Enhancing Geodetic Parameter Estimation with Iterative VLBI Data Processing

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Project Goals:

- **Expand Vienna VLBI and Satellite Software (VieVS) to iteratively process multiple geodetic VLBI observing sessions**
- **Test software by estimating Westford – GGAO baseline length and investigating the impact of cable calibration**

Principles of Geodetic VLBI

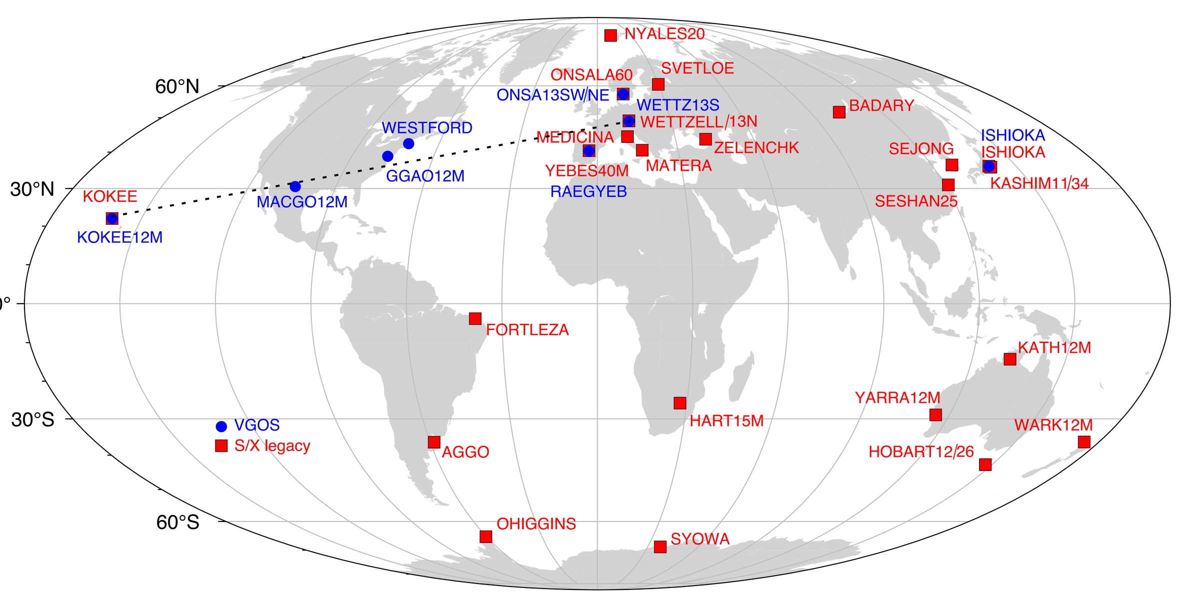


Figure 1: Map of worldwide geodetic VLBI observing stations

Adapting radio astronomy techniques to measure the Earth and its rotation

- Measure time delay between quasar signals received by two telescopes due to:
  - Geometry
  - Earth's rotation
  - Atmospheric delays
  - Clock variations
- Correlation: Align signals from each pair of telescopes (baseline) and produce time delays between measurements.
  - Astronomy: construct high-resolution images of radio sources with aligned signals from many baselines.
  - **Geodesy: extract parameters including Earth's rotation, site and source positions, and the atmosphere from time delays.**

