Characterizing Short-term Variability in VGOS Group Delay Observables

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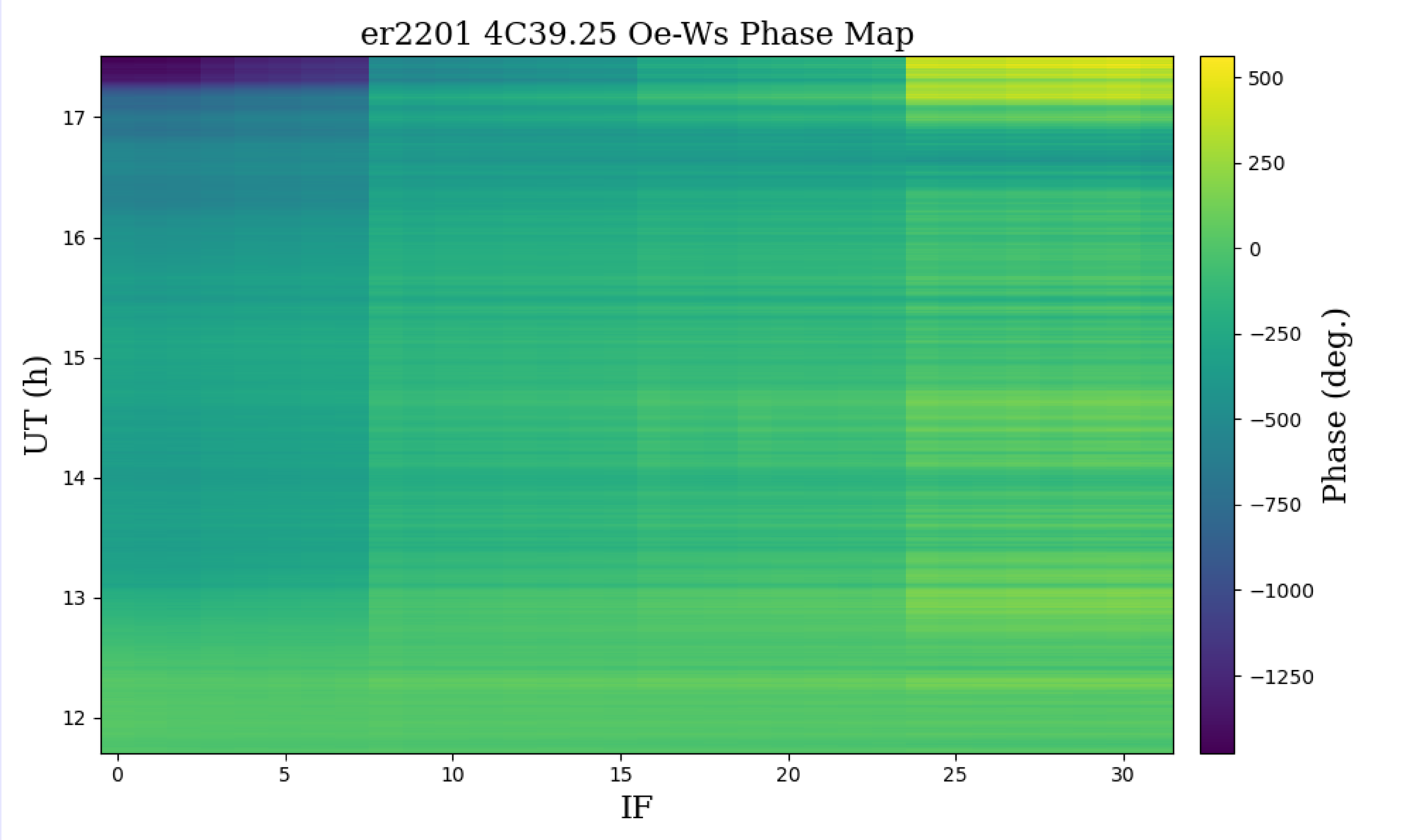
Motivation

- The VLBI Global Observing System (VGOS) uses ultra-wideband linear receivers (from 2 GHz to 14 GHz) for high-precision station geodetic positioning.
- To achieve accurate geodetic and astrometric measurements, VGOS observes each radio source in scans as short as 7 seconds.
- However, group delay observables are affected by instrumental effects and potential systematic errors introduced, for instance, by atmospheric turbulence.
- **Objective**: perform a time-series analysis of the VGOS group delay to characterize its short-term variability to investigate its stability.

