DACH Tagung ÖGK/DGK/SGK in Innsbruck
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VLBI zu Satelliten

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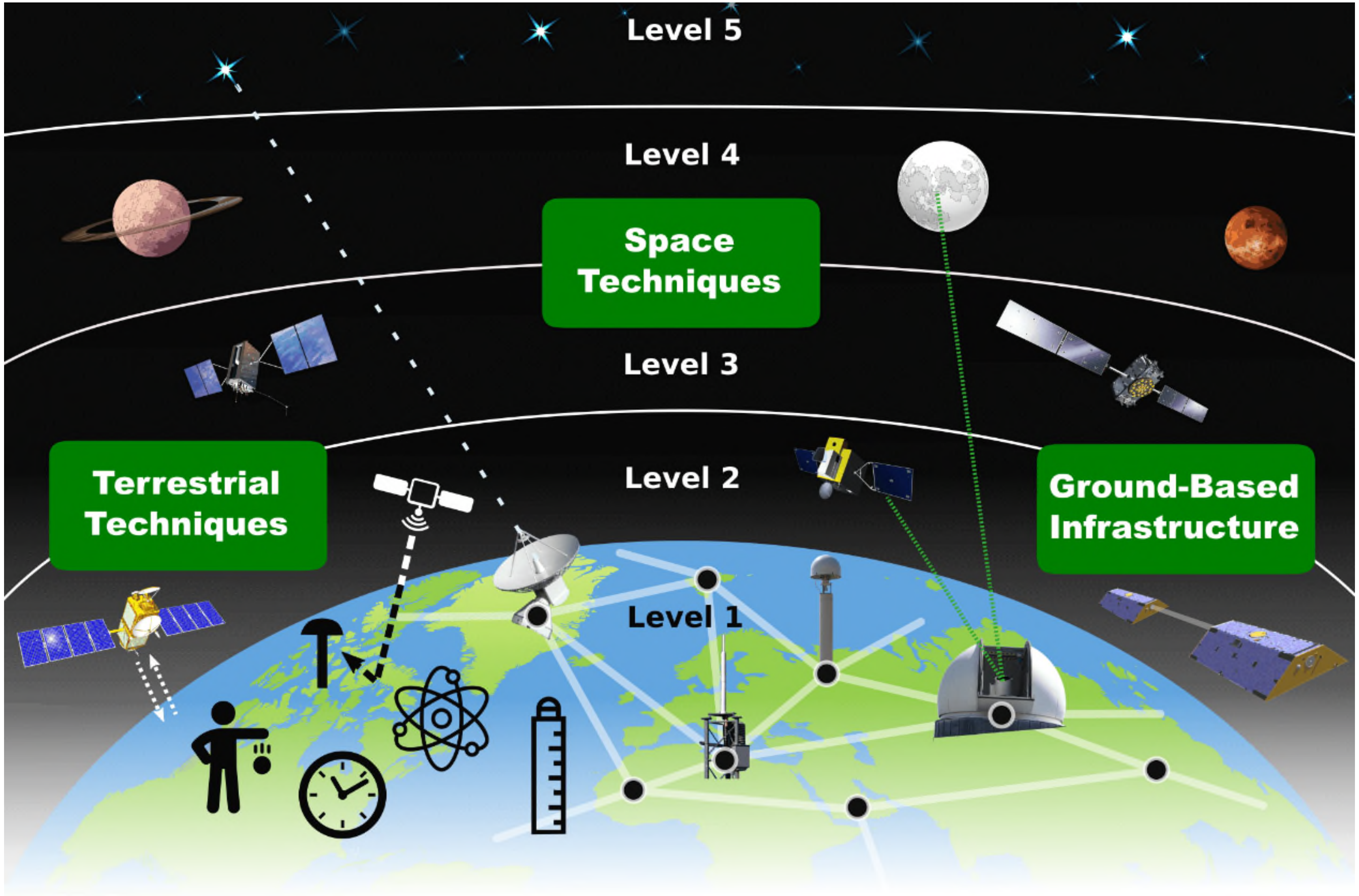
Der Wissenschaftsfonds.

GGOS Levels



Connecting the levels!

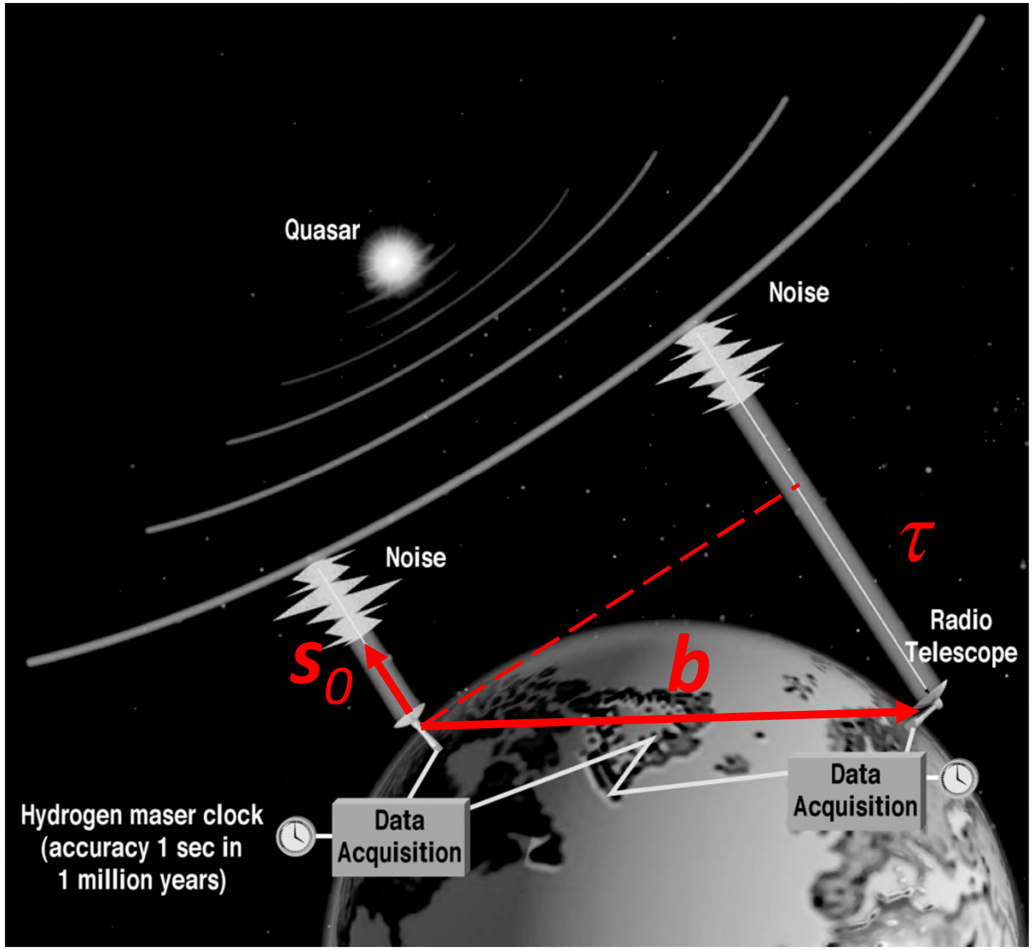
https://ggos.org

Very Long Baseline Interferometry (VLBI)