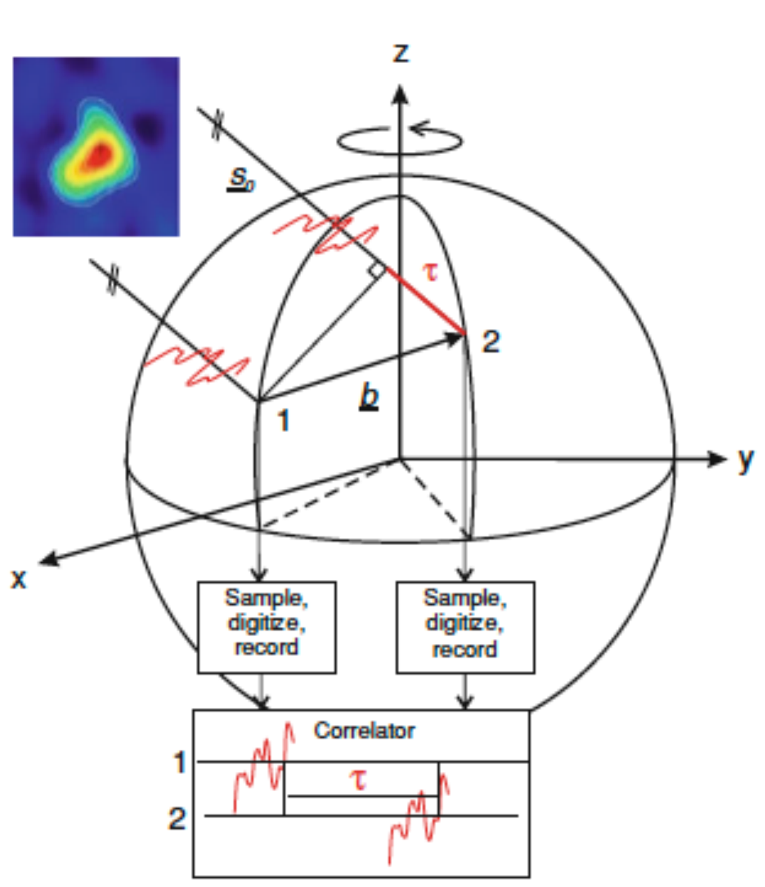


Figure 2: Geometric model of geodetic VLBI
Schuch & Böhm, 2013

What does geodetic VLBI measure, and why does it matter?

- **Earth Orientation Parameters (EOPs):** describe the Earth's rotation and orientation in space
  - VLBI is the **only** technique for measuring all EOPs, by showing us our location with respect to celestial sources.
  - EOPs link the terrestrial and celestial reference frames, allowing for precise navigation and positioning on Earth and in space.
- **Site and source positions:** define terrestrial and celestial reference frames

