Radio Occultations Basics

C. Marquardt

radio.occultation@eumetsat.int

Agenda

- Global Navigation Satellite Systems
- Radio Occultation measurements and how they work
- Processing steps
- Error sources

GNSS - Global Navigation Satellite Systems

GPS (Global Positioning System)

- US constellation of satellites for navigation purposes
- 6 orbit planes
- Nominal constellation: 24 satellites...
- ...but up to 32 satellites in practise
- 12 hour orbits
- 20.200 km above Earth's surface (MEO)
- Typically 6-8 satellites are in view at any point on the world

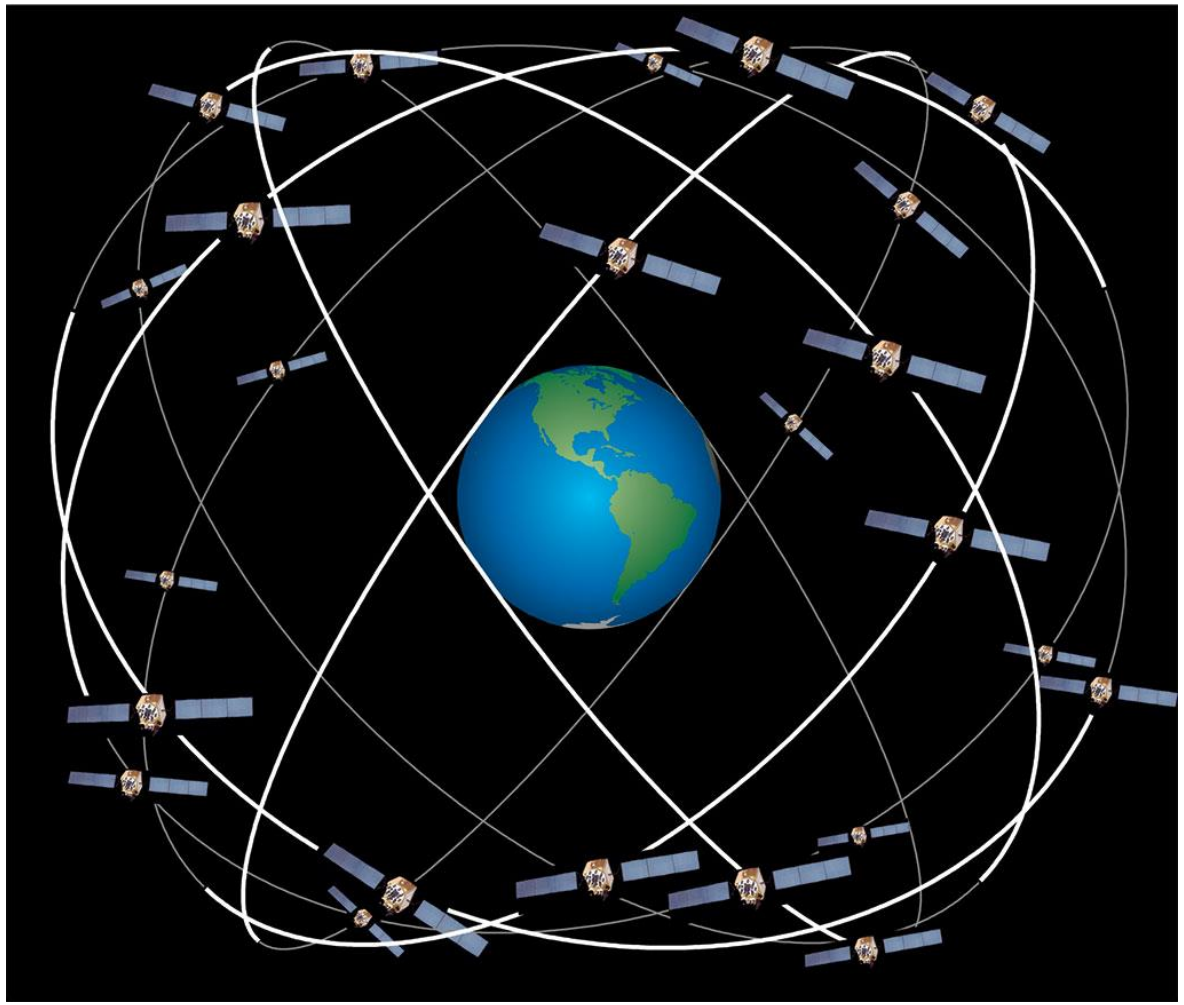

Figure: http://hepl.stanford.edu/images/GPS-Constellation.jpg

Positioning by Ranging

- Assume you know the distance from each satellite...

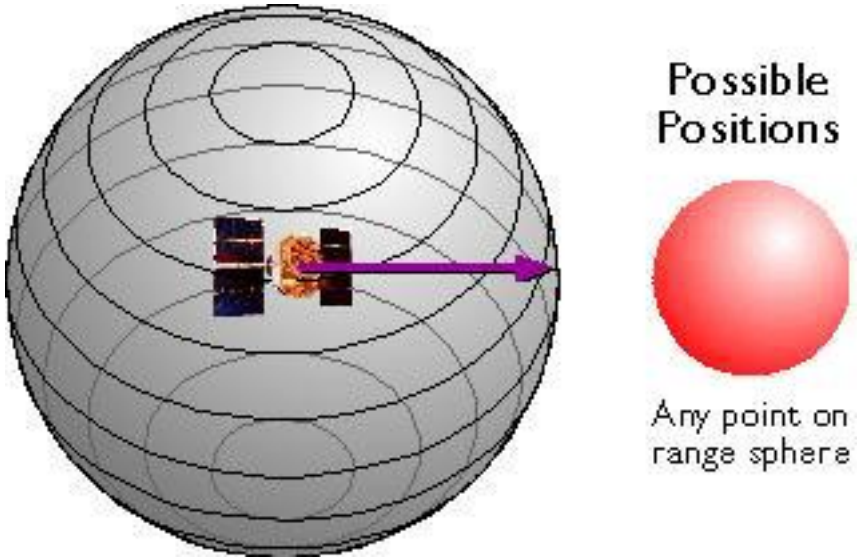

Figure: https://www.e-education.psu.edu/natureofgeoinfo/sites/www.e-education.psu.edu.natureofgeoinfo/files/image/gps_ranging_1.jpg

