Impact of Time-dependent Atmospheric Turbulence on Geodetic VLBI Precision

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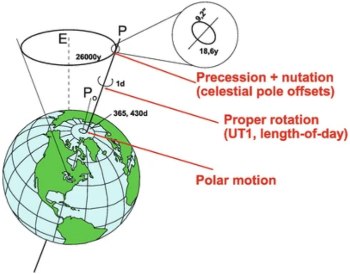
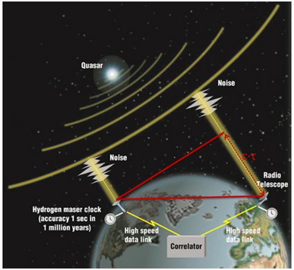
Outline

Introduction

- VLBI Geodesy concerns with precise measurements of Earth Orientation Parameters (EOP) and station positions
- The primary observable is the time difference (or delay) between two stations from quasar signals
- Radio signal subject to ionospheric and tropospheric delays



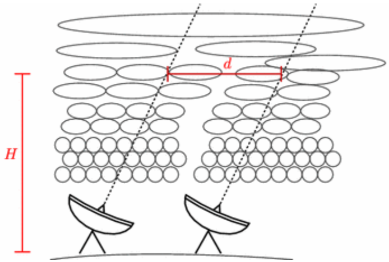
[Modified after Vondrák, 2018]



[Modified after *SGP Techniques: VLBI* 2025]

Atmospheric Delays & Modelling

- Hydrostatic and wet delay
  - Hydrostatic: calculated from atmospheric pressure at surface
  - Wet: estimated with geodetic techniques or measured by water vapor radiometer
- C_n^2: refractive index structure constant, magnitude (strength) of turbulence
- C_n^2 can vary seasonally in some locations



[Modified after Halsig et al., 2016]

Traditional Simulation Approach

- Run simulations before real sessions to optimize scheduling
  - New scheduling strategies
  - Station network geometries
  - Influence of specific effects (atmosphere, source structure)
- Current VLBI simulations utilize constant C_n^2 values, despite well-established seasonality

$$o - c = (\mathrm{zwd}_2 \cdot \mathrm{mf}(\epsilon_2) + \mathrm{clk}_2) - (\mathrm{zwd}_1 \cdot \mathrm{mf}(\epsilon_1) + \mathrm{clk}_1) + \mathrm{wn}_{bsl}$$

Project Goals

- Calculate monthly C_n^2 values from nearby GNSS stations
- Incorporate seasonal C_n^2 variations into session simulations
- Assess impact on EOPs (dUT1) using VLBI "Intensive" sessions
  - Simpler network geometry, fewer stations
  - More frequent sessions per baseline
  - Lower latency
- Compare results with traditional approach

Data

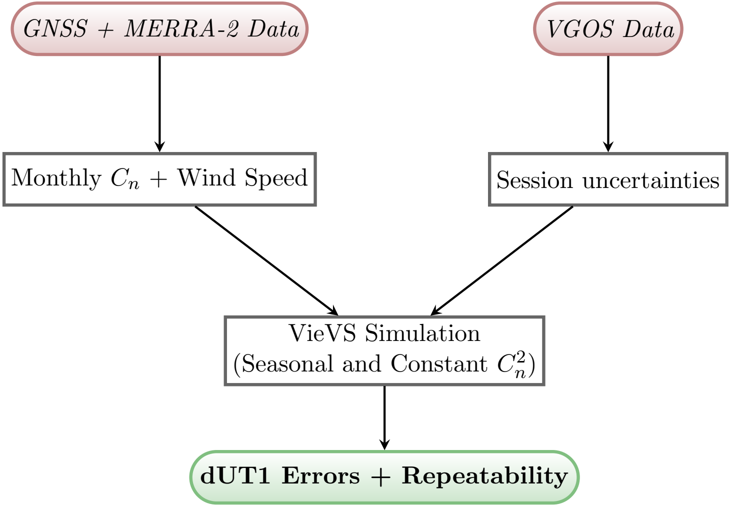
- GNSS Data: Wet delay data from Nevada Geodetic Laboratory to calculate C_n^2
- MERRA-2 Reanalysis Data Model: to calculate C_n^2 and obtain wind speed
- VLBI Data: Intensive sessions from 2021-2024 from CDDIS

