

Strategy for gaining accuracy in VLBI observations

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I. Overview and current VLBI accuracy and goal

SGP System specifications and requirements (SGP TRM v4.2):

PRIT3.2 (Threshold Requirement EOP): Co-located global geodetic network shall be capable of determining daily values of Earth Orientation Parameters (Polar Motion, and UT1) with a precision better than 50 micro-arcseconds in combination (daily)

PRIB3.2 (Baseline Requirement EOP): . . . with a precision better than 10 micro-arcseconds in combination (daily)

Current EOP accuracy: 40–60 μas

EOP accuracy goal: 10 μas

Current position accuracy: 2–3 mm hor, 7–8-mm vert

Position accuracy goal: 1 mm hor, 1 mm vert

Current long-term position stability: $> 1 \text{ mm/yr}$

Long-term position stability goal: 0.1 mm/yr

Three factors that affect VGOS accuracy:

- Atmospheric path delay
- Source structure
- Instrumental errors

Why atmospheric errors dominate

- Evidence #1: seasonality in postfit residuals (VGOS)
- Evidence #2: seasonality in rms of zenith path delay derived from GMAO numerical weather model Nature 7km Run
- Evidence #3: Elevation dependence in post-fit residuals

See backup slides

Why source structure contribution is a significant error source

- Evidence #1: phase misclosures shows a pattern that can be reconstructed using images
- Evidence #2: Source-based residual errors are consistent
- Evidence #3: Source-based residual errors may be mitigated when apply τ_{str} computed from source images
- Evidence #4: source structure has a secular change

See backup slides

Why Instrumental errors are important

- Evidence #1: Unstable phase calibration.
- Evidence #2: Systematic source-independent phase misclosure
- Evidence #3: Systematic differences in group delays wrt phase delays

See backup slides

Strategies in mitigation of errors in modeling atmospheric path delay

The use of GMAO for

- simulation
- data reduction
- parameter estimation — the use of a priori full covariance matrix for parameter estimation
- refined parameterization of path delay (f.e. using a slab model)
- establishing the most variable atmospheric layer
- advance stochastic modeling (f.e. SRIF)

Strategies in mitigation the contribution of source structure

- antenna calibration
- imaging the sources
- source monitoring
- computation of source structure delay using images for data reduction
- computation of correlated flux density delay using images for scheduling

Strategies in mitigation of instrumental errors

- Used advanced visibility analysis for computation of group delay
- Characterization of instrumental error in special experiments:
 - high SNR experiments
 - short baseline experiments
 - cluster-cluster experiments
- Fixing phase-cal hardware
- Improvement of phase stability
- Development of new generation phase calibration system

II. Key performance parameters:

- **Realism in prediction of group delay uncertainty**
- **Realism in prediction of data product uncertainty**

Benefits to the agency:

- An ability to **realistically** predict an experiment outcome saves money because
 - it allows to **realistically** assess ROI
 - it allows to spend resources efficiently
- An ability to **realistically** predict an experiment outcome greatly enhances
 - our ability to develop advanced data analysis strategy because it provides a feedback
 - our ability to evaluate scheduling strategies.

III. Goals, objectives, and output of the development

Focal points of development

1. to reach realism in prediction of group delay uncertainty

What we are aiming at:

- Current state-of-the-art: 100–500% errors
- Excellent agreement: better than 15%
- Acceptable agreement 15–40%
- Agreement worse than 50%: failure

What needs to be done:

- regular monitoring for antenna characterization
- imaging of observed sources
- upgrade scheduling software
- upgrade parameter estimation software
- stay focused on reaching the goal

2. to reach realism in prediction of data product accuracy

What we are aiming at:

- Current state-of-the-art: 50–250% errors
- Excellent agreement: better than 15%
- Acceptable agreement: 15–35%
- Agreement worse than 50%: failure

What needs to be done:

- characterization of systematic errors
- characterization of atmospheric errors through the use of NWM and running special VLBI experiment
- development of advanced stochastic model of VLBI observables
- upgrade analysis software
- stay focused on reaching the goal

IV. Outcomes of these activities

- Algorithms, programs, datasets that allows realistically predict the outcome of a VLBI experiment or campaign
- Substantial mitigation of the impact of source structure on VLBI results
- Improvement in accuracy of VLBI results via incorporation of off-diagonal terms in the a priori weight matrix
- Improvement in accuracy of VLBI results via deep optimization of schedules based in solid foundation
- VLBI data products with realistic uncertainties

V. Required resources

- Group of 3 researchers with strong programming skills working with the VLBI Lead Scientist
 - radioastronomer — source imaging and source monitoring
 - physicist/atmospheric scientist — atmospheric turbulence theory and models
 - a scientific software developer
- A high-end server computer (40K-50K) and a workstation for each researcher (8-10K each)
- Access to NASA HPC
- Resource for a domestic R&D VLBI program:
 - 1-hr VLBI experiments: once per week
 - 24-hourly experiments for “indirect geodesy”: once per month
 - Kk/K2 short baseline 22-hourly observations: two times per month
- Global R&D VLBI program: 6–12 24-hr VLBI experiments per year
- Single dish characterization monitoring experiments on a weekly basis (2–20 hours)

VI. Dependencies (software, other subsystems, etc.)

- high-end server/workstations
- Access to NASA HPC

VII. Infusion plan: Gaining VLBI accuracy task force

- focused on problem solving
- maintaining scientific leadership
- getting adequate resources
- forking traditional and advanced pipelines
- **running operational advanced pipeline from day one**
- making available online results of the advanced pipeline

