On the Multi-Technique Combination with Atmospheric Ties

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Motivation

- Regardless of space geodetic observing system (GNSS, VLBI, SLR, and DORIS) estimates of
  - plate tectonics,
  - satellite orbits,
  - Earth's rotation, and
  - atmospheric state

should –in principle- differ only within measurement error bounds, e.g., Krügel et al. (2007), Thaller et al. (2007), Thaller (2008), Nilsson et al. (2015)

- Multi-technique combination facilitates distinction of ***genuine geophysical signals*** from ***technique-specific artefacts***, e.g., Rothacher (2002)
- Improvements in ground co-location (more sites with more systems)

In this presentation

- Atmospheric ties from a *modeller's* perspective
- Atmospheric ties from a *geodesist's* perspective

Chapter 0
Ray-Tracing

How Are the Atmospheric Delays Calculated?

- In-house GFZ's **ray-tracing software**: Direct Numerical Simulation (DNS) Tool by Zus et al. (2014)
- Input: **ERA5** + **IRI2016** (Bilitza, 2018) + **IGRF12** (Thébault et al., 2015)

ERA5 → pressure, temperature, specific humidity, geopotential, etc.

IRI2016 → electron density

IGRF12 → Earth's magnetic field

Chapter I
Definition of Atmospheric Ties

What Are Atmospheric Ties?

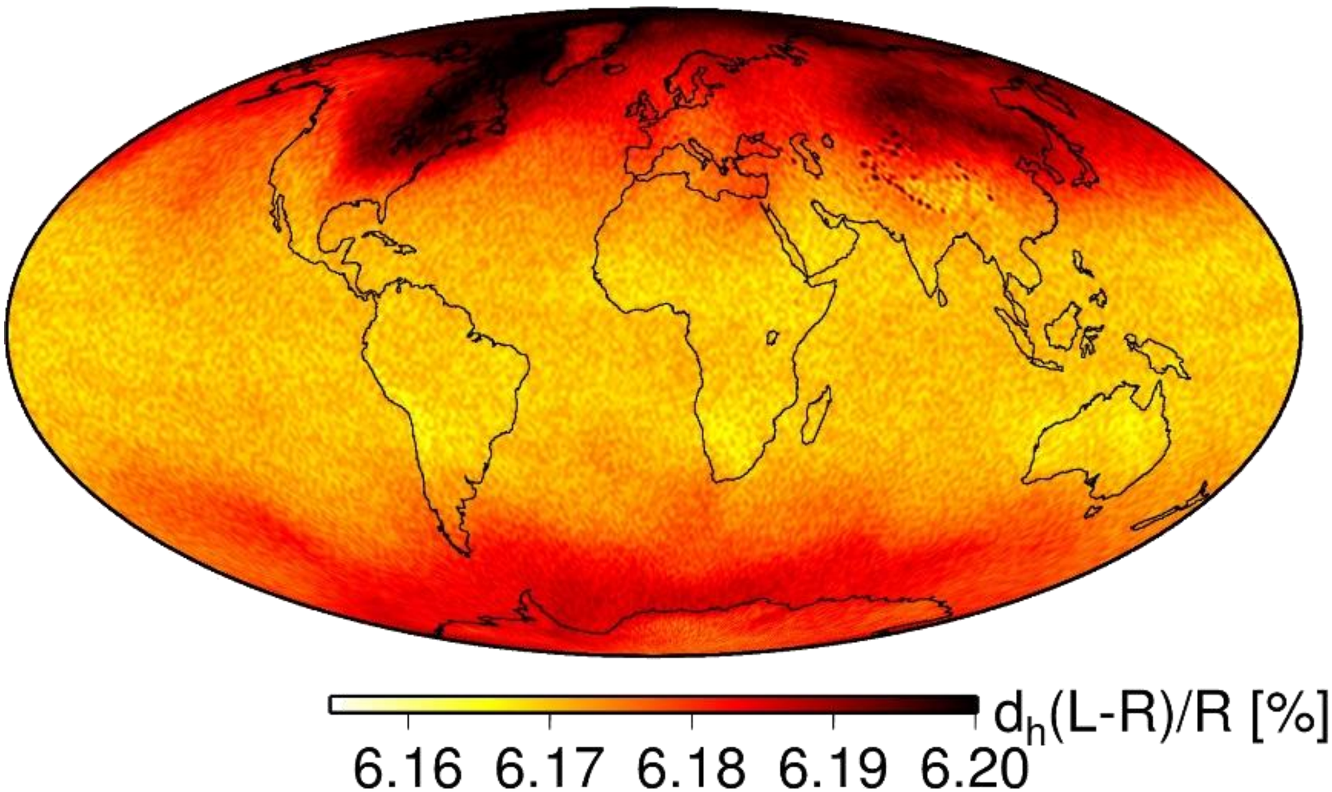
- Expected differences between atmospheric parameters at co-locations obtained ***independently*** of space geodetic methods
- Useful for intra- and inter-technique combination (e.g., Krügel et al., 2007; Thaller, 2008)
- Systematic discrepancies due to:
  - **frequency** difference (microwave, optical);
  - **position** difference (mainly height); and
  - **observing system** differences (technique, geometry, hardware)
- IAG JWG Tropospheric Ties (Heinkelmann et al., 2016)