- VLBI measures the difference in arrival time τ of signals (noise) from quasars at radio telescopes

$$\tau = -\frac{\boldsymbol{b} \cdot \boldsymbol{s}_0}{c} = t_2 - t_1$$

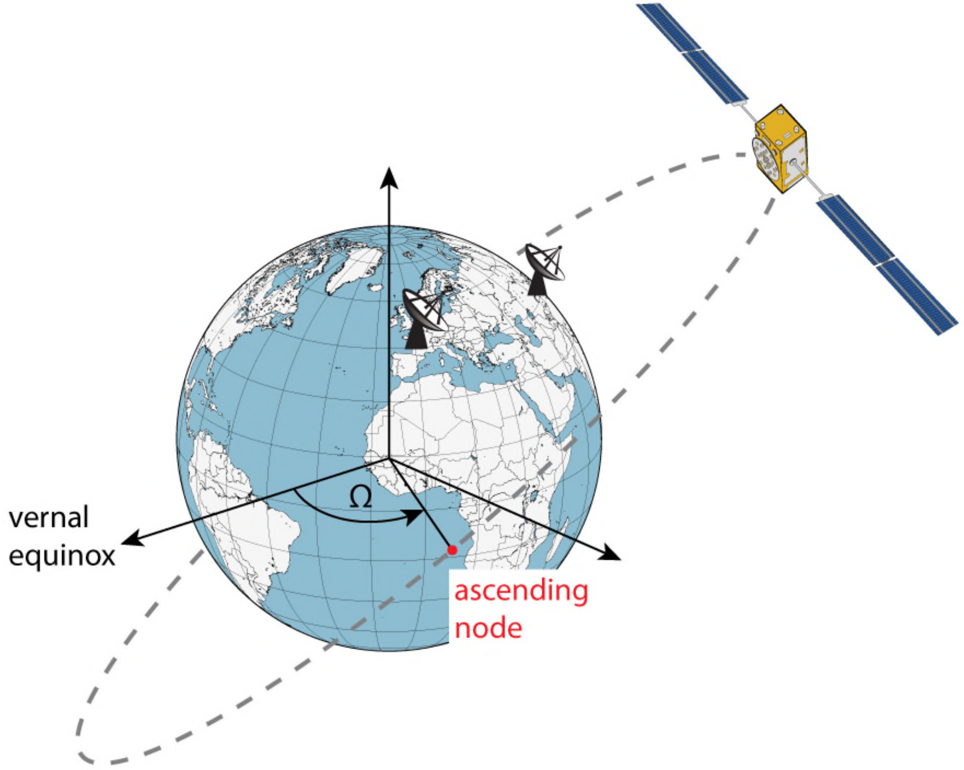
- VLBI essential for
  - Celestial reference frame
  - Earth orientation parameters
  - Terrestrial reference frame



NASA GSFC

Why should we observe satellites with VLBI radio telescopes?

- VLBI observations to satellites are the missing link in space geodesy
  - Satellites are routinely observed with GNSS, SLR, and DORIS
- VLBI observations enable the direct estimation of satellite orbits in the celestial frame
  - Without going via UT1-UTC



VLBI → UT1-UTC → Orbit in CRF

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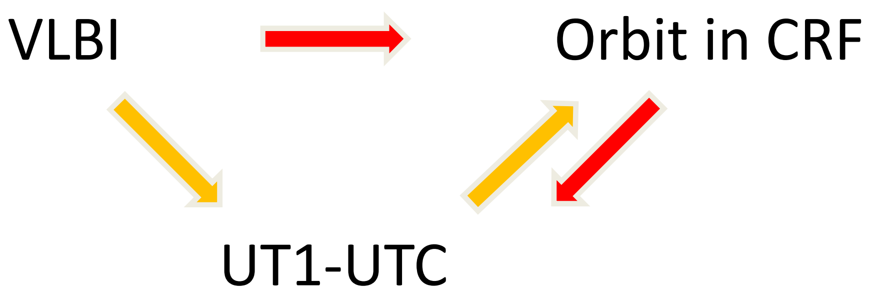
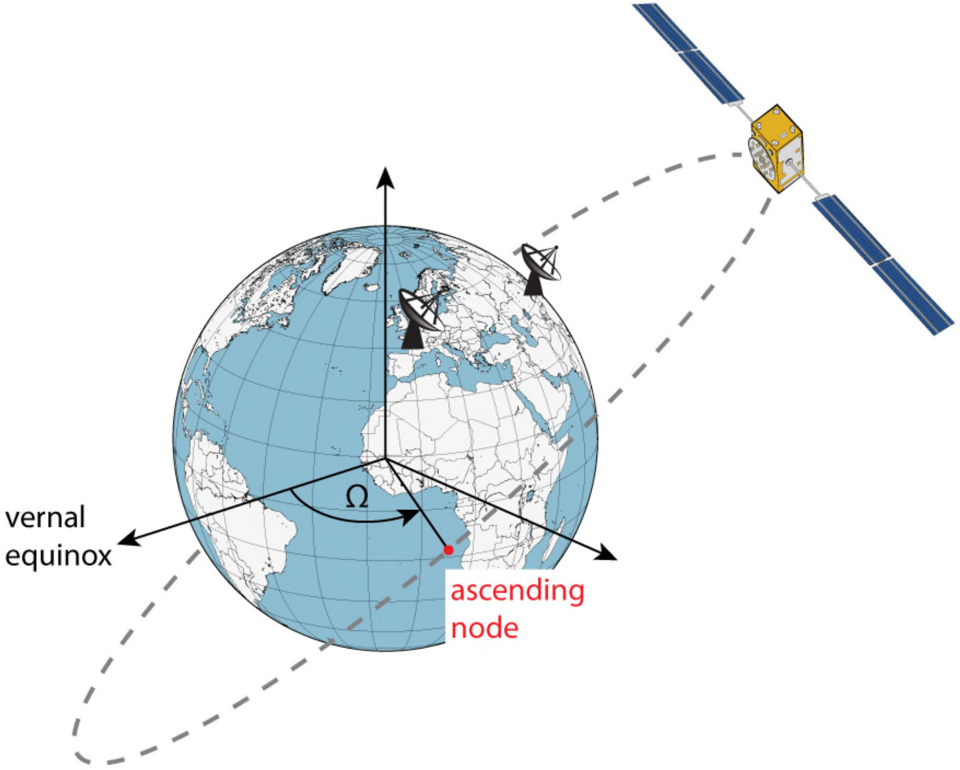
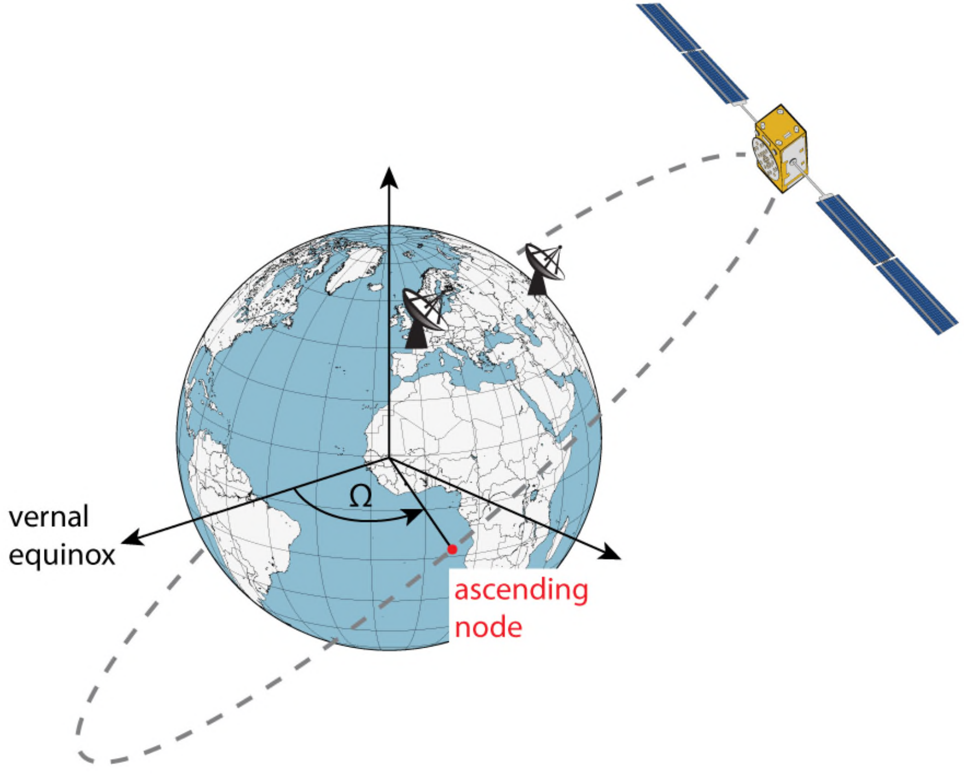




Why should we observe satellites with VLBI radio telescopes?