VIII. Issues/Concerns/Risks:

- finding and training personal will be a challenge

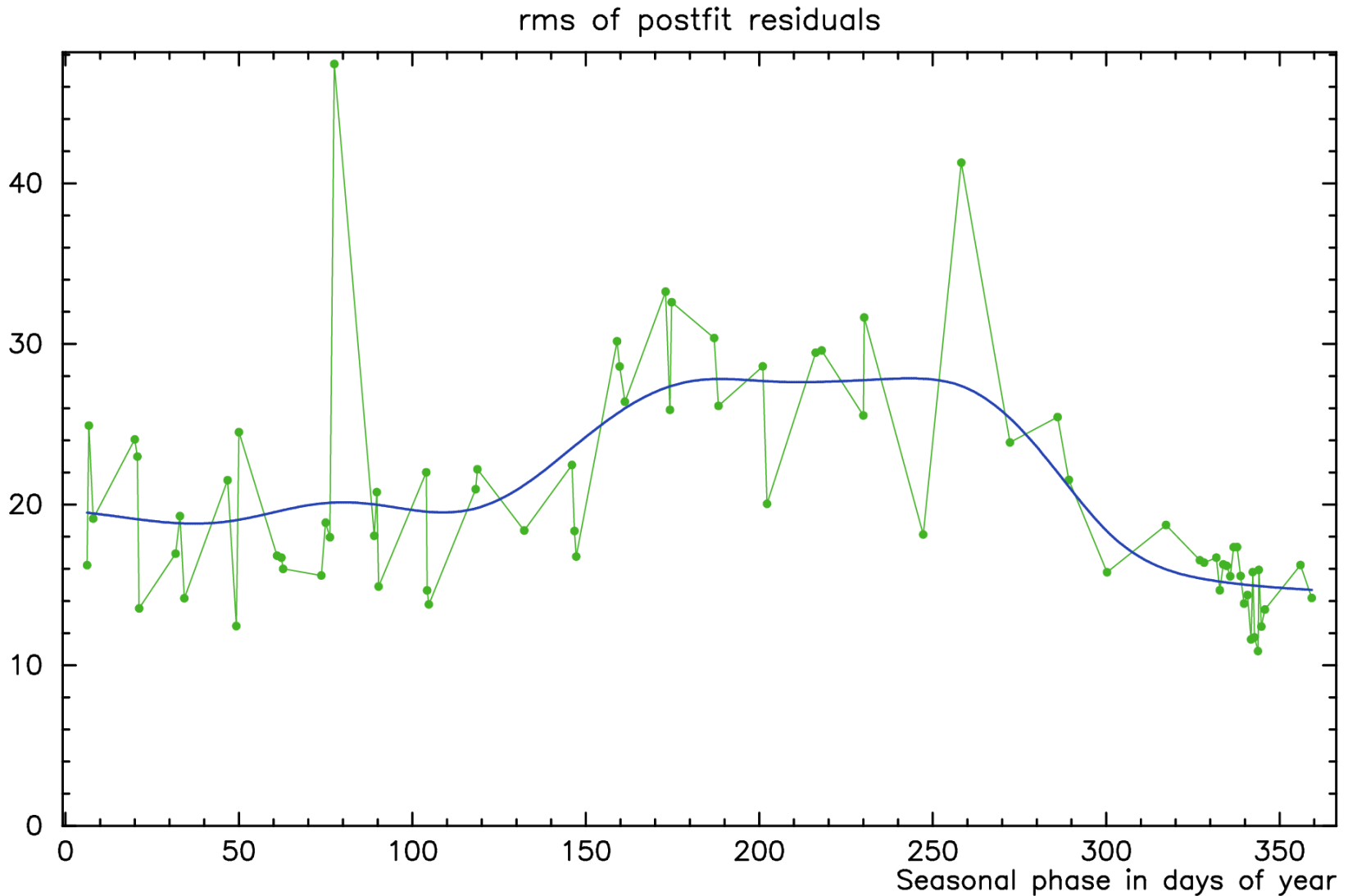
IX. Timeframe/Schedule:

- It would take 2 years to complete the project not counting time for getting the team ready
- There are five sub-tasks within the project:
 - source imaging and the use of images;
 - the use of NWM for computation of empirical covariance matrix;
 - advanced atmosphere parameterization;
 - advanced stochastic atmosphere estimation;
 - evaluation of remaining systematic errors.They are loosely coupled and can be implemented in parallel.

