EUMETSAT Radio Occultation activities: status and future plans

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Agenda

Current and future RO missions

EPS/GRAS, Sentinel-6; EPS-SG, EPS Aeolus

GRAS - Azimuth dependent errors

Error characteristics depending on viewing direction

Reprocessing – COSMIC-2 as example

Biases are complicated

Commercial RO

…will come tomorrow, as will ROMEX

Summary

This will be short.

Radio Occultations on EPS

GRAS instruments:

- Polar sun-synchronous (9:30 LT) orbit, 820km
- Metop-A: 2006 – 2021
- Metop-B: 2012 – 2028(+?)
- Metop-C: 2018 – 2034(?)

- Metop-B: drifting since last year, current LT 9:20
- Metop-C: One gyro failed; impact on lifetime unclear.
- GRAS requires encrypted codes that might go away before the end of Metop-C; then, GRAS would turn into a single-frequency receiver.

Radio Occultations on Copernicus Sentinel6

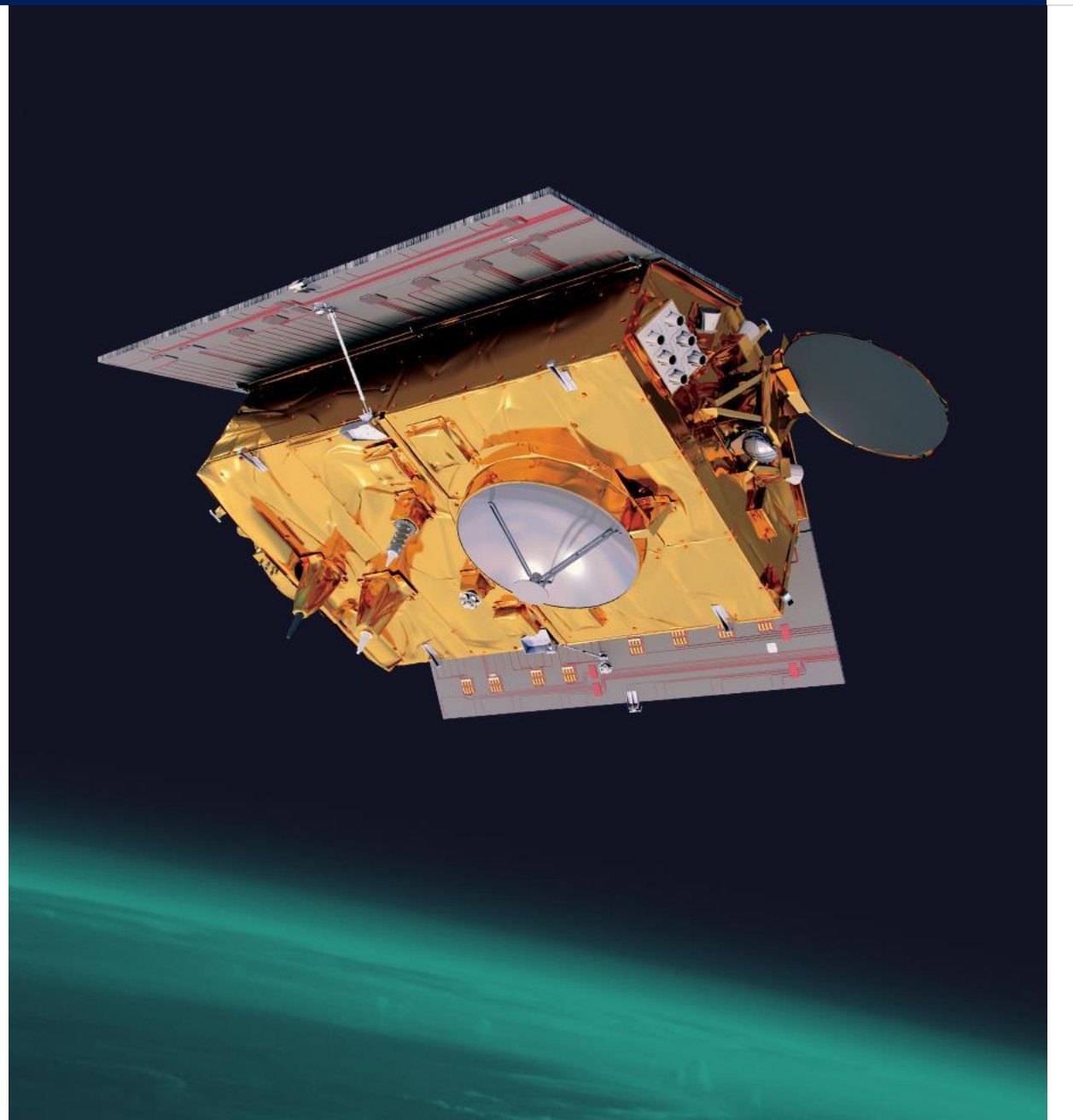
S6-A (altimetry, medium-inclination orbit, 1300km) followed by:

- S6-B in late 2025;
- S6-C in 2030.

- JPL-donated RO instrument (TriG) on S6–B;
- As before: Processing in NRT by JPL; EUM provides Non-Time-Critical processing for validation and climate applications;
- RO instrument TBD on –C.

Upcoming enhancements:

- Galileo (200/day) from late 2024 onwards on -A;
- Ionosphere (up to 500+ km) with S6-B.