- With satellite techniques alone, we cannot distinguish between a rotation of the orbital plane and the rotation of the Earth (UT1-UTC)
  - E.g., due to errors in solar radiation pressure modelling
  - Integrated Length-of-Day values from GNSS drift by about 30 μs/week (Kammeyer, 2000)
- VLBI observations to satellites have potential to detect systematic differences between the techniques

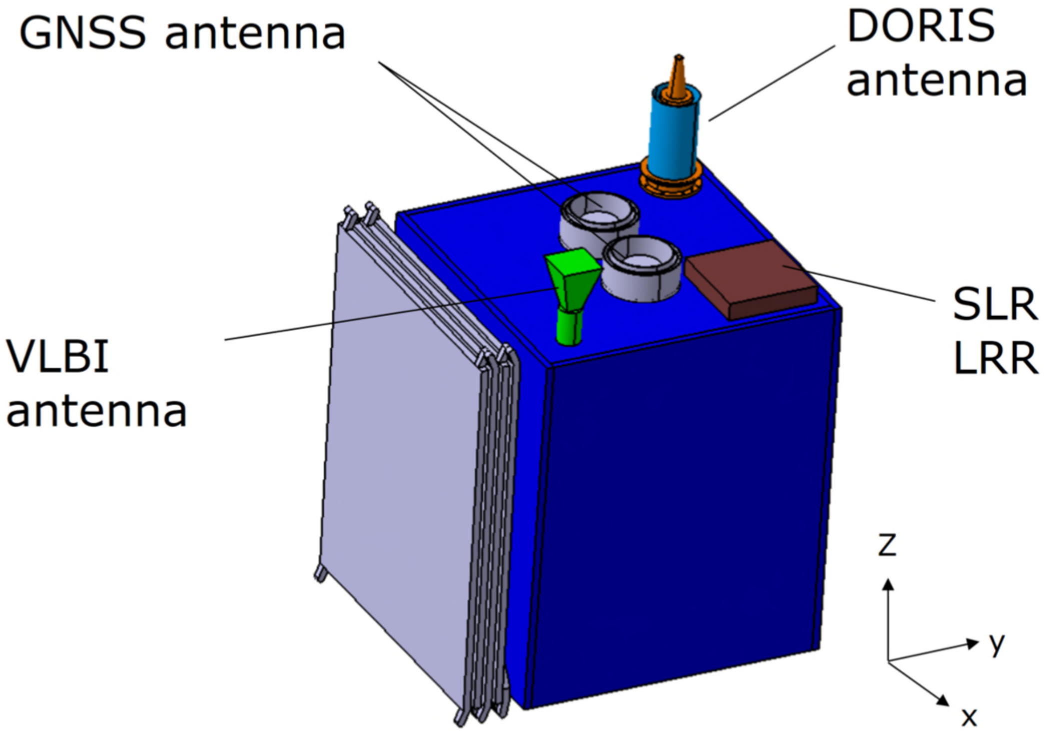


- ⇒ VLBI to Galileo satellites

Why should we observe satellites with VLBI radio telescopes?

- Realising ties on-board a satellite in addition to local ties on the ground
  - Errors in local ties on the ground are limiting factor for the accuracy of the terrestrial reference frame

- ⇒ VLBI observations to Genesis

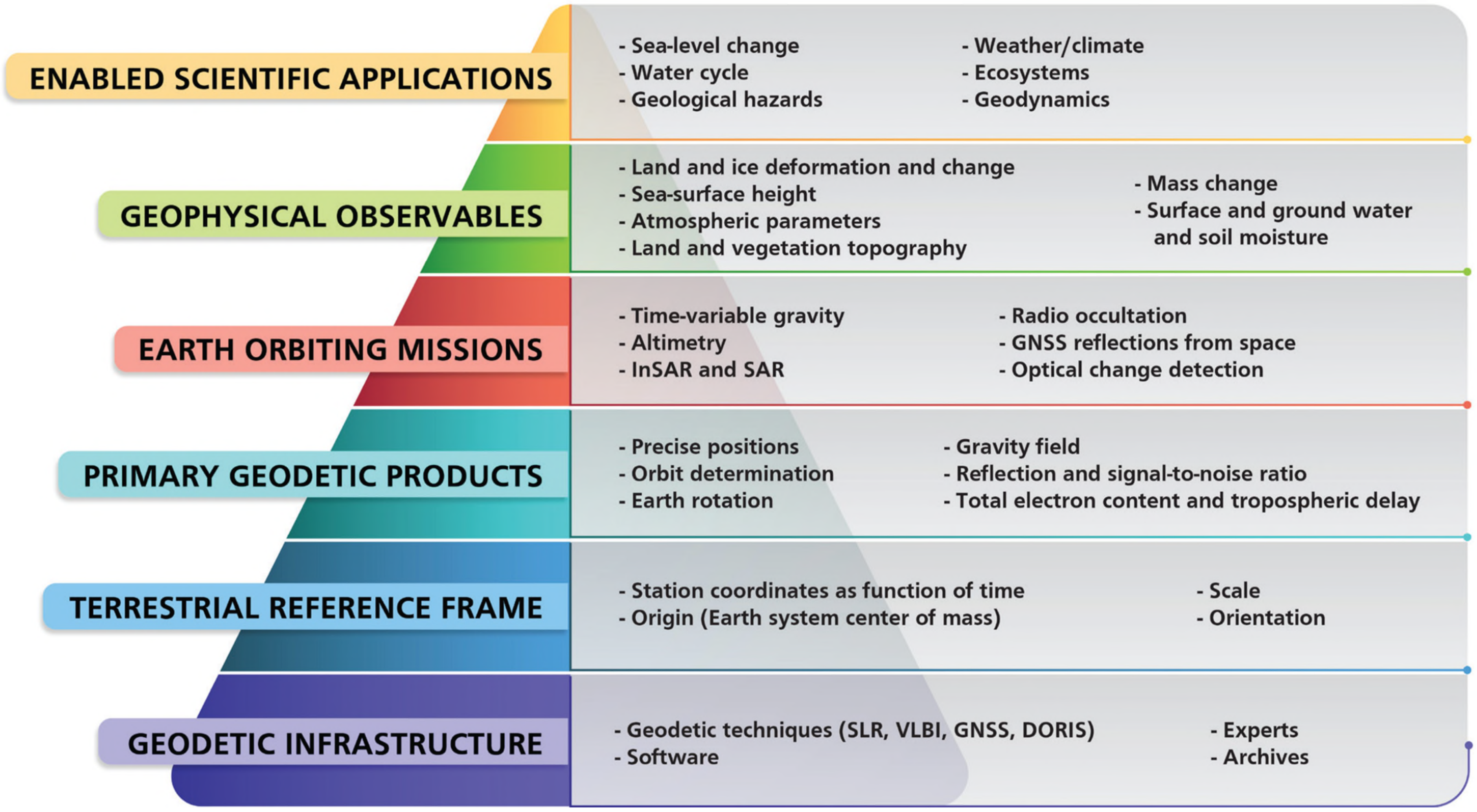


Delva et al. (2022): GENESIS White Paper

Why should we observe satellites with VLBI radio telescopes?