Backup slides

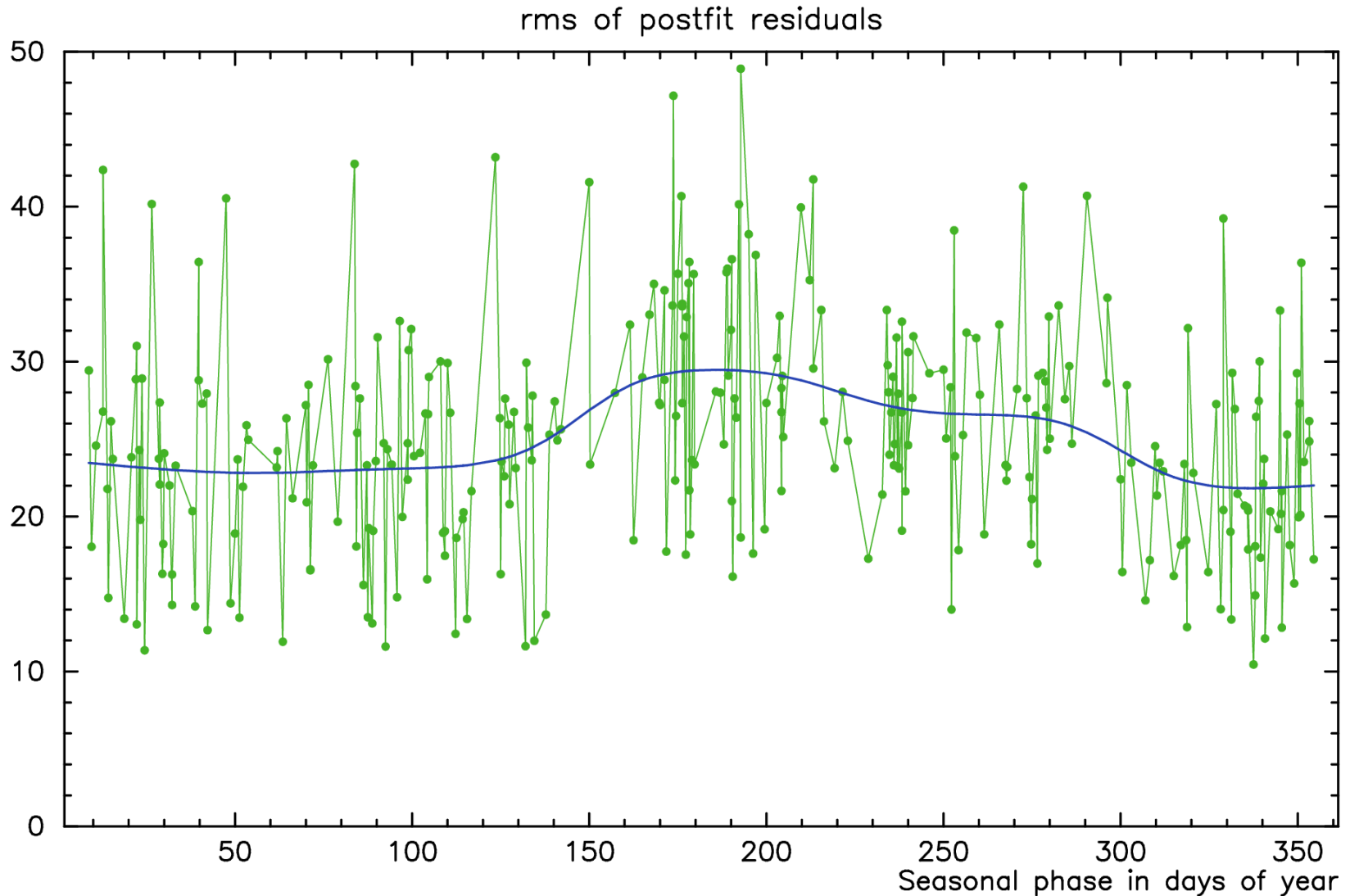
Why atmospheric errors dominate

Evidence #1: seasonality in postfit residuals (VGOS)



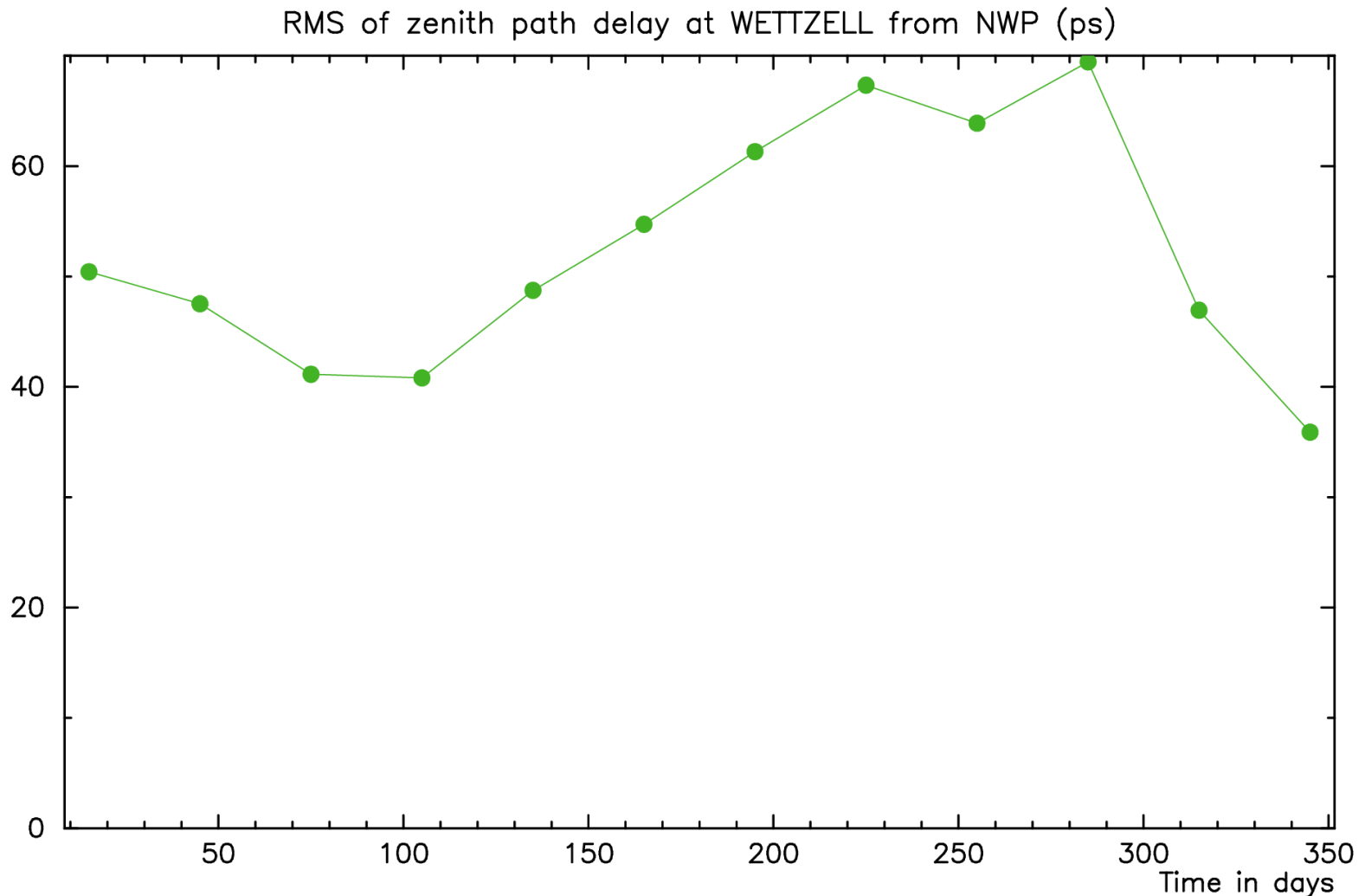
Why atmospheric errors dominate

Evidence #1: seasonality in postfit residuals (legacy system)