. . . continued for a second term by Kyriakos Balidakis & Daniela Thaller

Chapter II
Frequency-Induced Differences

Zenith Hydrostatic Delays

- SLR@532nm **6% larger** than VLBI/GNSS/DORIS



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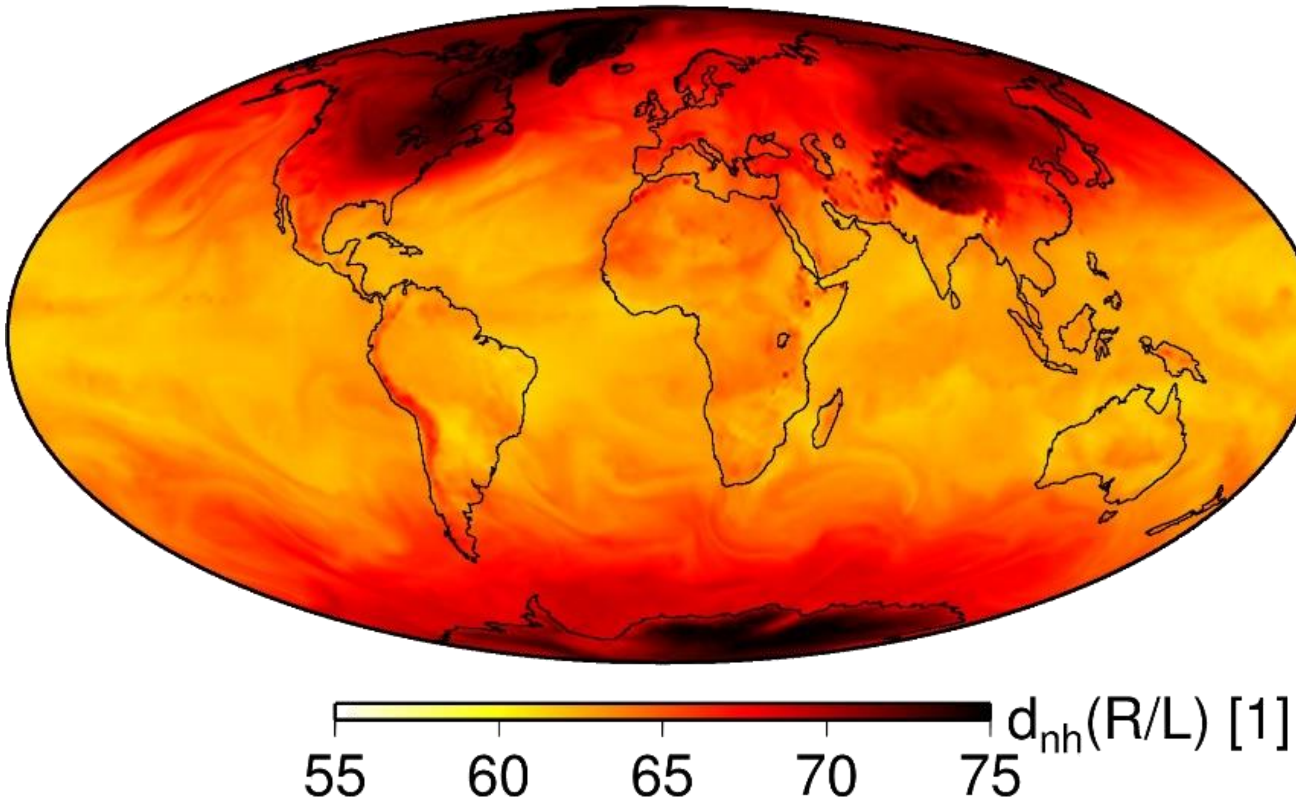
Zenith Non-Hydrostatic Delays