VLBI Data Processing with VieVS

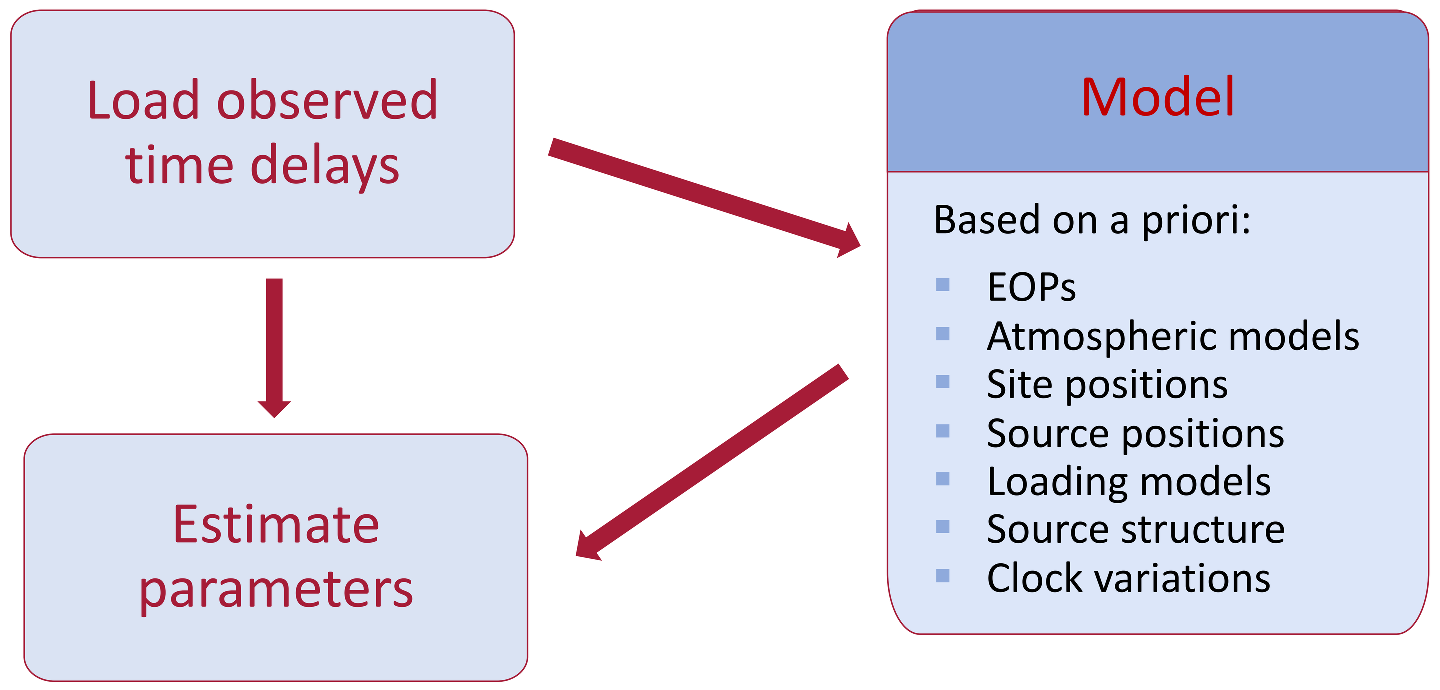


Figure 3: Structure of VieVS geodetic processing modules

Challenges of VieVS Data Processing:

- Reducing χ_ν^2 goodness-of-fit to unity by adding noise to observations
- Time-consuming iteration process
- Outlier elimination
- Limited reproducibility

Solution: Automated version of VieVS software for batch processing of VLBI sessions

Figure 4 illustrates the data flow for the processing of a single session with the new system for batch-processing VLBI session observations.
This process is automatically performed for each selected session, reducing processing time per session from hours to ~5 minutes.