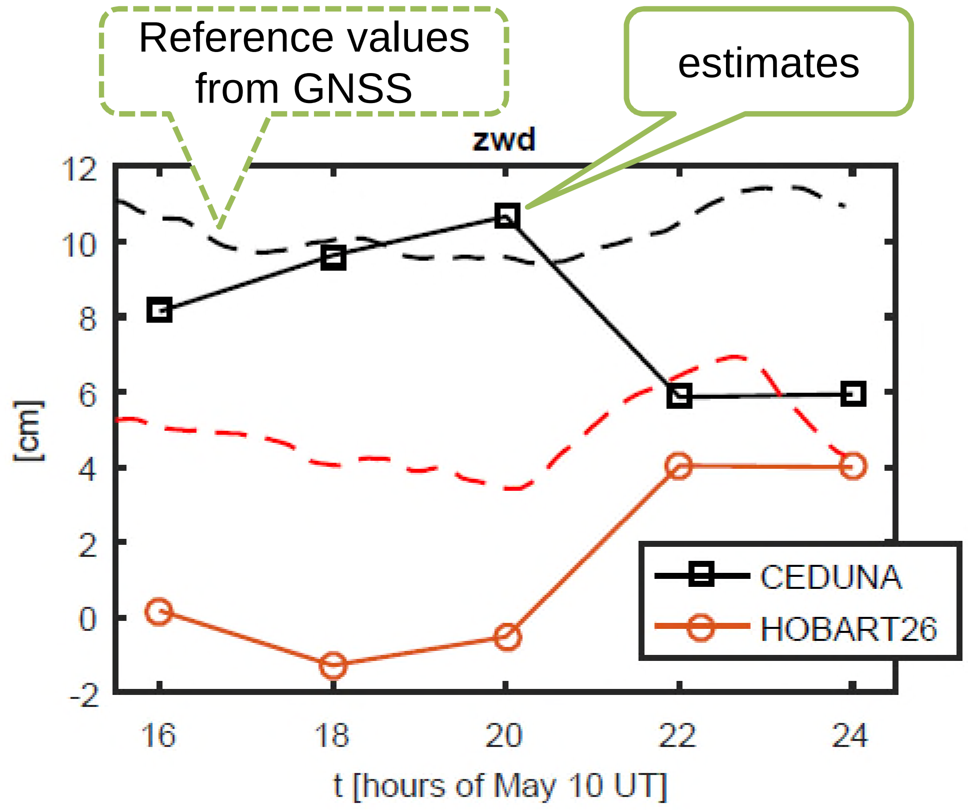
- ⇒ VLBI observations to Genesis

US National Academy of Sciences, 2020



Past achievements with real observations

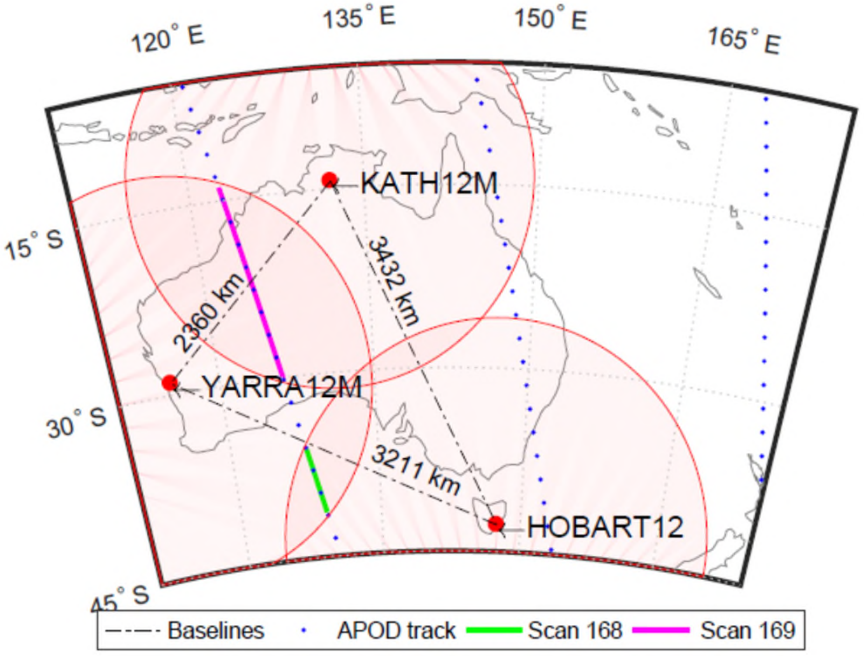
- L-band GNSS satellite signals, e.g., by Tornatore et al. (2014), Kodet et al. (2014), Haas et al. (2014, 2019)
- GNSS satellites at L1/L2 with Australian baseline Hobart-Ceduna (Plank et al., 2017)
  - From scheduling to analysis
  - Post fit residuals at 10 to 20 cm
  - Accuracy a couple of decimeters
    - at Earth surface

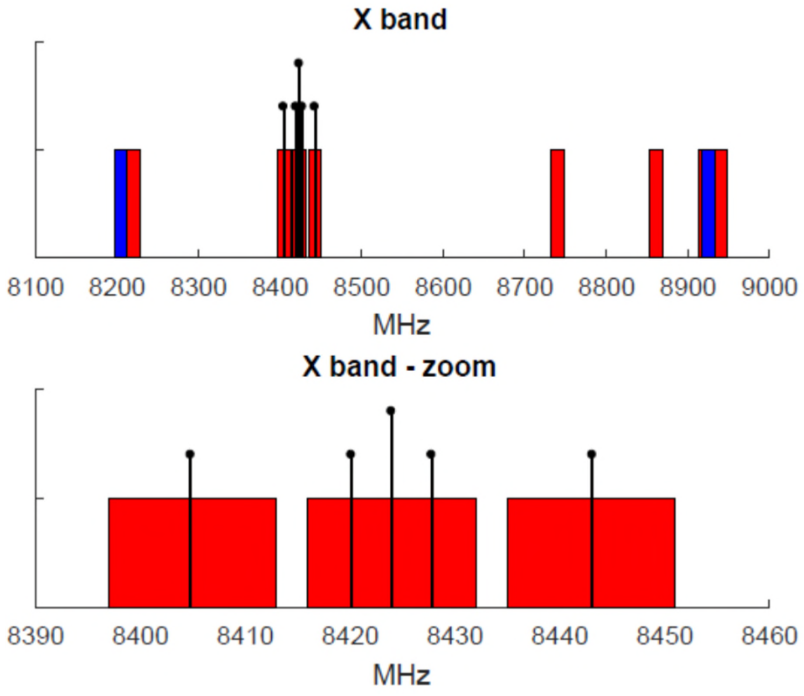


Estimated zenith wet delays of session 131a.