Radio Occultations on EPS-SG

EPS-SG

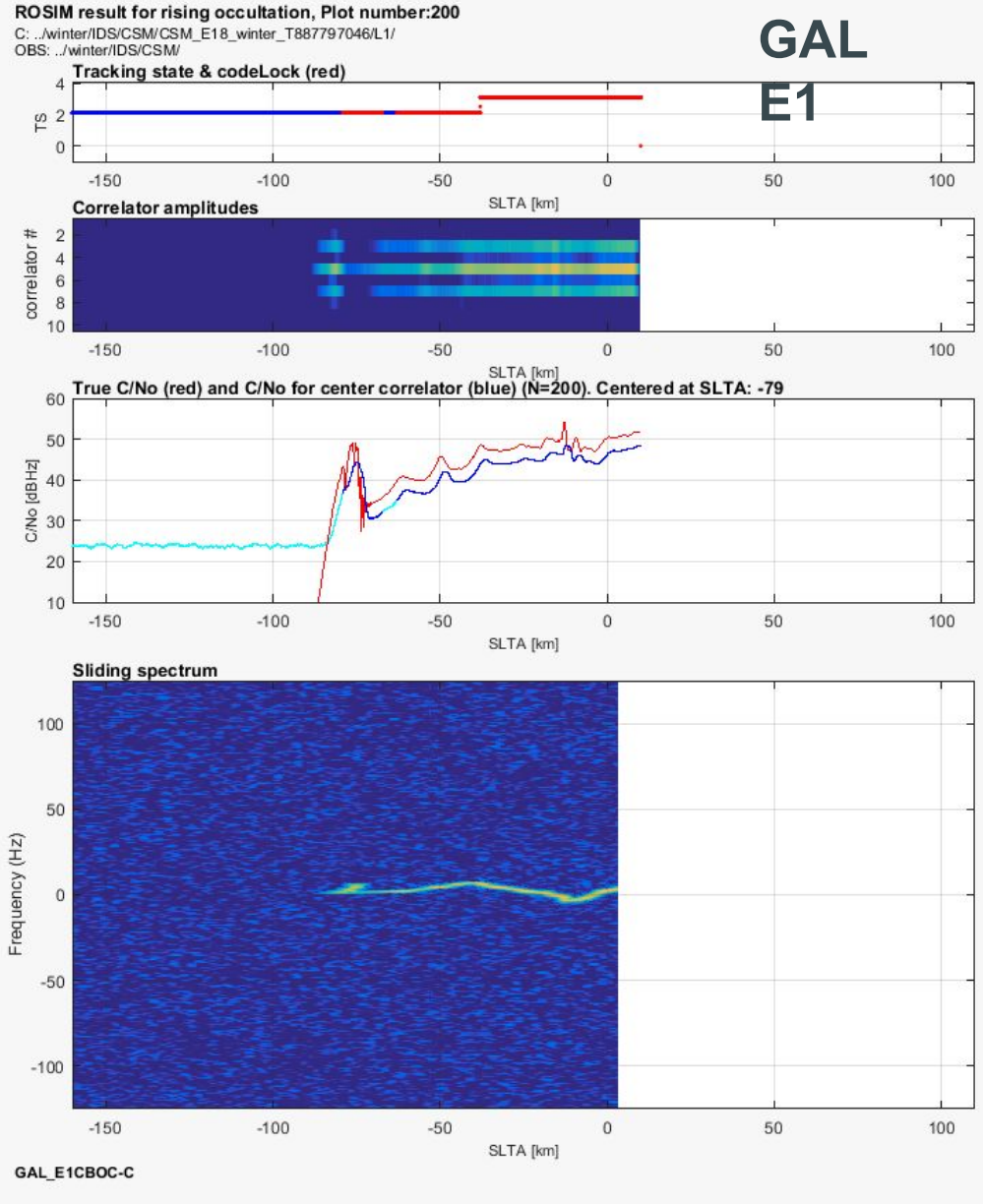
- Two satellites in parallel; same sun-synchronous orbits as current Metops (9:30 LT)
- First launches in late 2025 (SG-A1) and in 2026 (SG-B1); will be called Metop-D, -E etc.
- Three pairs of satellites; later launches scheduled for in 2032/2033 and 2039/2040
- RO only instrument on both platforms
- Tandem flight (20 seconds) of Metop-C (GRAS) and SG-A1 (GRAS-2) for the initial six months

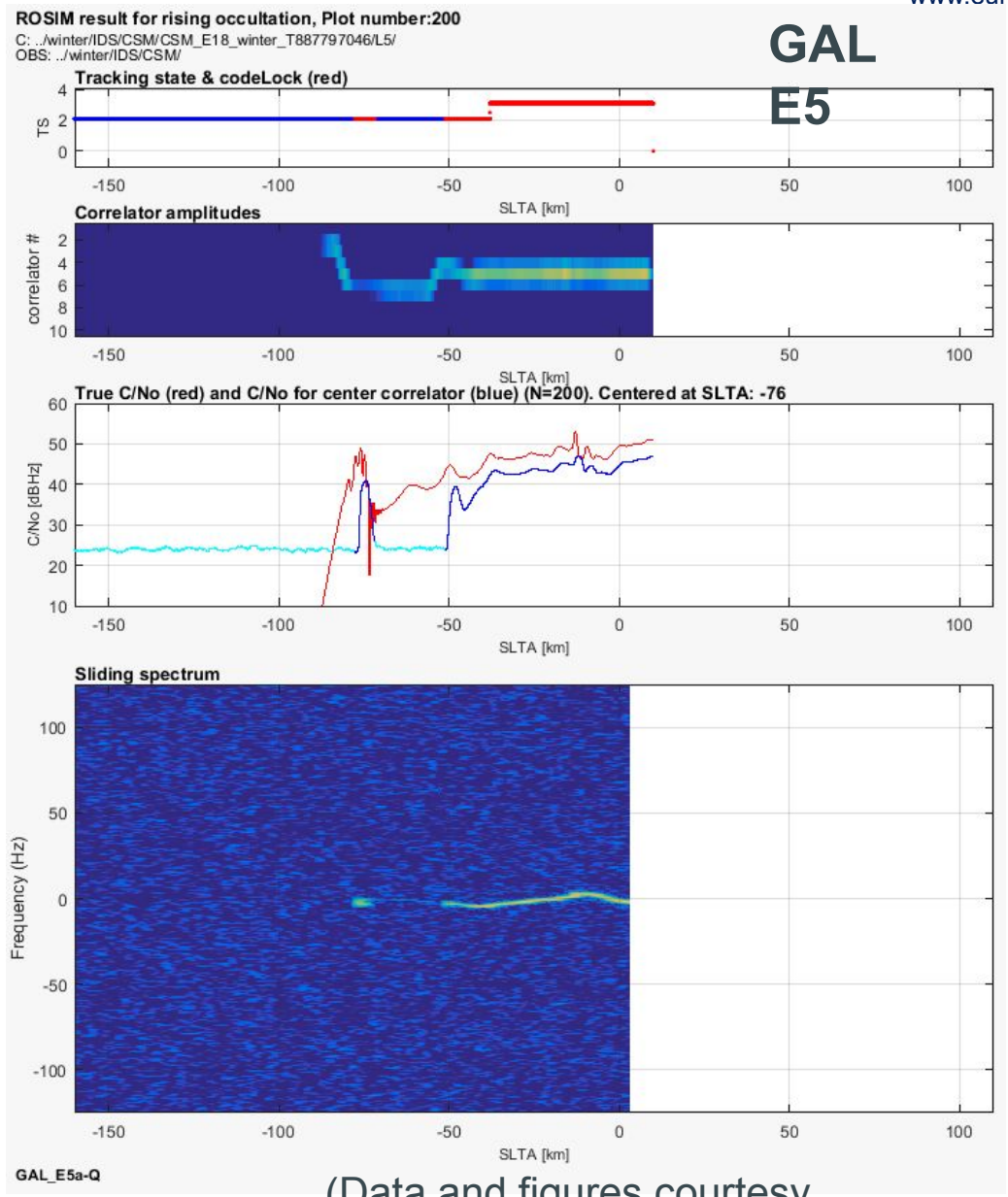
Radio occultations on EPS-SG (cont'd)

GRAS-2

- L1 & L5, three constellations: GPS, Galileo, Beidou (no GLONASS)
- Very narrow RF frontends, adaptive mitigation of L5 DME/TACAN RFI
- Sampling rates 200Hz (GPS, Beidou) and 250Hz (Galileo), data and pilot signals
- Vertical coverage -300 – 500 km SLTA (so partial ionospheric coverage)
- Proper open loop (although code lock is used if available), ten correlators in the lower troposphere
- Not much gain / SNR increase

GRAS-2 open loop with ten correlators





(Data and figures courtesy BeyondGravity)