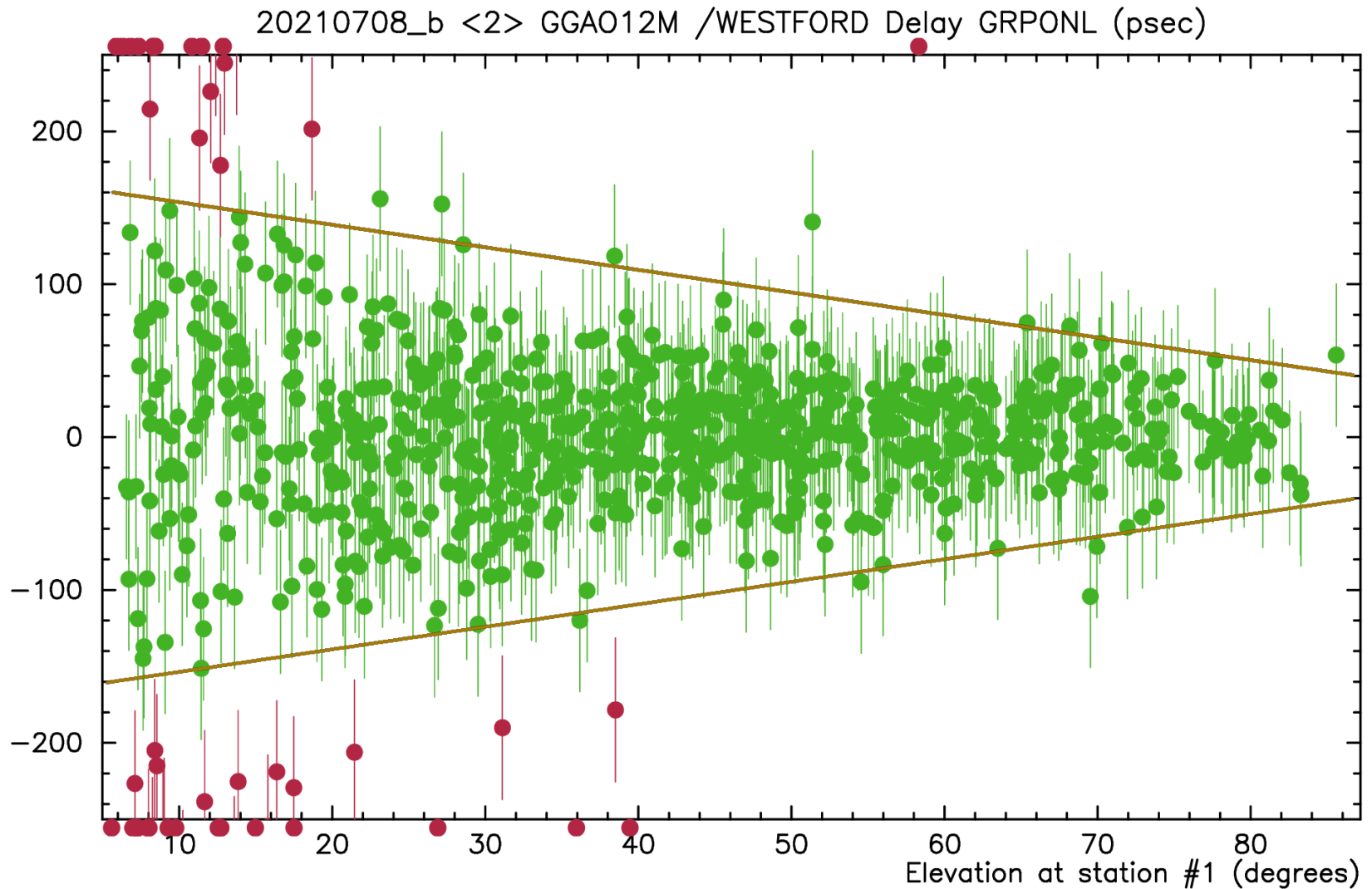
Why atmospheric errors dominate

Evidence #2: seasonality in rms of zenith path delay derived from GMAO numerical weather model Nature 7km Run



