Strategy for gaining accuracy in VLBI observations

Leonid Petrov, NASA GSFC, Code 61A

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 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 with time
- Evidence #3: Source-based residual errors are mitigated when we 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 and TEC misclosures
- 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:

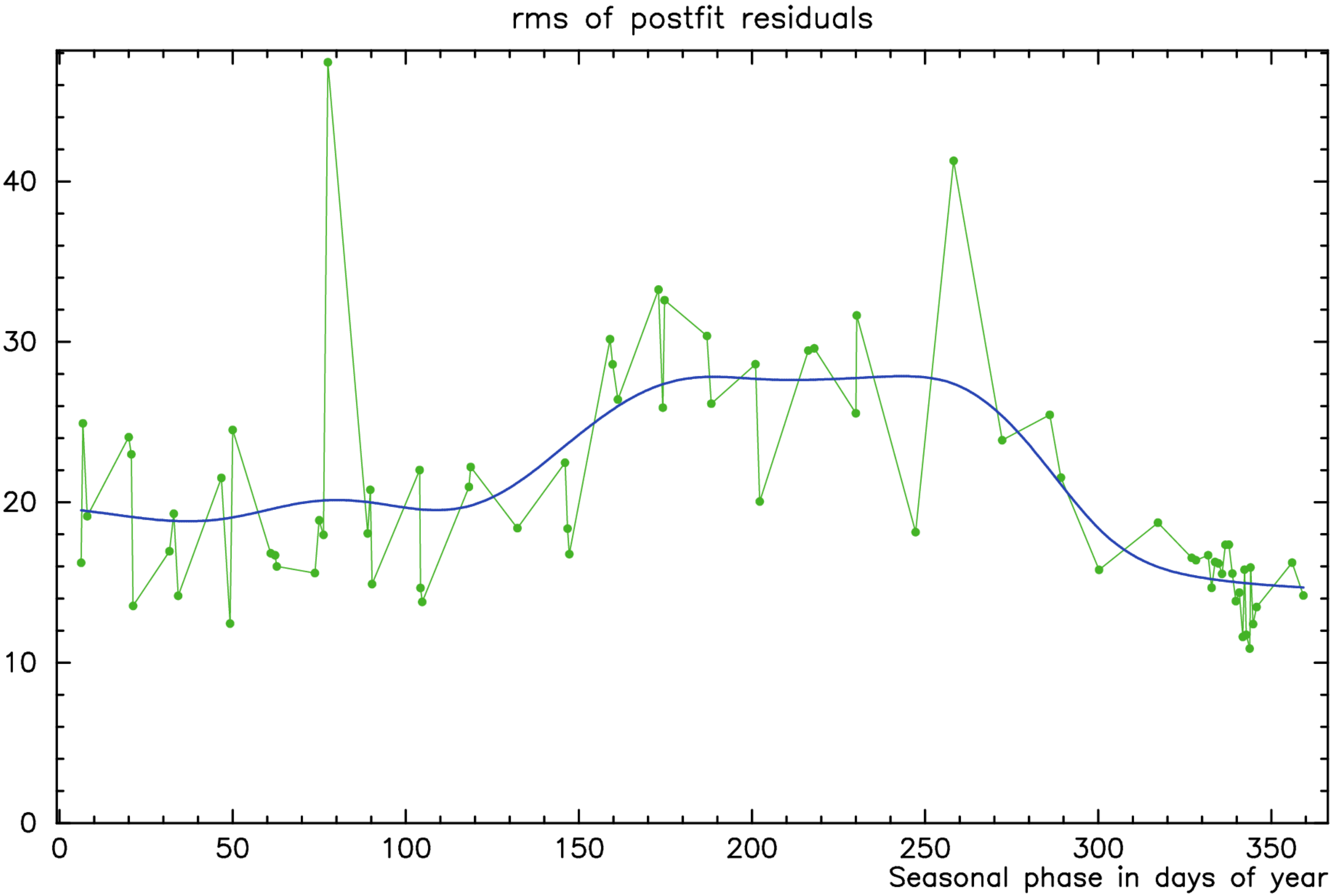
- It would take 2 years to complete the project not counting time for getting the team ready
- There are five sub-tasks within the project:
  - source imaging and the use of images;
  - the use of NWM for computation of empirical covariance matrix;
  - advanced atmosphere parameterization;
  - advanced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

  They are loosely coupled and can be implemented in parallel.