Past achievements with real observations

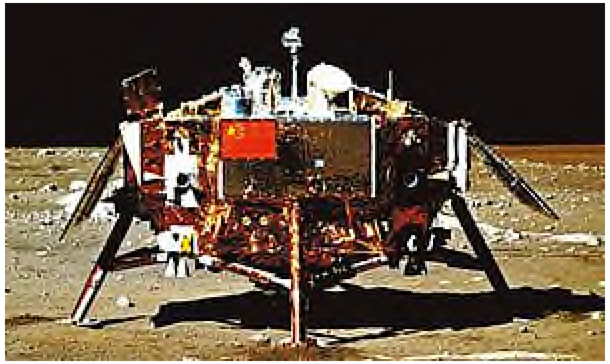
- APOD-A satellite at 450 km with Australian network (Hellerschmied et al., 2018)
  - Quite challenging: tracking, a priori orbit, ambiguity spacing with DOR tones , ...
  - Accuracy of a couple of decimeters





Past achievements with real observations

- Observations to DOR tones from the Chang‘e-3 lander on the Moon (OCEL)
  - Position accuracy of several meters on the Moon (Klopotek et al., 2019)
  - Similar challenges with DOR tones



CNSA

Comments on the elements in the VLBI processing chain (1/2)

- Scheduling
  - Good progress, e.g. with VieSched++ (Schartner and Böhm, 2019; Wolf, 2021)
  - VEX2 format important
- Observation
  - Tracking of low satellites tricky
  - VLBI needs X/S bands or VGOS frequency range
- Data transfer
  - Feasible, since real-time is not the goal currently

Comments on the elements in the VLBI processing chain (2/2)

- Correlation and fringe-fitting
  - Tricky because of frequency setup, e.g., for DOR tones
  - Bandwidth of several hundred MHz needed
  - Ionosphere calibration needed
  - No experience with modulated signals for ranging
- Analysis
  - Near-field delay models available (e.g., Jaron and Nothnagel, 2018)
  - Software packages under development (Bernese, C5++, NAPEOS, VieVS, ...)

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- $\Rightarrow$ We need dedicated VLBI transmitters

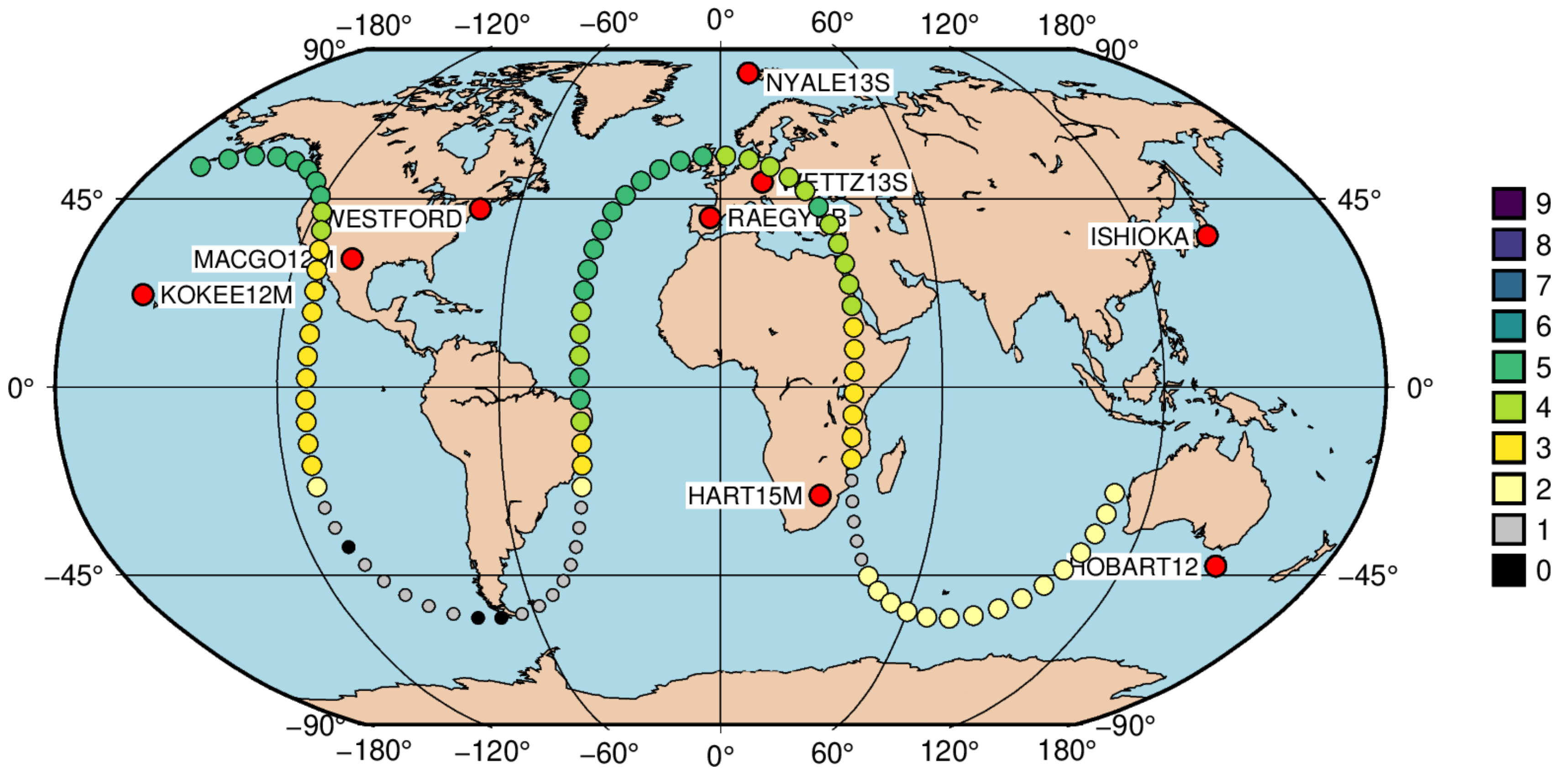
Past achievements with simulations of VLBI observations to

- VLBI to GNSS satellites, e.g. by Plank et al. (2014, 2015), Schunck et. al (2022), Sert et al. (2022)
- VLBI to co-location satellite by Anderson et al. (2018)
  - Including ranging data
- VLBI for orbit determination of MEOs by Klopotek et al. (2020)
- ...

- Review of simulation activities at TU Wien for VLBI observations to Galileo

Visibilities for Galileo satellites

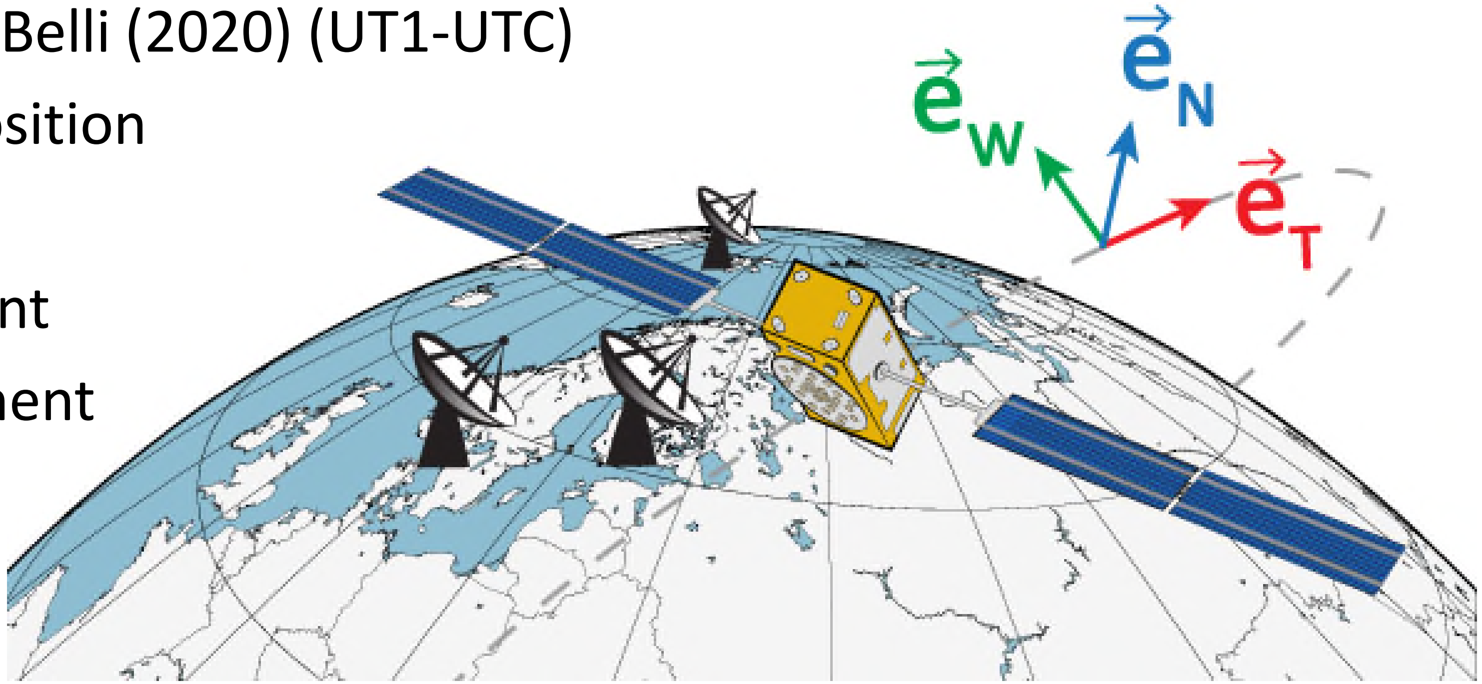
- One day for one Galileo satellite with 9 stations