Radio occultations on EPS Aeolus

Aeolus: Doppler Wind LIDAR

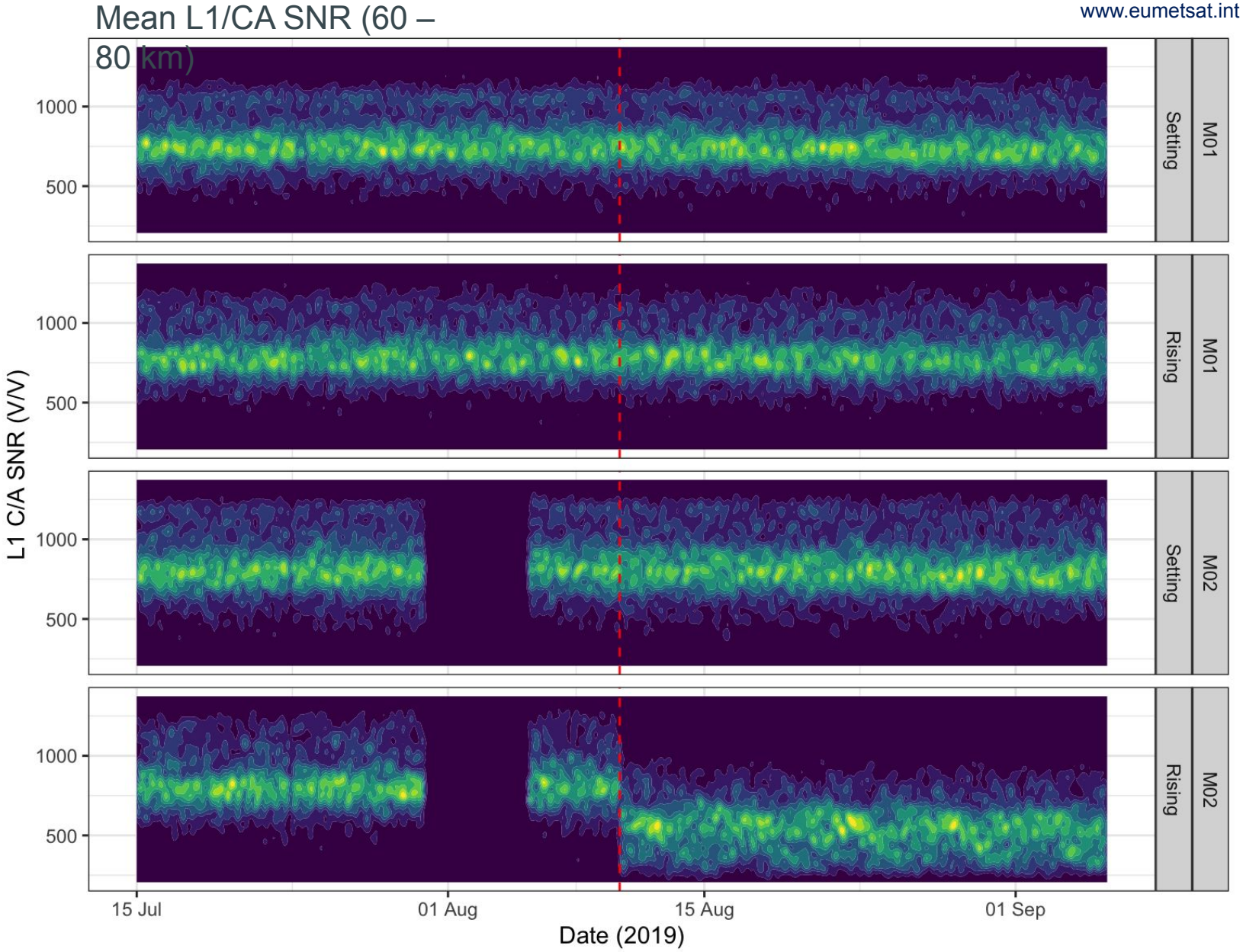
- Polar sun-synchronous (6:30 LT) orbit, 400km
- Launch early-mid-2030s

- Likely to carry an RO payload (GRAS-2) if the mission goes forward.
- EUMETSAT to perform NRT processing.

- Still requires approval and funding commitment by Member States; discussion during 2025.

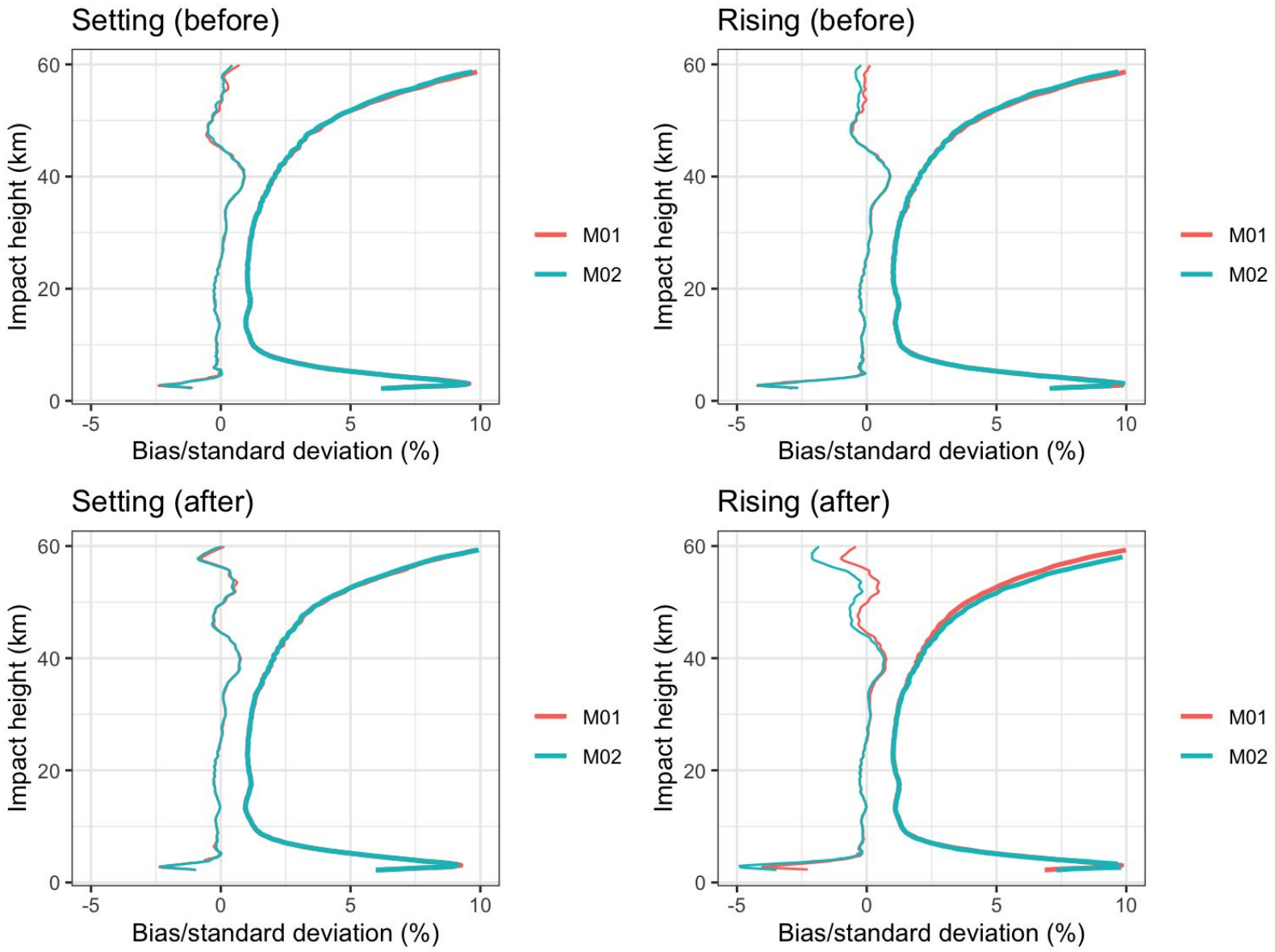
GRAS: Azimuth dependent errors

- On 10 August 2019, L1/CA SNR levels for rising occultations on Metop-A suddenly dropped; setting occultations and measurements from Metop-B remained unaffected.
- Root cause is unclear; possibly mechanical damage of an L1 signal feeder through a micro-meteorite.
- Analysis of signal and noise power levels indicated that only L1 is affected, L2 only indirectly through code-less tracking.