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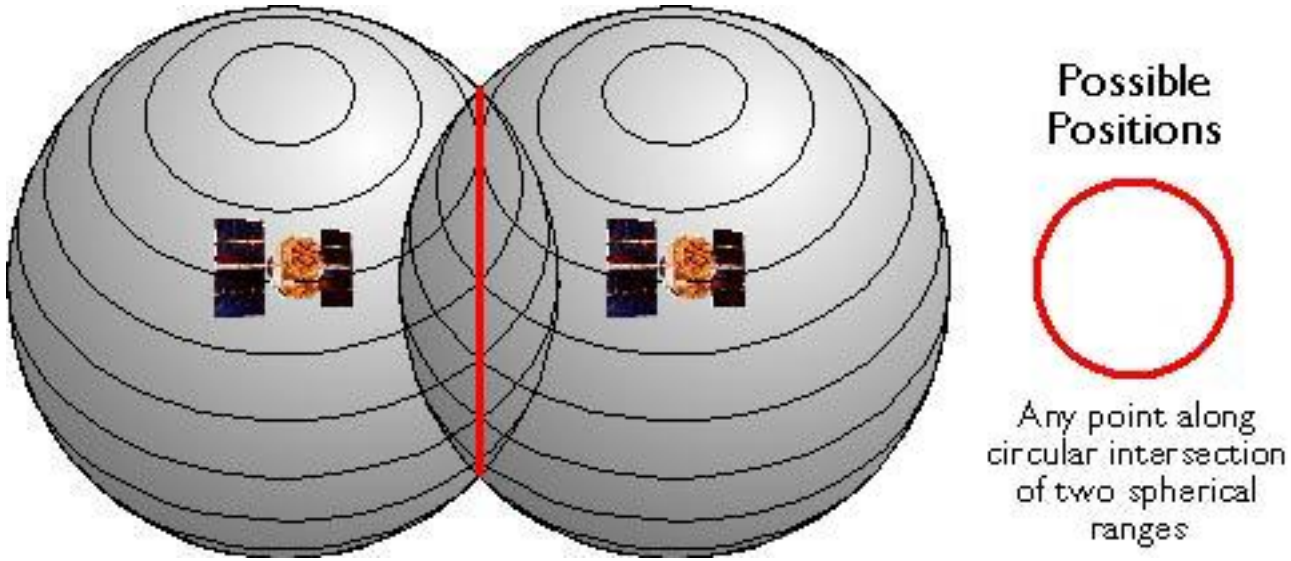

Figure: https://www.e-education.psu.edu/natureofgeoinfo/sites/www.e-education.psu.edu.natureofgeoinfo/files/image/gps_ranging_2.jpg

Positioning by Ranging

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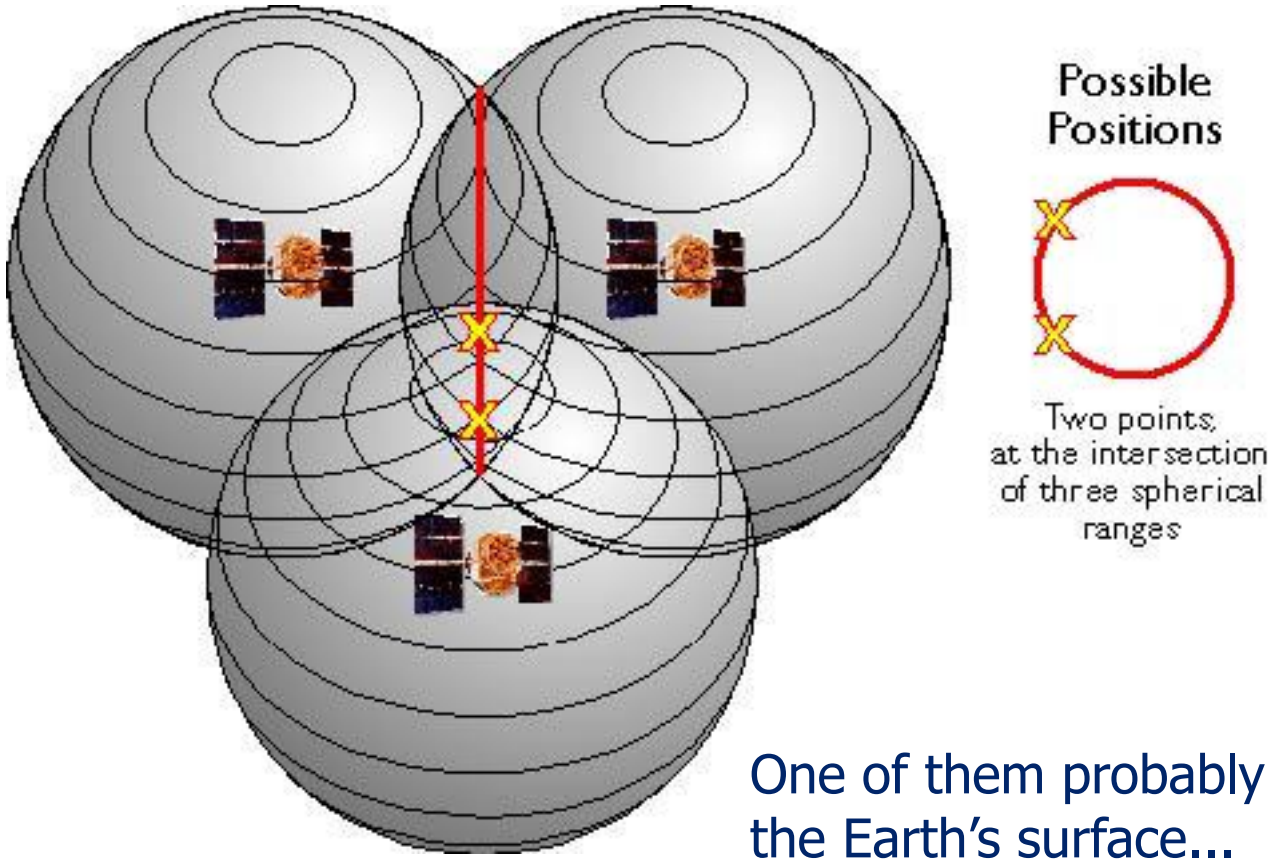


One of them probably isn't even near the Earth's surface...