Backup slides

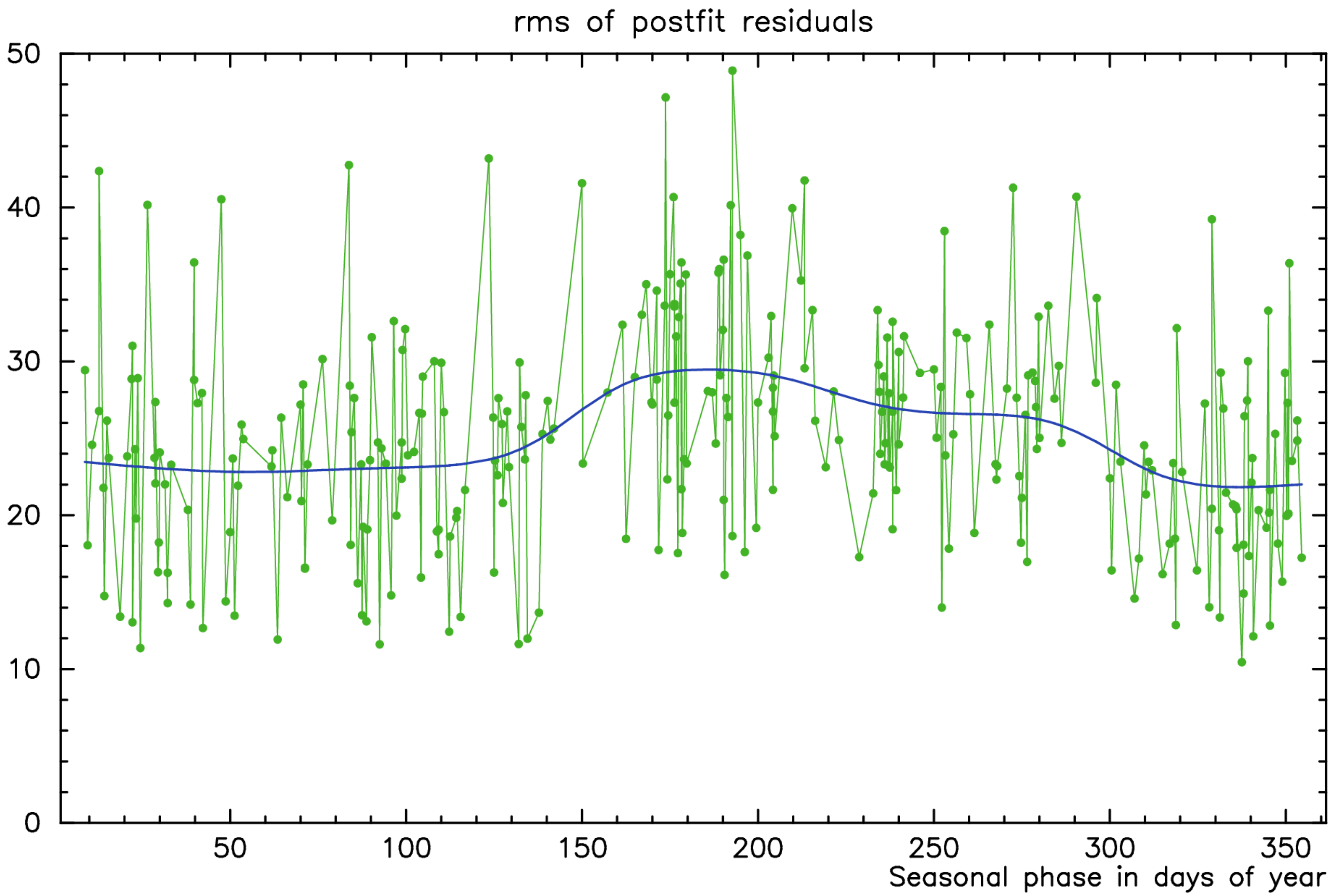
Why atmospheric errors dominate

Evidence #1: seasonality in postfit residuals (VGOS)