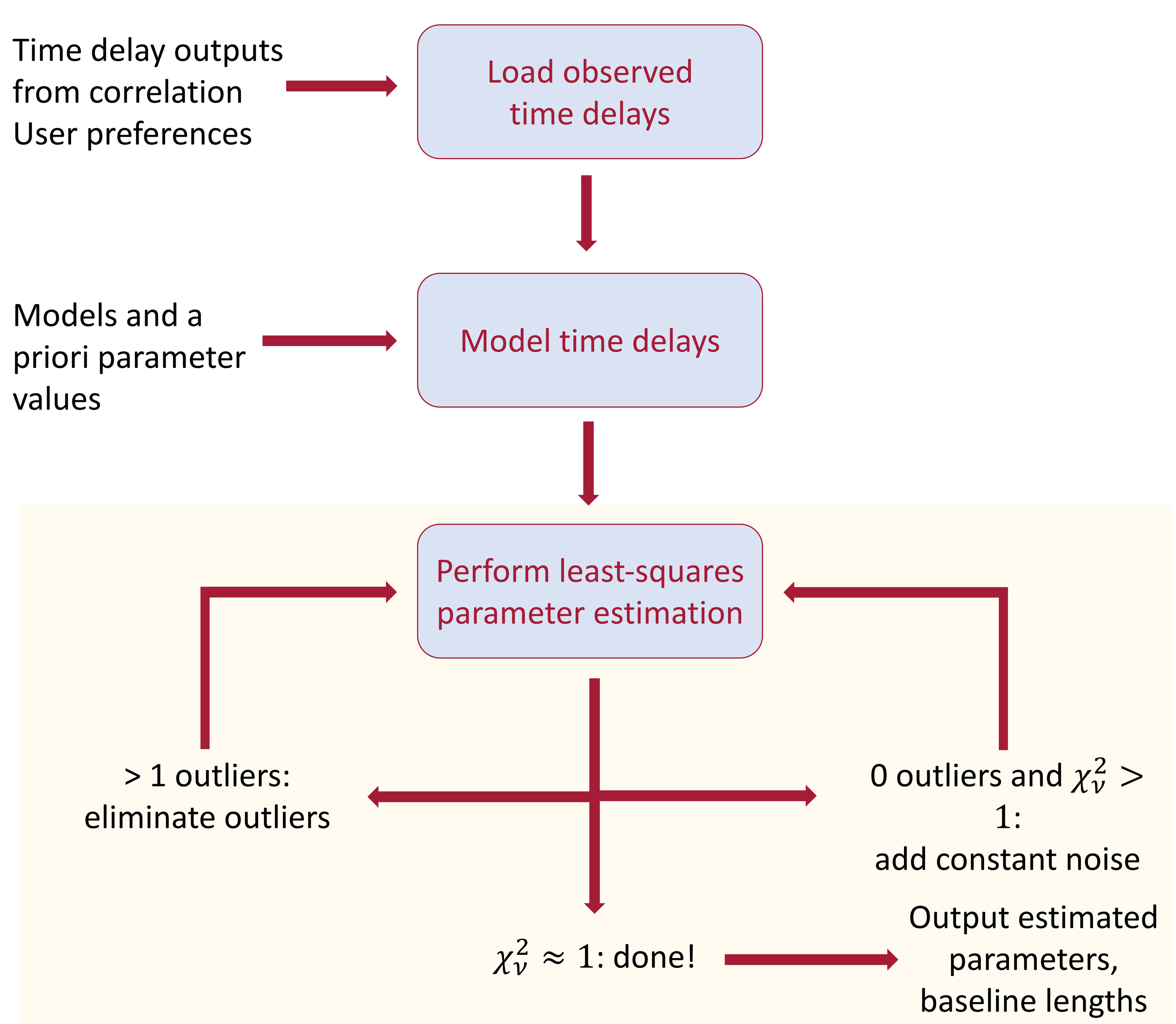


Figure 4: Data flow for iterative processing of a single VLBI session. Yellow box indicates functionality added to VieVS software.

Testing Software with VLBI Estimates of the Westford – GGAO Baseline

Test 1: Estimating Westford – GGAO baseline length

- Niell et al. 2018: demonstrated VGOS system by estimating baseline length between Westford Antenna and Goddard (GGAO) stations for 2014 – 2017 sessions.
- We extend time series by estimating baseline length for 121 sessions from 2019 – 2024.
- Include only Westford and GGAO stations, fixing Westford clock and station position.
- Also estimate clock models (20 min interval), zenith wet delay (15 min), gradients (1 hr).