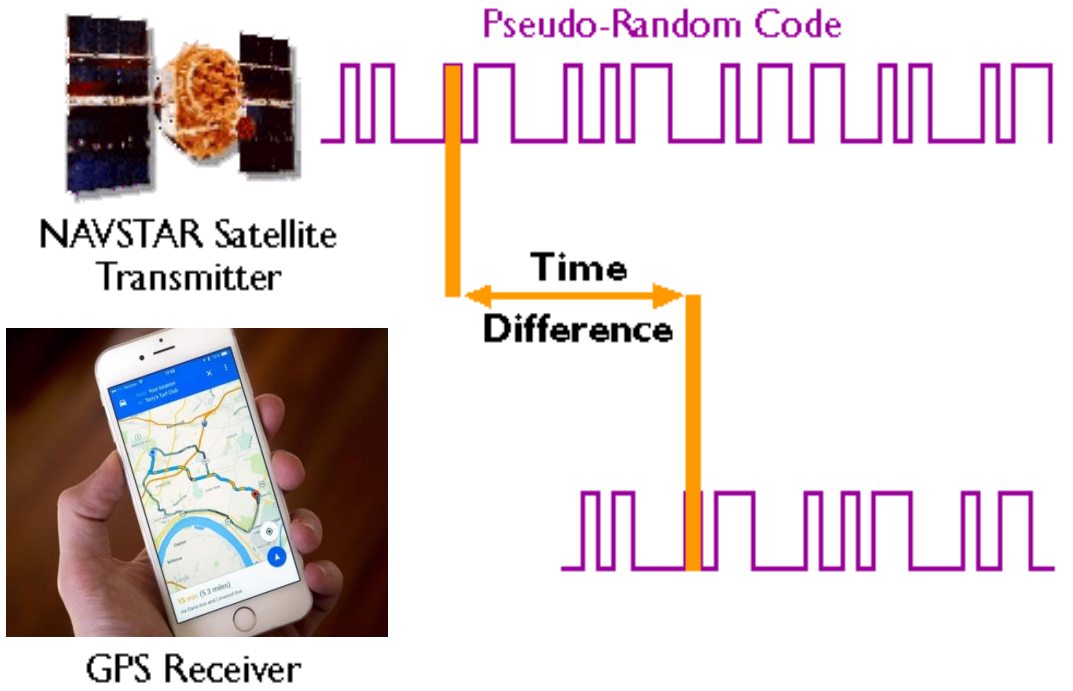
Figure: https://www.e-education.psu.edu/natureofgeoinfo/sites/www.e-education.psu.edu.natureofgeoinfo/files/image/gps_ranging_3.jpg

How to measure range from a satellite signal?

- GNSS satellites modulate a unique code on top of the carrier frequency...
- …plus a second bit sequence providing information on GNSS transmission time and satellite position (“navigation message”).

- Thus the receiver knows when a certain bit was transmitted and when it was received → range.

- In practice, two clocks do not agree perfectly – measurements from a 4th satellite are required.



Distance = Speed of Light • Time Difference

Figure: https://www.e-education.psu.edu/natureofgeoinfo/sites/www.e-education.psu.edu.natureofgeoinfo/files/image/gps_time_difference.gif

GNSS Fundamentals (cont'd)

GNSS receivers:

- Pseudorange - track the modulated codes directly (by code replication)
  - absolute range plus clock difference
  - GPS positions from navigation message
  - Positioning accuracy ~ few meters

- Carrier phases – tracked in addition to codes for high-quality (geodetic) receivers
  - only relative range, but…
  - ...but very high carrier phase accuracy: ~0.3 mm (GPS L1 C/A) on GRAS
  - Precise GPS positions
  - Positioning accuracy ~ sub-cm

- Different GNSS system differ in code details and frequency plans, but the principle remains the same.

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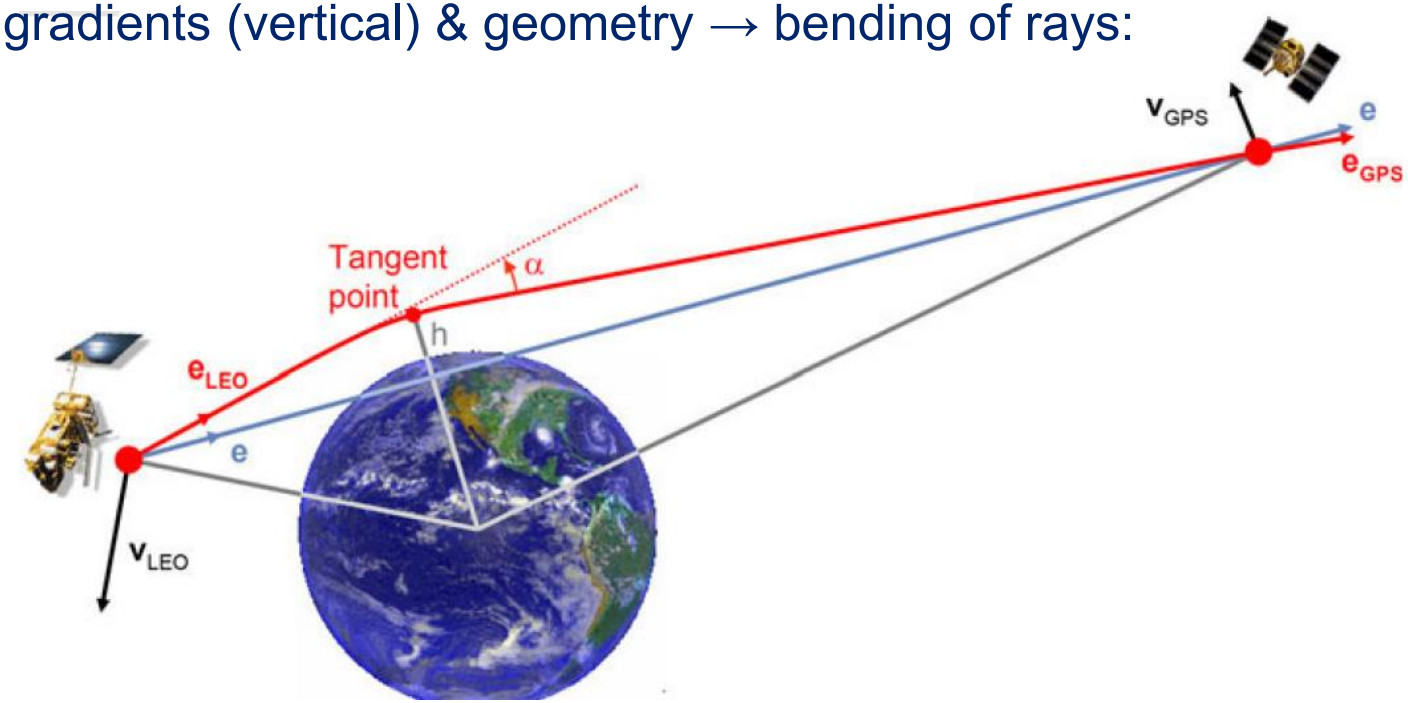
Radio Occultations - a Limb Measurement

The physics behind the measurement

- Temperature, moisture, electron density ⟶ refractive index of the atmosphere (and ionosphere)
- Refractive index gradients (vertical) & geometry → bending of rays:



- Ray bending → longer travel path compared to vacuum (“excess path”)
- Satellites move → excess path changes during occultation → excess doppler

The physics behind the measurement

- Excess doppler & precise position & velocity of all satellites → bending angle as function of (impact) height.