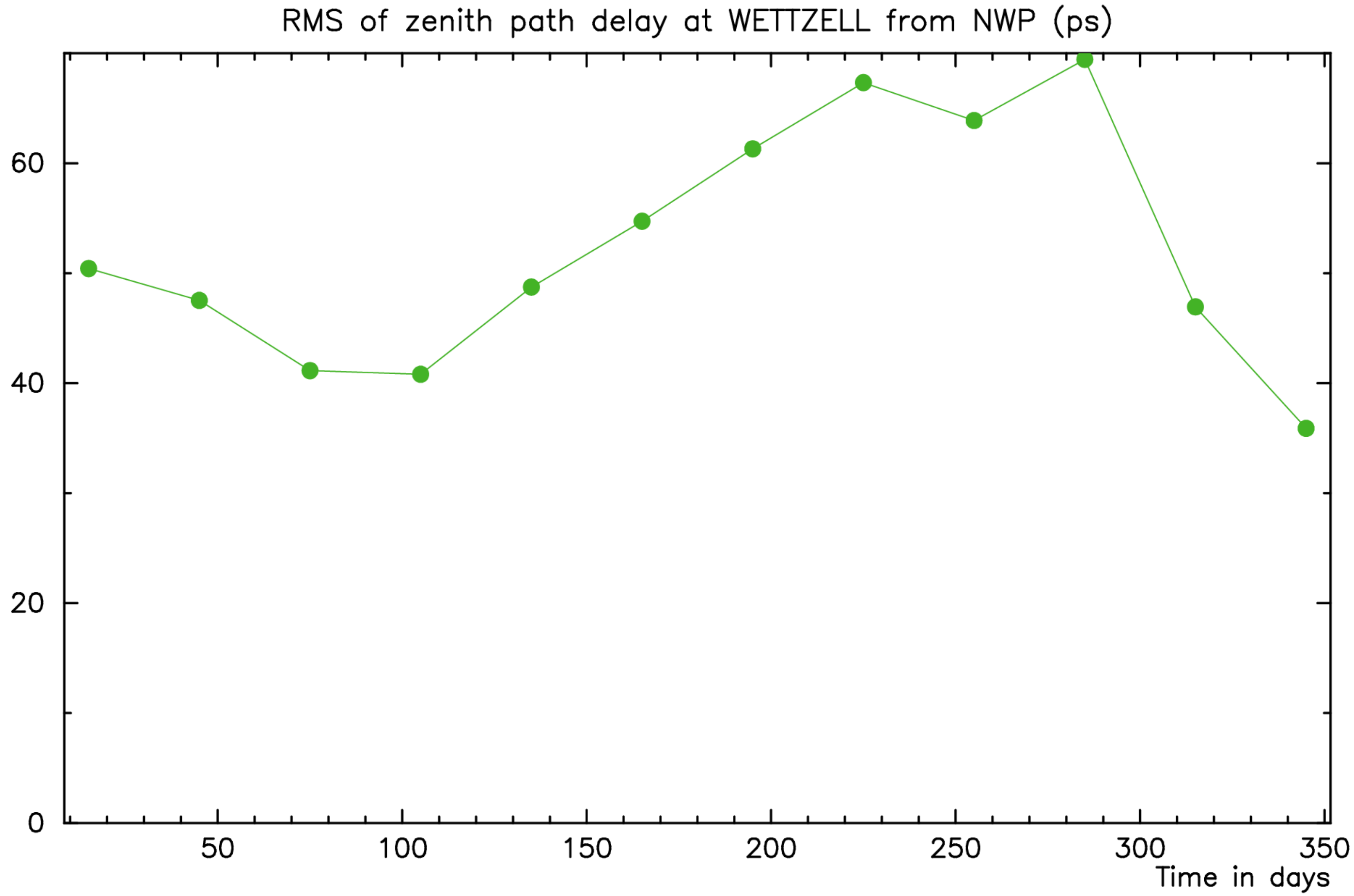
Why atmospheric errors dominate

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



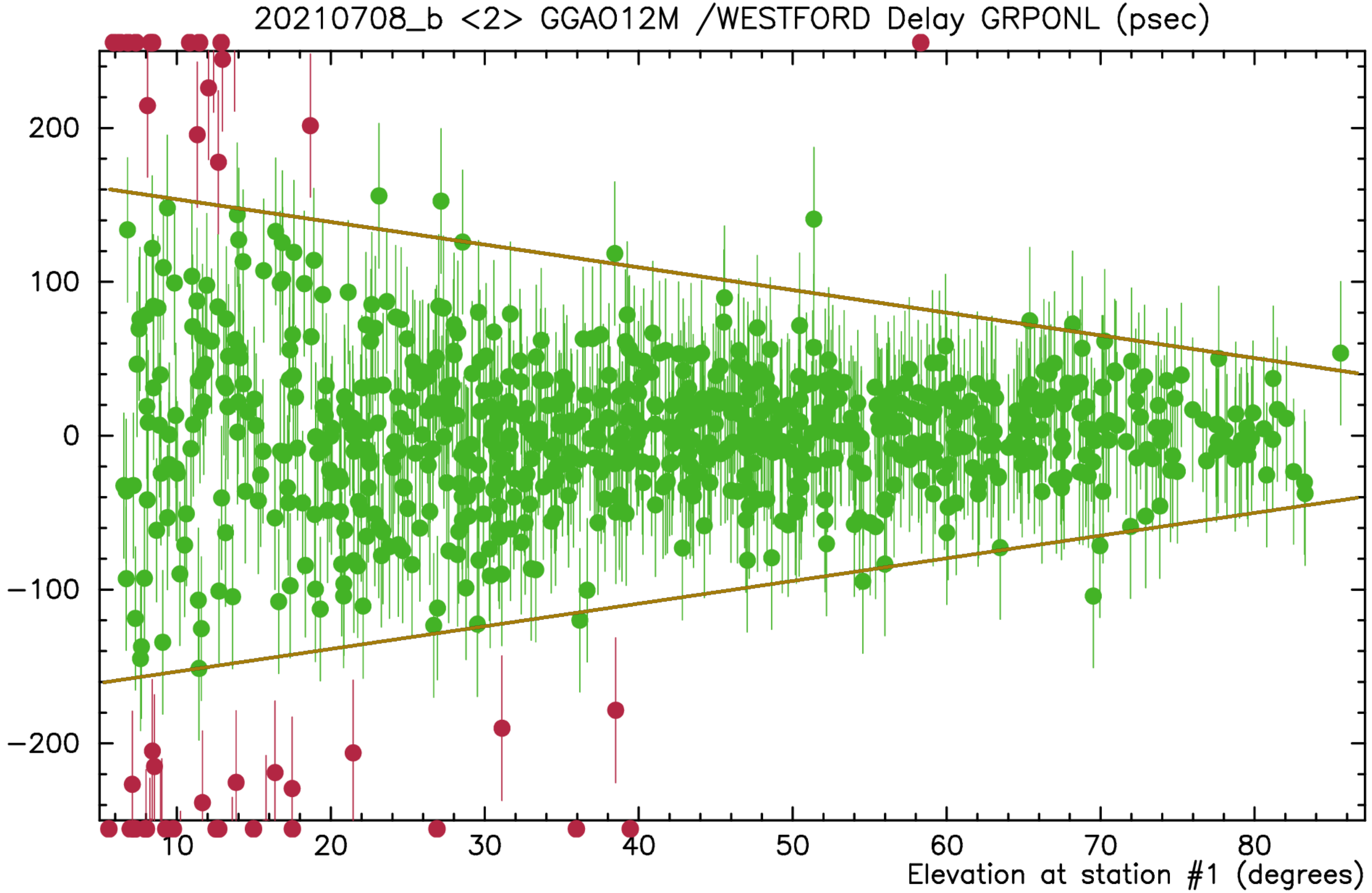