- SLR@532nm **66 times smaller** than VLBI/GNSS/DORIS



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Asymmetric Delays I

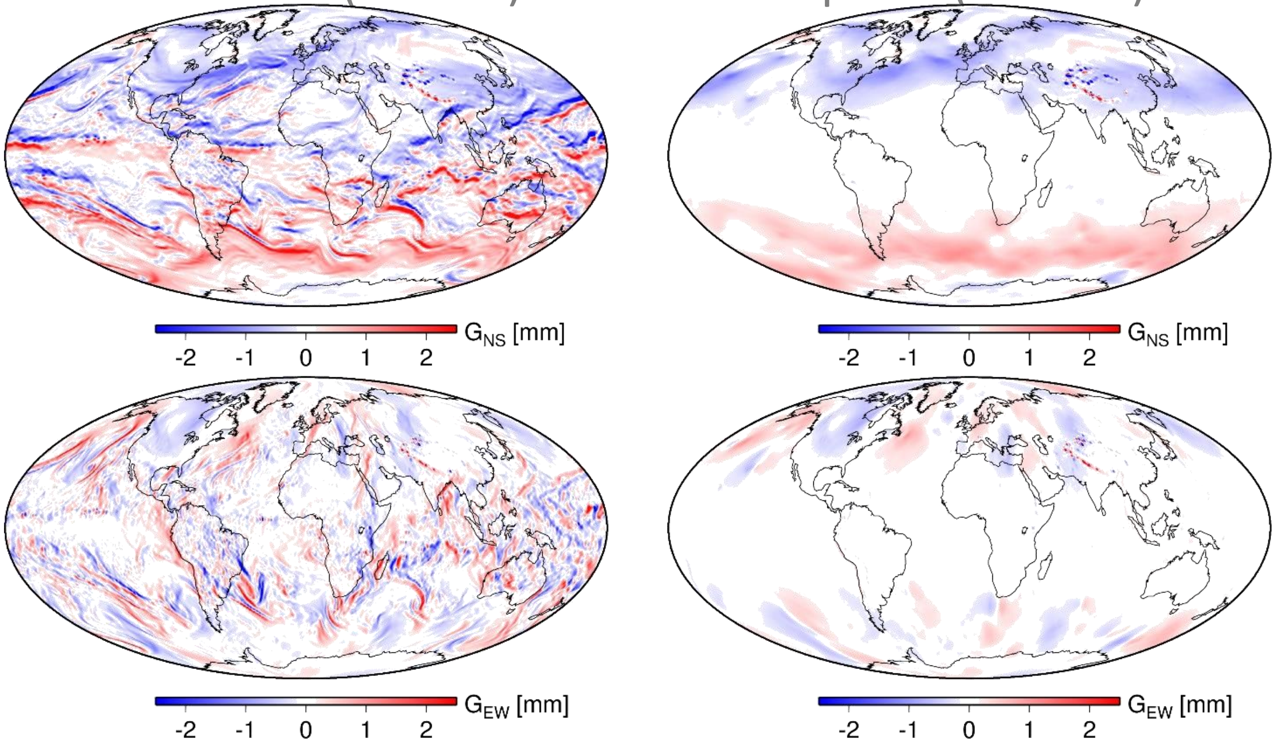
1mm gradient ≈
3cm@10 degrees

- ❑ Linear gradient components

microwave (L-Band) | optical (532 nm)

North-South

East-West



- ❑ **Spatio-temporally noisy for microwave, smooth for optical**

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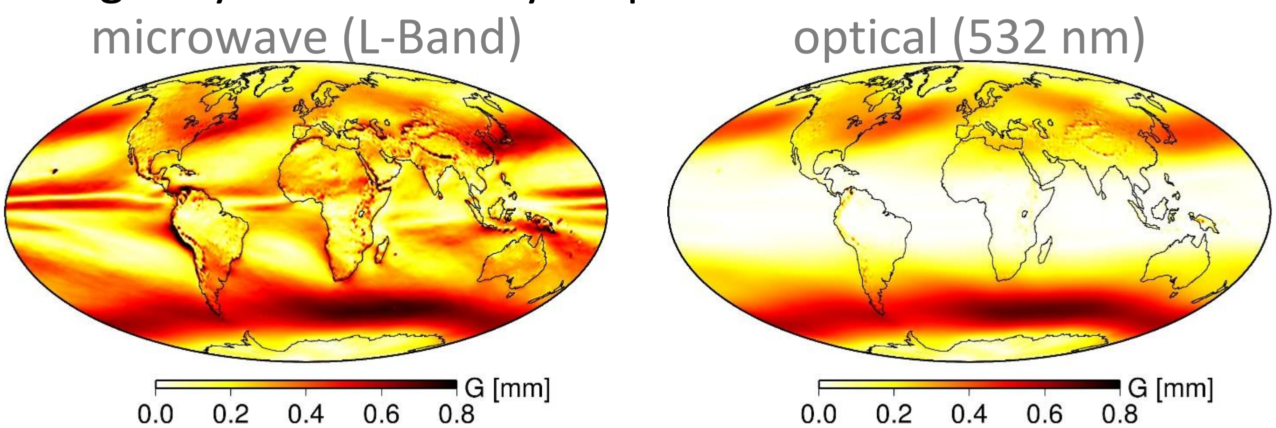
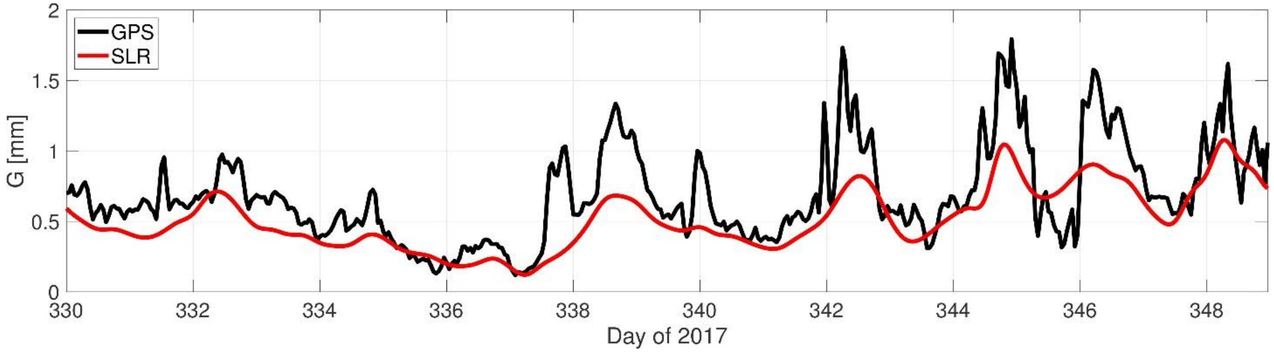
Asymmetric Delays II