Group Delay and dTEC Estimates

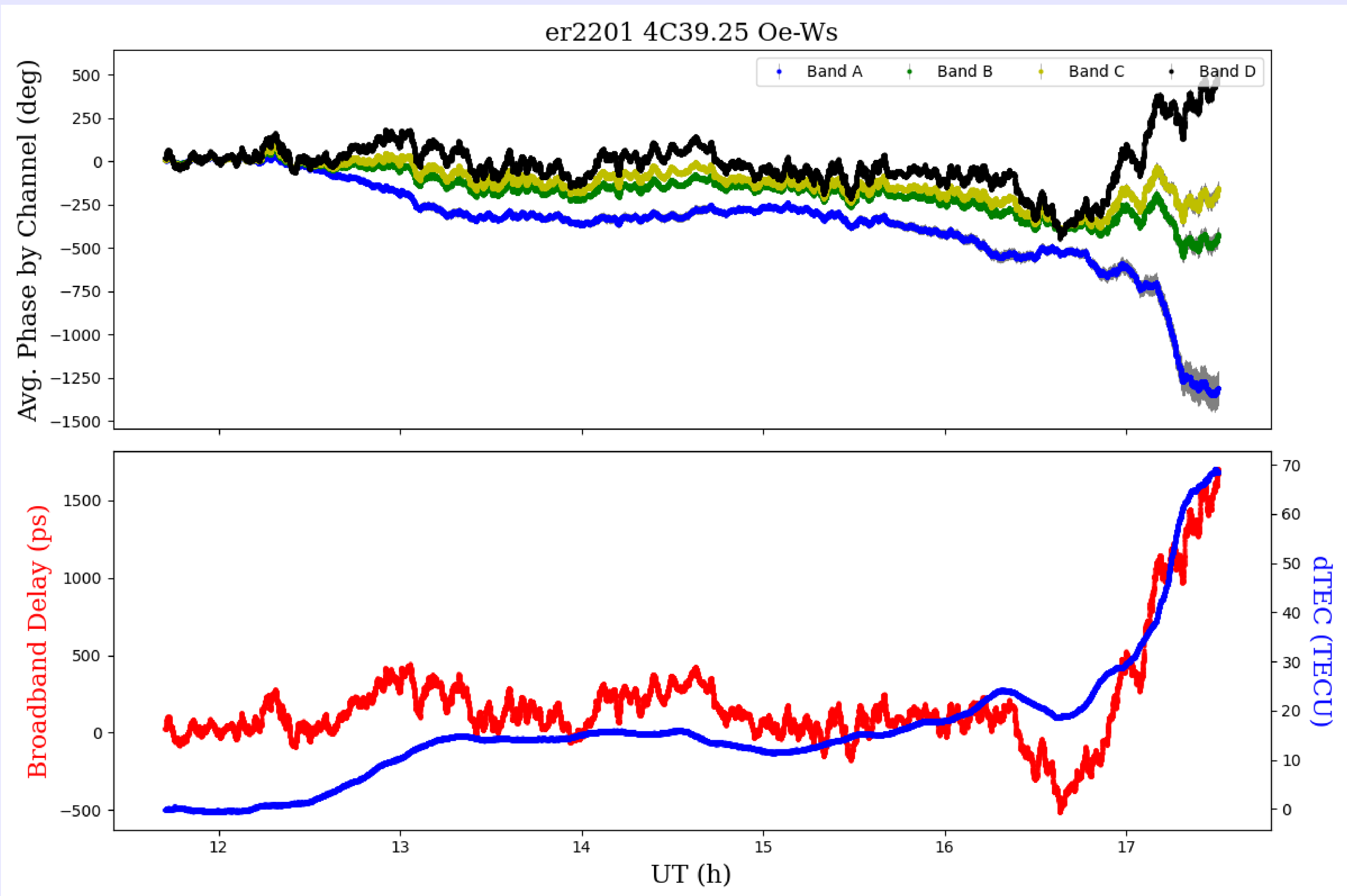
- To obtain VLBI observables with a 1-second sampling rate, we follow two steps:
  1. Retrieve phases for each IF by fringe-fitting 600-second scans using **`fourfit`**. The output from this step is the type 2 data in Mk4 file format.



Phase evolution over the full VGOS frequency range (horizontal) and throughout the 6-hour experiment (vertical).

  2. Estimate residual **group delay** (τ_g) and TEC (**dTEC**) from the retrieved phases, $\phi(\nu)$, at different IFs using a least-squares fit to the model:

$$\phi(\nu)\ \text{[rad]} = 2\pi \cdot \tau_g\ \text{[ns]} \cdot \nu\ \text{[GHz]} - \text{dTEC [TECU]} \cdot \frac{1.3445}{\nu\ \text{[GHz]}}.$$



- Top: Phases of the Oe-Ws baseline, averaged per IF across the VGOS band.
  - Phases are connected over time, with no discontinuities throughout the 6-hour observations.
  - Phase connection is achieved by resolving 2π ambiguities and ensuring continuity across scans.
- Bottom: Group delay (red) and dTEC (bllue) derived from the phases.
  - Both VLBI observables remain well-connected throughout the experiment.
  - Group delay exhibits clear short-term variability, associated to tropospheric effects.
  - Residual ionospheric dTEC shows smoother behavior, indicating stability over short timescales.

