ETH zürich

Institute of Geodesy and Photogrammetry

Nanosatellites: The next big chapter in atmospheric tomography

Gregor Moeller[1] and Chi Ao[2]

[1] *ETH Zürich, Institute of Geodesy and Photogrammetry*
[2] *NASA Jet Propulsion Laboratory, California Institute of Technology*

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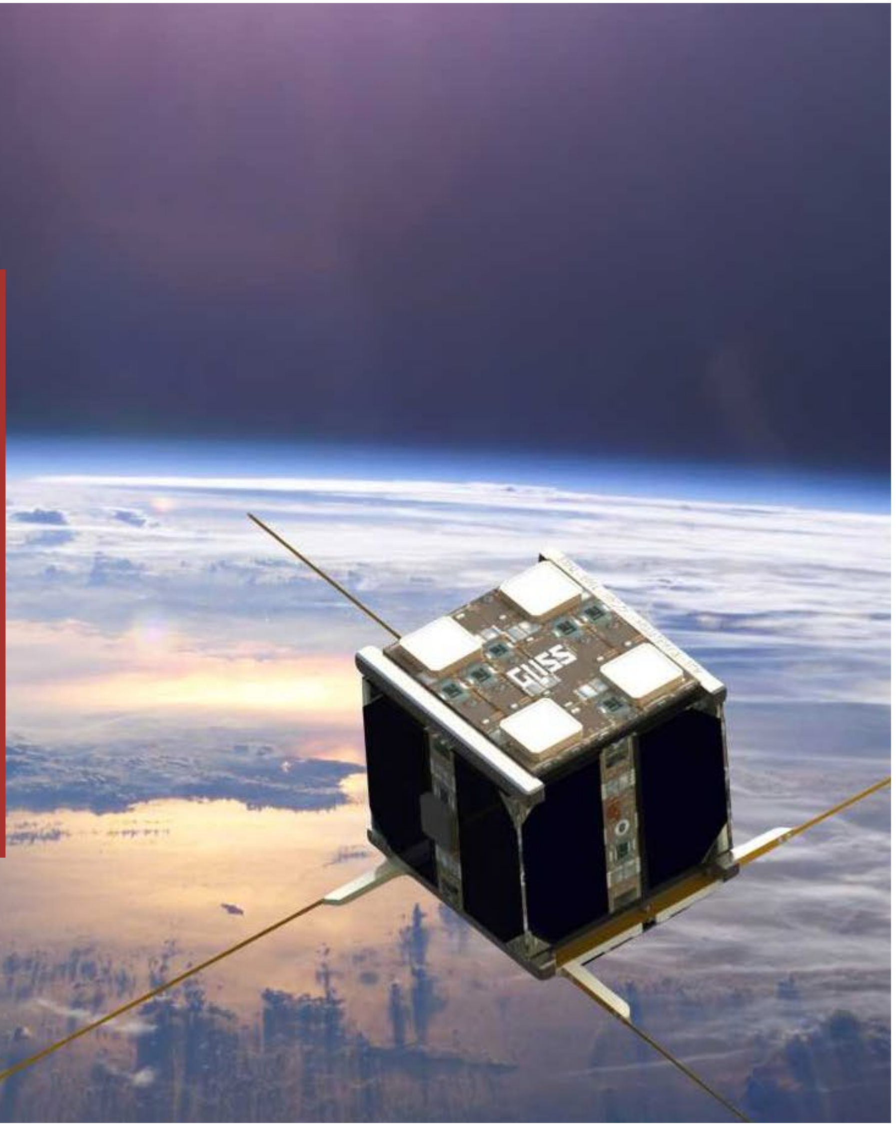
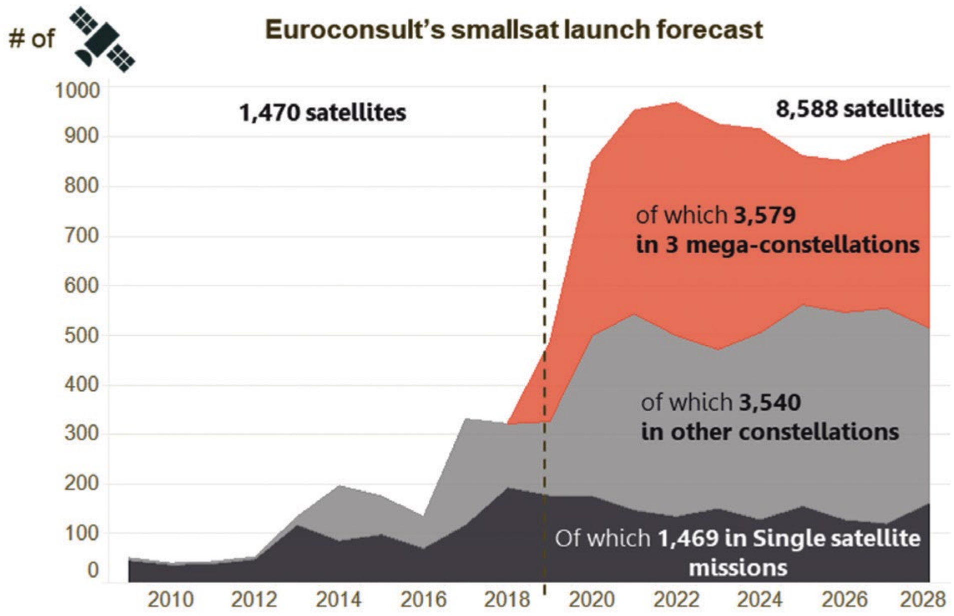
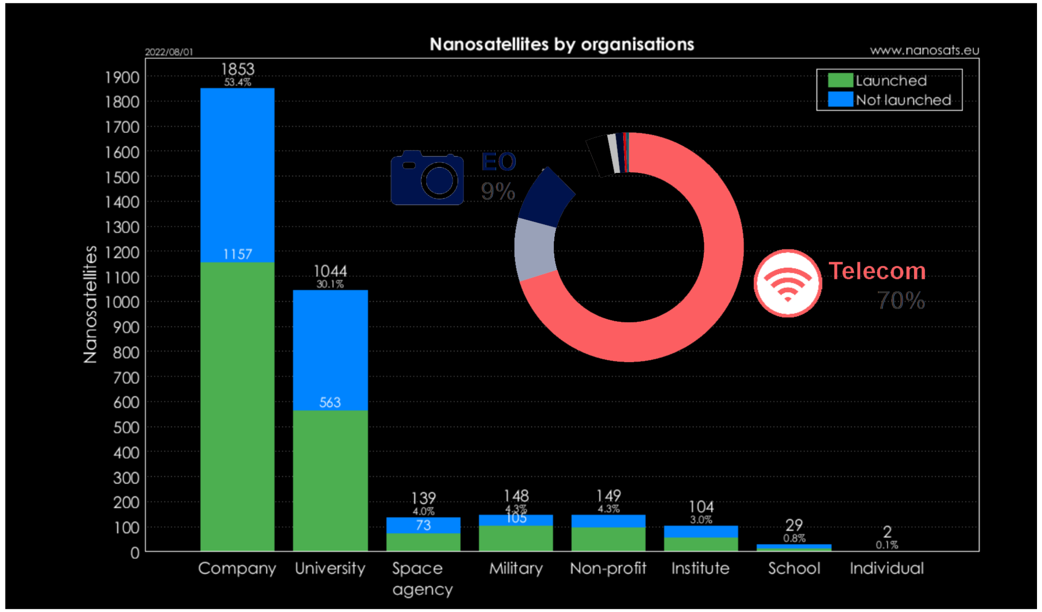