Why atmospheric errors dominate

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

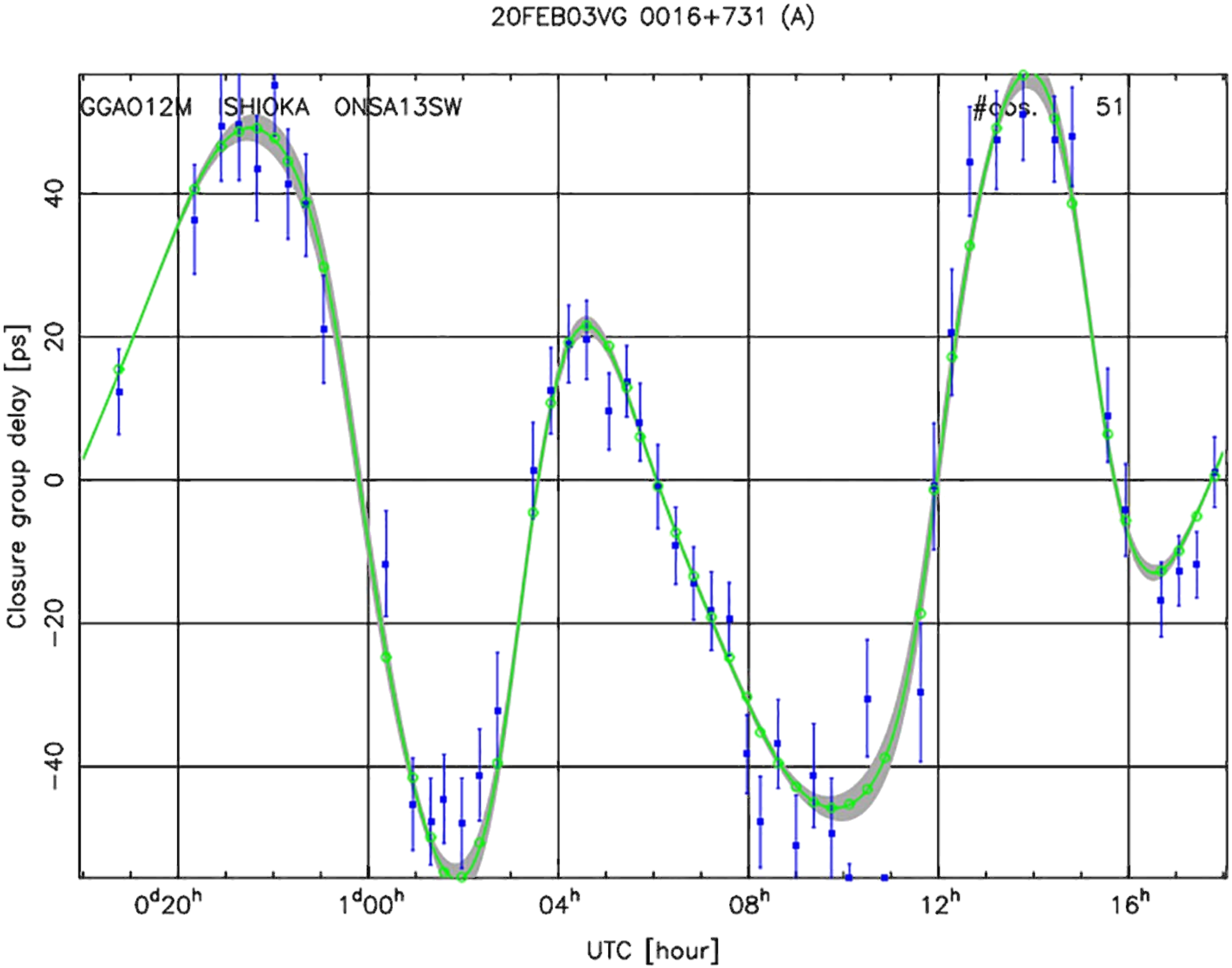


Why atmospheric errors dominate