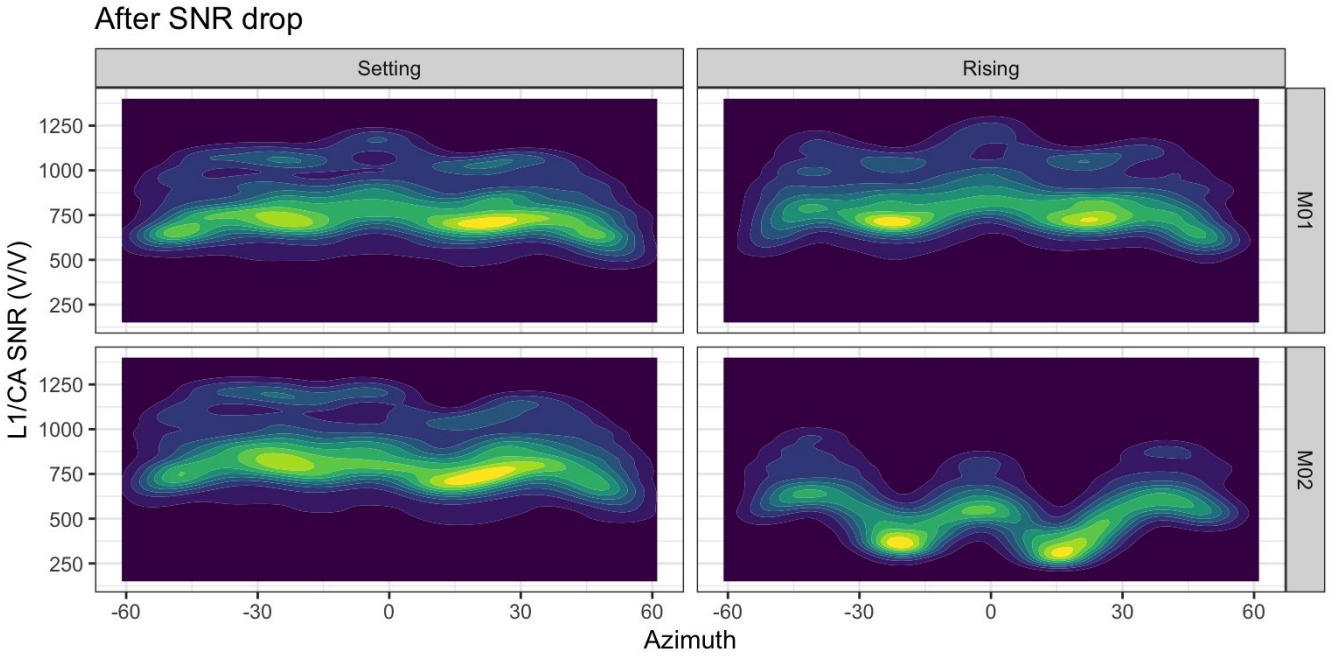
GRAS: Azimuth dependent errors (cont'd)

- Ruag concluded that two or more antenna patches might have gone offline for L1 measurements.
- This would suggest that the antenna gain pattern changed, and with it the phase centre of the antenna.
- However, unless the new position of the antenna phase centre is taken into account properly, this would cause an upper-level bending angle bias.
- Stig saw it, too.



GRAS: Azimuth dependent errors (cont'd)

- Based on data from the ionospheric extension of Metop-A measurements to 600 km in 2020, RUAG estimated an antenna gain pattern.
- They concluded that the upper two middle antenna patches were not delivering L1 measurements anymore.
- Thus, antenna gain became more dependent on azimuth direction – and possibly the antenna phase centres as well.