Content

Concept of a dense nanosatellite formation

SmallSat Launches

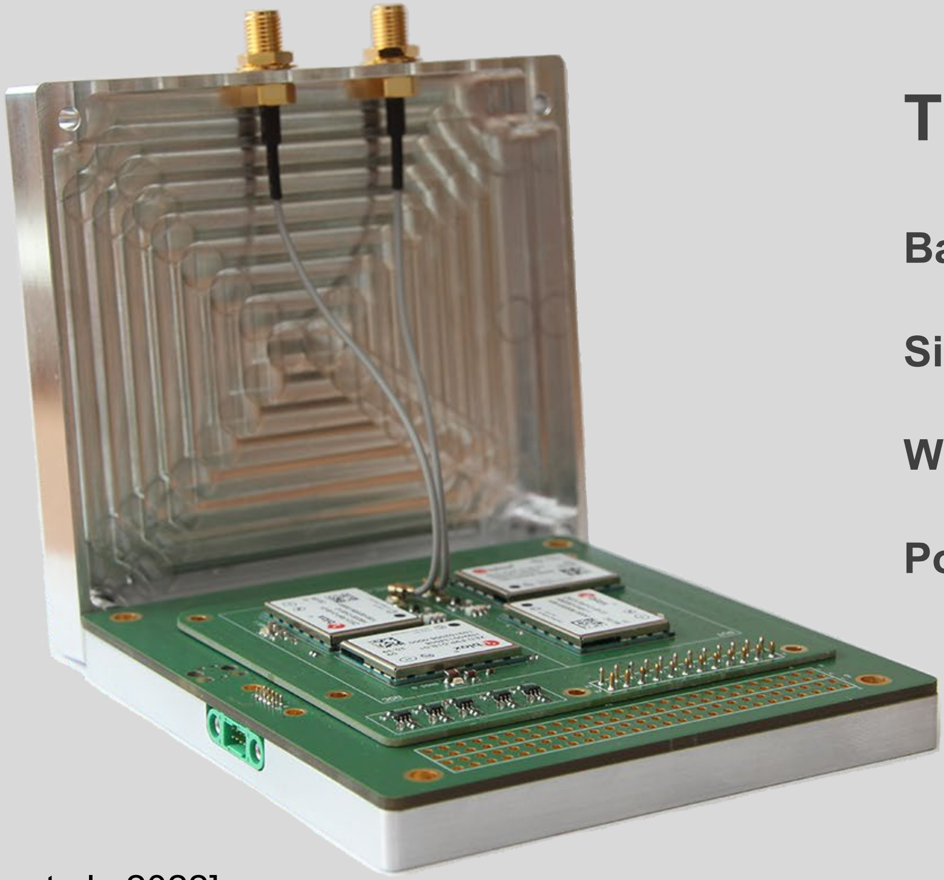




- In the next decade, 4-5 times more SmallSat launches are expected
- Average costs per nanosatellite launch: <500k €

Concept of a dense nanosatellite formation

In-house developed GNSS payload board for nanosatellite missions



[Moeller et al., 2022]