Evidence #3: Elevation dependence in post-fit residuals



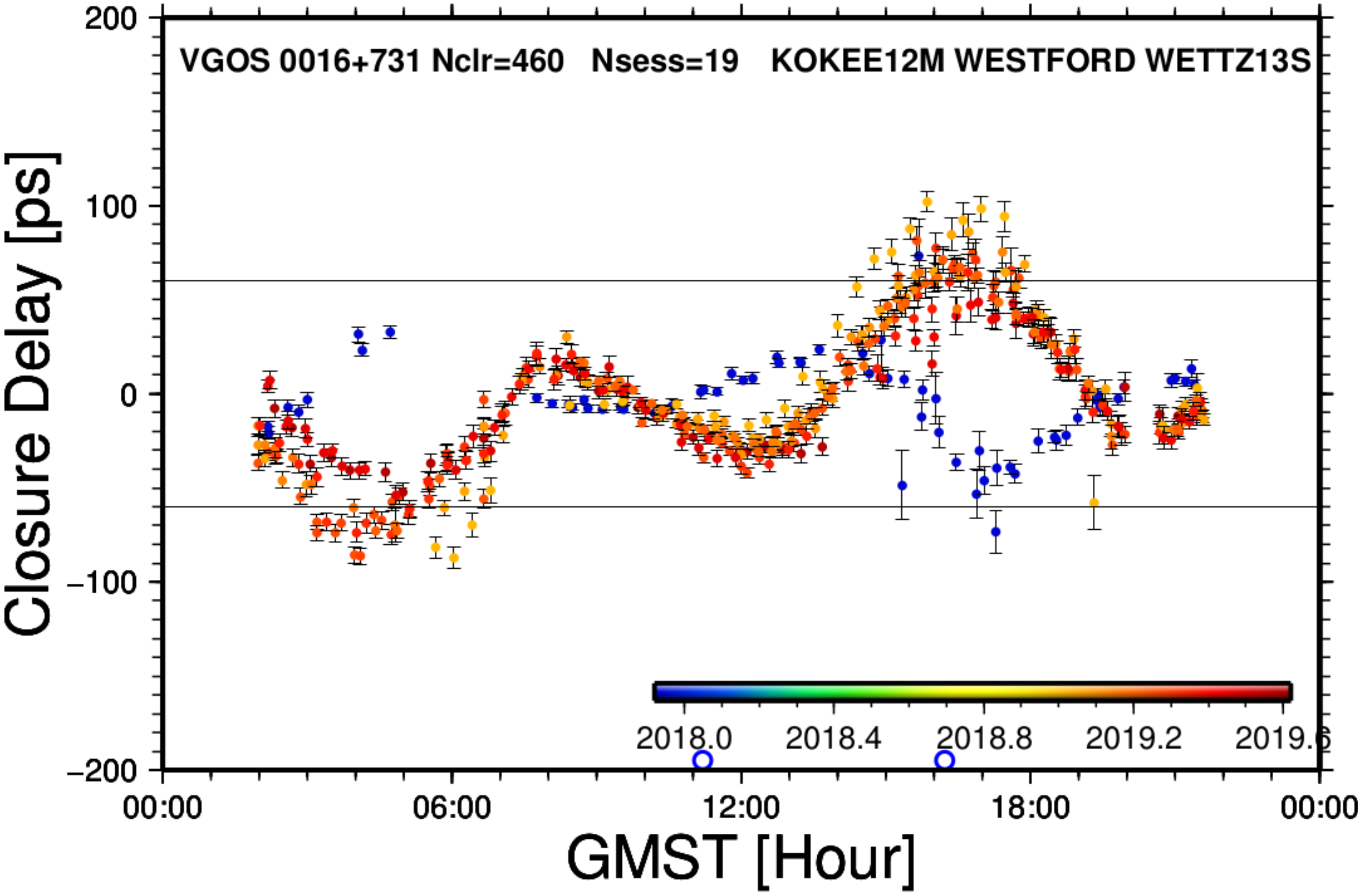
Contribution of source structure to delay