- Precise Orbit Determination (POD) is a science of its own!
- Typical requirements for RO:
  - Satellite position error: better than 5 – 10 cm
  - Satellite velocity error: better than 0.05 – 0.1 mm/s

- **Key assumption: Spherical symmetry of the atmosphere and ionosphere in between.**

- Additional complication: Ionosphere refraction depends on frequency
  - We use 2 frequencies to correct for that in the neutral atmosphere (ionospheric correction)…
  - …or to estimate ionospheric parameters.

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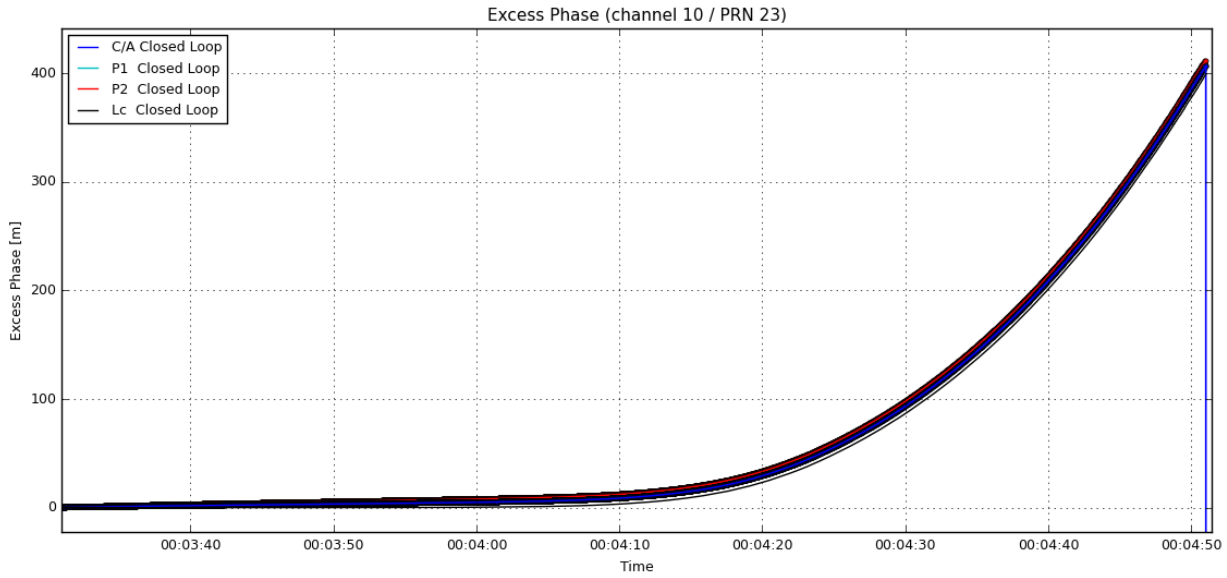
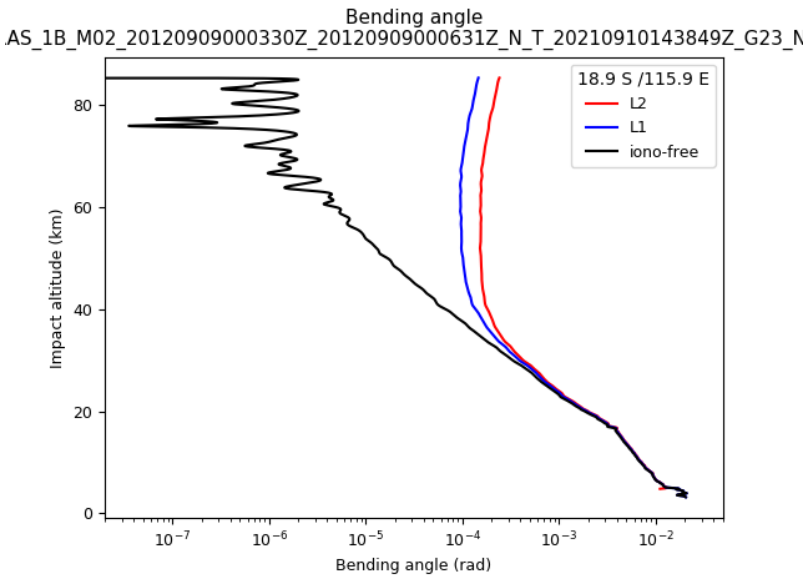
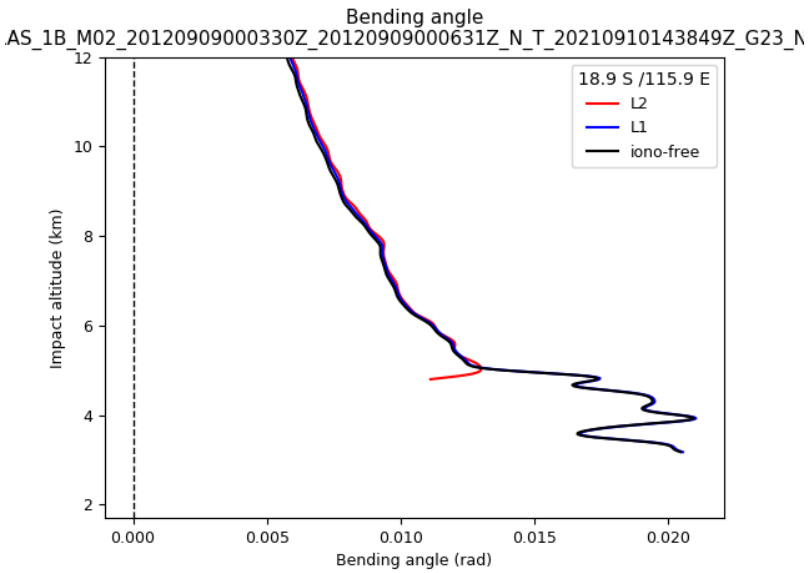
Example (from GRAS)