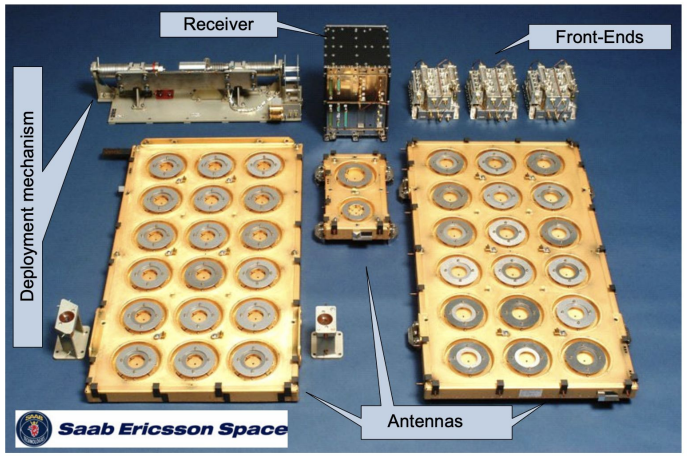


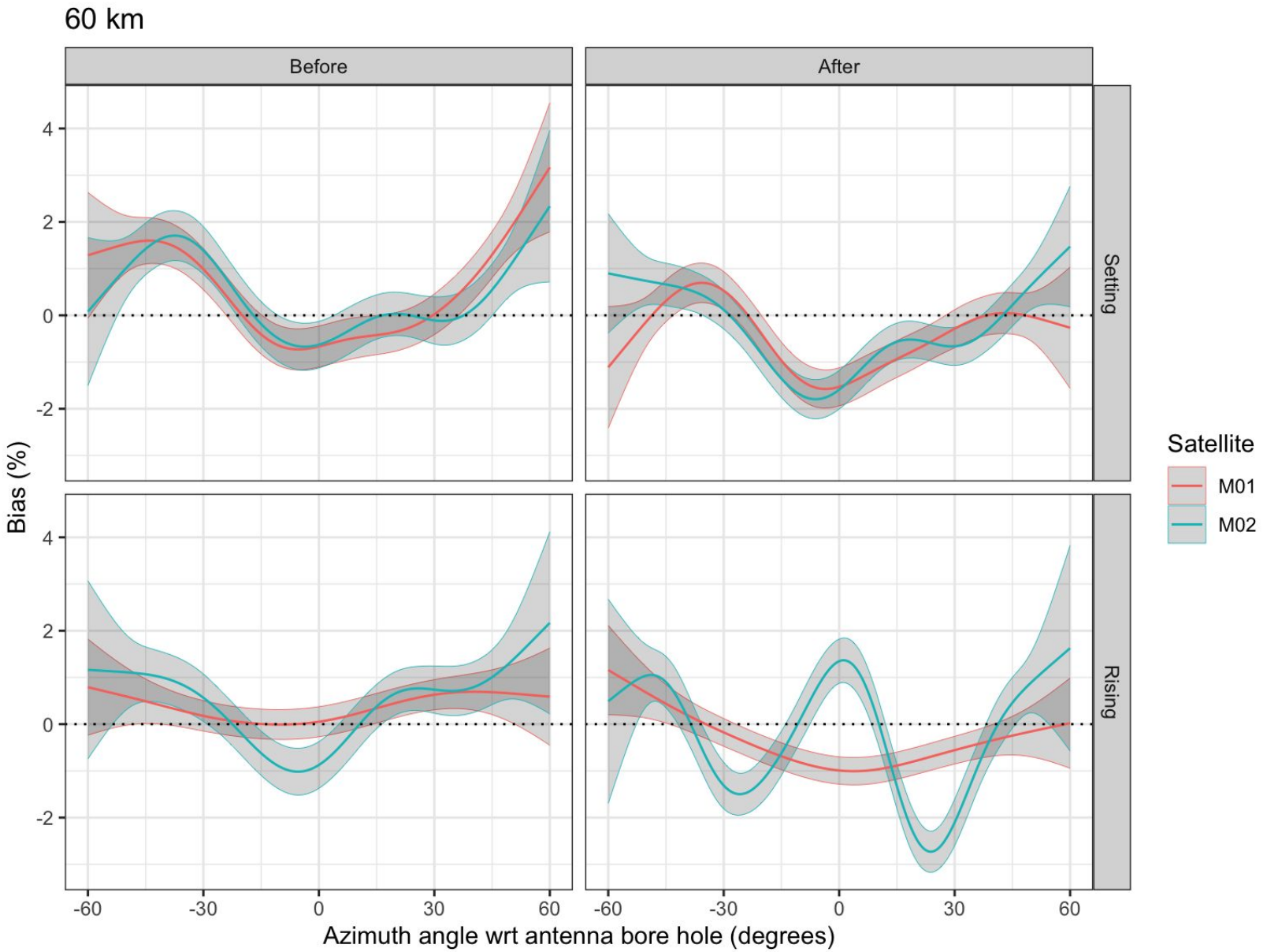
Figure 3: The MetOp-GRAS instrument hardware.

GRAS: Azimuth dependent errors (cont'd)

- GAM fits to model bias as function of azimuth direction
- Grey bands denote 95% confidence intervals of the fit

- Reasonably consistency between Metop-A and –B biases before the SNR drop
- Clear change in the bias dependency afterwards

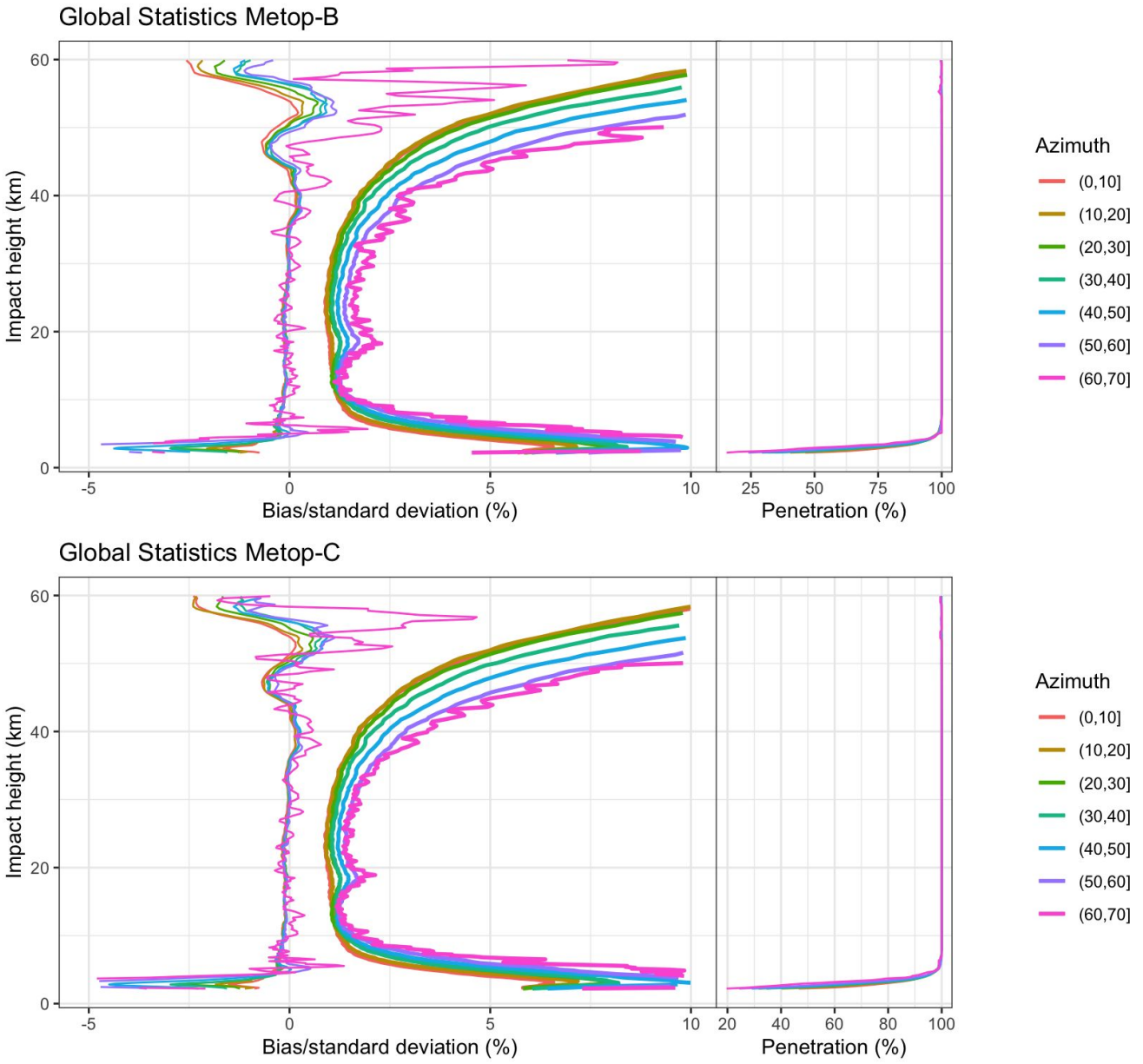
- Did we know there is a 1-2% systematic effect on bias for different azimuth angles?



GRAS: Azimuth dependent errors (cont'd)

- Azimuth-dependent O-B statistics for Dec 2022 – Apr 2023
- Dependencies of both standard deviations and upper-level biases on azimuth direction.

- Note: Azimuth dependence is complicated. We currently ignore tangent point drift. Outer parts of antenna also have lower SNR, lower tangent point descend/ascend rates, and different latitudinal and local time coverage.