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

Contribution of source structure to delay

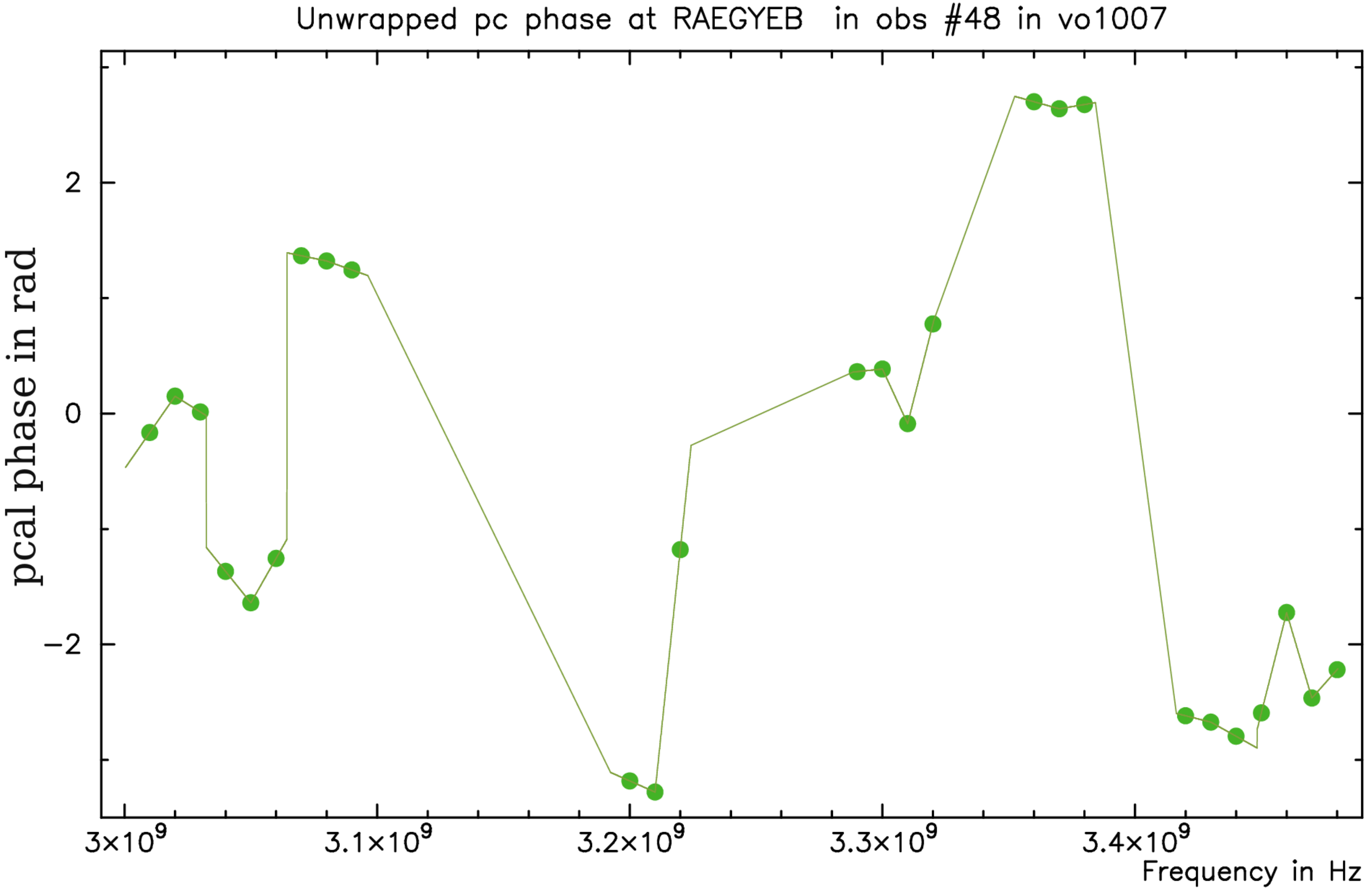
Long-term changes of source structure to delay (Xu et al. 2021a)