Conclusions

- VLBI observables (phases, τ_g, and dTEC) remain smoothly connected throughout long, continuous VGOS observations after fringe fitting, if no source structure effects contaminate the signal.
- Tropospheric and ionospheric effects influence phases differently, as reflected in group delay and dTEC variability:
  - Group delay, mainly impacted by the troposphere, exhibits high, short-term variability on timescales of $\sim$1 minute or less.
  - dTEC, indicative of residual ionospheric effects, varies over longer timescales (15-min to 1-h).
- Tropospheric effects vary more rapidly on longer baselines, as evidenced by the shorter timescales of their group delays compared to those of the short baselines (Oe−Ow and Mg−Wf).

Observations: : IVS experiment ER2201 (8 September 2022)

- 6 participating antennas: McDonald (Mg), the twin Onsala telescopes (Oe and Ow), Westford (Wf), Wettzel (Ws) and Yebes (Yj).
- Radio-signal sampling: 4 spectral bands, A, B, C and D, centered at 3.3, 5.5, 6.6 and 10.5 GHz, divided into 32 spectral windows (spws) of 32 MHz each, with a total recorded bandwidth of 1 GHz.
- Yebes experienced issues in bands B and D, preventing its use for group delay and dTEC estimation.
- 6-hour continuous observation of the same target, **4C39.25**.
- **4C39.25** high flux density allows us to determine group delays and dTEC with one-second cadence and characterize tropospheric effects.

Characterization of Group Delay Variability

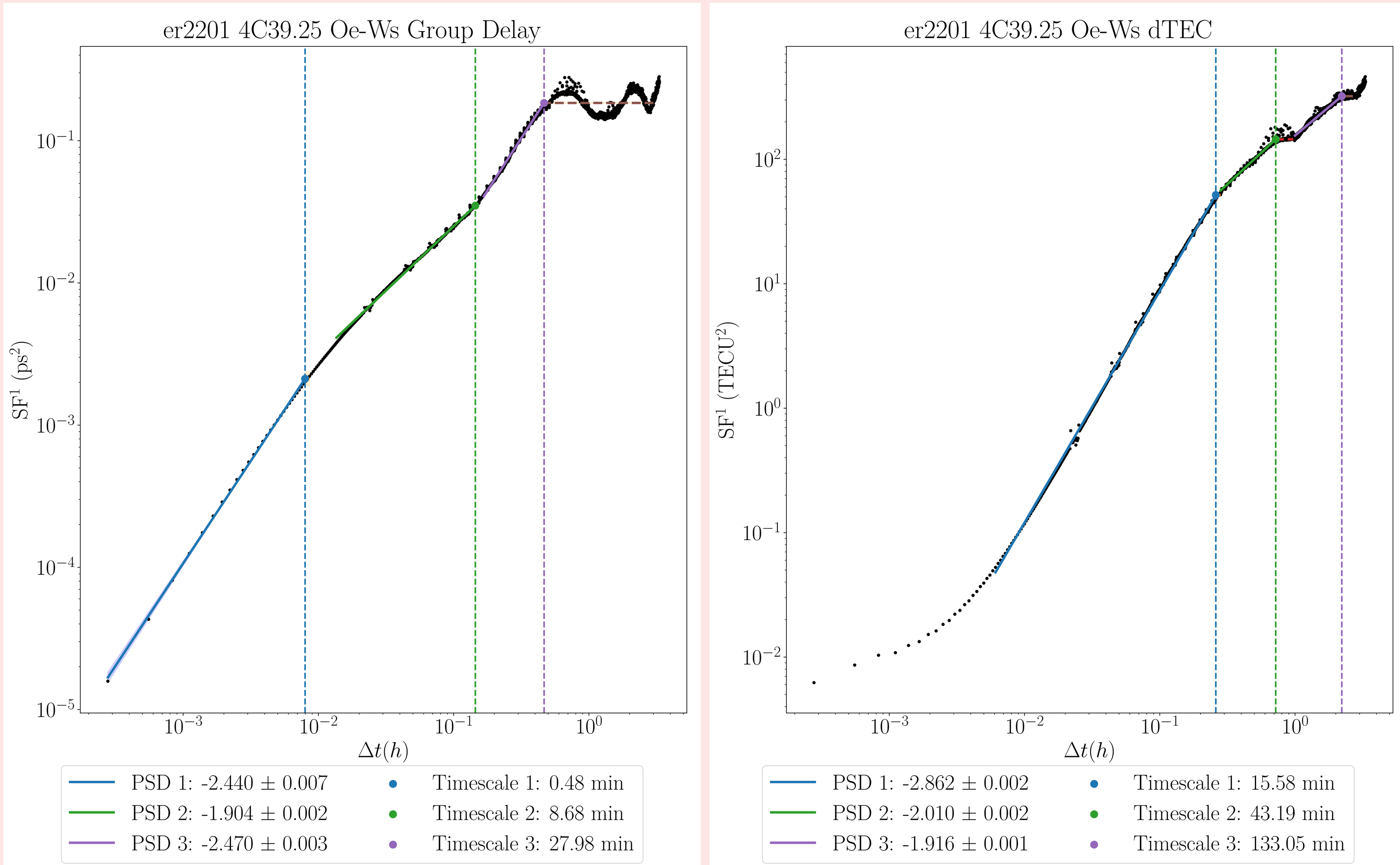
- To characterize the variability of the VLBI observables, we use two tools:
  1. The Structure Function [1], which provides estimates of the Power Spectral Density (PSD) and characteristic timescales. The SF at a time lag Δt is computed as the sum of all the pairs in the time series $\{x_i\} = x_1, x_2, \ldots, x_n$, for which $(t_j - t_i) \leq \Delta t$, with $N_{\Delta t}$ the number of such pairs:

$$SF(\Delta t) = \frac{1}{N_{\Delta t}} \sum_{i,j=i+1} (x_j - x_i)^2, \text{ with PSD} \propto f^{-1-\beta_{SF}}.$$

  2. The High-Pass Filter Periodogram [3], an improved implementation of the classic Periodogram [2], which applies a frequency-dependent high-pass filter to suppress low-frequency variability components below a given frequency, ω, before computing the periodogram

$$P_X(\omega) = \frac{1}{2}\left\{ \frac{\left[\sum_j X_j \cos\omega(t_j - \tau)\right]^2}{\sum_j X_j \cos^2\omega(t_j - \tau)} + \frac{\left[\sum_j X_j \sin\omega(t_j - \tau)\right]^2}{\sum_j X_j \sin^2\omega(t_j - \tau)} \right\}, \text{ where } \tan(2\omega\tau) = \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}.$$

  This tool provides robust estimates of the PSD of the VLBI observables and helps identify periodicities in the signal.



Structure Function of the group delay (left) and dTEC (right). The fitted slopes β_{SF} provide estimates of the PSD, using the relation PSD $= -1 - \beta_{SF}$. The plateau marks the timescale of the variability.

Results from the Analysis of the VLBI observables.

Oe - Ws	PSD	Timescale (min)	Ow - Ws	PSD	Timescale (min)
τ_g	-2.440 ± 0.007	0.48		-2.435 ± 0.008	0.48
dTEC	-2.862 ± 0.002	15.6		-2.863 ± 0.002	15.6
Oe - Wf	**PSD**	**Timescale (min)**	**Ow - Wf**	**PSD**	**Timescale (min)**
τ_g	-2.104 ± 0.007	1.10		-2.183 ± 0.005	1.08
dTEC	-2.787 ± 0.003	17.3		-2.796 ± 0.002	17.2
Oe - Ow	**PSD**	**Timescale (min)**	**Wf - Ws**	**PSD**	**Timescale (min)**
τ_g	-2.530 ± 0.006	4.33		-2.125 ± 0.006	0.92
dTEC	-2.500 ± 0.003	10.9		-2.758 ± 0.002	41.2
Mg - Wf	**PSD**	**Timescale (min)**	**Mg - Ws**	**PSD**	**Timescale (min)**
τ_g	-2.356 ± 0.005	3.89		-2.089 ± 0.002	1.26
dTEC	-2.971 ± 0.002	40.5		-2.862 ± 0.002	15.6
Mg - Oe	**PSD**	**Timescale (min)**	**Mg - Ow**	**PSD**	**Timescale (min)**
τ_g	-2.165 ± 0.005	0.94		-2.179 ± 0.004	0.95
dTEC	-3.000 ± 0.002	55.8		-2.797 ± 0.002	59.8

- Group delays exhibit lower PSDs and shorter timescales, compared to the higher PSDs estimates and long-term variability observed for the dTEC.
- Due to their proximity, the results obtained for baselines involving one of the Onsala telescopes are consistent with those involving the other, as the atmospheric conditions between them are more similar than those at other stations.
- The group delay on the two short baselines (Oe−Ow and Mg−Wf) shows longer timescales (~ 4 minutes), indicating lower variability compared to the longer baselines.
- The periodogram reveals a clear periodicity in the Oe−Ow group delay of ~ 10 minutes.
- Baselines involving Mg missed the final two hours of observations, reducing the reliability of the estimated dTEC timescales, as the light curve duration approaches the longer time lags.

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