The GNSS payload board

Based on the u-blox ZED-F9P multi-GNSS chip

Size: 96 x 90 x 11 mm

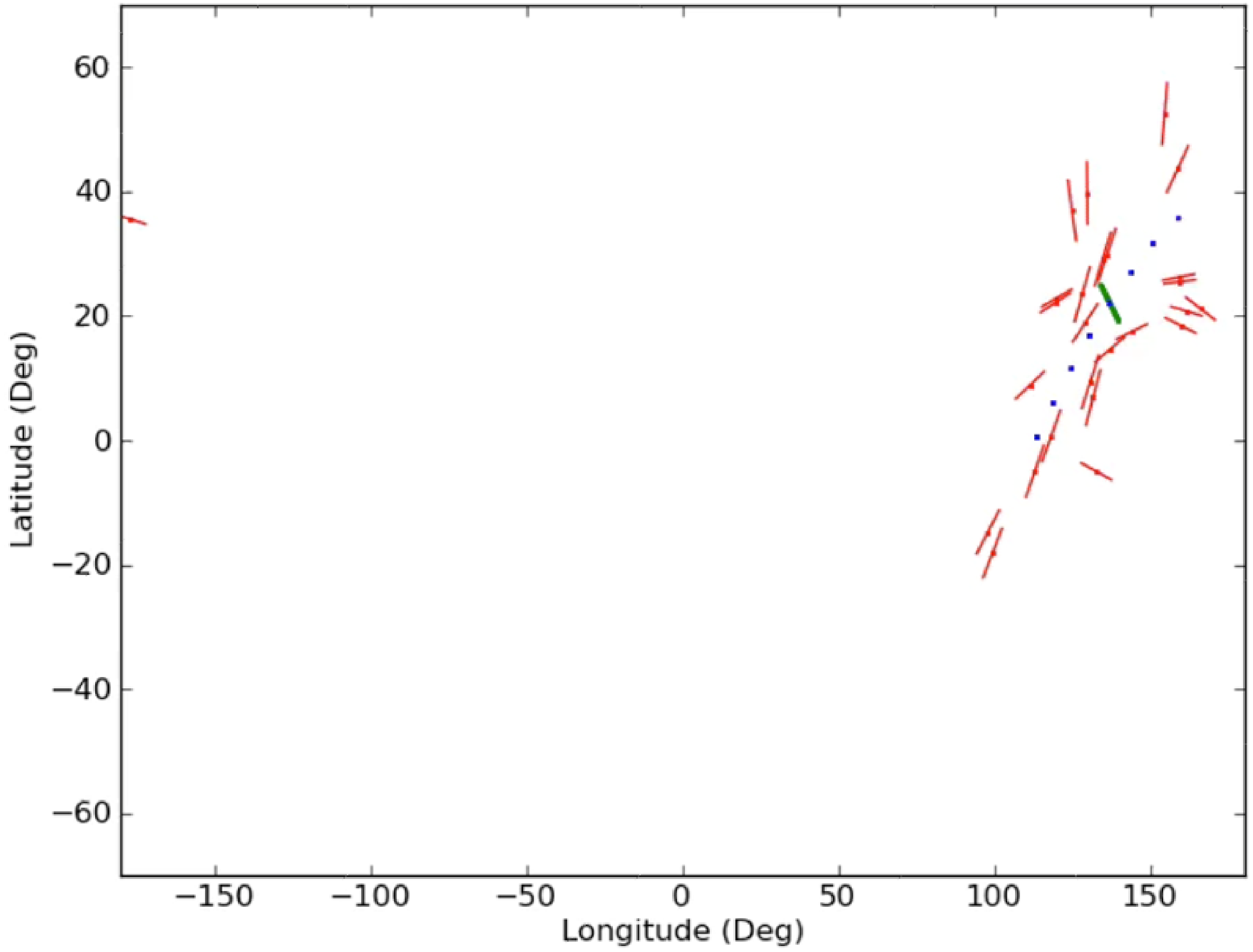
Weight: 65 g

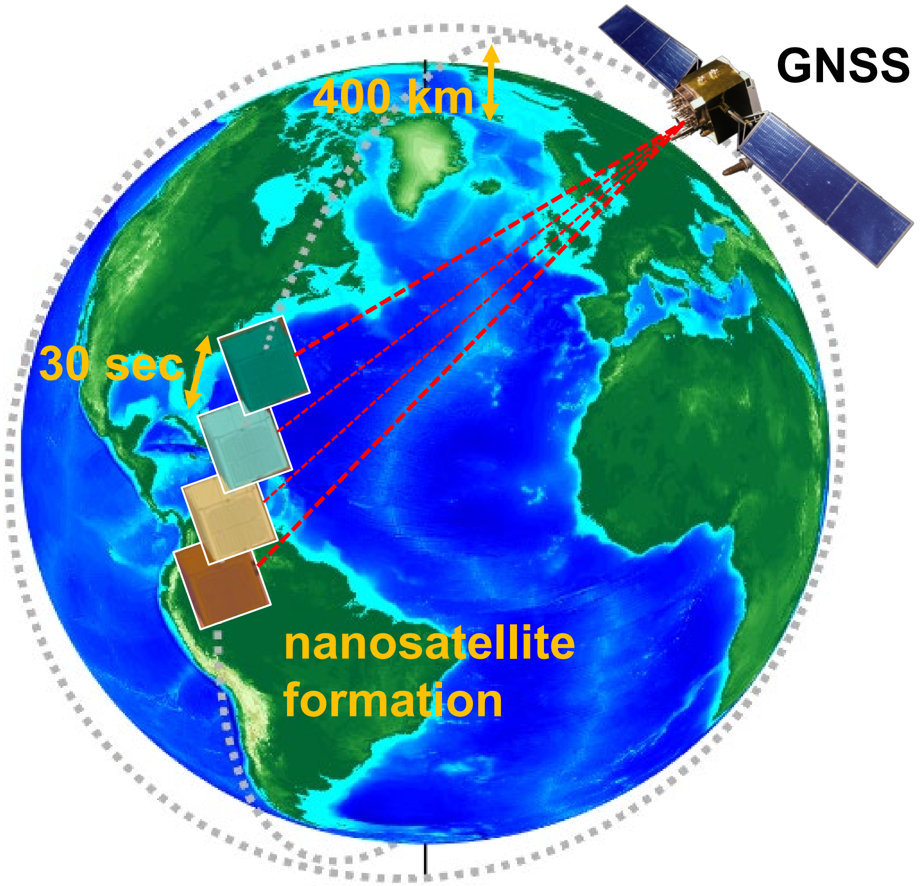
Power consumption: Ø 0.5 W

<u>Applications</u>: Precise orbit determination, RO & Space Weather monitoring

Concept of a dense nanosatellite formation

Nanosatellite formation for highly detailed atmospheric structure monitoring