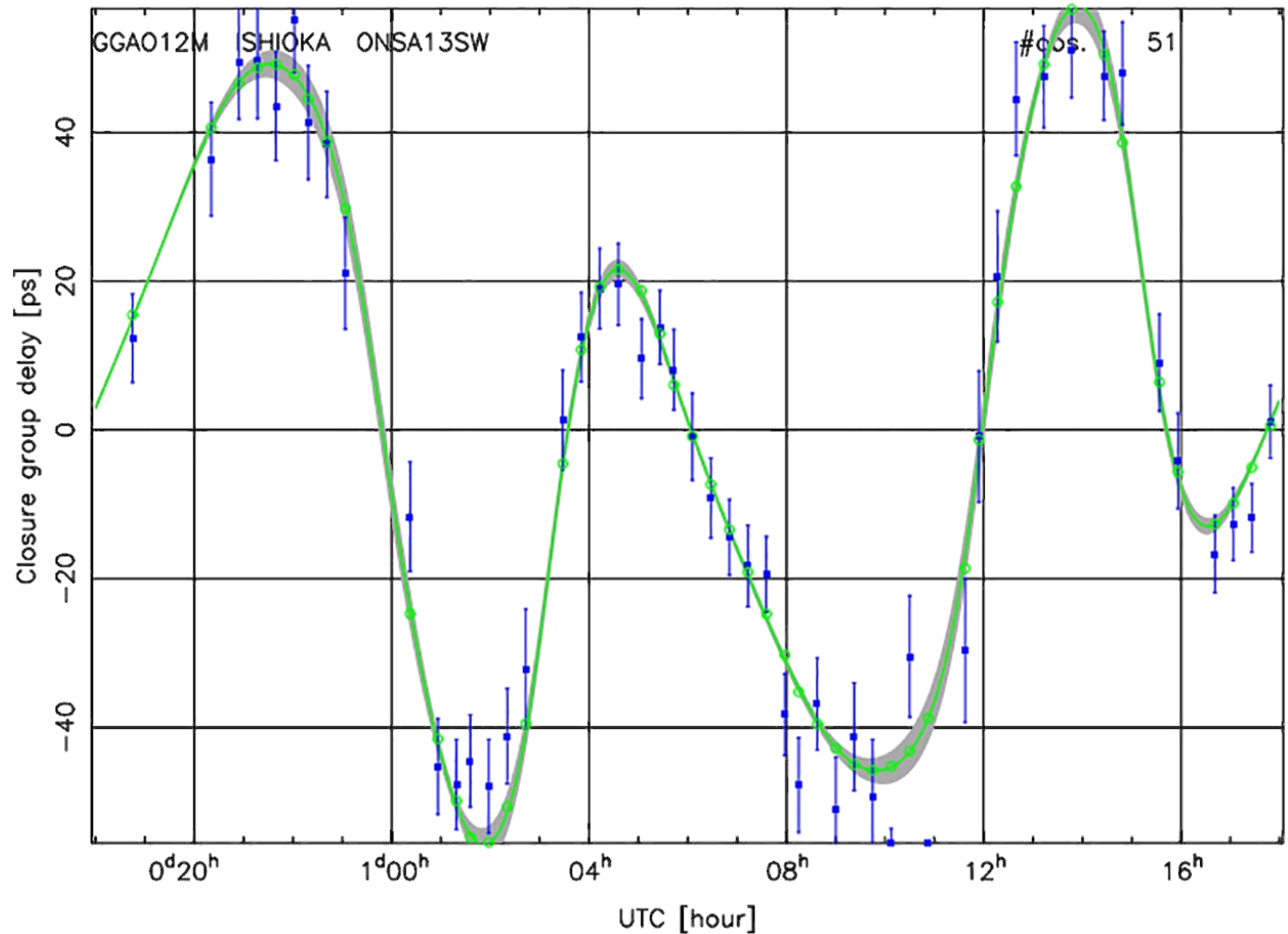
Why atmospheric errors dominate

Evidence #3: Elevation dependence in post-fit residuals



Contribution of source structure to delay

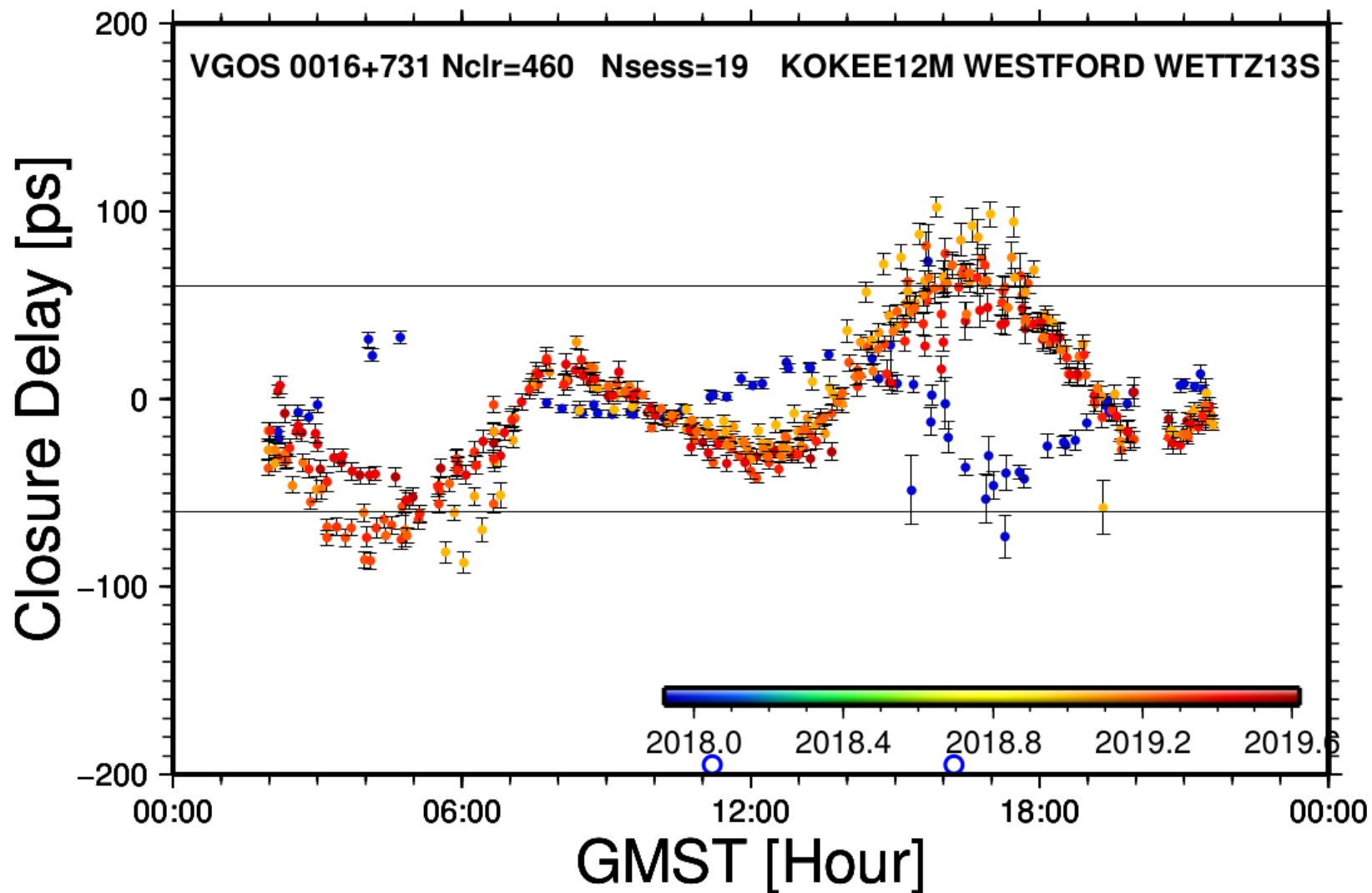
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observed and **modeled** path delay due to source structure (Xu et al 2020).