- Excess carrier phase (as function of time)



- Bending angle profiles (0 – 80 km (log-scale) and troposphere only)





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Radio occultation characteristics

- Limb measurements
  - high vertical (~0.5 – 1.5 km)…
  - …but low horizontal resolution (250 – 400 km)
  - Tangent points also moves by 250 – 400 km during an occultation
  - Most information comes from the area around the tangent point, though

- GNSS Frequencies are in the 1-1.5 GHz range, *outside* of atmospheric absorption windows
  - Weather independent (i.e., not affected by liquid water in clouds)
  - Frequency (i.e., time) measurements – which is linked to the world's atomic clock network
    - High accuracy in principle
    - SI traceability

- No known instrument or calibration drifts – so no bias corrections!

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Global Navigation Satellite Systems (GNSS)

GNSS	Comments	Frequencies
GPS	Global Positioning System – 31 satellites	L1, L2, L5
Galileo	Europe's counterpart – 24 satellites	L1, L5
GLONASS	Russia's counterpart – 24 satellites, legacy system	L1, L2
Beidou	China's counterpart – 30 satellites in MEO	L1, L5
QZSS	Japan's local system – 4 satellites	L1, L2, L5

- Rule of thumb: 1 GNSS constellation with 24 satellites and rising & setting = 500 occultations/day.
- Global distribution depends on orbit geometry; a polar orbit gives quasi-random global distribution with slightly lower density in the tropics.
- Local time distribution depends on orbit; sun-synchronous orbits mean fixed local observation times.

Note: Simplified frequency plans!

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A typical RO retrieval (neutral atmosphere)

RSN

- Precise orbits of GNSS satellites (provided by Radio Occultation Support Network, or RSN)

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- Precise Orbit Determination (POD) of the satellite using zenith antenna data
- Excess phase carrier phases using RO antenna measurements and geometry (“Level 1a”)
- Per-frequency bending angle profiles
- Neutral bending angle profile (ionospheric correction)
- Smoothing, thinning, georeferencing, quality control… (“Level 1b”)

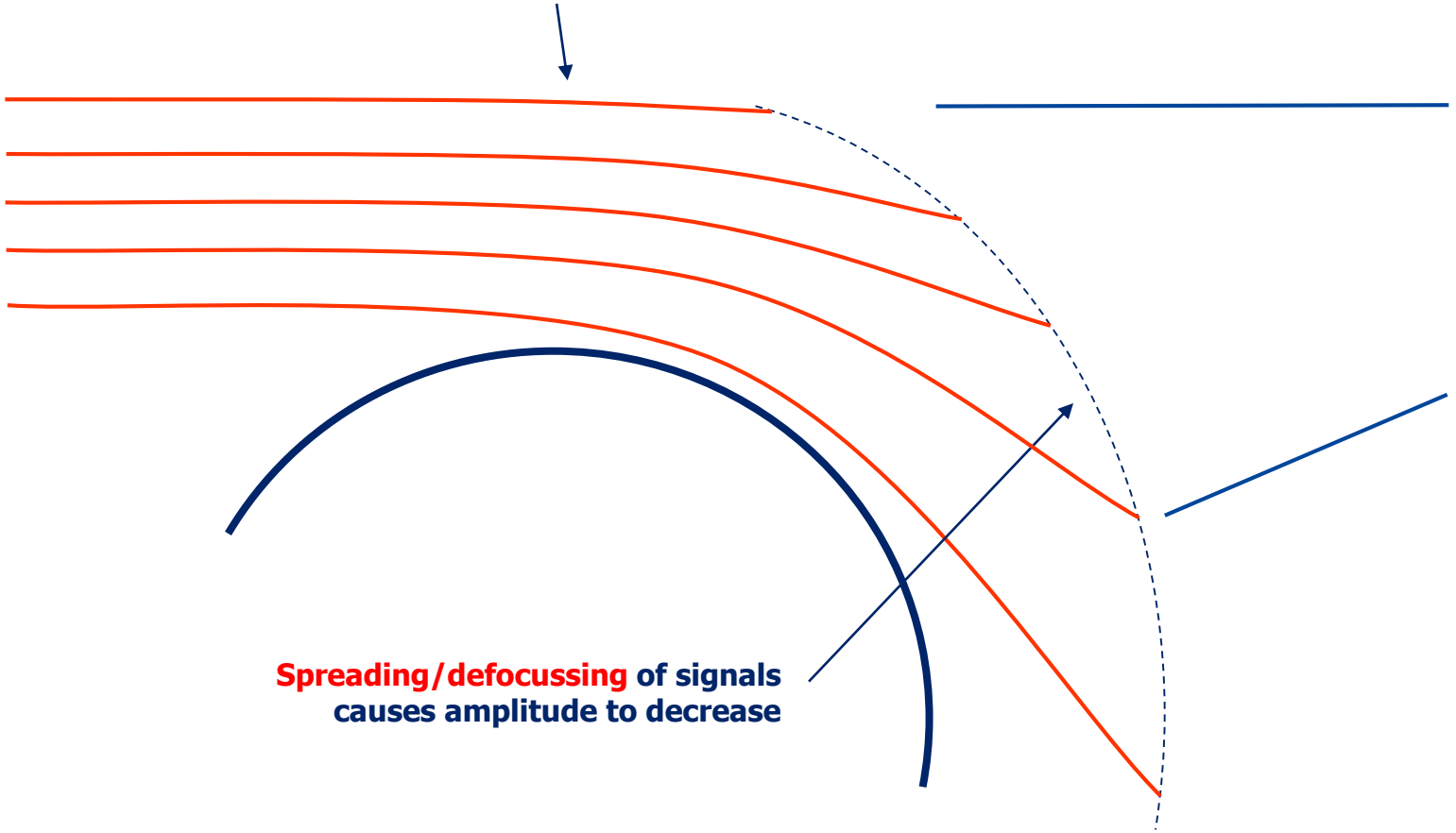
ROM SAF

- Refractivity, temperature and moisture profiles (“Level 2”)
- Climate projects (“Level 3”)
- Software (“ROPP”)