# stations	% of time (24h)
0	3,4%
1	20,0%
2	17,2%
3	21,6%
4	17,3%
5	20,5%
6	0 %
7	0 %
8	0 %
9	0 %

Orbit precision based on DOP values

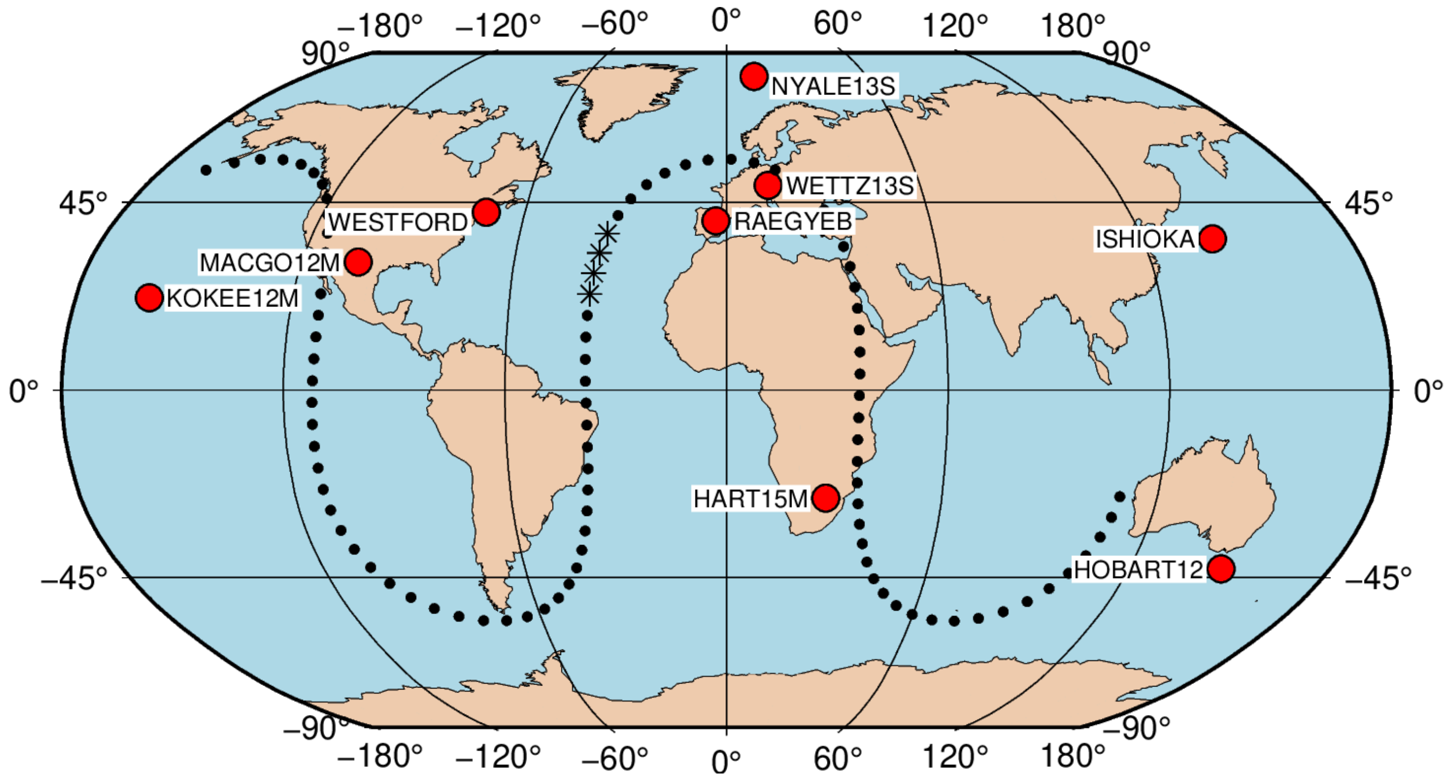
- Motivated by UDOP values by Belli (2020) (UT1-UTC)
- Sensitivity towards satellite position
  - NDOP: normal component
  - TDOP: tangential component
  - WDOP: cross-track component



- DOP values represent formal error per VLBI measurement error in cm/cm
  - The smaller the value the higher the sensitivity
  - Based on variances

Orbit precision based on DOP values

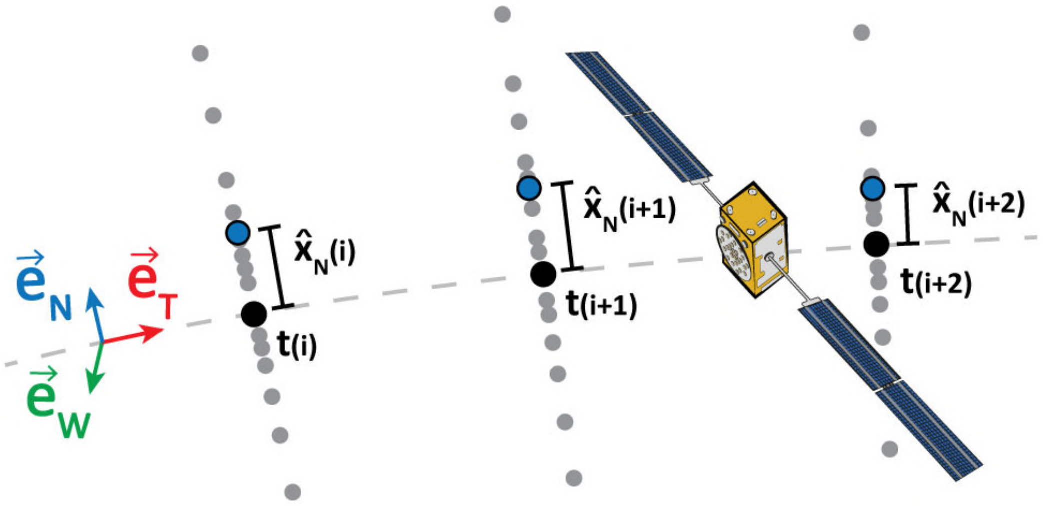
- Example: Feb. 2, 2022 0:00 – 24:00
  - 9 station network
  - Satellite observations from 12:10 – 13:00 with 5 stations
    - DOP values averaged
      - Ø NDOP = 40.7
      - Ø TDOP = 2.0
      - Ø WDOP = 2.3