- 40-year average asymmetric delay amplitude

$$G = \sqrt{G_{NS}^2 + G_{EW}^2}$$



- Hourly gradient estimates from ERA5 at Wettzell during CONT17



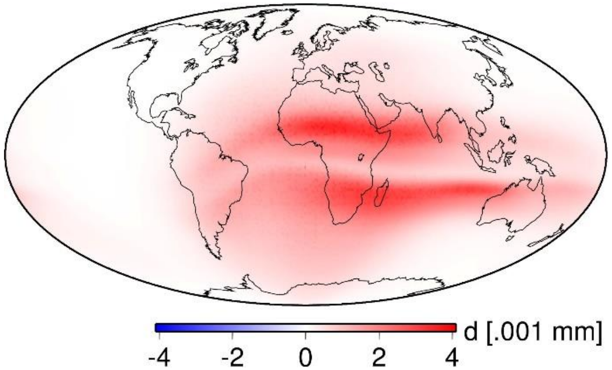
Ray-Bending due to Ionospheric Refraction

Based on ERA5, IRI2016, IGRF2014, $\varepsilon = 3°$, $\alpha = 0°$

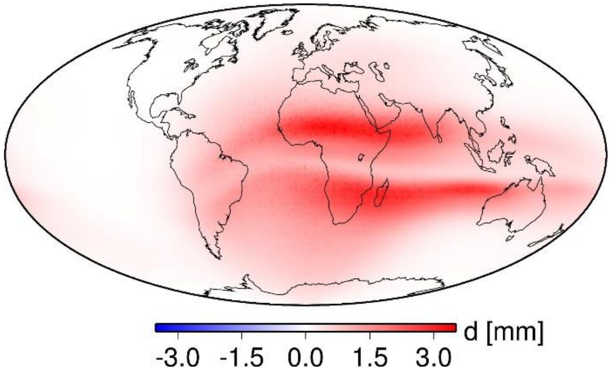
$$\int (1 + 10^{-6} N)\, ds_i - \int (1 + 10^{-6} N)\, ds_\infty$$

N: refractivity, s_i: arc length, s_∞: arc length in the hypothetical absence of ionosphere

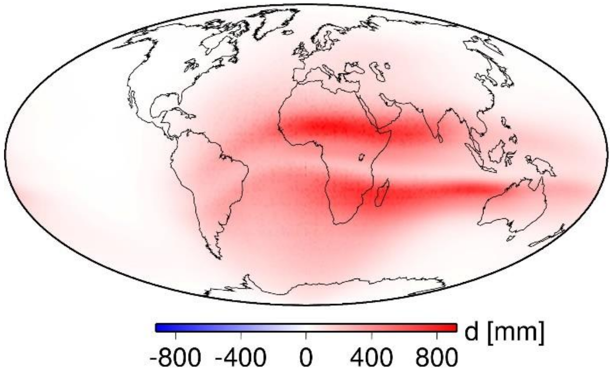
VLBI X-band



GPS L-band



DORIS UHF-band



expected $\delta H \approx 0.4\ \mu m$ expected $\delta H \approx 0.4$ mm expected $\delta H \approx 100$ mm

Note the different colour scales!

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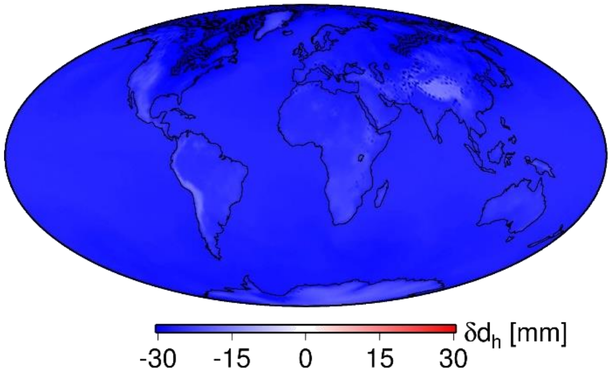
Chapter III
Position-Induced Differences

Height-Related Differences

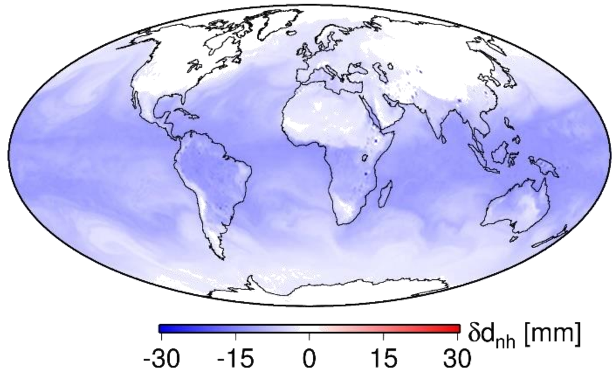
- 100 m height difference (Galileo)