Methods: Obtaining C_n^2

- Calculate monthly (τ) variance of zenith wet delays (ZWD)
- Net wind speed (v) from NASA MERRA-2 reanalysis data model
- Effective height of troposphere (H)

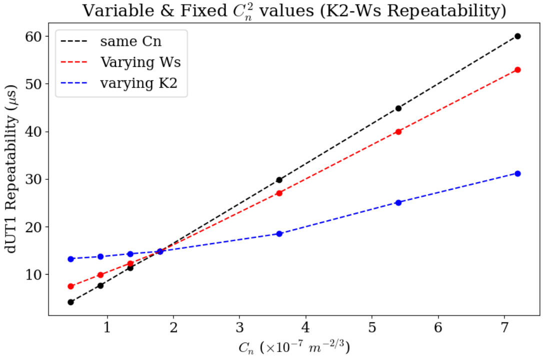
$$\sigma^2_{ZWD}(\tau) = \frac{1}{\tau^2}\int_0^{\tau}(\tau - t)\int_0^{H}\int_0^{H} C_n^2(z, z')\left[\left((z-z')^2 + v^2t^2\right)^{\frac{1}{3}} - \left|z - z'\right|^{\frac{2}{3}}\right] dz dz' dt$$

Processing


GNSS + MERRA-2 Data
VGOS Data
Monthly C_n + Wind Speed
Session uncertainties
VieVS Simulation
(Seasonal and Constant C_n^2)
dUT1 Errors + Repeatability

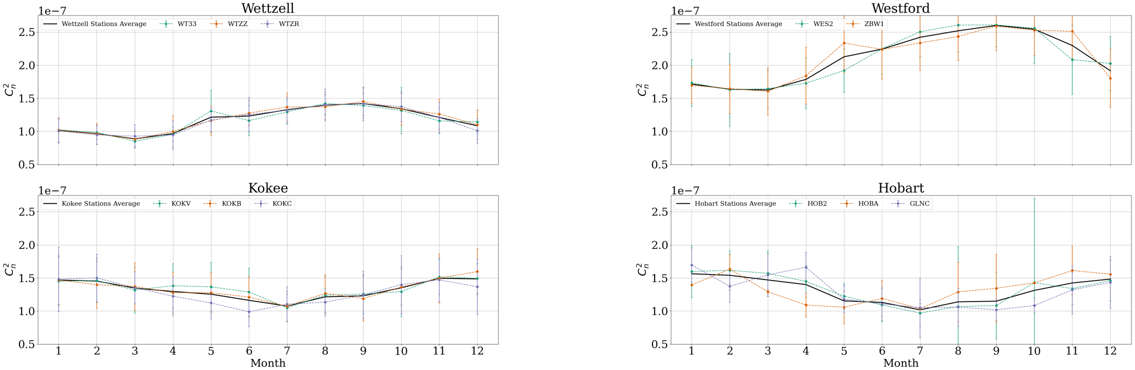
Impact of C_n^2 on Repeatability

- Wettzell (Ws) contributes more to variability than Kokee (K2)
- Suggests site-specific turbulence impacts



- Changes in tropospheric turbulence parameters (such as C_n^2) have greater impacts at certain stations, dependent on the baseline geometry

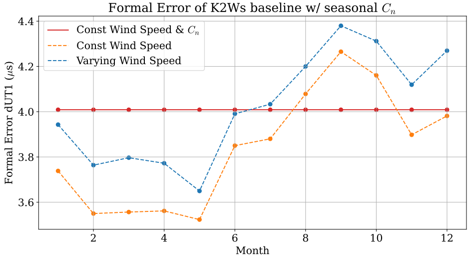
Seasonal C_n^2 Variations

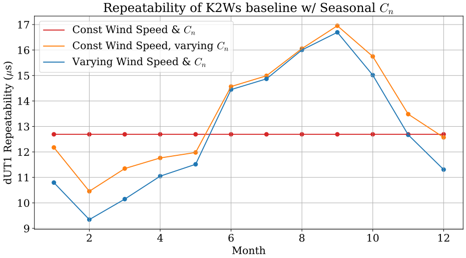


- C_n^2 is higher in summer and is dependent on local climate conditions

Impact of Seasonal C_n^2 on Formal Error and Repeatability

- Simulations in VieSched (Schartner et al., 2019) and VieVS (Böhm et al., 2018)
- Monte Carlo simulations assume Gaussian distribution

