direction.



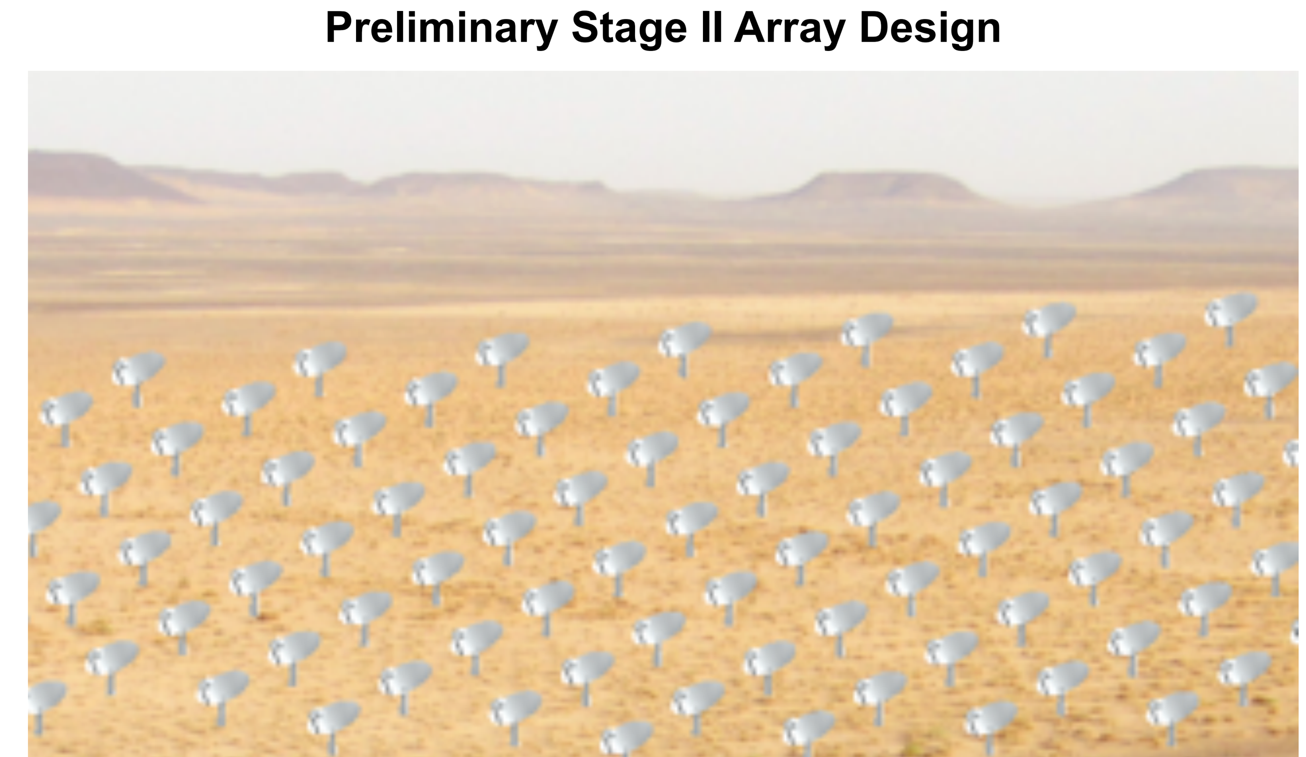
E x W Parameter Fit Results

Param.	Mean Value ($N = 7$)
τ	8.6 ± 0.4 ns
V	0.95 ± 0.05 K
p_θ	-0.7 ± 0.4 deg
σ	2.9 ± 0.4 deg
b_x	8.72 ± 0.04 m

Parameter results from the correlated signals of the east and west dishes are reported in the table. In the future, resolution in the north to south direction will be obtained through the use of a radio source attached to a small fixed-wing airplane. This control over the transit geometry will allow for the determination of parameters from every individual dish.



Preliminary Stage II Array Design



References: [1] James J. Condon and Scott M. Ransom, *Essential Radio Astronomy* (Princeton, New Jersey: Princeton University Press, 2016), pg 126-129.

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