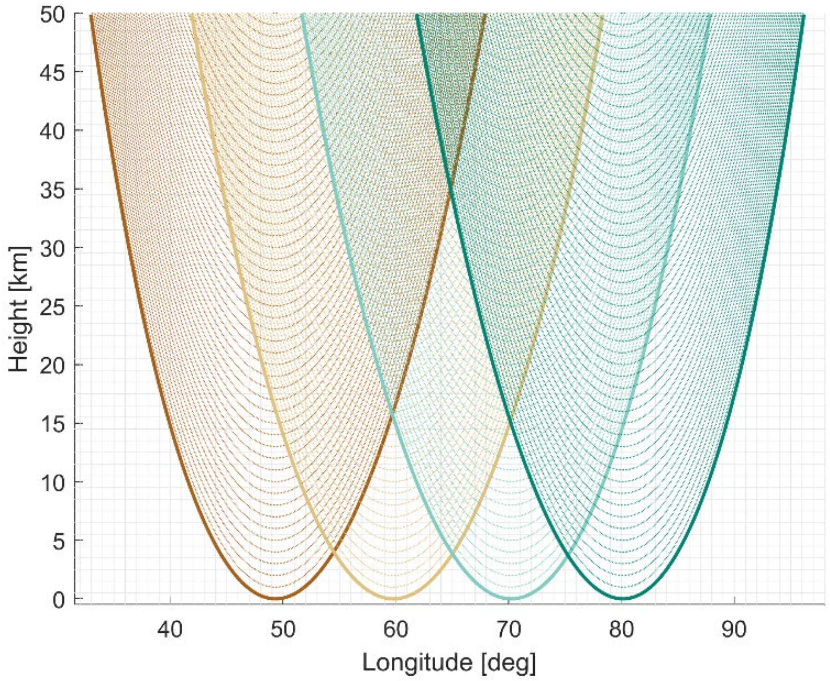


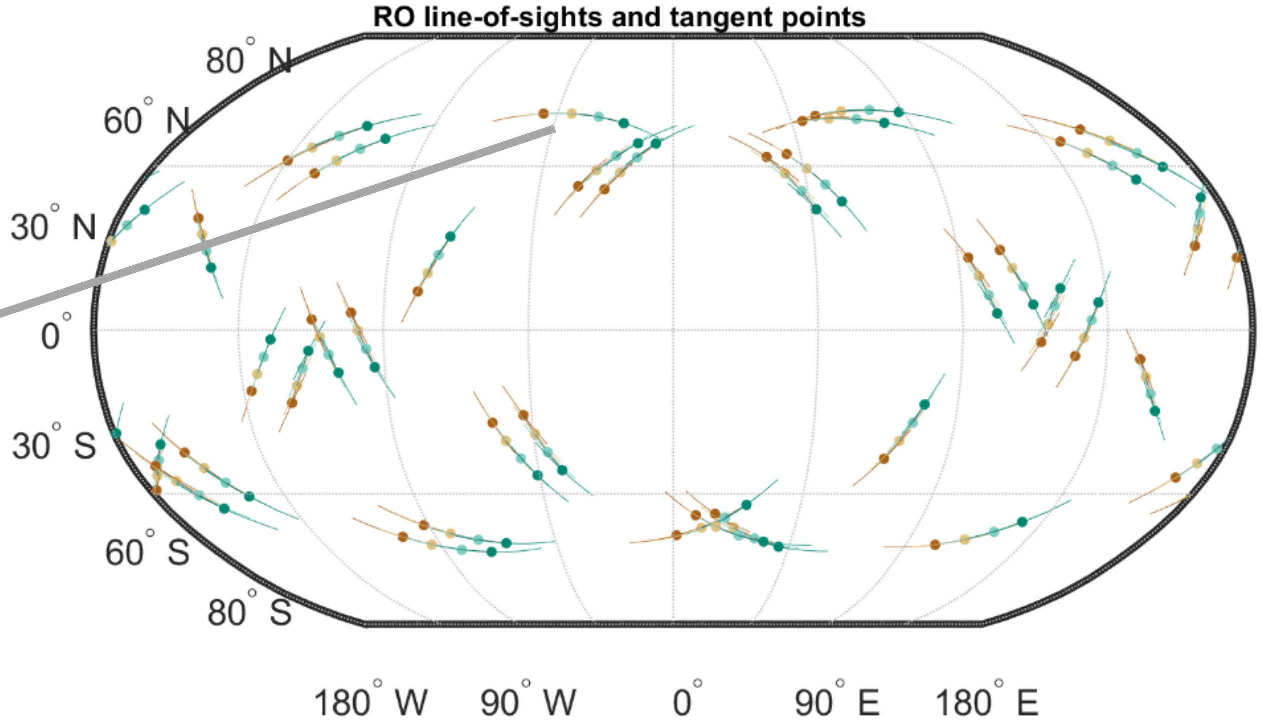
[Turk F. J. et al., 2019]

Concept of a dense nanosatellite formation

Cross-link occultation geometry between four nanosatellites and one GNSS satellite

Ray-path geometry through the lower 50 km of the atmosphere



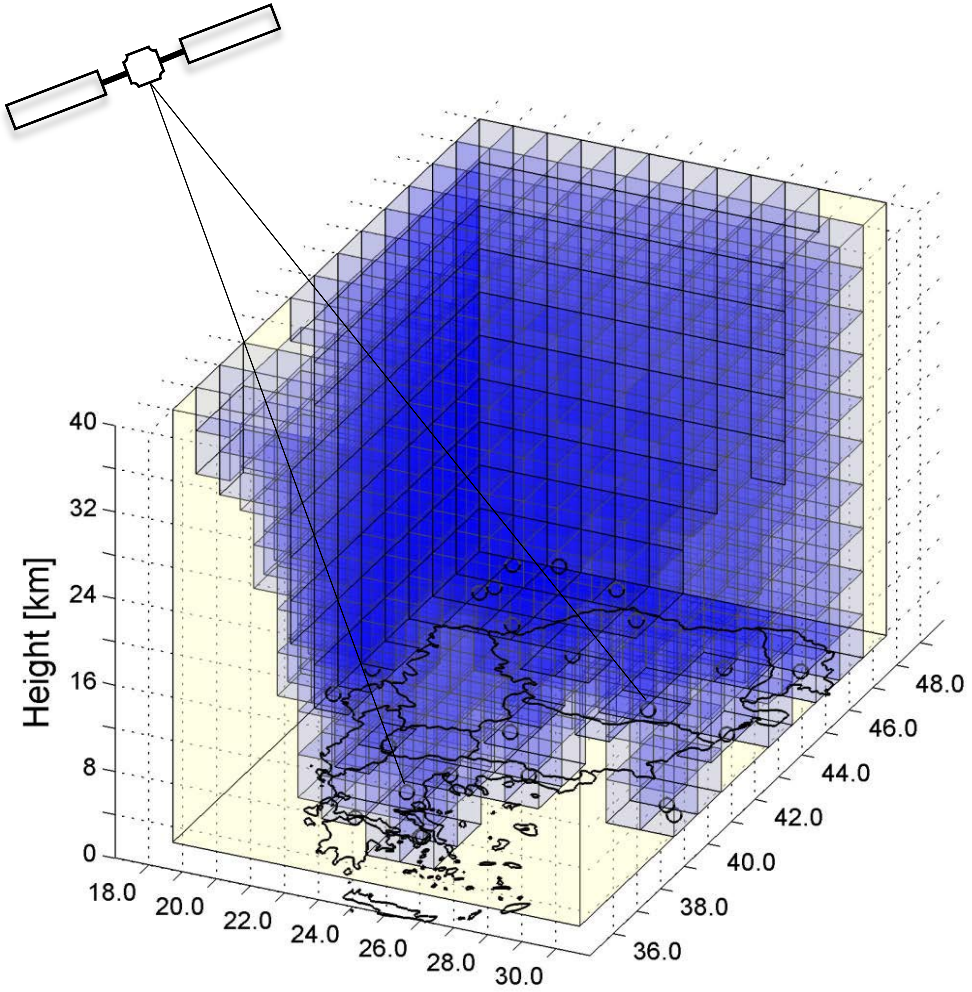


Time between RO observations: <1 min

Observation geometry <u>suited</u> for **tomographic processing**.