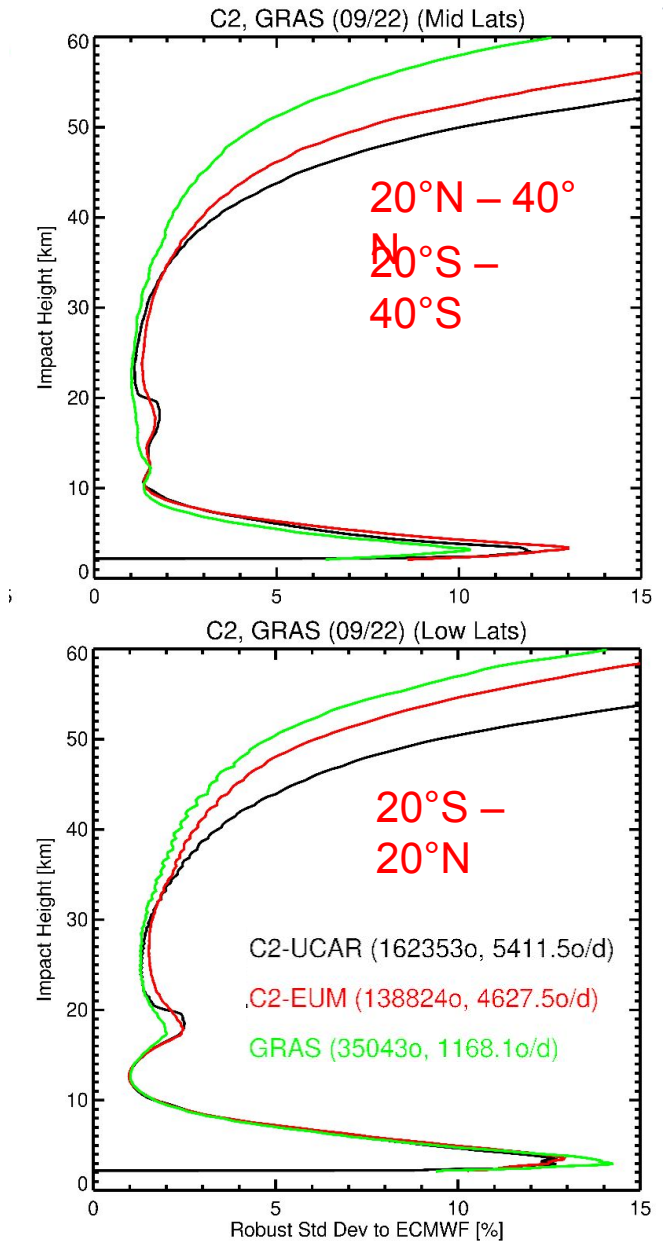


Reprocessing: COSMIC-2

- We are preparing our next round of reprocessing for CHAMP, GRACE, COSMIC-1, GRAS, Sentinel-6 and Spire (all from level 0).
- COSMIC-2 was only foreseen for later, but we brought it forward due to recent discussions about different biases in the lower stratosphere between COSMIC-2 and other RO missions.

- At present, we have about 15% fewer occultations that pass our QC, possibly due to SNR issues as well as L2 coverage issues below 20 km.
- The following results (from Sep 2022) are preliminary!

- Improvements in StdDev are primarily due to GLONASS occultations (we use 1 sec clocks; see Padovan et al., 2024)



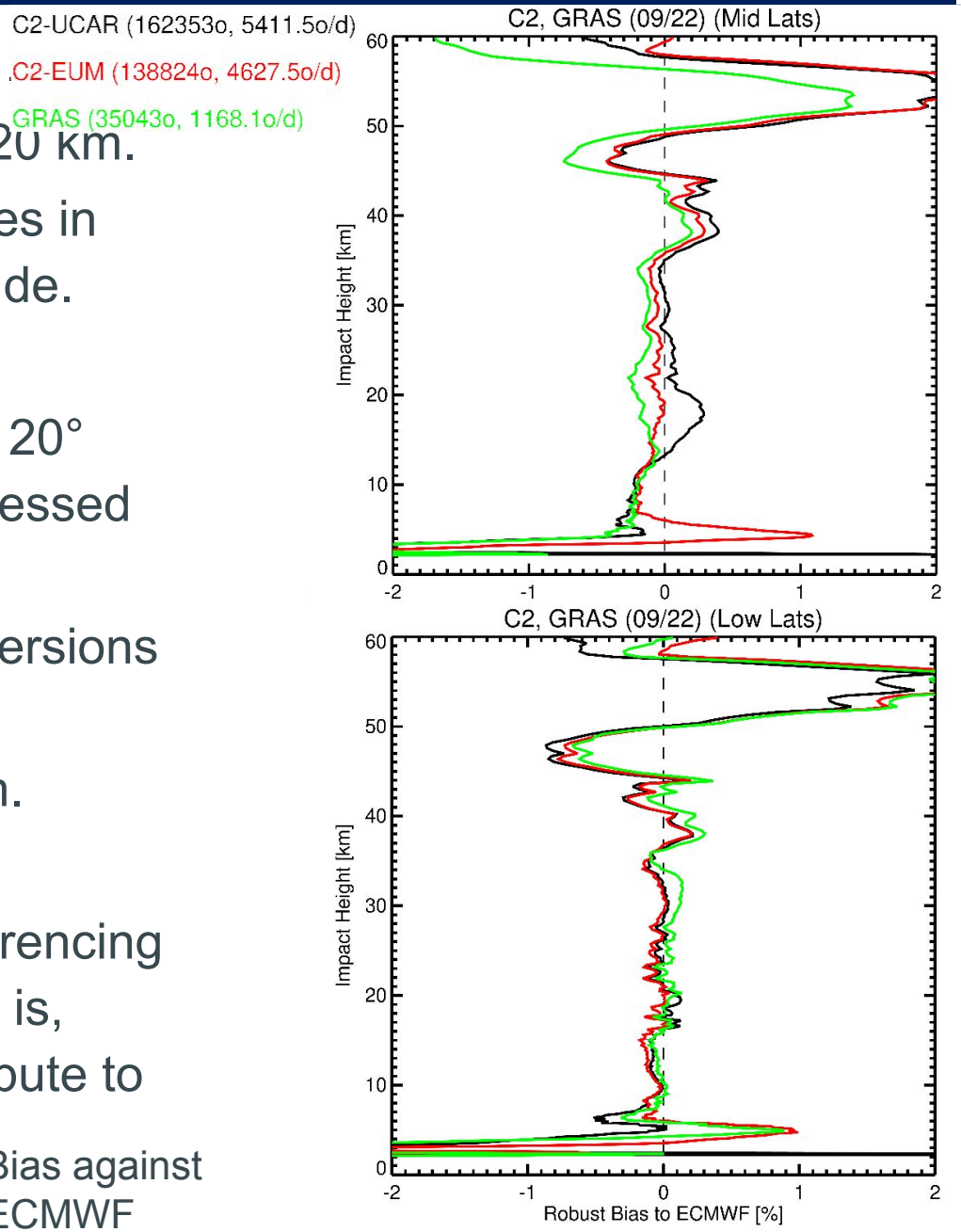
StdDev against ECMWF

Reprocessing: COSMIC-2 (cont'd)

- Biases are more interesting, especially immediately below 20 km.
- Within ROMEX, several people raised concerns about biases in COSMIC-2 data in that height region between 20°-40° latitude.