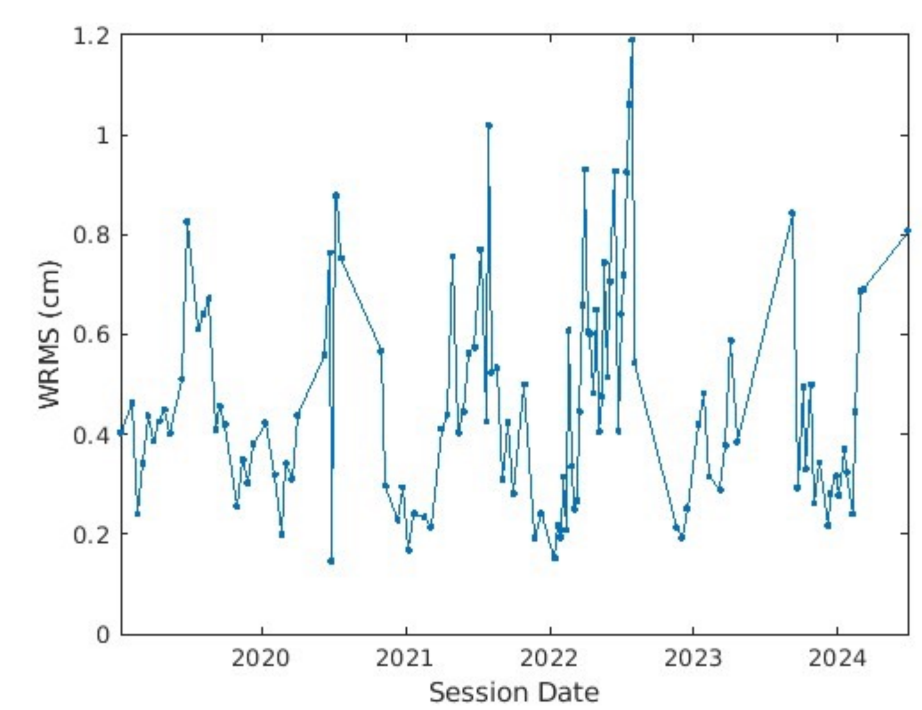


Figure 5: Post-fit group delay residuals after iterative least squares processing of 2019 – 2024 sessions

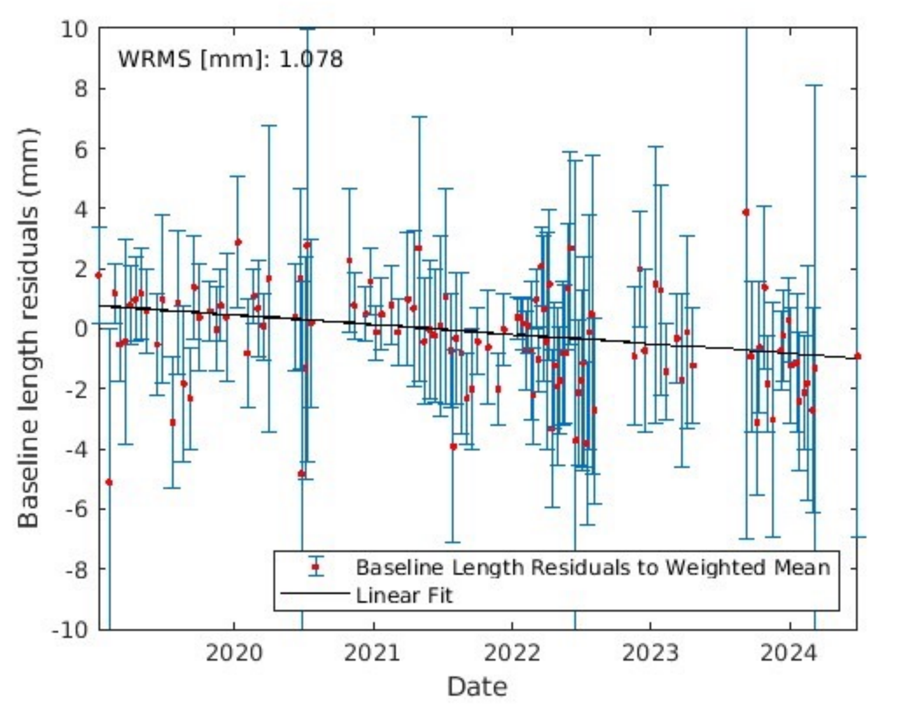


Figure 6: Time series of residuals to weighted mean of Westford – GGAO baseline length estimates for 2019 – 2024 sessions

