Calibrating Radio Telescopes with the Global Navigation Satellite System

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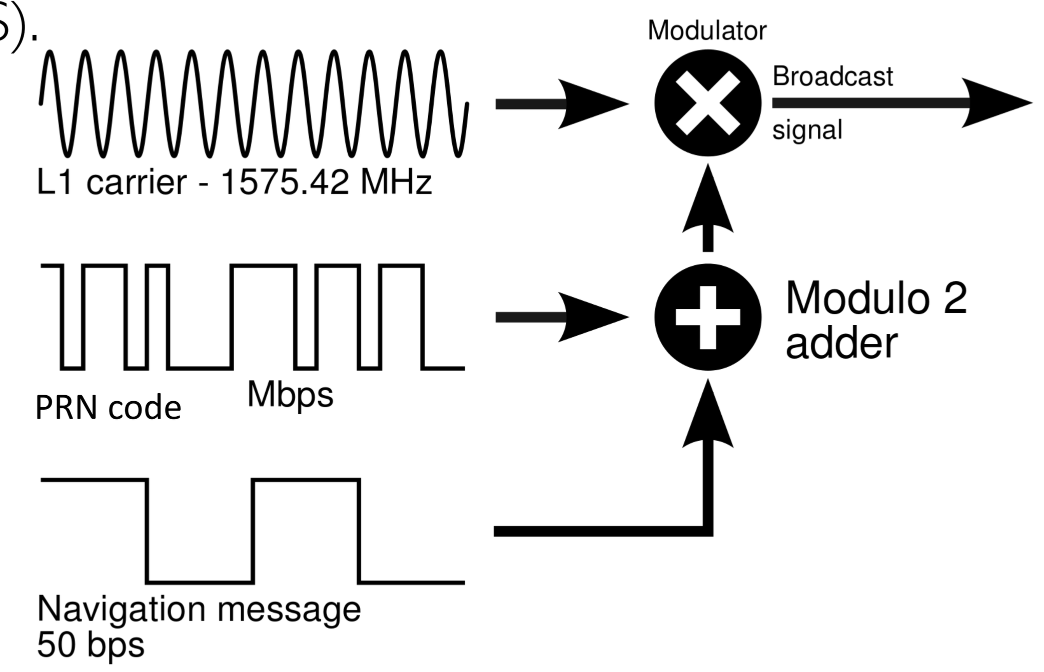
What is GNSS?

The Global Navigation Satellite System (GNSS)

- is an umbrella term for the many constellation of satellites used in localization and atmospheric observations, including the Global Positioning Systems (GPS).
- emits at multiple frequencies between 1100-1500MHz.
- signals contain a carrier wave modulated with a pseudorandom noise (PRN) code that corresponds to a particular satellite.
- can provide measurements of power and phase at up to ~40 locations in the sky at all times.