Multi-signal combination

The concept of GNSS tomography (exemplary for water vapor density ρ_w)



Basic function of GNSS tomography

$$N = \boxed{A^{-1}} \cdot AEP \quad \ggg \quad \rho_w = \boxed{A^{-1}} \cdot PIWV$$

- Setup tomography model (grid/voxel-based or node-based)
- Ray-trace signal paths and determine components of design matrix A

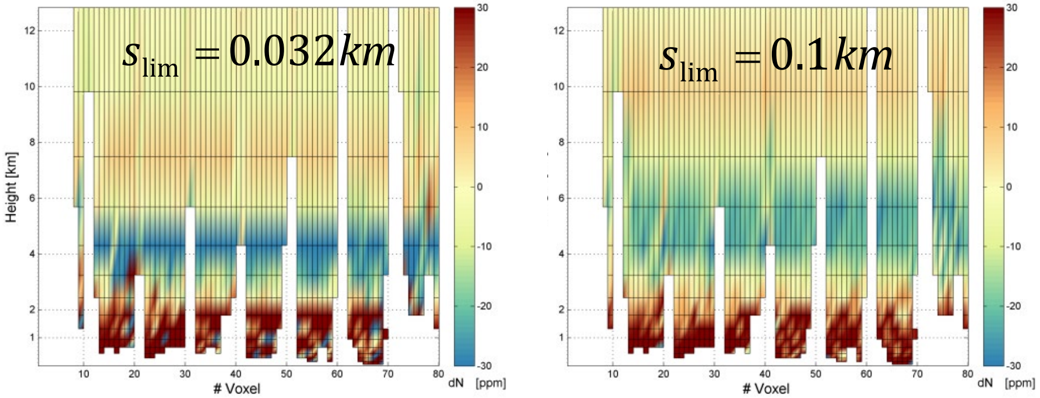
Solution of inverse problem

- Pseudo inverse A^+ $\ggg$ $A = U \cdot \boxed{S} \cdot V^T$
- Truncated singular value decomposition (TSVD)

Multi-signal combination

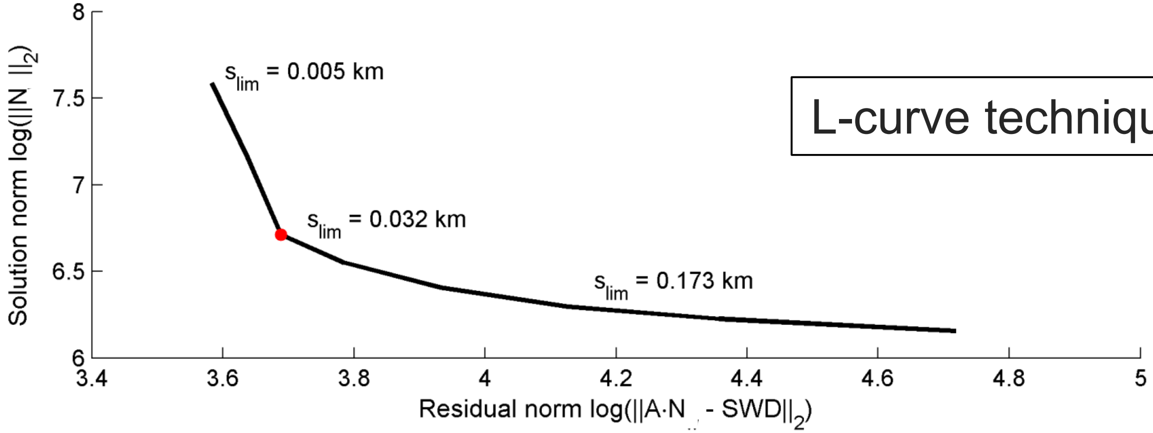
The concept of GNSS tomography (exemplary for water vapor density)

- Impact of the singular value threshold (s_{lim}) on the tomography solution



Differences in N between reference solution and synthetic tomography solution

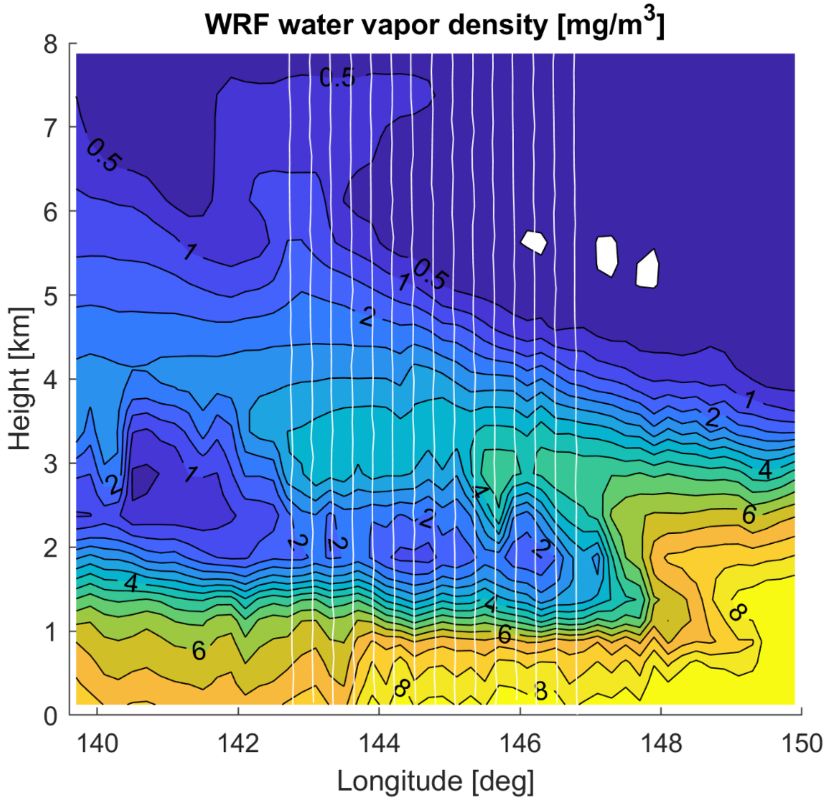
- Goal: Find trade-off between ill-conditioning and over-smoothing



