Phase Stability and Fading Analysis of WWV Ionospheric Propagation for Adaptive HF Radio

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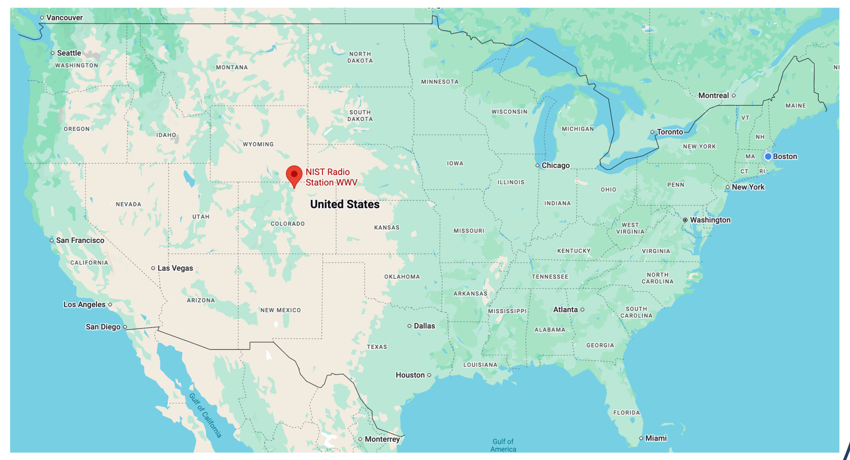
Abstract

We present an analysis of the characteristics of the WWV time signal observed simultaneously at two geographically separated receivers in eastern Massachusetts. Our work has applications in assessing the feasibility of adaptive correction for ionospheric phase distortion in HF communications — analogous to adaptive optics in astronomy. Using KiwiSDR software-defined radio receivers connected to magnetic dipole antennas at Cambridge and Sudbury MA (~32 km apart), we recorded IQ samples at 2.5, 5.0, 10.0, 15.0, 20.0, and 25.0 MHz over multiple 88-second intervals. The receiver in Cambridge uses a hybrid coupler to extract circular polarization from orthogonal magnetic loops. We measure carrier phase, characterize fading statistics, and compute the phase structure function D(τ) to quantify phase stability over 20 ms intervals. This time lag corresponds to the round-trip travel time for active compensation of ionospheric variation over a 2000 km path. Results show that 5 MHz exhibits excellent phase stability (RMS ~0.08–0.20 rad at 20 ms lag) during morning hours, while 25 MHz shows even better stability (RMS ~0.12 rad at 20 ms lag) during the afternoon when the ionosphere supports skywave propagation at higher frequencies. Fading events are uncorrelated between the two sites, indicating that the RF scintillation pattern on the ground has its dominant structure on spatial scales smaller than 32 km.

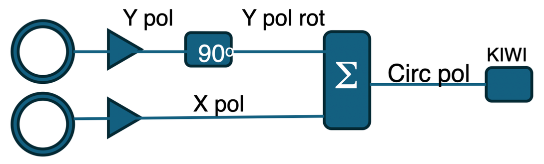
Introduction

- One of the cornerstones of long-distance radio communication is skywave propagation: the process of HF radio emissions being reflected and refracted in the ionosphere to reach farther receivers.
- The interaction of the carrier waves with the ionosphere introduces various effects that impede communication, including phase decoherence and amplitude fading. These effects are difficult to predict, with time, position, and polarization dependence.
- In theory, these effects can be accounted for by analyzing the phase stability of incoming signals and dynamically changing carrier frequency to optimize phase coherence.
- There are potential applications in designing adaptive radio technology to improve both signal stability and communication speed.
- Experiment: Measure phase variability of WWV time signal at different frequencies, locations, and polarizations. We are looking for sub-radian phase stability at ~20 ms time scales (20 ms is the approximate round-trip time for signals traveling between Fort Collins and Boston) .