Instrumental errors in VGOS

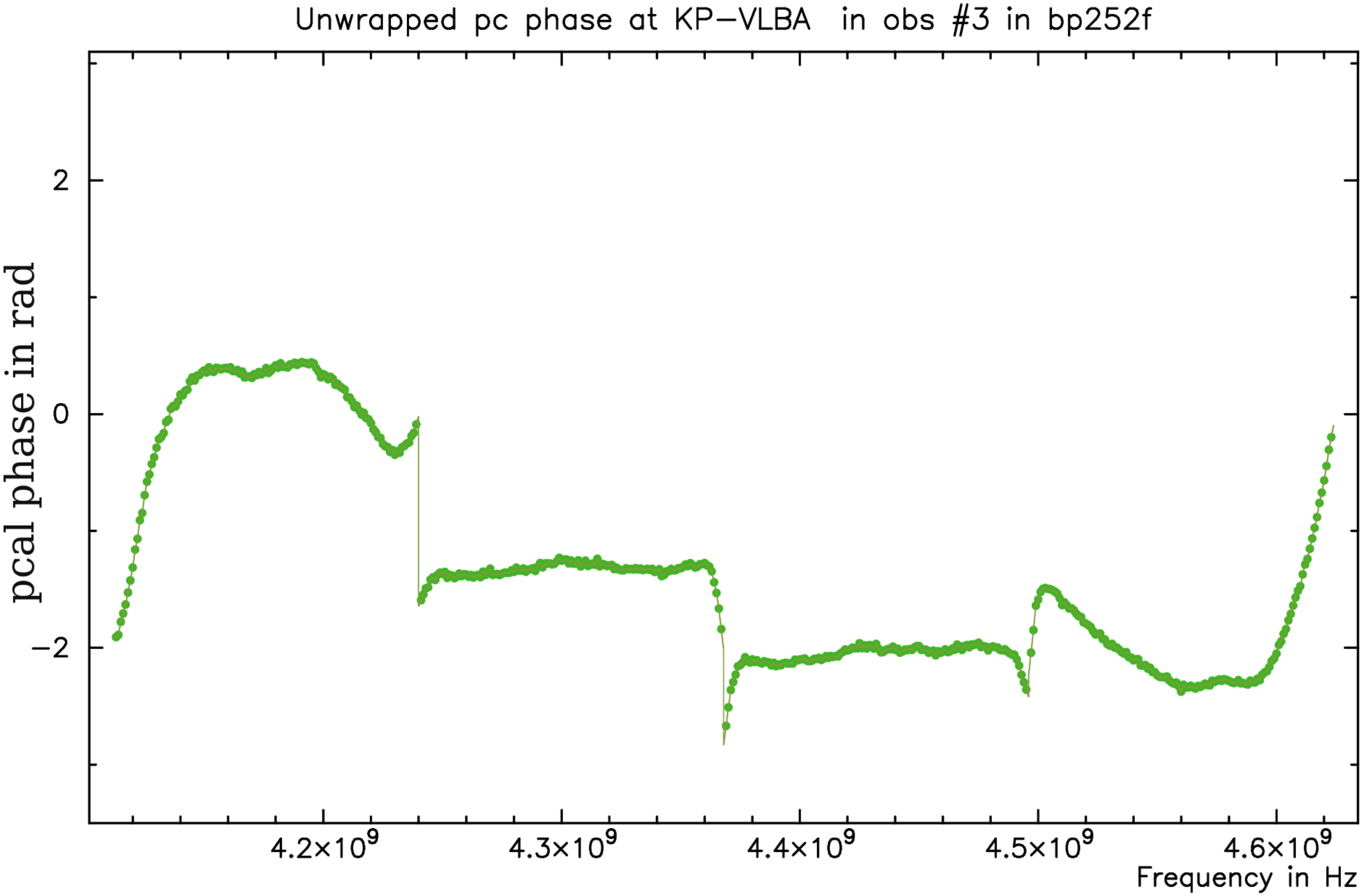
Evidence #1: Unstable phase calibration.

Phase calibration phase at RAEGYEB (rdbe backend)