Zenith hydrostatic delay



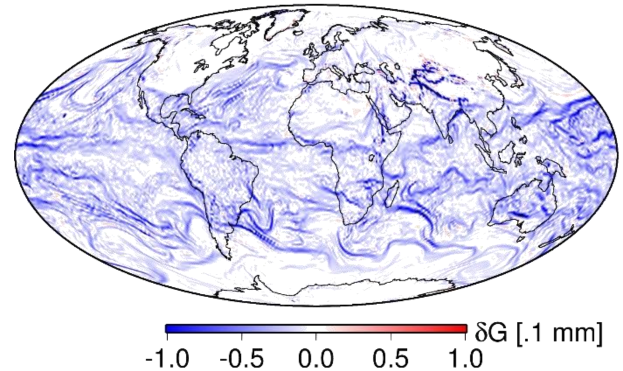
-27 mm on average

Zenith non-hydrostatic delay



-3 mm on average

Gradient amplitude



$$G = \sqrt{G_{NS}^2 + G_{EW}^2}$$

-0.06 mm on average or -3 mm@$7°$

- Symmetric/asymmetric delay decreases upwards

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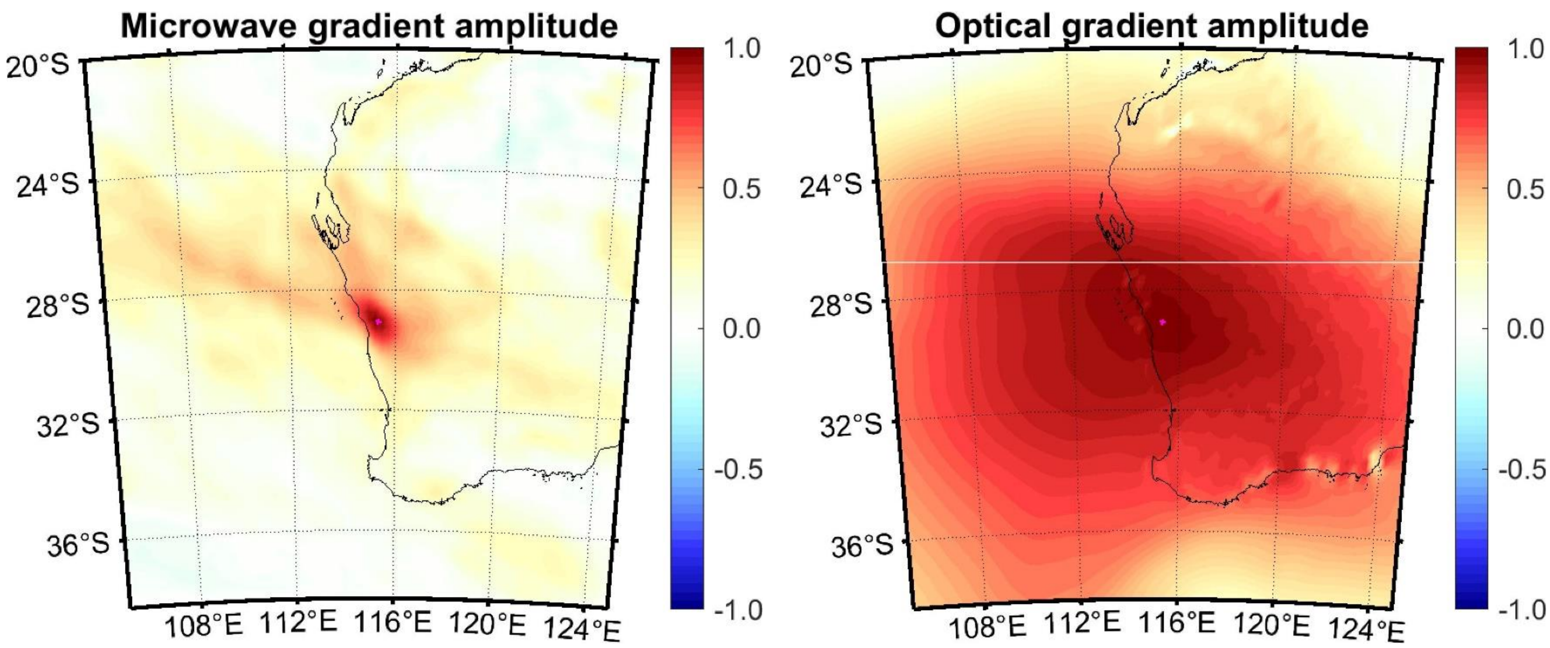
Spatial Correlation



Yarragadee, Australia

- ❑ Microwave gradients decorrelate very fast → difficult to predict

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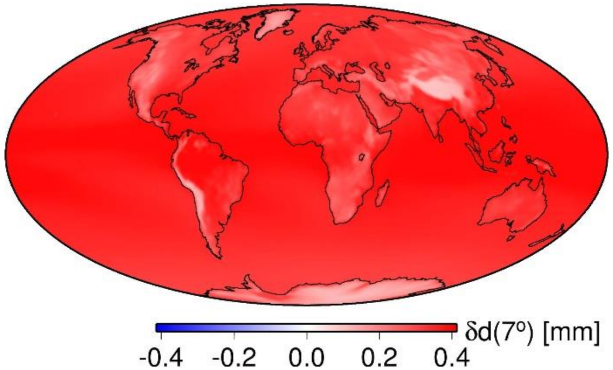
Chapter IV
Observing System-Induced Differences

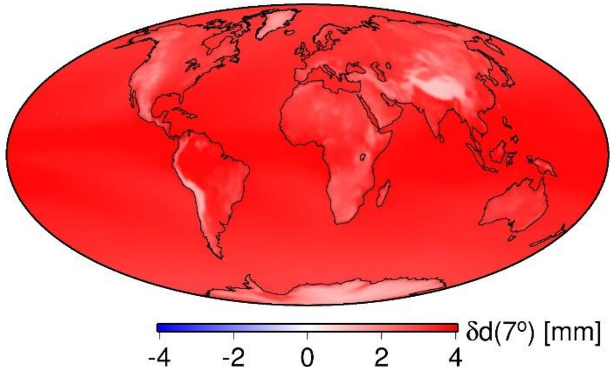
Mapping Functions Depend on the Orbital Altitude