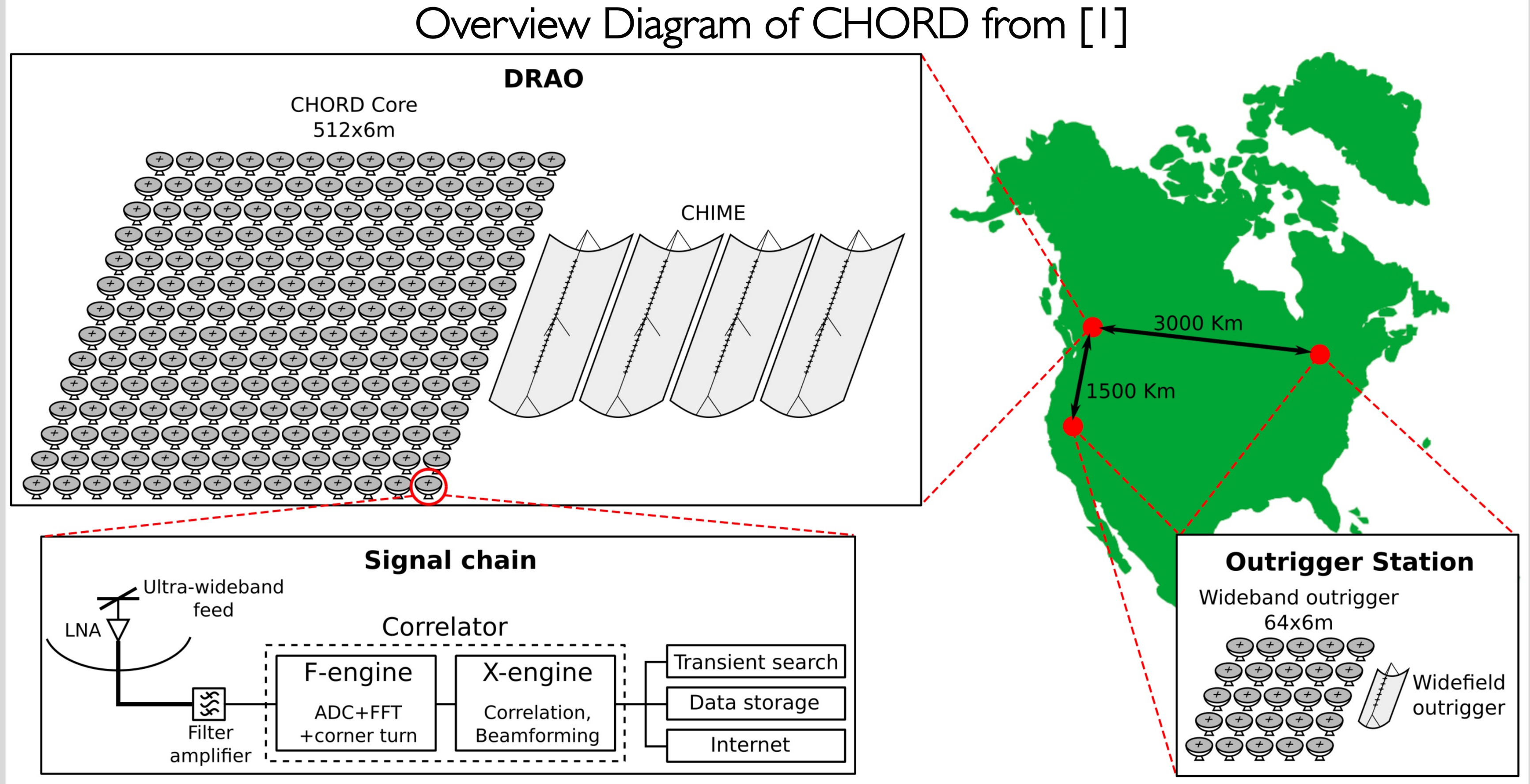


We attempt to use GNSS as a calibration tool in cosmology and radio transient localization experiments in Canada.

The Deep Development Array [D3A(6)]