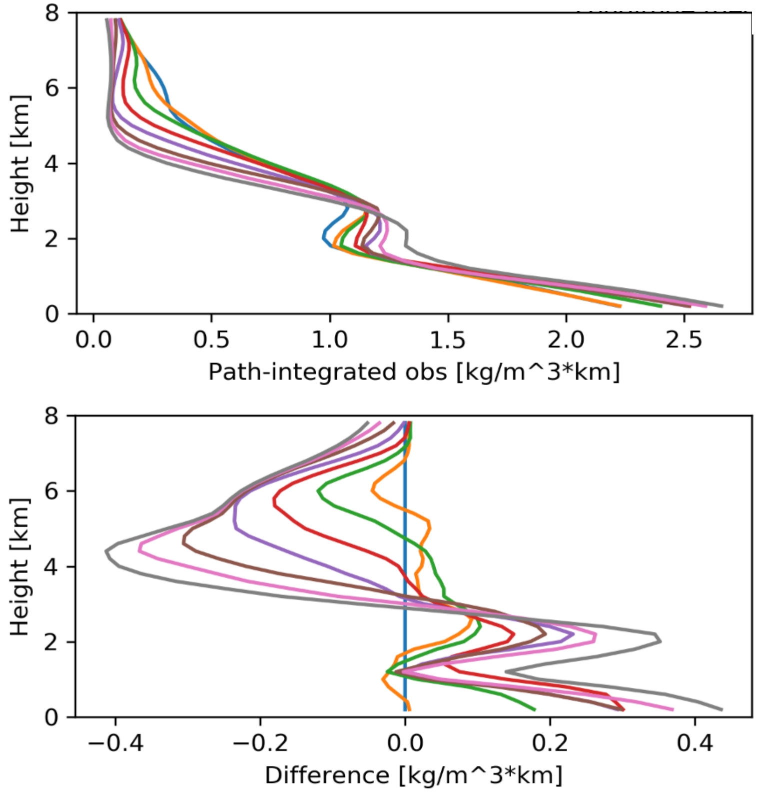
L-curve technique

Multi-signal combination

Case study: Water vapor inversion layer between 2-4 km altitude



WRF (reference) **water vapor density (ρ_w)** field + tangent points of the straight-line RO ray paths through the atmosphere (white lines) - assuming **15 nanosatellite** in one orbit separated by 30 s



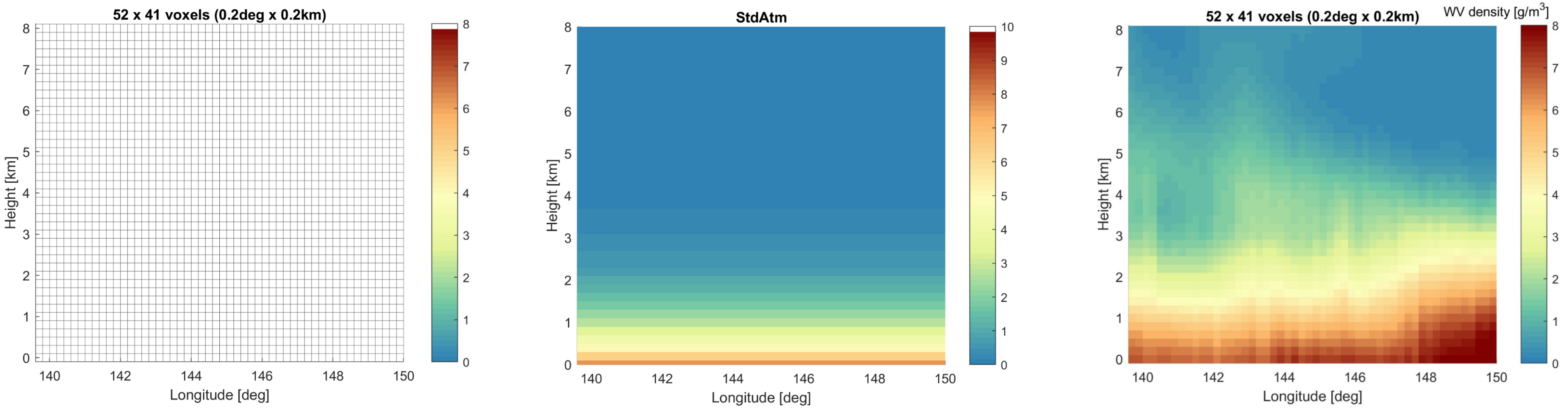
Ray-traced **path-integrated water vapour (PIWV)** (visualized for 8 (every 2nd) nanosatellites)

Multi-signal combination

Tomography solution – A priori field

	#Voxels	First guess	#CubeSats	σ_{RO}	σ_{apr}
Test1a	52 x 41	No	8 (0s,60s,…,420s)	1	–
Test1b	52 x 41	StdAtm	8 (0s,60s,…,420s)	$0.01 g/m^3 km$	$0.2 wvd$
Test1c	52 x 41	SmoothWRF	8 (0s,60s,…,420s)	$0.01 g/m^3 km$	$0.2 wvd$

How sensitive is the tomography solution on the quality of the a priori field?