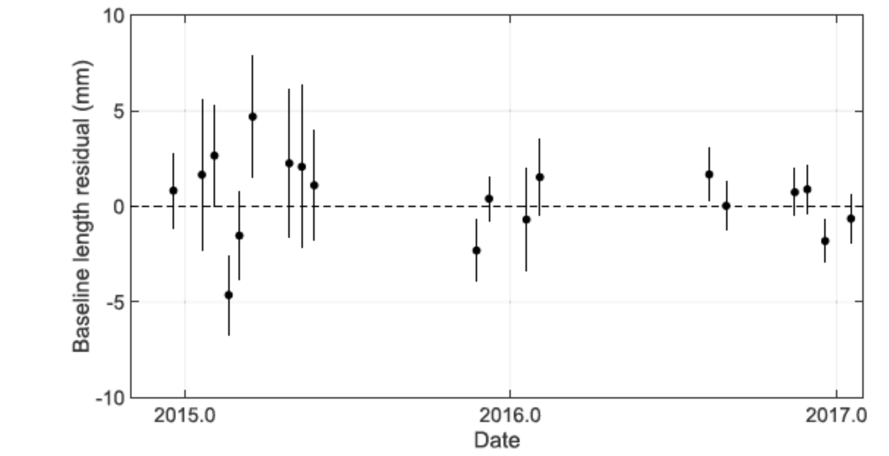


Figure 7 (left): Time series of baseline length residuals to weighted mean for 2014 – 2017 sessions (Niell et al.)

Our WRMS of 1.1 mm is comparable to Niell et al.'s value of 1.2 mm.

Test 2: Cable Delay Calibration

- Coaxial cables in instrumentation introduce time and phase delays in measured signal.
- With cable calibration, measure cable phase delay and correct VLBI measurements.

Figure 8: Residuals of 2019 – 2024 baseline lengths to linear model, with (top) and without (bottom) cable calibration for GGAO station

Figure 9: Variation in phase delay over azimuth and cable replacement times for GGAO 12-m dish from 2019 – 2024 (adapted from Pfeiffer et al. 2024)