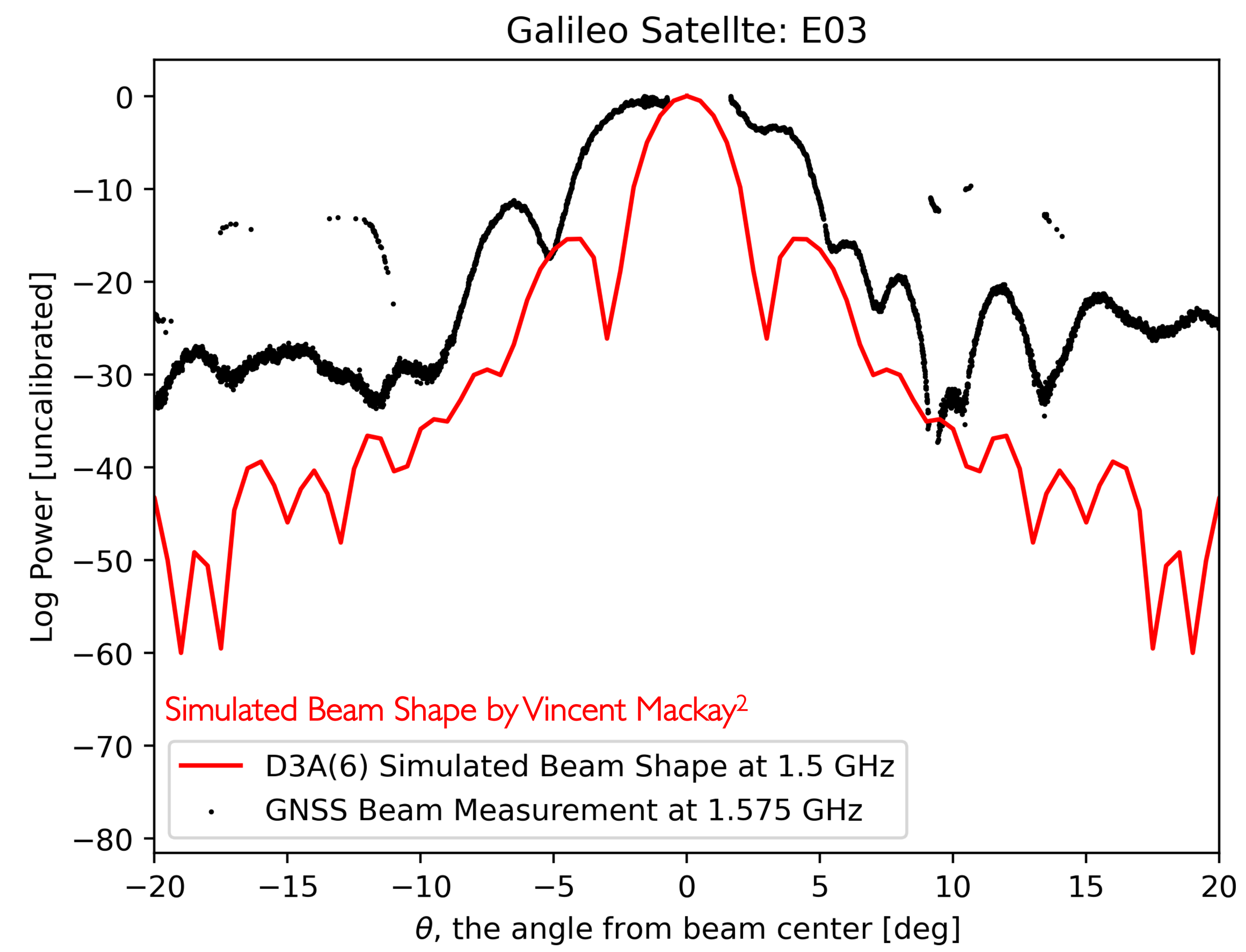
- consists of 3 six-meter dishes designed as a test bed for the Canadian Hydrogen Observatory and Radio Transient Detector (CHORD) [1].
- will test the consistency of the composite dishes and novel techniques for ultra-wideband receivers and signal processing.
- observes as a 2-element interferometer between 300-1500MHz.
- is located at the Dominion Radio Astrophysical Observatory (DRAO) near Kelowna, British Columbia next to the Canadian Hydrogen Intensity Mapping Experiment (CHIME).

Overview Diagram of CHORD from [1]