Orbit precision based on Monte Carlo simulations

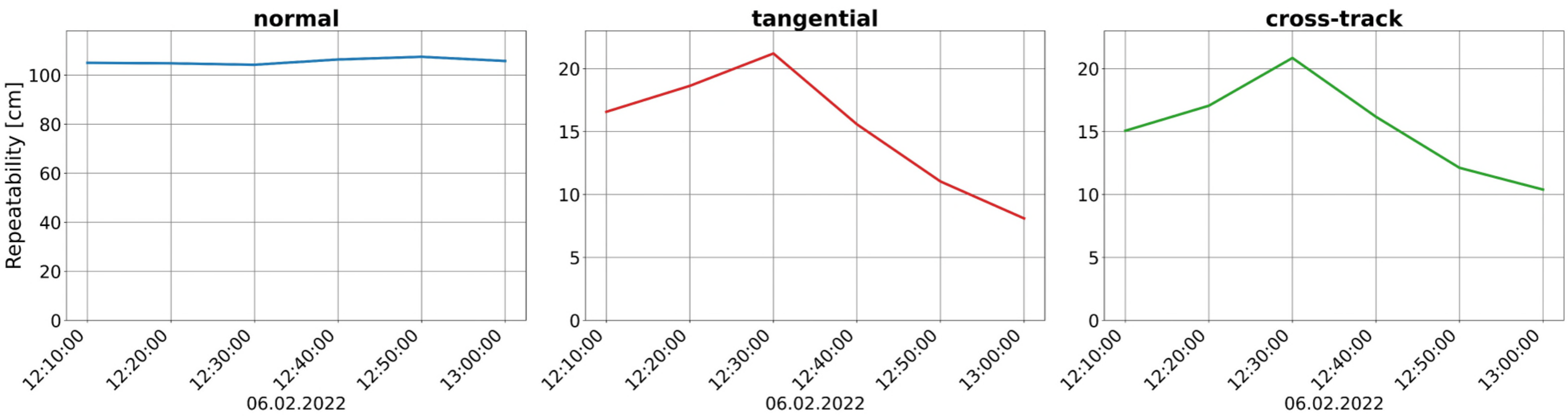
- Generation of 24h schedules including quasar and satellite observations
  - One satellite observation every 45 seconds

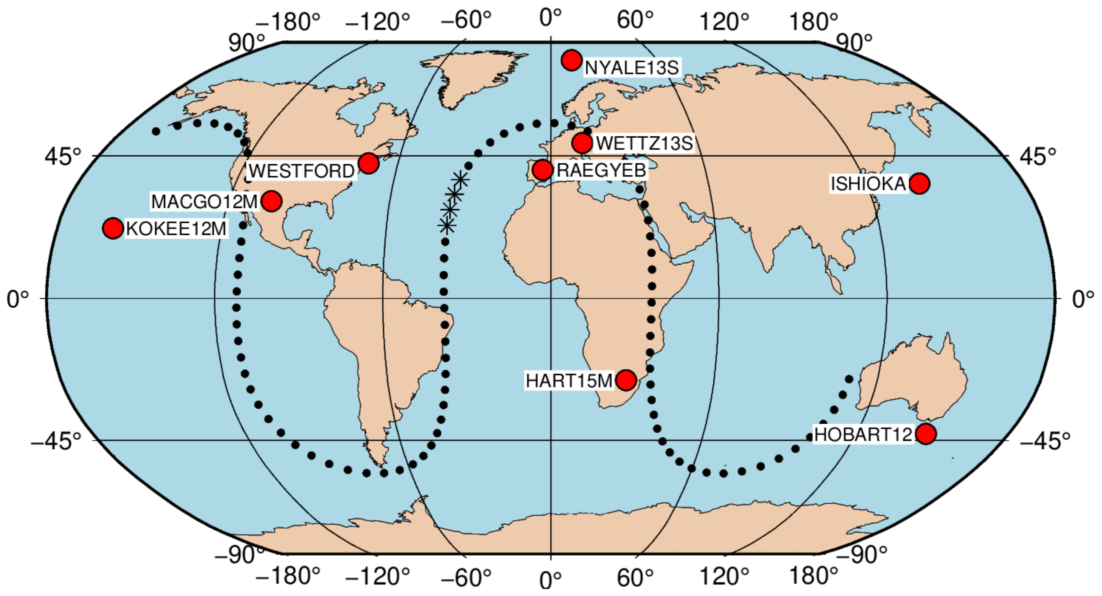
- 1000 simulations with tropospheric turbulence, clock errors, and 50 ps white noise
- Estimation of piecewise linear offsets from a-priori orbit for individual components



- Repeatabilities

Orbit precision based on Monte Carlo simulations





DOP values:

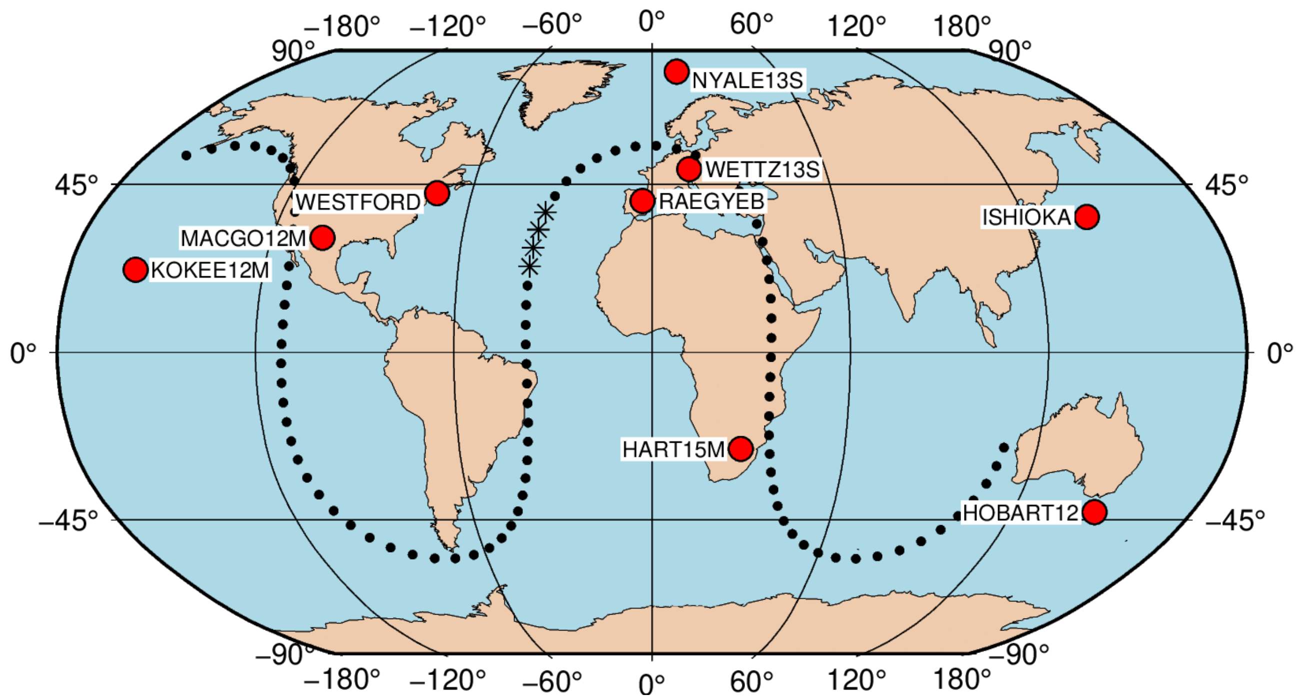
- ØNDOP: 40.7
- ØTDOP: 2.0
- ØWDOP: 2.3

⟶ Deficiencies in estimation of troposphere with longer periods of satellite observations

Estimation of Keplerian Elements

- Estimation of right ascension Ω as piecewise linear offsets
  - Station and source positions fixed

Time of Estimation	mfe [mas]	rep [mas]
12:10:00	0,21	0,39
12:20:00	0,31	0,67
12:30:00	0,46	0,99
12:40:00	0,33	0,73
12:50:00	0,22	0,52
13:00:00	0,22	0,39