Figure 8

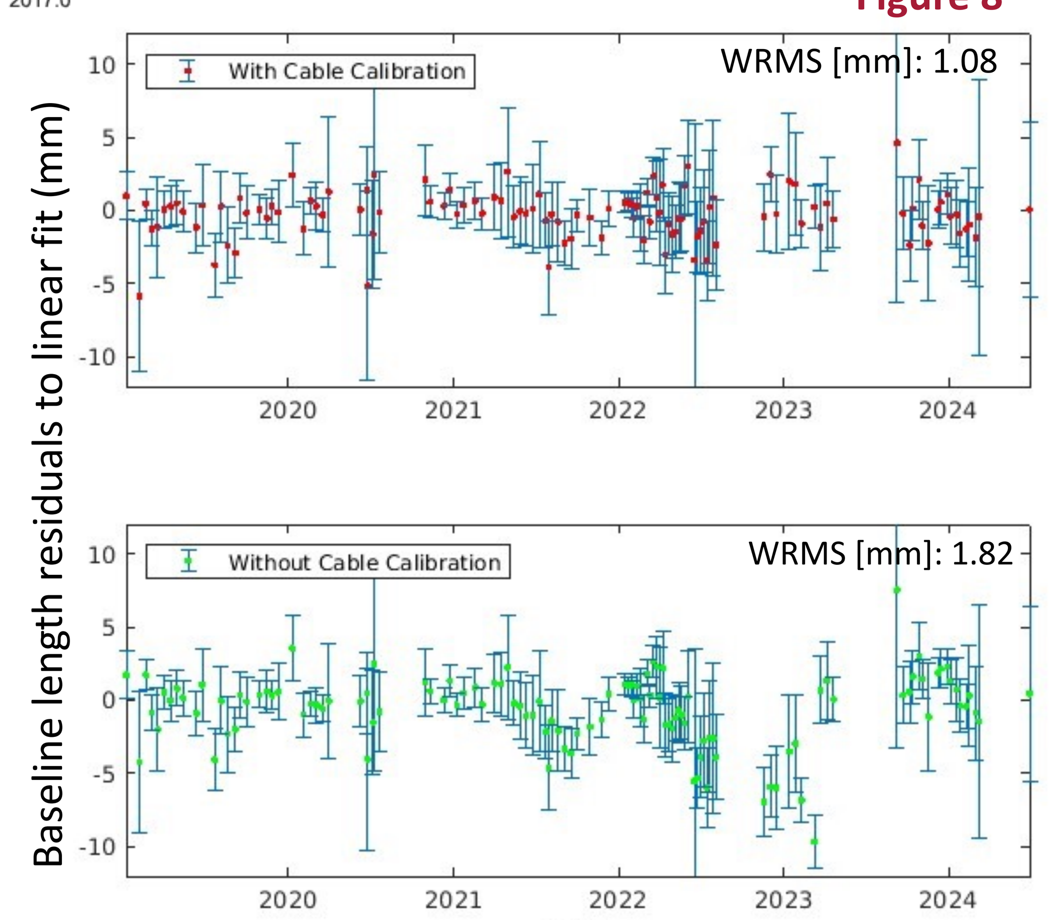
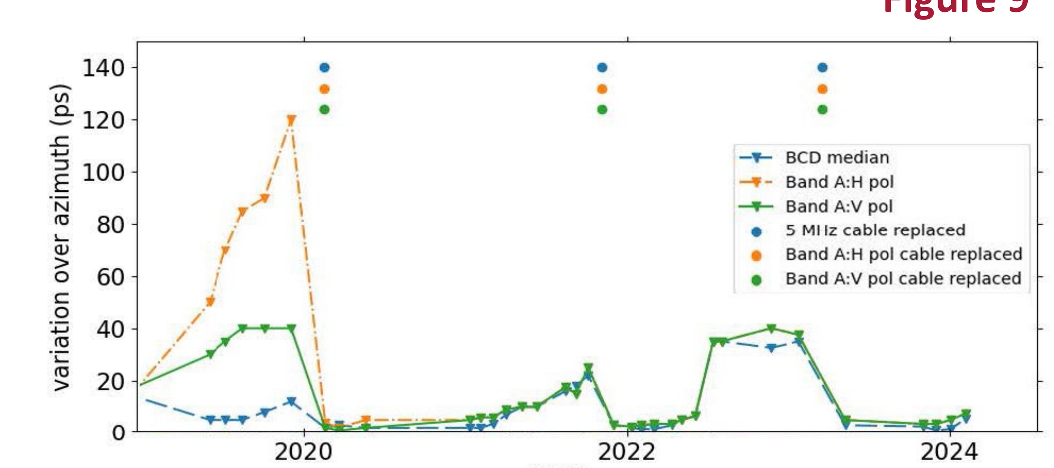


Figure 9



Summary:

- New software greatly improved the efficiency of iterative VLBI processing with VieVS, as confirmed by baseline length estimates.
- Cable calibration effectively corrects variations in baseline length estimates due to cable deterioration.

References:
Böhm, J. et al., Vienna VLBI and Satellite Software (VieVS) for Geodesy and Astrometry, Publications of the Astronomical Society of the Pacific, Vol. 130(986), 044503, 2018; H. Krasna et al. VLBI Celestial and Terrestrial Reference Frames VIE2022b, A&A, 679, A53 (2023).
Niell, A., Barrett, J., Burns, A., Cappallo, R., Corey, B., Derome, M., et al. (2018). Demonstration of a broadband very long baseline interferometer system: A new instrument for high-precision space geodesy. *Radio Science*, 53, 1269–1291. https://doi.org/10.1029/2018RS006617
Pfeiffer, V., Corey, B., Niell, A., 2024; VGOS memo 61, https://www.haystack.mit.edu/wp-content/uploads/2024/06/VGOS_061.pdf; Schuch, H. & Böhm, J. (2013). In G. Xu (Ed.) *Sciences of Geodesy – II* (pp. 339 – 376). Springer-Verlag. https://doi.org/10.1007/978-3-642-28000-9_7
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