- In the EUMETSAT reprocessing, the COSMIC-2 bias in the 20° -40° latitude bands is reduced compared to the UCAR-processed data.
- In low latitudes, biases appear to be more similar for both versions of the data, but some remain.
- Note: There is a notch in low lat bias for C2-UCAR at 20 km.

- In 2019, Bill Schreiner (at IROWG) argued that double-differencing should be used to remove the role of the background – that is, slightly different geolocations of GRAS and COSMIC contribute to perceived biases between these missions.

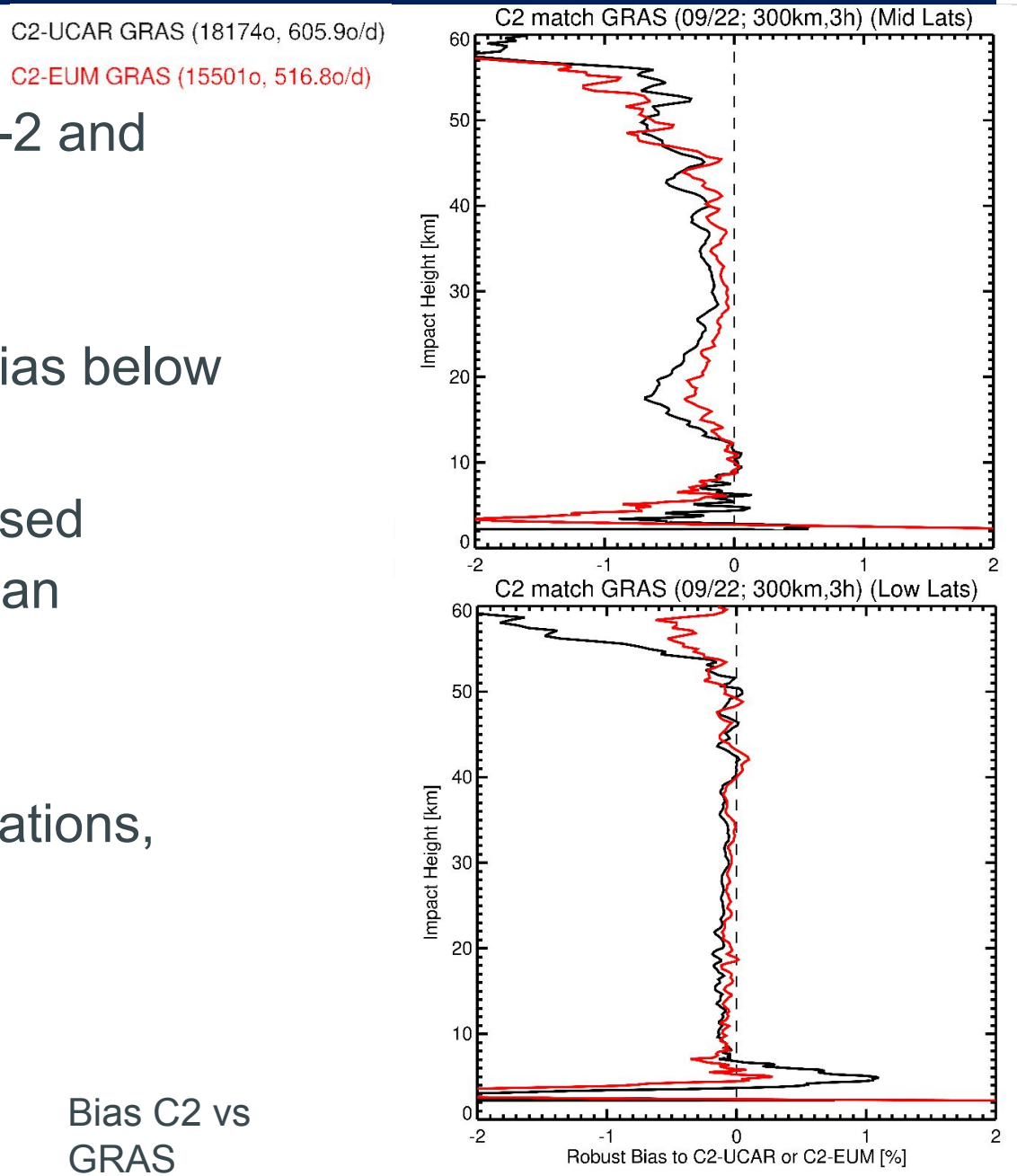


Reprocessing: COSMIC-2 (cont'd)

- Direct matches (300 km/3 hrs) between COSMIC-2 and GRAS

- In mid-latitudes, both data sets have a negative bias below 20 km, C2-UCAR more than C2-EUM.
- In low latitudes, COSMIC-2 always negatively biased against GRAS in low latitudes, C2-UCAR more than C2-EUM.

- Can one of them be explained by different geolocations, i.e. the 300km/3 hrs matching?



Bias C2 vs GRAS

Reprocessing: COSMIC-2 (cont'd)