Contribution of source structure to delay

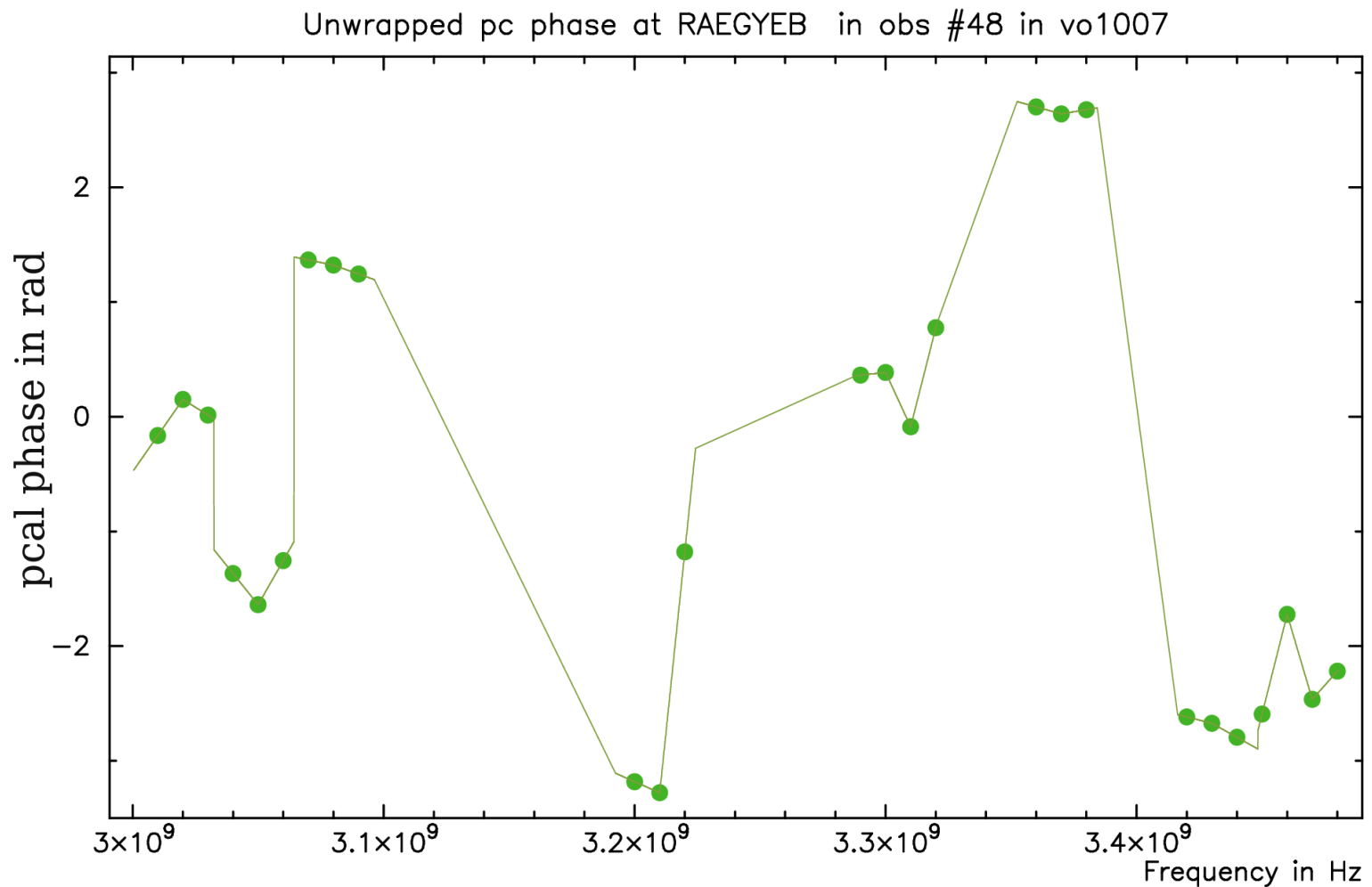
Long-term changes of source structure to delay (Xu et al. 2021a)