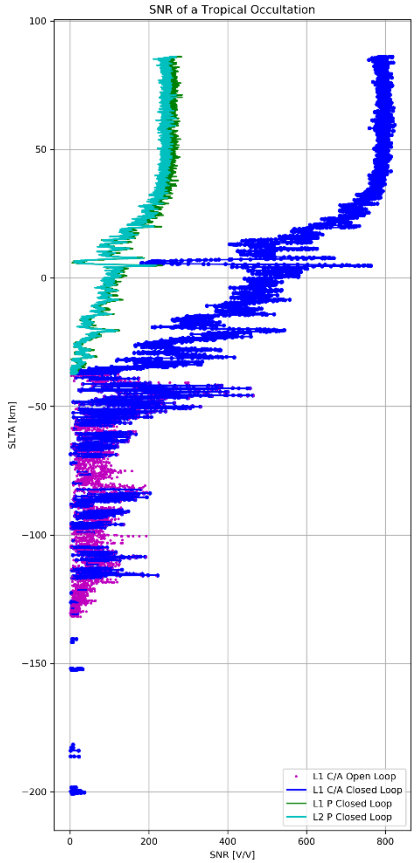
Radio Occultations (cont‘d)

No bending high up (but the picture is simplified – ionosphere also plays a role)

Traditional retrieval (aka geometric tracking) assumes straight rays (also pure troposphere)



Spreading/defocussing of signals causes amplitude to decrease



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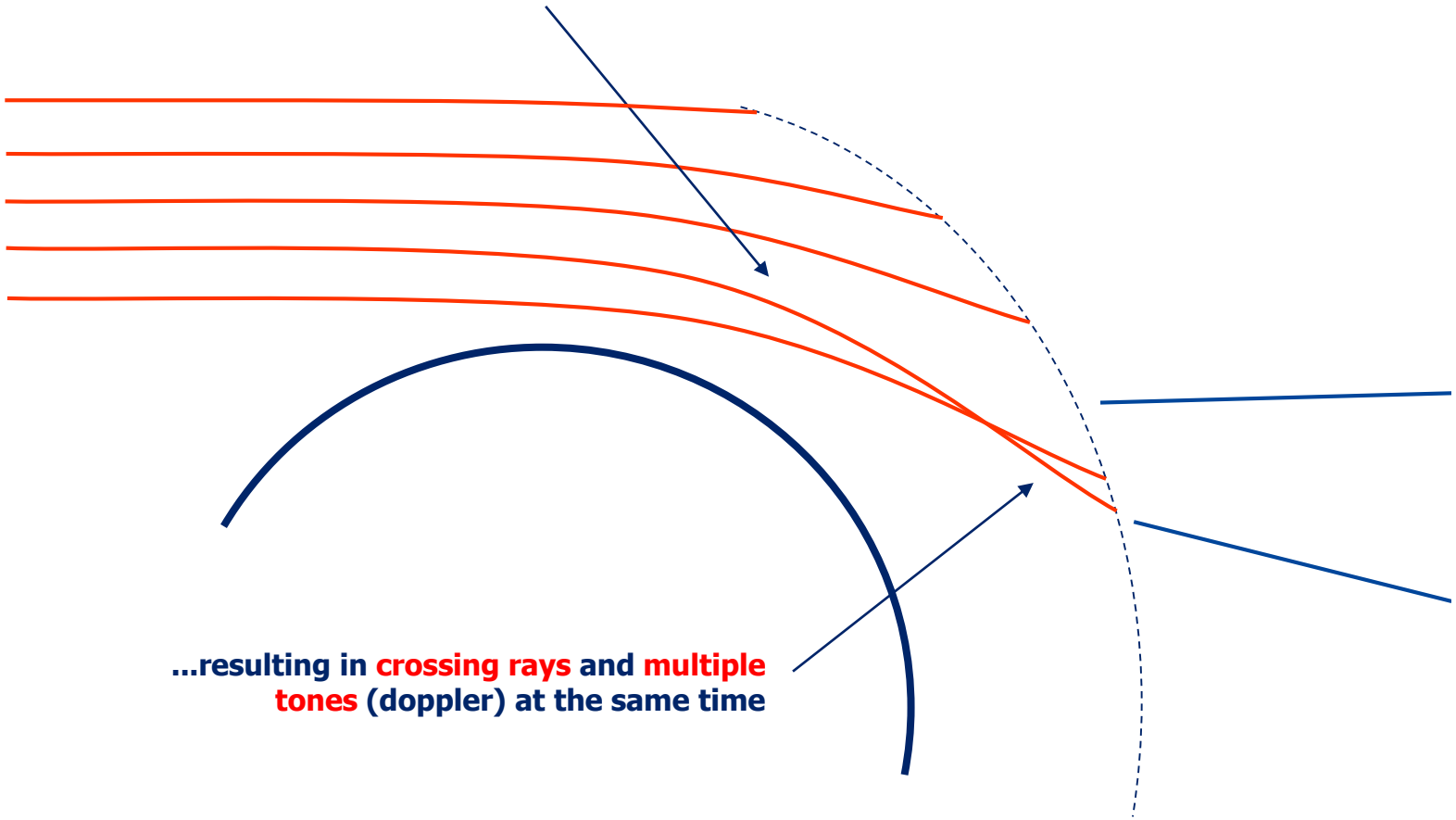
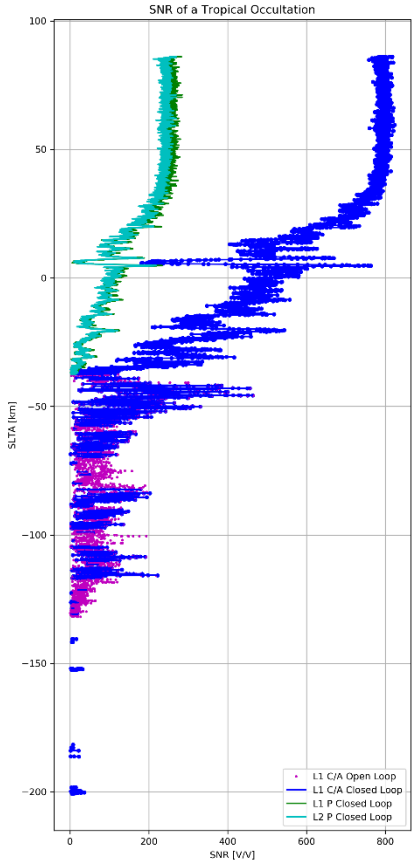
Radio Occultations – Atmospheric Multipath

Strong vertical gradients (in humidity) may cause strong bending on the top side…