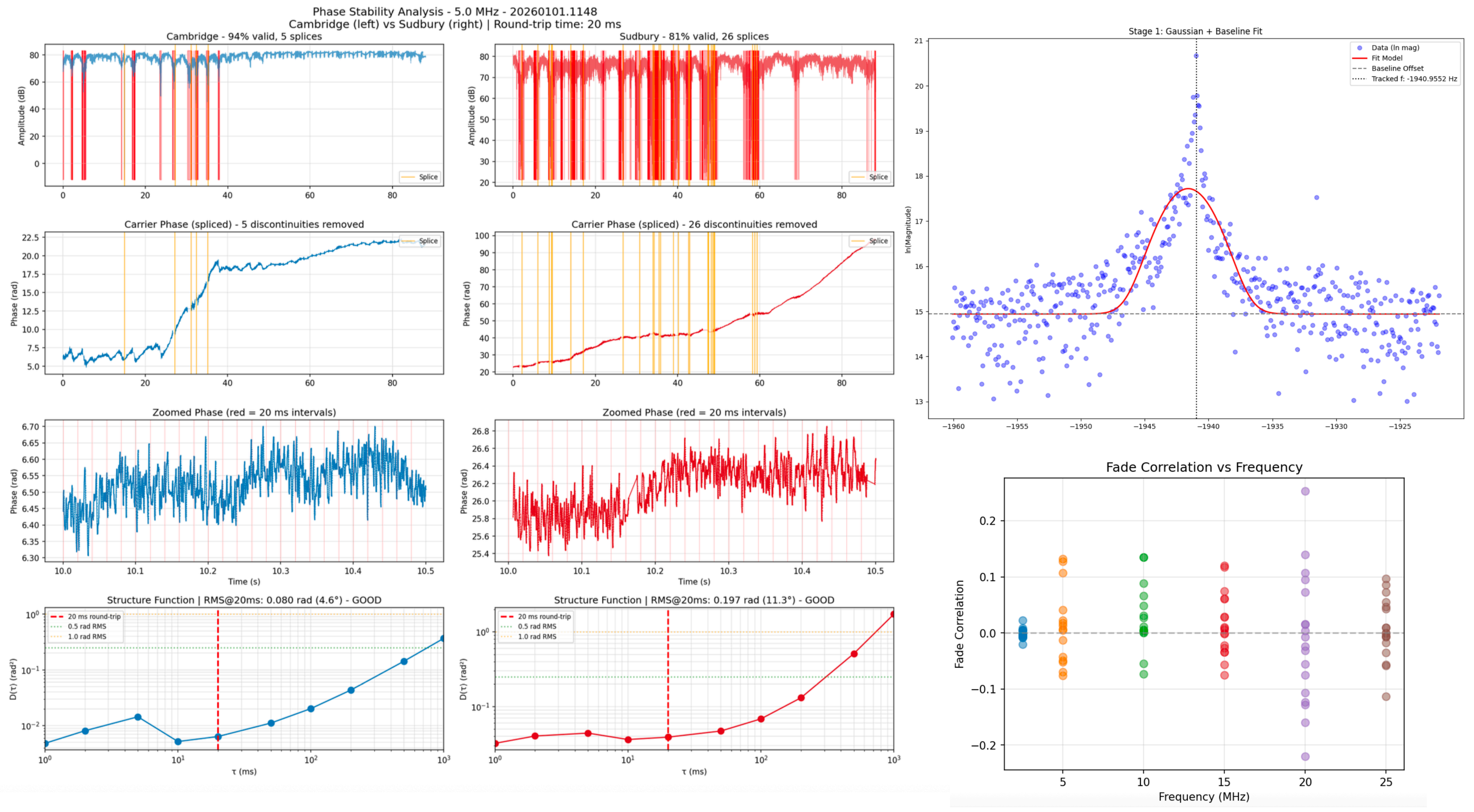


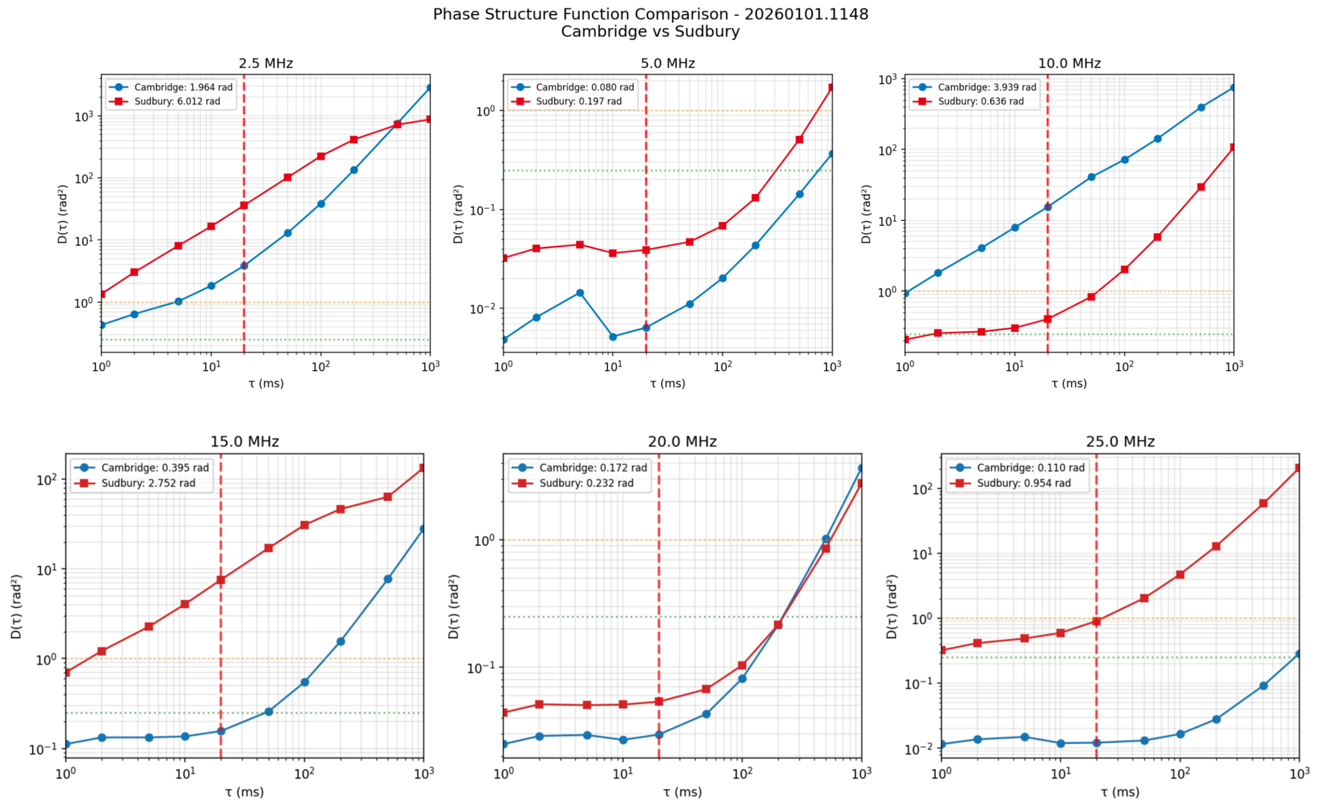
Method/Experiment

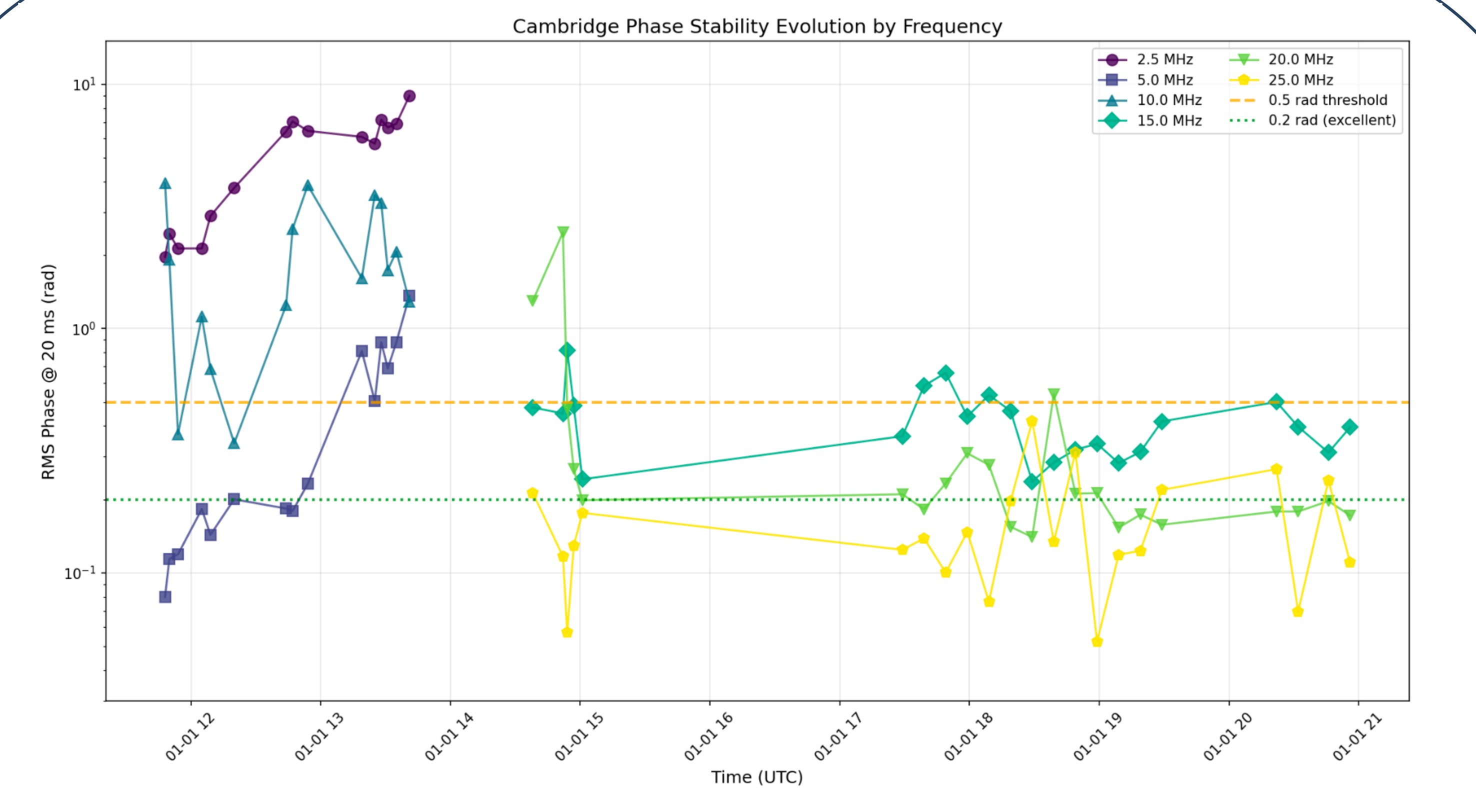
- Built a receiver with two orthogonal magnetic loop antennas in Cambridge, and one loop antenna in Sudbury 32 km away.
- Recorded IQ data from WWV time signal at 5, 10, 15, 20, and 25 MHz; phase information sampled from a 2 kHz offset
- Calculated phase structure function D(τ) to quantify phase stability for each observation.
- Recorded fading information and checked correlation between the two locations
- KiwiSDR 2: Software-defined radio for RF data collection
- Both loops in Cambridge feed into a 90° offset hybrid coupler in order to measure circular polarization component. The signal from one loop is unchanged, while the signal from the other loop receives a quarter cycle phase shift. When these two are added together by the coupler, the output is the projection of the signal onto a circular basis.



Data and Analysis







Conclusion

- The two-loop antenna in Cambridge experienced higher average amplitude and less fading than the one-loop antenna in Sudbury, which is consistent with Faraday rotation putting incoming signal off axis for linear antennas and demonstrates the ability of our two-loop antenna to counteract it.
- Very little correlation was observed in phase or amplitude between each site, suggesting that that ionospheric conditions are largely uncorrelated at ~32 km scales.
- Consistent with our understanding of the D and F levels, we find strong phase stability from the 5 MHz signal in the very early morning, and we find that 20 and 25 MHz are strongest in the afternoon once the ionosphere layers become more ionized.
- With the right selection of frequency and polarization, we are able to observe phase variance below our target of ~0.5 on 20 ms time scales.
- Future research goals include observing signals from other locations, deploying a one-loop and two-loop antenna at every observing site, and completing a simulation of ionospheric propagation to compare with our experimental results.

References

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HamSCI Workshop 2026