GNSS minus VLBI



expected $\delta H \approx 0.2$ mm

DORIS minus VLBI



expected $\delta H \approx 2$ mm

- Mapping factor magnitude ranking

$$mf^{L} < mf^{R}_{h,nh} < mf^{P}_{h,nh} < mf^{D}_{h,nh}$$

L: SLR, R: VLBI, P: GNSS, D: DORIS

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Chapter V
Simulation of Space Geodetic Observations

Space Geodetic Adjustment

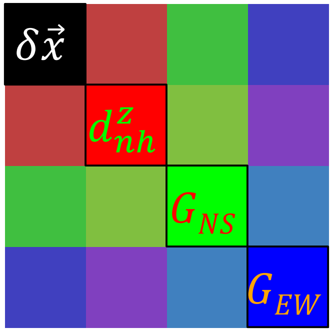
- Assumption: everything perfectly understood except for non-tidal station motion, atmospheric refraction, and frequency standards' stability
- Weighted least-squares, statistical tests for outliers, loose relative constrains, no absolute constrains, etc.

$$o - c = mf_{nh} d_{nh}^{z} + mf_{g}[G_{NS}\cos(\alpha) + G_{\mathrm{EW}}\sin(\alpha)] + clk + \delta\vec{x}$$

estimated parameters

o: observed, c: computed, mf_{nh}: non-hydrostatic mapping factor, mf_g: gradient mapping factor, α: azimuth

- NEQs for combination

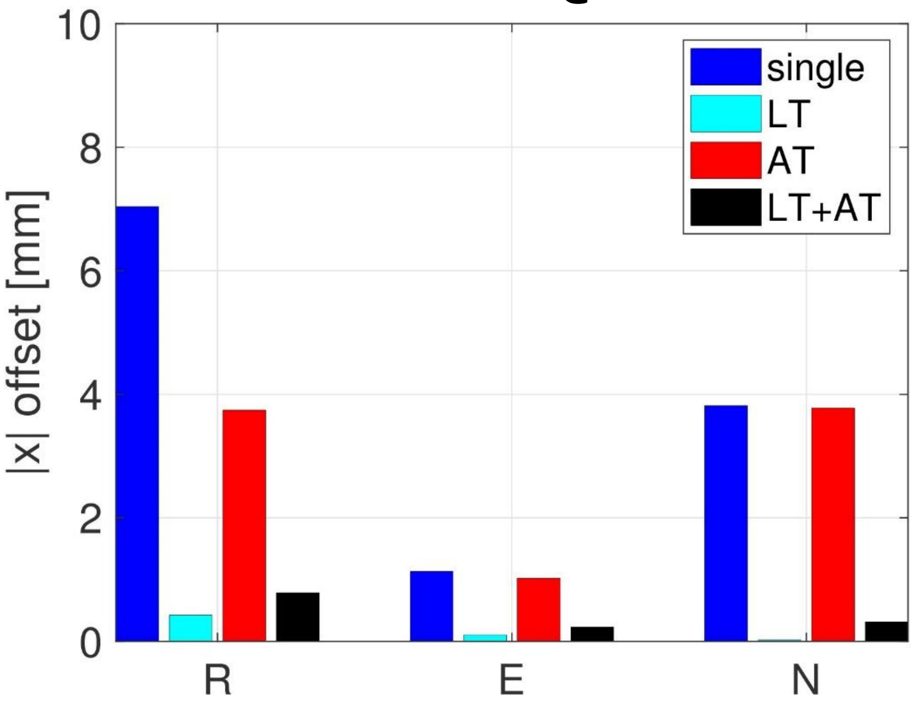


Chapter VI
Multi-Technique Combination

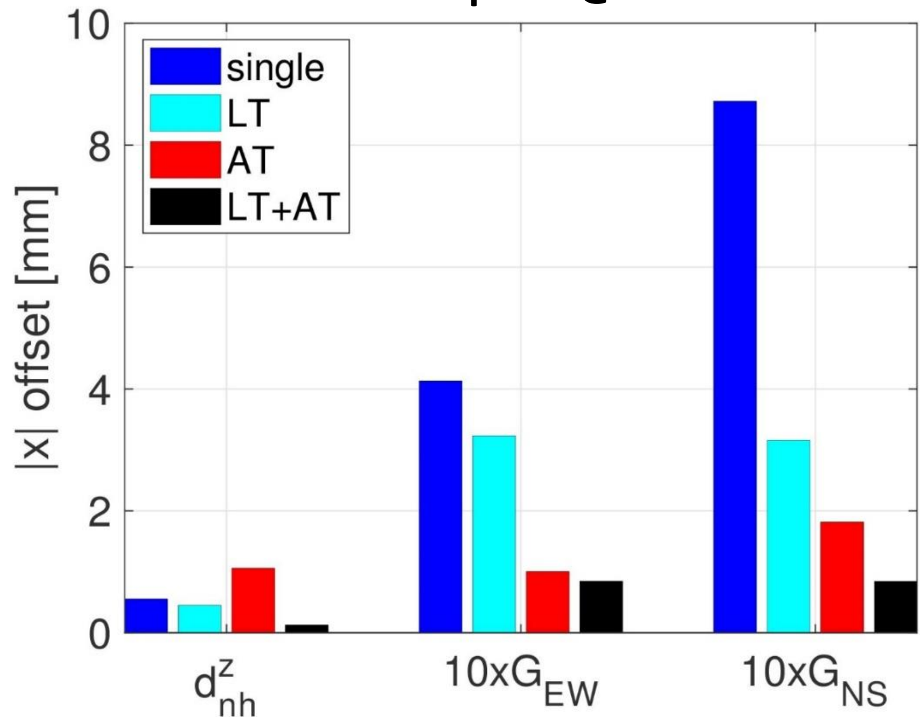
. . . Introducing Local + Atmospheric Ties