More advanced retrievals (aka wave optics) and enhanced measurement modes required



…resulting in crossing rays and multiple tones (doppler) at the same time



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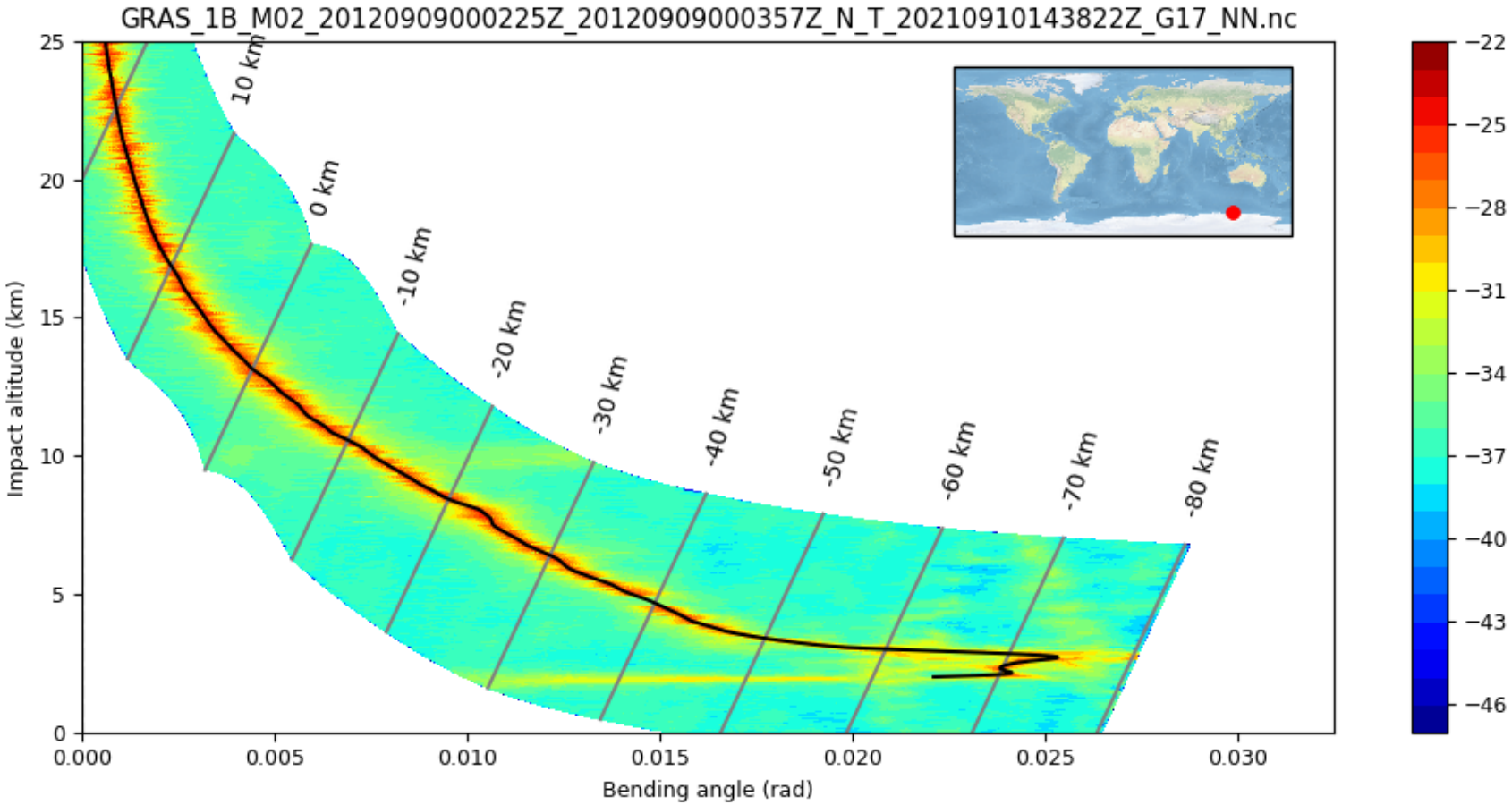
An example – 2012/09/09 00:02:25

- Time-Frequency Distribution mapped into impact parameter/bending angle space
- Retrieved bending angle (black)
- Quasi-horizontal strikes in TFD indicate reflections on sea surface or ice
- “Reassigned” TFD for better resolution (another topic)
- Note: Surface corresponds to 2-3 km impact height



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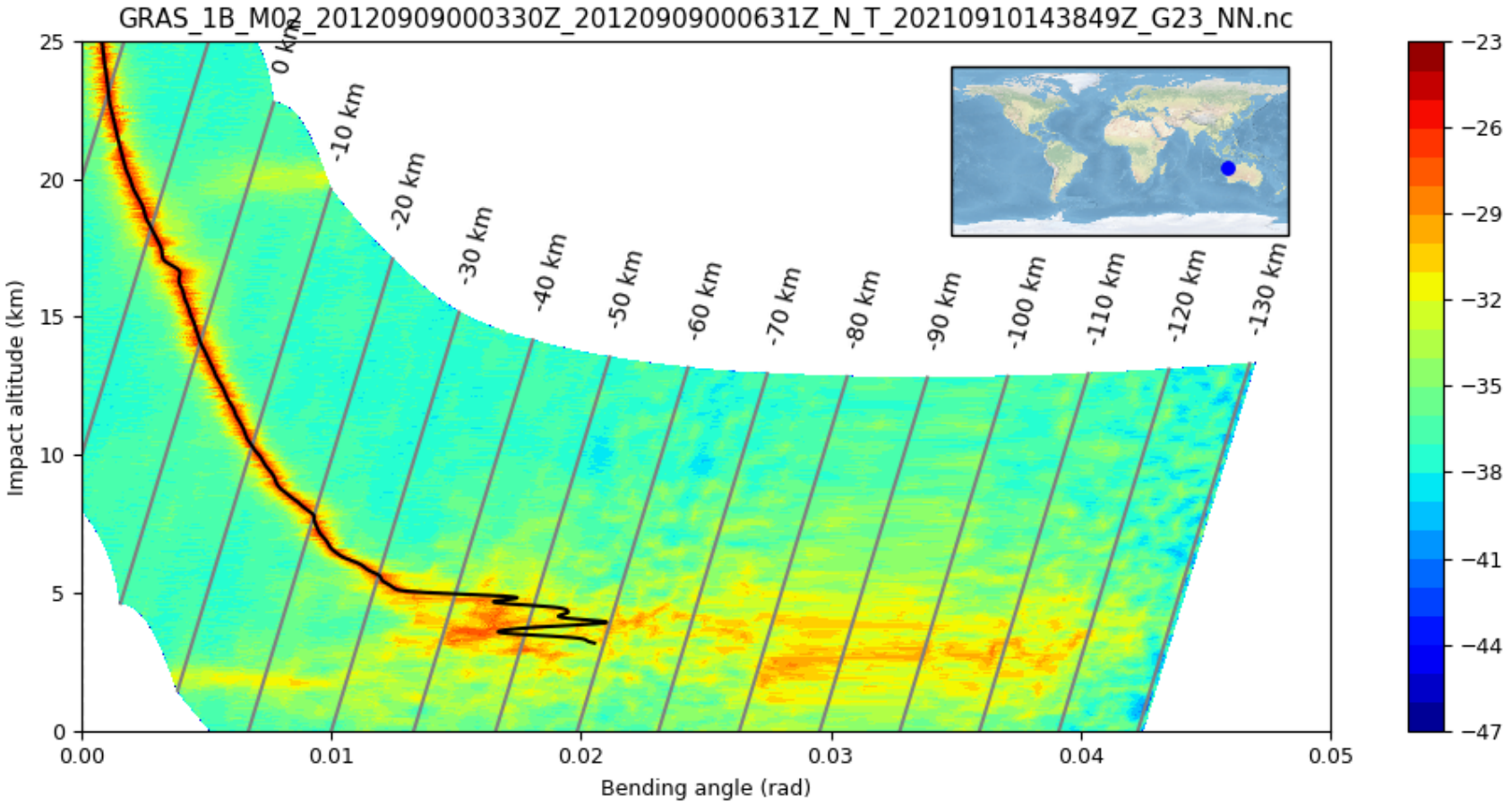
A more problematic example (2012/09/09 00:03:30)