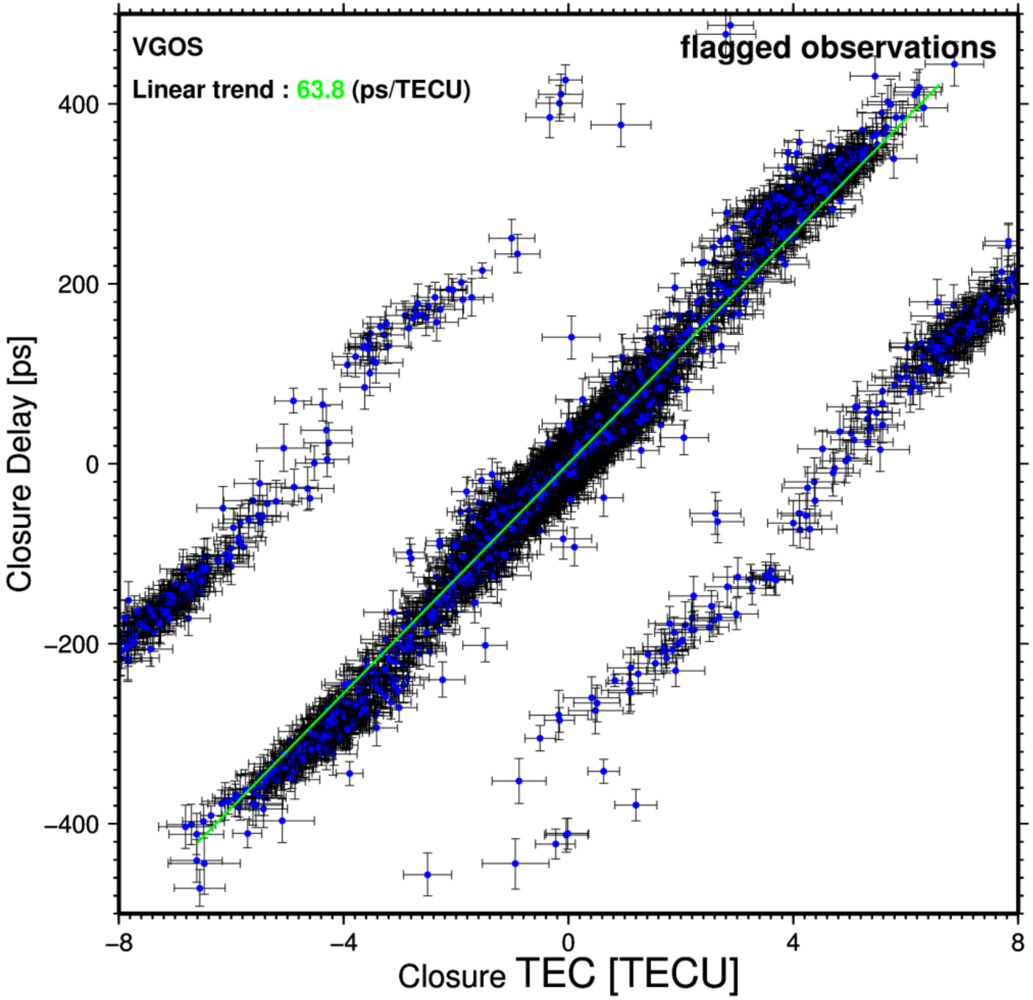
Instrumental errors in VLBI

Reference phase calibration phase at KP-VLBA



Instrumental errors in VGOS

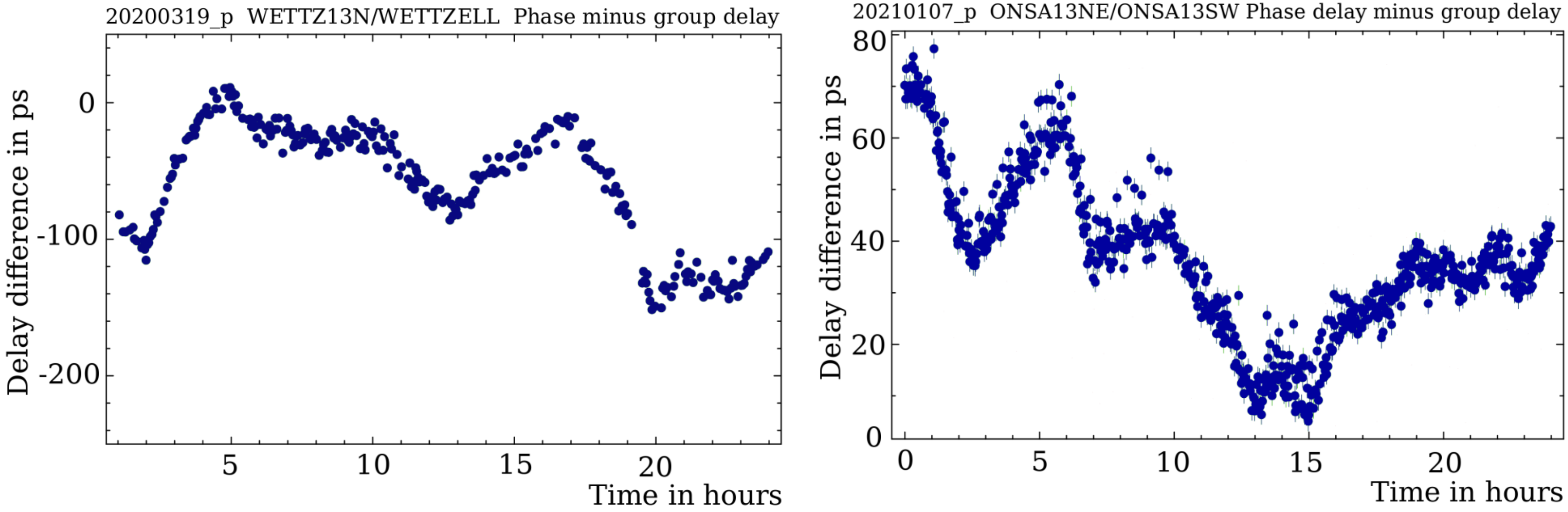
Evidence #2: Systematic misclosure errors in group delay



(Xu et al, 2021b)

Instrumental errors in VGOS

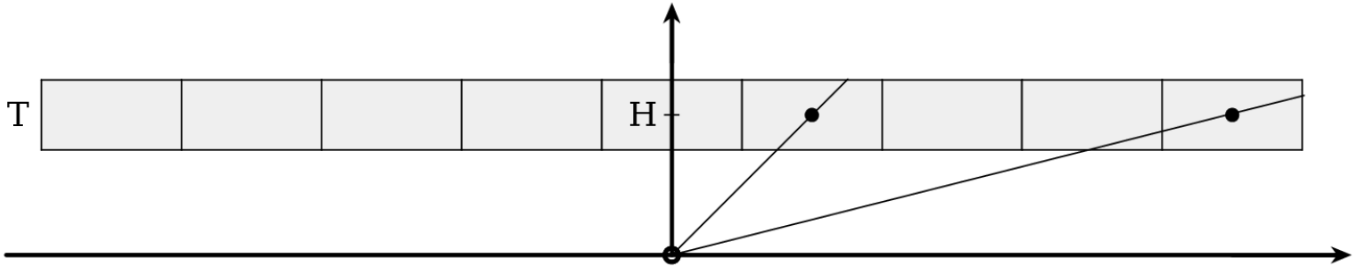
Evidence #3: Systematic differences in group delays wrt phase delays



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 ¡ 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