- Imp. for coordinates/troposphere → offset/scatter reduction

Coordinates@VLBI



Atmosphere@VLBI

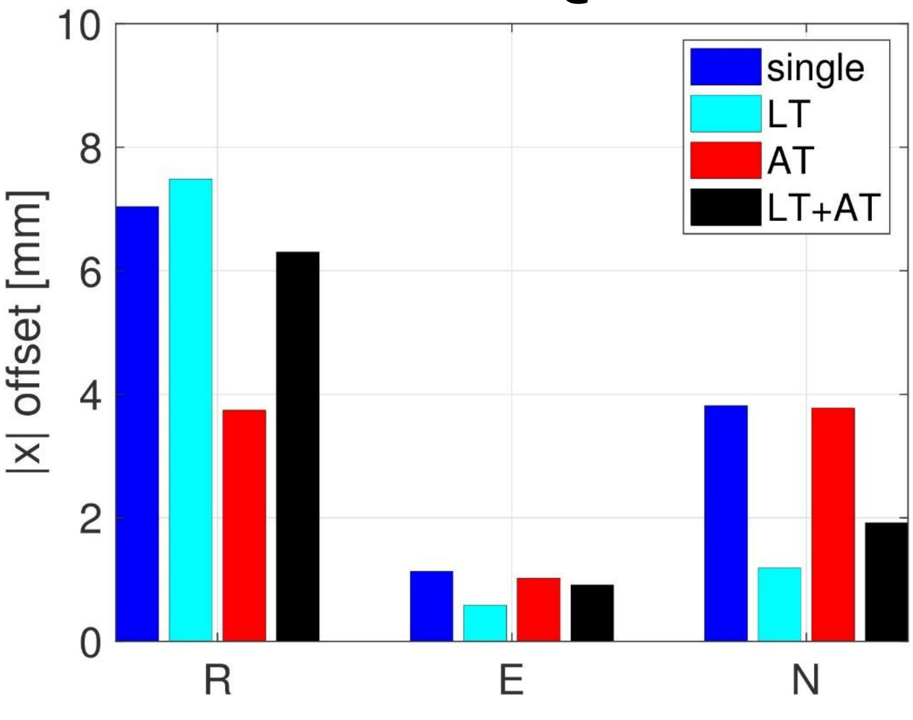


47% and 66% reduction in zenith delay and gradient scatter resp.

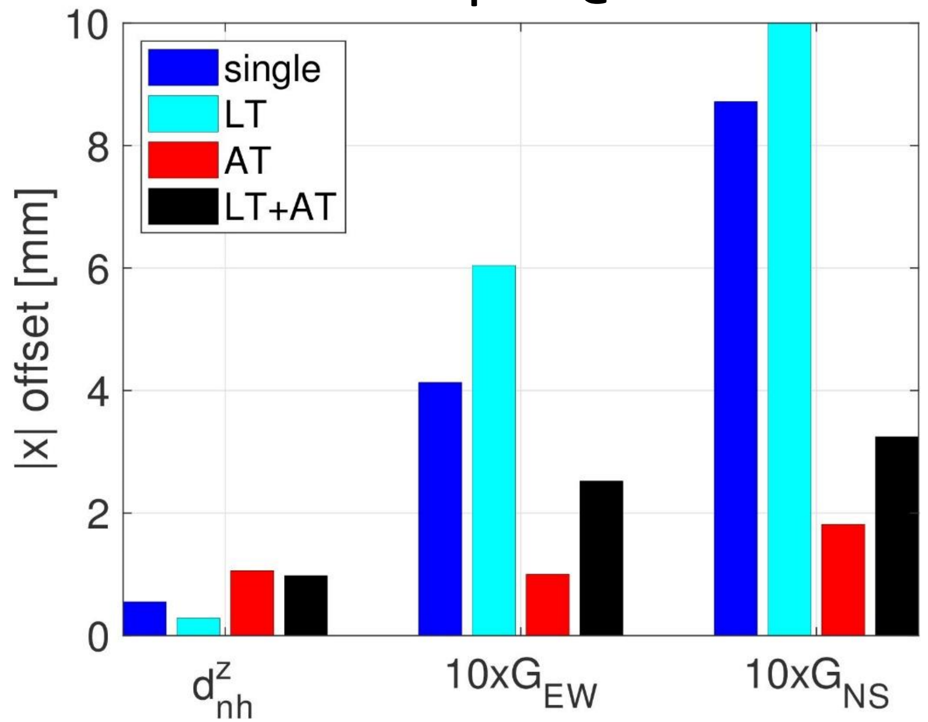
. . . Introducing 1cm Bias in VLBI Height