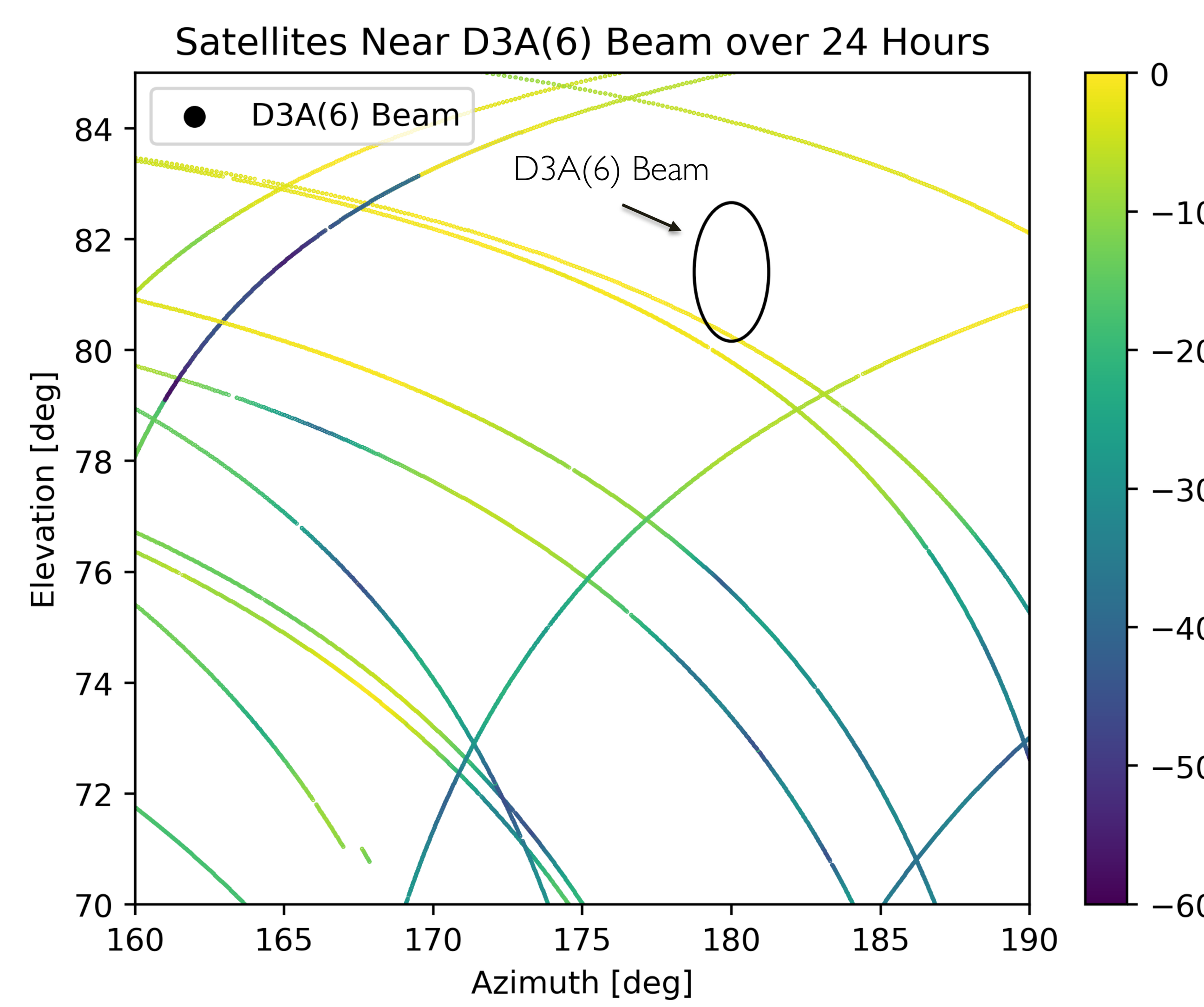
Beam Calibration

Key GNSS observable: satellite power



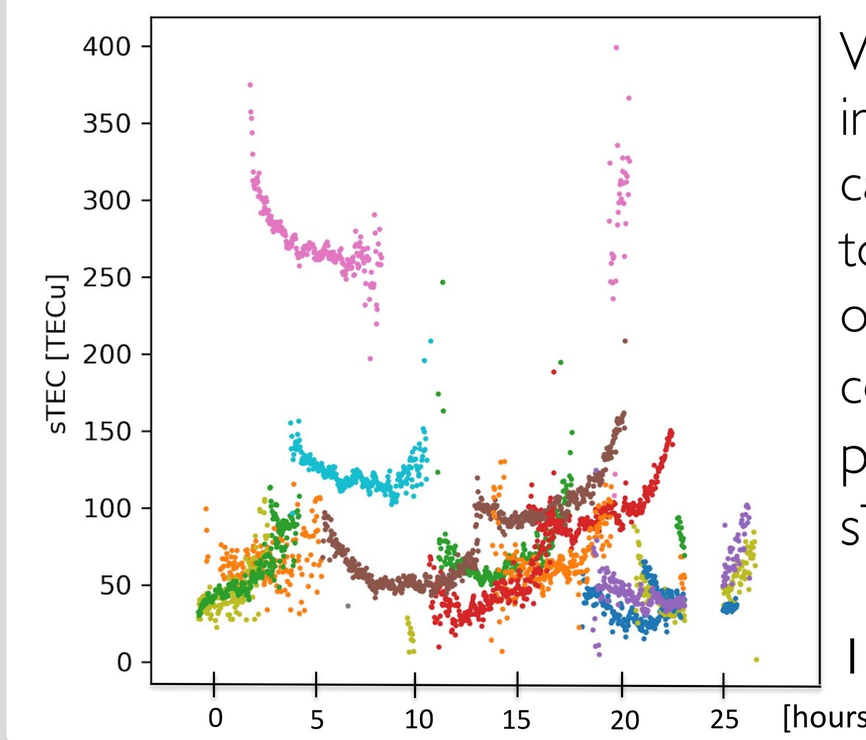
Above: As a satellite passes close by, it maps the D3A(6) beam. There is a large discrepancy in shape between the two beams. We are still working on understanding this mismatch. This is the first time a beam map for a radio telescope has been created with GNSS satellites!

Below: Power (color) and position of GNSS satellites visible from D3A(6) over 24 hours of data collection. The power of satellites increases significantly towards the center of the beam. We zoom in near the beam's center.



Ionospheric Calibration

Key GNSS observables: satellite pseudorange (ρ) and phase



We use the ionospheric delay contained in the phase and distance the receiver calculates for the satellite (pseudorange) to extract lines of sight measurements of the ionosphere's slant total electron content (sTEC). Each color on the left plot is a different satellite tracking the sTEC during a day long observation.

1 TECu = 10^{-16} el/m^2

Why are GNSS calibrations advantageous?

- **Beam Calibration** - Studying the early universe with 21cm line intensity mapping requires extremely precise measurements of the beam. CHORD has other science, including galactic science, transient detection and localization, which could benefit from these beam maps.