Instrumental errors in VGOS

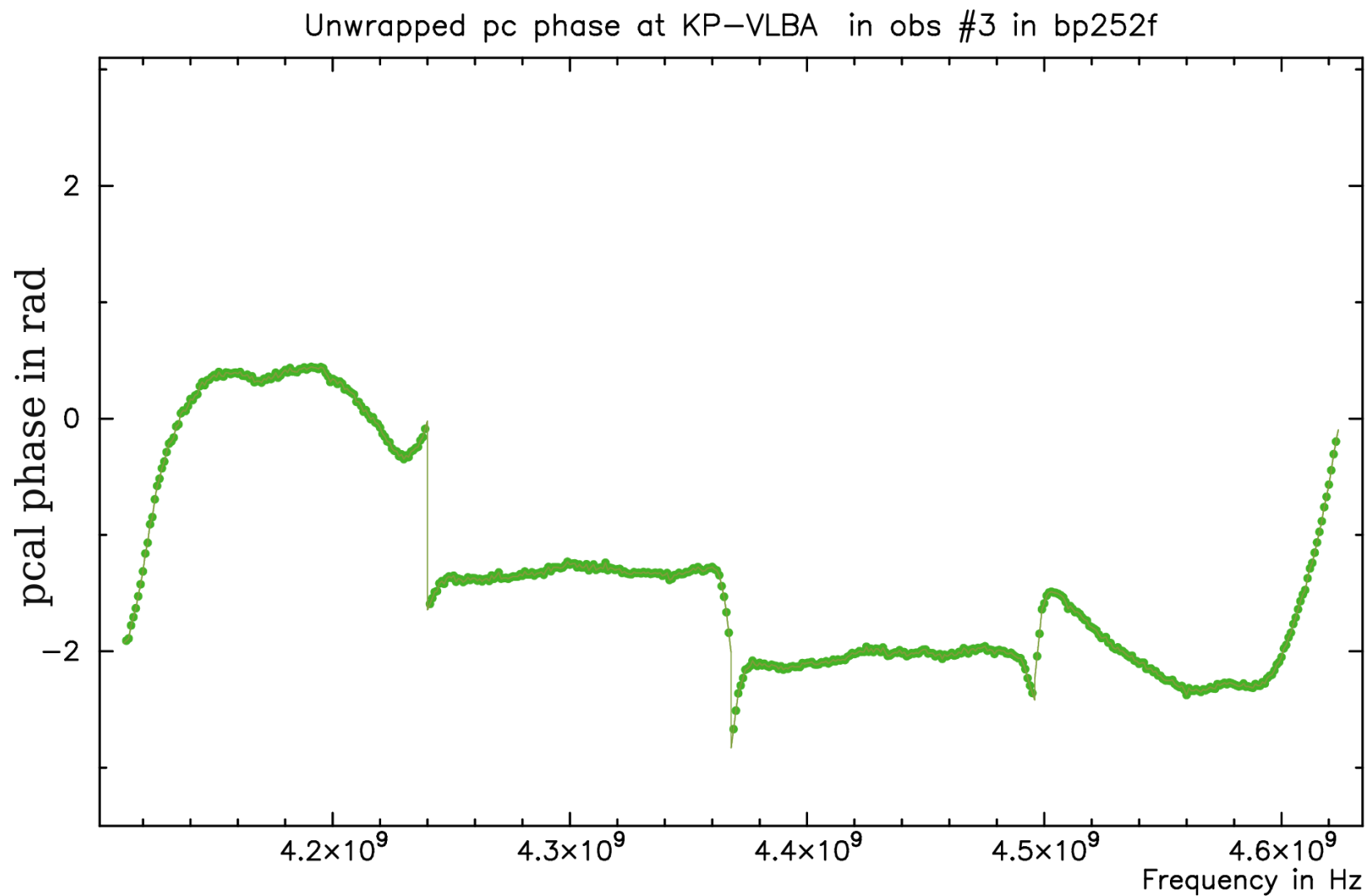
Evidence #1: Unstable phase calibration.

Phase calibration phase at RAEGYEB (rdbe backend)