- ❑ Detr. for coordinates/troposphere → offset increase

Coordinates@VLBI

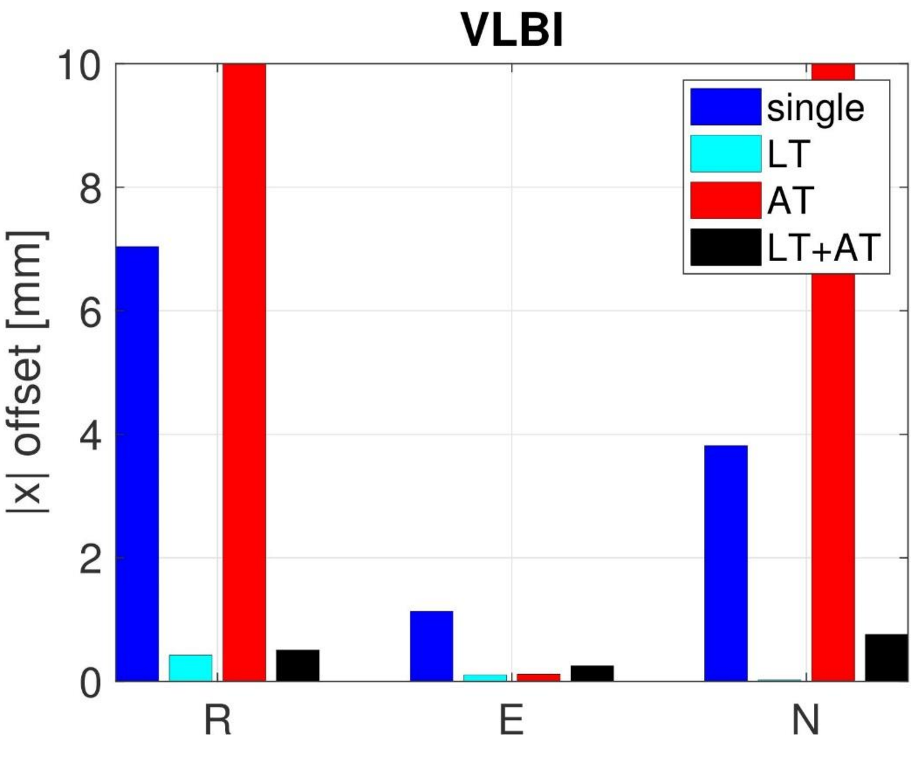


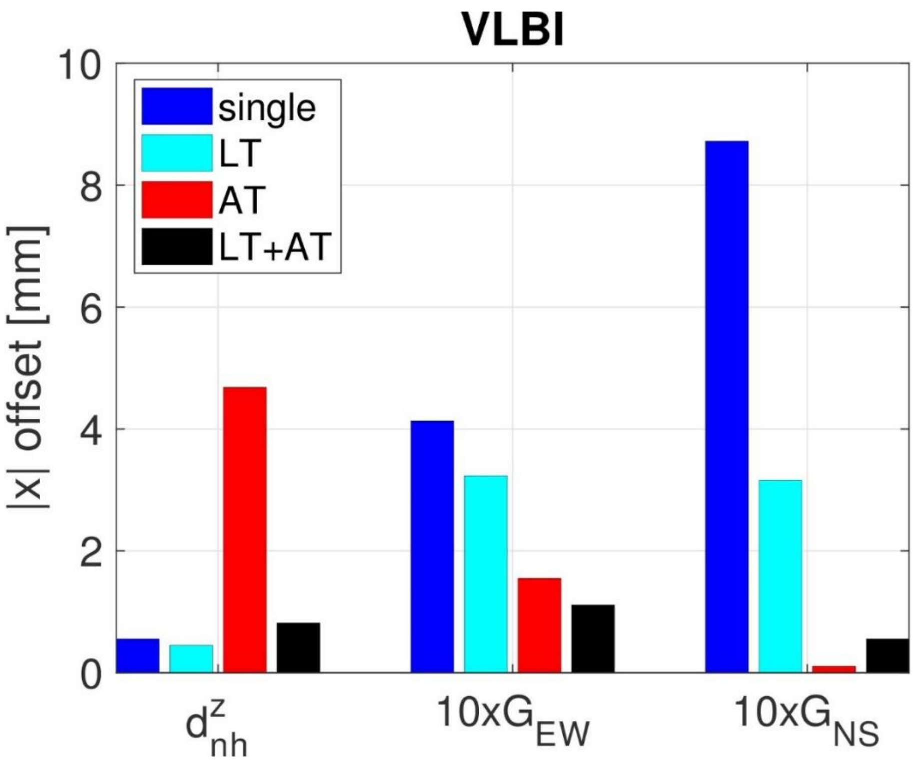
Atmosphere@VLBI



. . . Introducing 1cm Bias in VLBI d_{nh}^{z}

- Detr. for coordinates/troposphere → offset increase





Recapitulation

- Frequency: optical gradients smoother spatially and temporally than microwave
- Position: symmetric/asymmetric delays decrease with increasing altitude
- System: $mf^{L} < mf^{R}_{h,nh} < mf^{P}_{h,nh} < mf^{D}_{h,nh}$
- Based on simulations (PRLD combination with atmospheric and local ties):
  - ATs improve coordinate and troposphere estimation
  - ATs slightly mitigate the "damage" induced by biased LTs
  - ATs useful to detect biased LTs

Thank you!

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