- A meaningful retrieval should closely follow the ridges in the spectrum denoting the main "beam" of the occultation
- In this tropical case, the spectrum exhibits strong multipath in impact parameter space – spherical asymmetry? Ducting?
- In general, errors increase towards the ground because signal propagation becomes much more complicated.



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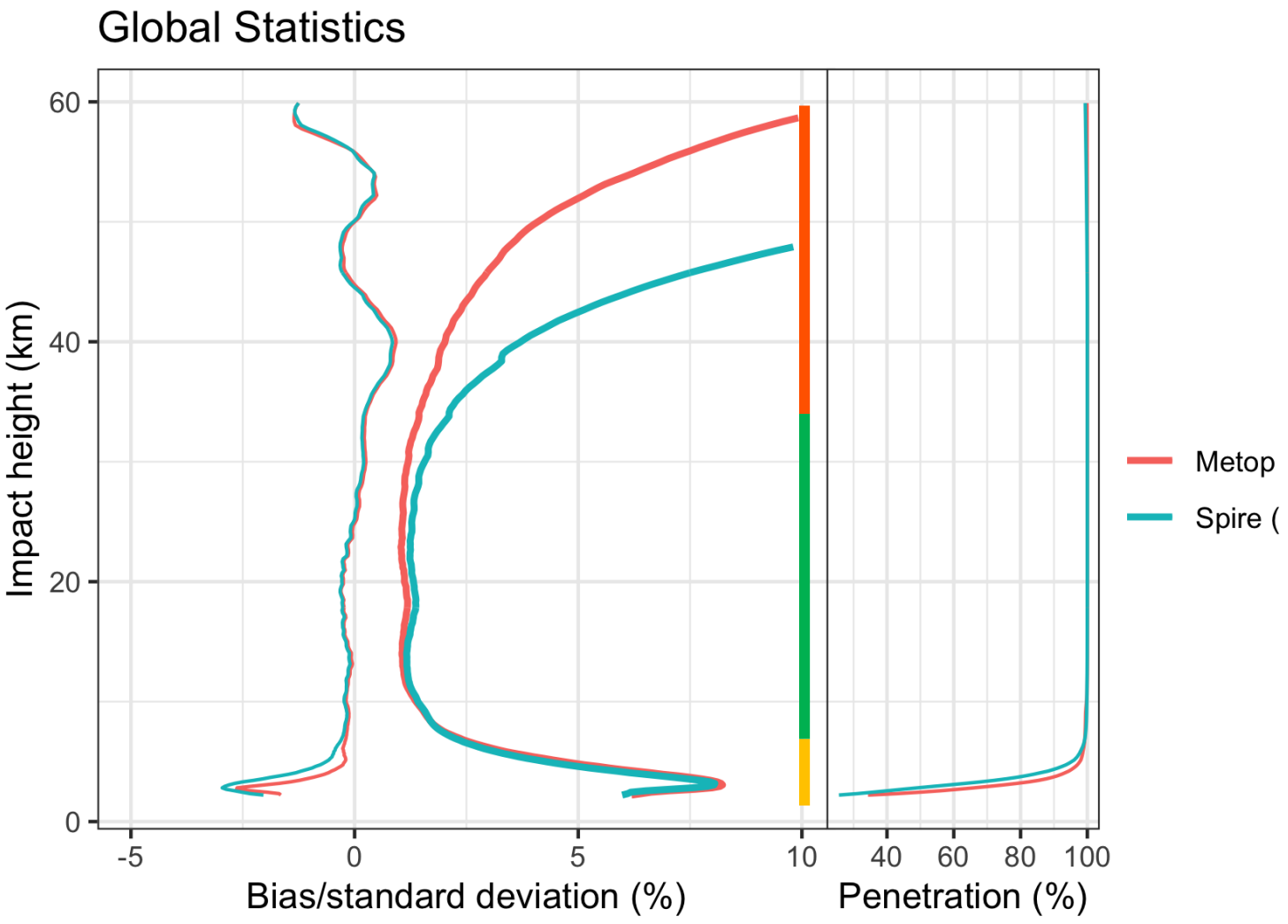
Error Budget

- High up (> 35 km):
  - instrument thermal noise (SNR)
  - ionospheric residual errors
- Upper troposphere to mid-stratosphere (8 – 35 km):
  - Horizontal gradients (i.e., violation of spherical symmetry)
  - Instrument noise becomes less important; most RO data looks the same (apart from different smoothing)
- Lower and mod-troposphere (< 8 km):
  - Instrument tracking algorithms
  - Wave optics processing – SNR & bias?