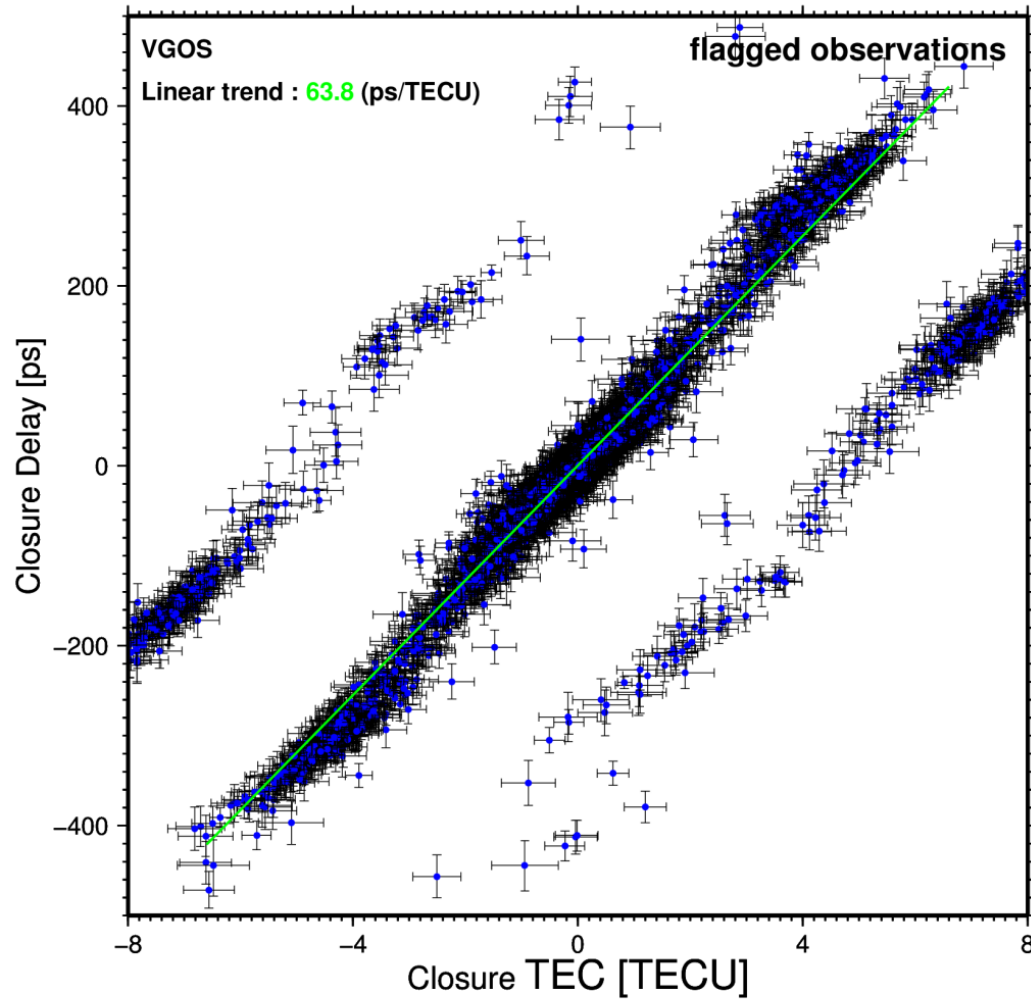
Instrumental errors in VLBI

Reference phase calibration phase at KP-VLBA



Instrumental errors in VGOS

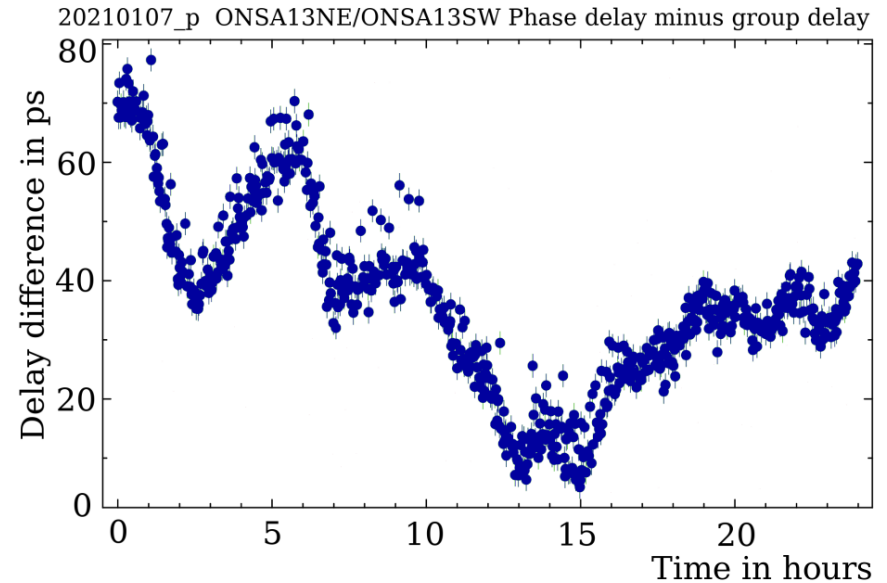
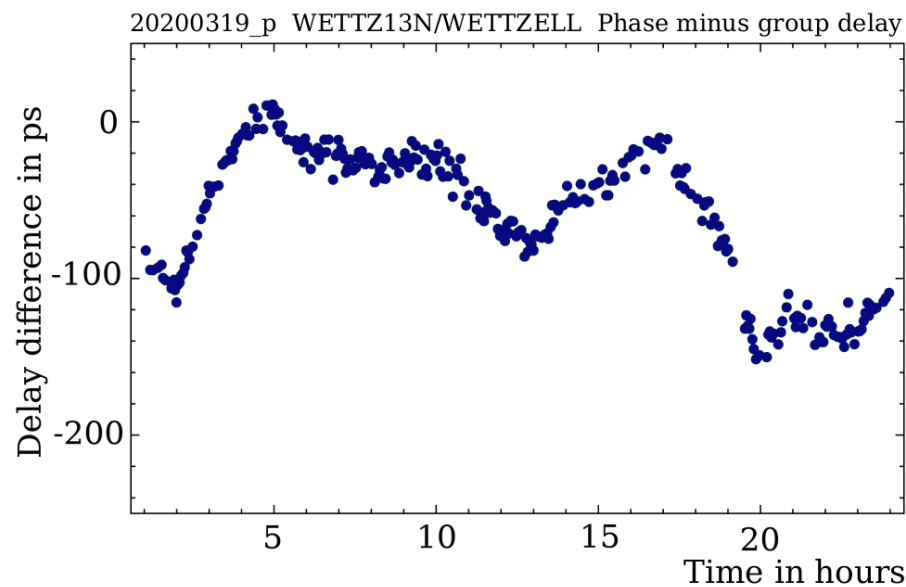
Evidence #2: Systematic misclosure errors in group delay



(Xu et al, 2021b)

Instrumental errors in VGOS

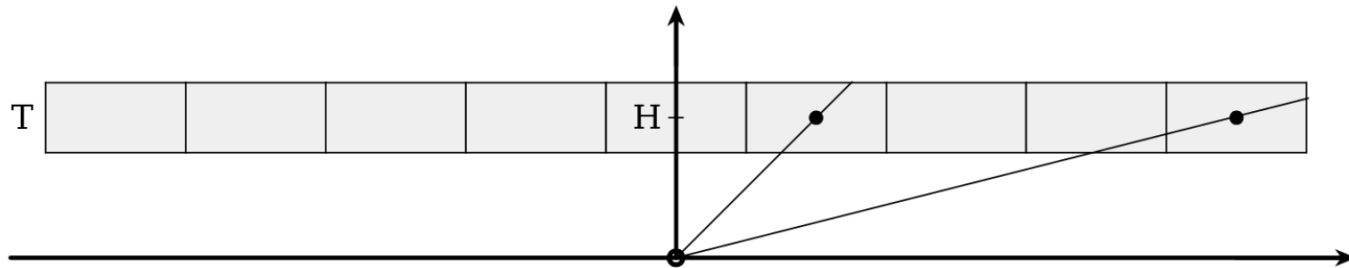
Evidence #3: Systematic differences in group delays wrt phase delays



Systematic differences between phase and group delay at a short baseline between two antennas. Left at Wettzell, right at Onsala. This differences should be zero for an ideal system.

Advanced technique of path delay estimation

Approach #1: refined parameterization:



The diagram of slab parametric model for estimation of residual atmosphere. A projection of a 2D slab on a given direction is shown. The slab has thickness T and height H .

Advanced technique of path delay estimation

Approach #2: Determination of the height range of the most variable layer

Problem: there is a range of heights where path delay is the most variable

Input variable: horizontal and vertical wind; refractivity index; ?

Output: mapping function tuned to the most variable layer

Advanced technique of path delay estimation

Approach #3: Characterization of refractivity anomaly field

Problems:

- What is a relationship between spatial and temporal variation?
- What are scales of validity of a 1D mapping function?
- What are regressors of the refractivity anomaly field?

Approaches:

- perform regression analysis of the NWM output
- run dedicated VLBI experiments to measure short-term variability of path delay (scales \geq 30 minutes)

Advanced technique of path delay estimation

Approach #4: The use of covariance matrix of atmospheric noise for parameter estimation

Generalized least squares requires minimization of functional

$$J_w = \sum_i (A_i x_i - y_i)^\top C_{ia}^{-1} (A_i x_i - y_i),$$

C_{ia} — a priori estimate of the covariance of observation at the i-th baseline

The goal is to find C_a

- interpolation of empirical C_a from high-res NWM
- deriving from low elevation long calibration observations
- deriving from residual estimates of path delay
- deriving from a regression to atmospheric parameters from NWM