- **Ionospheric Calibration** - Real-time ionospheric calibration with GNSS receivers *could* increase precision of fast radio burst localization below the 50 mas level with CHIME Outriggers. However, this level of precision puts us close to the limits of the currently best available measurements of the ionosphere made with GNSS (relative TEC of ~0.01 TECu [2]).

Discussion and Future Work

- **Longer observations** of the D3A(6) beam with GNSS signals will be required to properly determine the limits of this method, especially in understanding the differences between the beam map and simulation. In addition to the shape, we also need to compare the power of the beam simulation to the map we measure.
- Currently, a GNSS receiver is used in the power and phase measurement. We are limited in our understanding of the receiver's systematics by using this preprocessed data. **Using raw voltage data** and extracting the signal through our own software may prove a more precise method. This will be explored in future work for both power and phase measurements.
- We will **combine GNSS receiver measurements with global ionospheric maps** to improve the measured ionospheric TEC precision.

Calibrating CHORD beams with GNSS may prove a powerful method in helping us extract information about the early universe.

References: [1] Vanderline et al. (2019). LRP 2020 Whitepaper: The Canadian Hydrogen Observatory and Radio-transient Detector (CHORD).
[2] Coster et al. (2012). Accuracy of GPS total electron content: GPS receiver bias temperature dependence. Radio Science. 48. 190-196.

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