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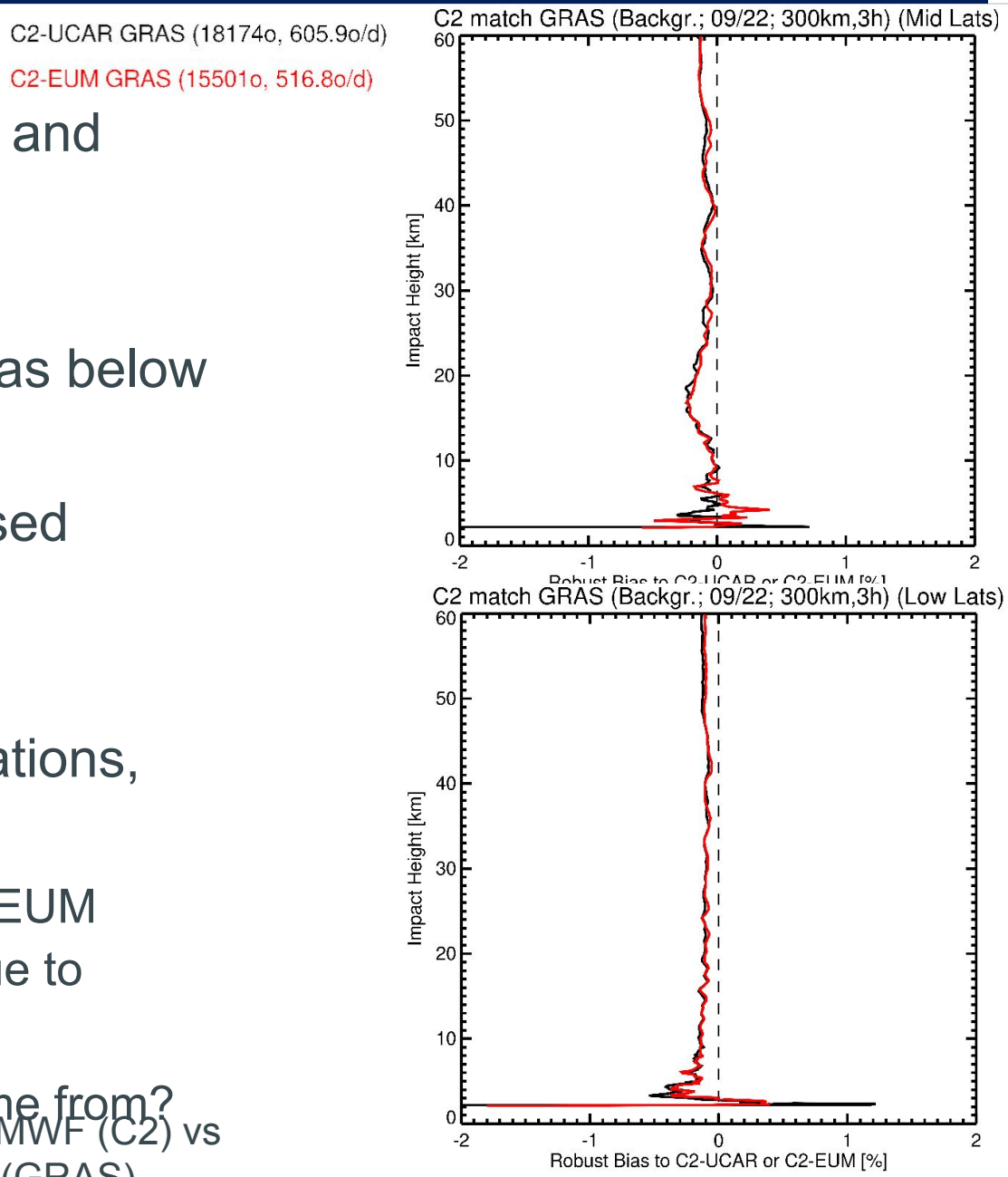
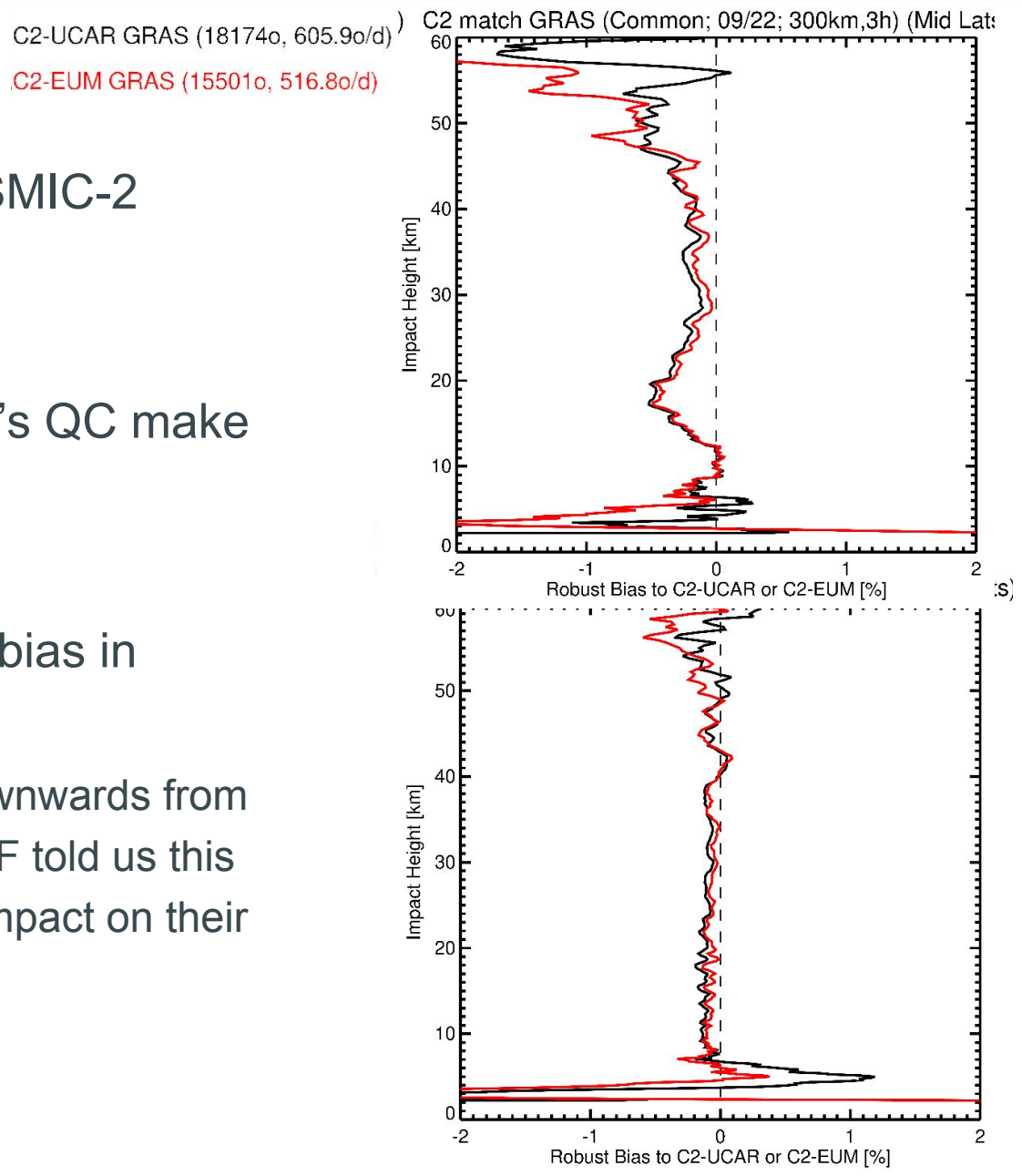
- Can one of them be explained by different geolocations, i.e. the 300km/3hrs matching?
  - Yes. Both the negative bias in low latitudes and C2-EUM biases in mid-latitudes are consistent with biases due to different locations (so Bill was right).
  - But where does the additional bias in C2-UCAR come from?



Bias ECMWF (C2) vs ECMWF(GRAS)

Reprocessing: COSMIC-2 (cont'd)

- I mentioned we currently process about 15% fewer COSMIC-2 occultations due to our QC settings.
- Direct matches using only the data passing EUMETSAT's QC make C2-UCAR and C2-EUM biases consistent.
- Possibly, the profiles we QC contribute to the additional bias in C2-UCAR.
  - This includes profiles where L2 has to be extrapolated downwards from higher than 20 km. We usually avoid that, as the ROM SAF told us this would introduce unwanted error correlations and has an impact on their refractivity products below 20 km.
  - However, this is speculation for now.



Summary

- EUMETSAT will continue to operate RO instruments on its satellite missions; in the future, these will include
  - EPS-SG (on each satellite, from mid-2020s into the 2040s),
  - Sentinel6-B (mid 2020s on S6-B and, hopefully, early 2030s on Sentinel6-C)
  - If the mission goes forward, on EPS Aeolus (in the 2030s).

- The analysis of an SNR drop of GRAS/Metop-A rising occultations in 2019 raises questions on the dependence of error characteristics on, e.g., antenna azimuth angles.

- Reprocessing of various missions (GRAS, Sentinel6, COSMIC-1 & -2, Spire, CHAMP, GRACE) is in preparation; we showed some initial results for COSMIC-2.
- On the side: All processors use the same code for the level 1b / bending angle processing

- Note: Commercial RO data has become part of EUMETSAT's portfolio, but we'll discuss that tomorrow…

Thank you!

Questions are welcome.