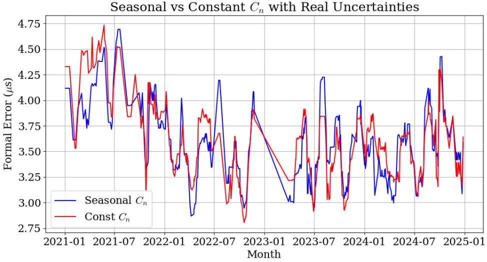




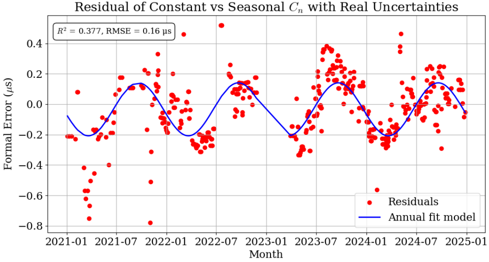
- The traditional simulation approach does not contain seasonal variations in formal error and repeatability
- Wind speed has minimal effect on repeatability

Impact of Seasonal C_n^2 on Formal Error

- We implement C_n^2 variations in simulations of past sessions, which includes variations in numbers of observations and other sources of errors



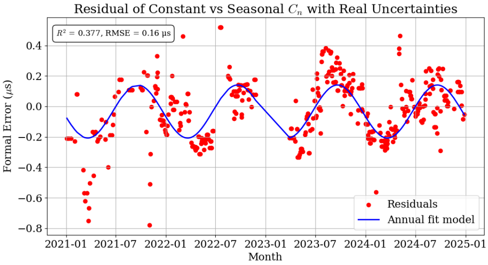
VieVS Simulation



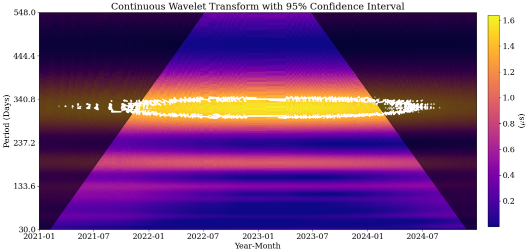
Residuals (Seasonal C_n^2 - Constant C_n^2)

- Seasonal C_n^2 variations result in seasonality in the dUT1 formal error residuals
- The constant C_n^2 approach underestimates formal error in the summer

Impact of Seasonal C_n^2 on Formal Error



Residuals

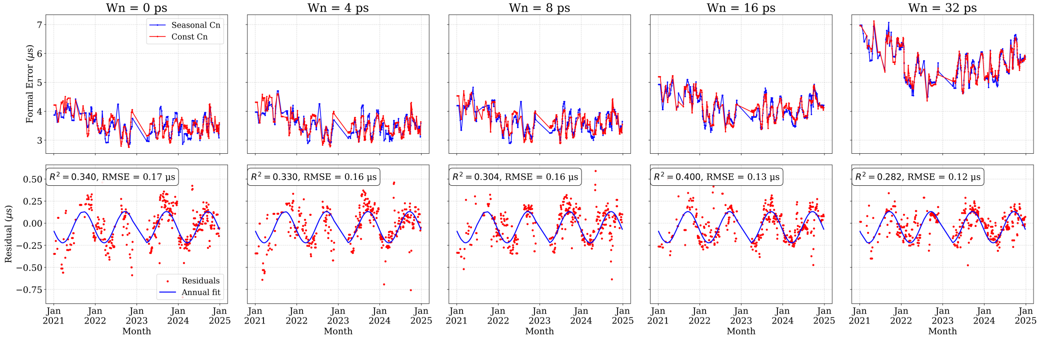


Continuous Wavelet Transform

- Once dUT1 formal errors are corrected for other sources of error, variations have a dominant period of approximately 1 year

Simulations with White Noise

- White noise is used to model measurement noise



White Noise Comparison

- Below a certain level of added white noise, atmospheric turbulence is the largest contributor to formal error

Summary

- Modelling seasonality of local C_n values for VLBI stations
- Incorporating C_n variations in simulations of dUT1 intensives
- Number of observations per session contribute to variations in formal error to a greater extent, however
  - Residuals reveal a strong seasonality in formal error for dUT1
- The traditional approach underestimates dUT1 formal error in the summer

Future Work

- Inclusion of Southern stations to mitigate seasonality
- 24-hr sessions and complicated network geometries
- Analysis of additional EOPs

References I

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Appendix A: Seasonal C_n^2 Variations