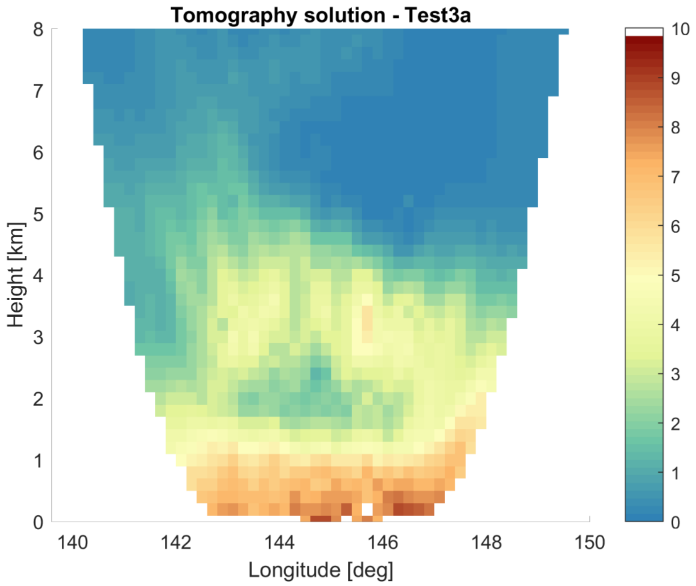


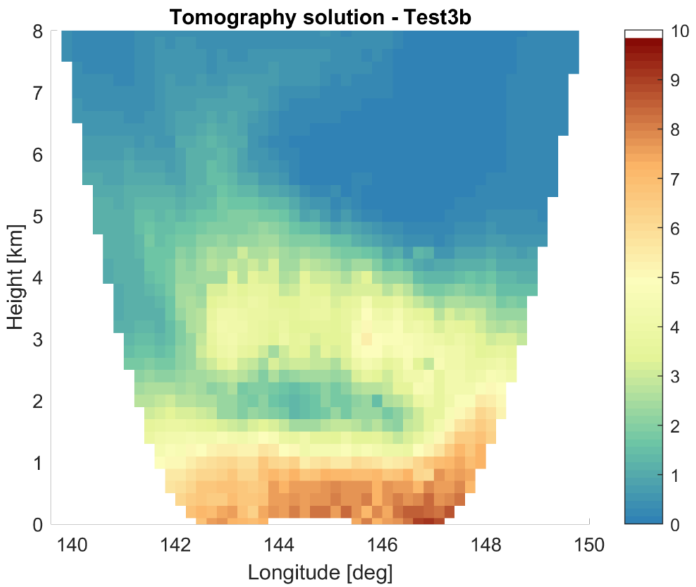
Multi-signal combination

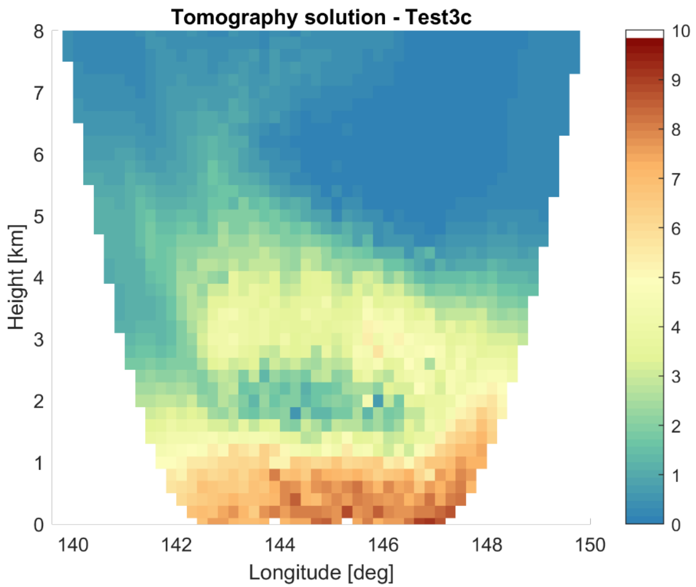
Tomography solution – Number of satellites

	#Voxels	First guess	#CubeSats	σ_{RO}	σ_{apr}
Test3a	52 x 41	SmoothWRF	**5 (30s,120s,…,390s)**	$0.01 g/m^3 km$	$0.2 wvd$
Test3b	52 x 41	SmoothWRF	**8 (0s,60s,…,420s)**	$0.01 g/m^3 km$	$0.2 wvd$
Test3c	52 x 41	SmoothWRF	**15 (0s,30s,…,420s)**	$0.01 g/m^3 km$	$0.2 wvd$

How much depends the tomography solution on the number of satellites?







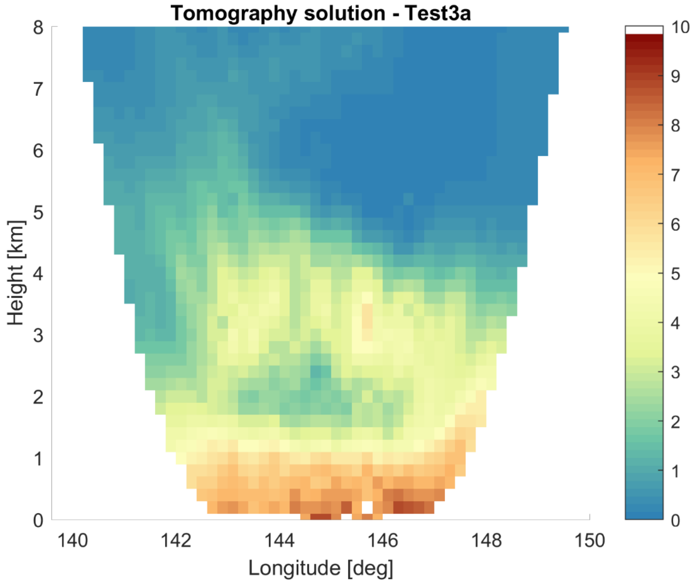
Multi-signal combination

Tomography solution – Spatial resolution

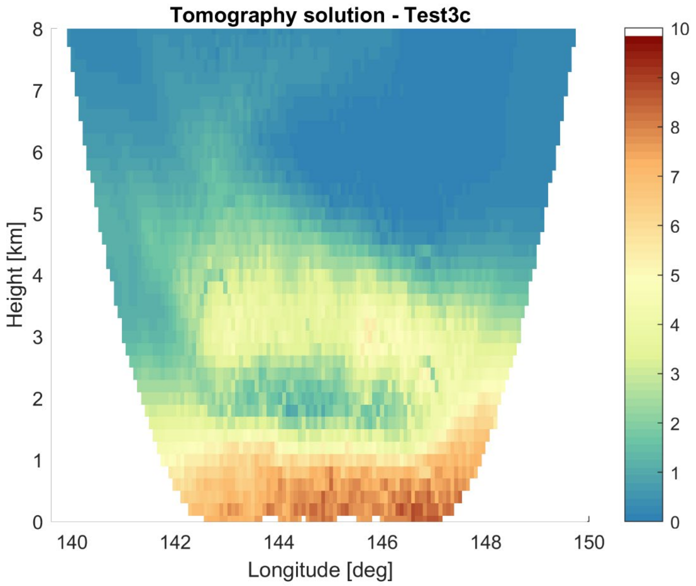
	#Voxels	First guess	#CubeSats	σ_{RO}	σ_{apr}
Test3a	**52 x 41**	SmoothWRF	5 (30s,120s,…,390s)	$0.01 g/m^3 km$	$0.2 wvd$
Test3c	**137 x 41**	SmoothWRF	5 (0s,60s,…,420s)	$0.01 g/m^3 km$	$0.2 wvd$

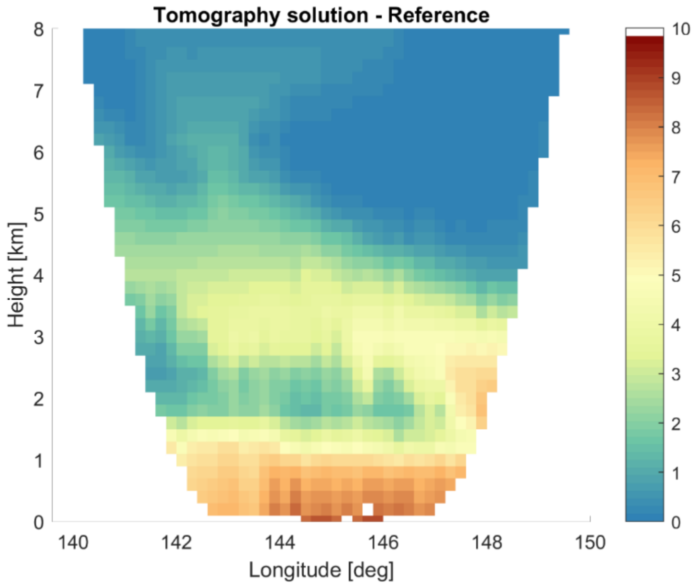
How good is the spatial resolution of the tomography solution?

22km



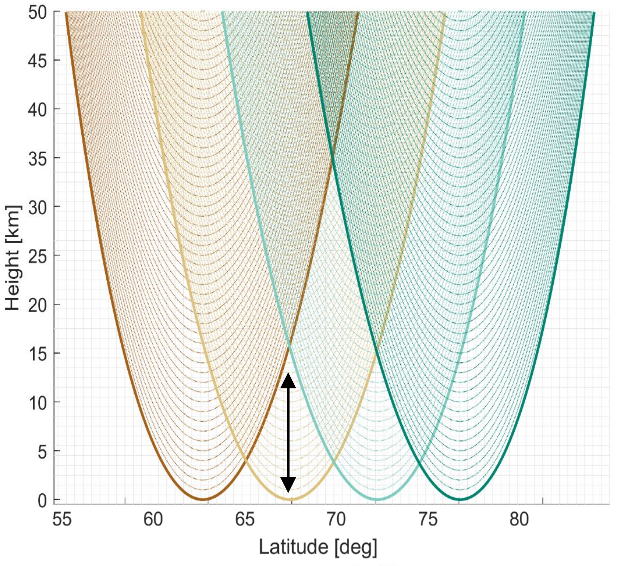
8km

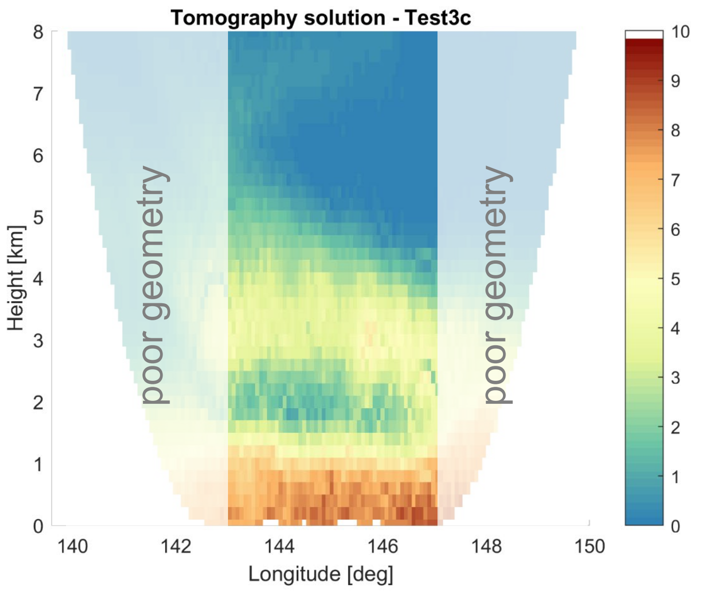


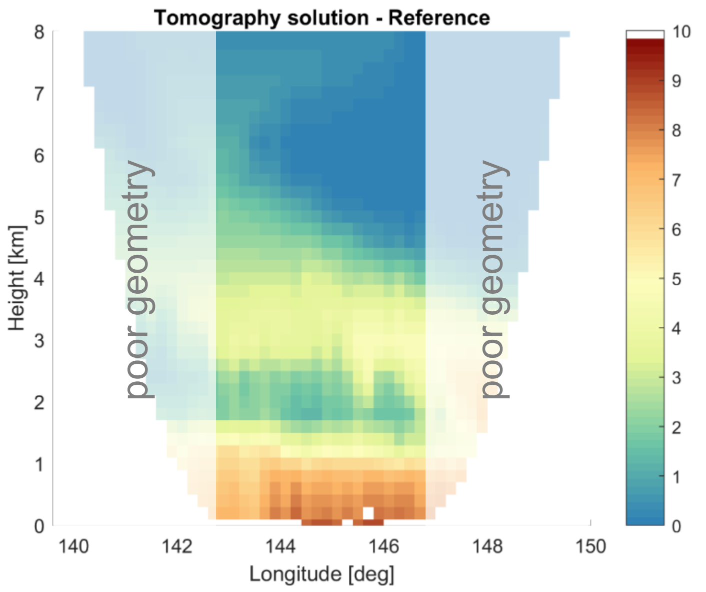


Multi-signal combination

Tomography solution – Satellite spacing







Satellite spacing defines: a) the number of overlapping observations, **b)** horizontal resolution, **c)** temporal resolution, **d)** height of the lowest layers resolved and **e)** the area covered

Summary

- Nanosatellite technology opens up new possibilities for Earth observation
- Now available: A high-precision GNSS payload board for nanosatellite PNT
- Observation geometry of a dense satellite formation suited for tomographic processing
    - \+ not dependent on symmetry assumptions
    - \+ increased horizontal resolution (> 8 km)
- New quality in the reconstruction of atmospheric structures (demostrated for water vapor distribution)

Dr. Gregor Moeller
Scientific staff
gmoeller@ethz.ch

ETH Zürich
Institute of Geodesy and Photogrammetry
HPV G58.1
Robert-Gnehm-Weg 15
8093 Zurich

www.mpg.igp.ethz.ch

References

Moeller G., Sonnenberg F., Wolf A., Rothacher M., A high-precision commercial off-the-shelf GNSS payload board for nanosatellite orbit determination and timing, Proceedings of the 44th COSPAR Scientific Assembly 2022, Athens, Greece

Turk F.J., Padullés R., Ao C.O., Juárez M.d.I.T., Wang K.-N., FranklinG.W., Lowe S.T., Hristova-Veleva S.M., Fetzer E.J., Cardellach E., Kuo Y.-H., Neelin J.D., Benefits of a Closely-Spaced Satellite Constellation of Atmospheric Polarimetric Radio Occultation Measurements. *Remote Sens.* **2019**, *11*, 2399. https://doi.org/10.3390/rs11202399