0,5 mas $\Rightarrow$ 8 cm @ Galileo height

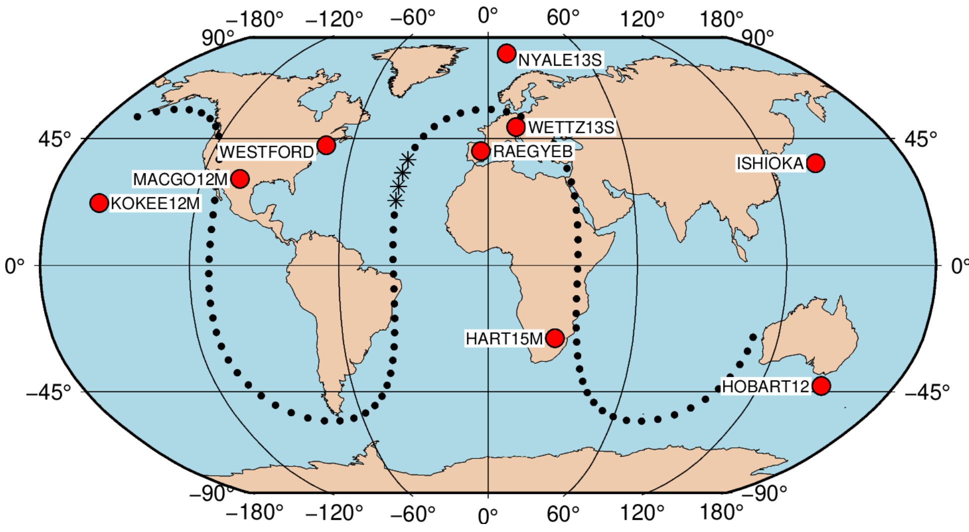
Estimation of stations coordinates with Monte Carlo simulations

- Generation of 22h schedules with quasar or satellite observations
  - Satellite scans with 10 seconds on-source time
  - All Galileo satellites used for scheduling
- 1000 simulations with tropospheric turbulence, clock errors, and 50 ps white noise
- Estimation of station coordinates with NNR/NNT on all stations
  - Orbits, quasars and EOP fixed
- Repeatabilities

Estimation of station coordinates with Monte Carlo simulations

- From quasars only

Station	#obs	rep. x [mm]	rep. y [mm]	rep. z [mm]	mean 3D-offset [mm]
HART15M	1259	6,0	3,4	4,0	6,9
NYALE13S	1264	2,4	1,6	8,1	7,2
RAEGYEB	1689	4,5	1,4	3,5	5,1
WESTFORD	1245	2,1	4,0	3,9	5,2
WETTZ13S	1734	3,8	1,5	3,8	4,8
HOBART12	691	5,8	3,7	6,1	8,1
ISHIOKA	1197	4,3	4,0	4,1	6,2
KOKEE12M	1028	6,0	3,0	3,0	6,3
MACGO12M	1287	2,3	5,1	3,4	5,6



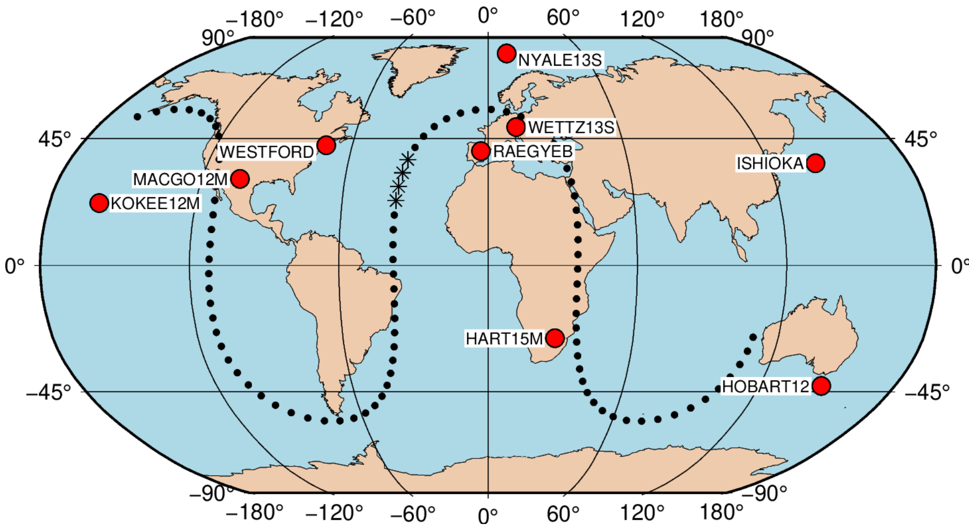
~5-7 mm

Estimation of station coordinates

- From Galileo satellite observations only

Station	#obs	rep. x [mm]	rep. y [mm]	rep. z [mm]	mean 3D-offset [mm]
HART15M	1778	9,8	5,4	5,8	11,1
NYALE13S	5194	2,7	1,8	8,9	7,9
RAEGYEB	4503	5,6	1,7	4,8	6,6
WESTFORD	4514	2,5	4,7	5,1	6,4
WETTZ13S	4485	4,5	1,9	4,8	5,9
HOBART12	1450	8,4	4,8	8,1	10,9
ISHIOKA	3480	7,1	5,5	5,1	8,9
KOKEE12M	3739	9,0	4,4	4,7	9,5
MACGO12M	4343	2,9	5,9	5,1	7,2

~6-11 mm

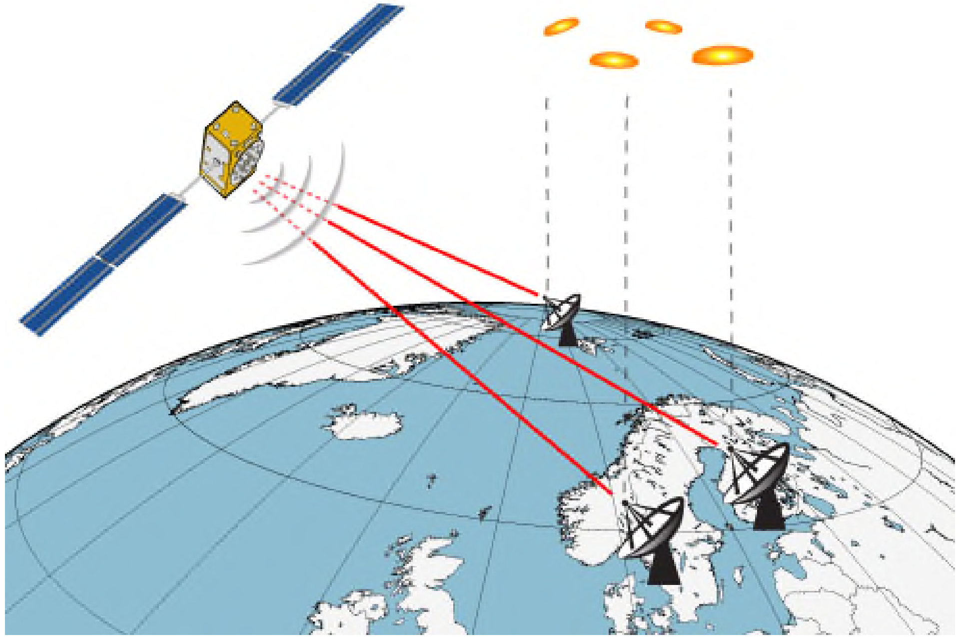


Estimation of station coordinates - next steps

- Investigations on mixed schedules needed
  - To check impact on quasar-schedules if time is used for satellites
- Simulations with Genesis needed
  - Station coordinates from observations to Genesis
  - Of course much worse for a few stations, but important for quality of frame ties (Anderson et al., 2018)

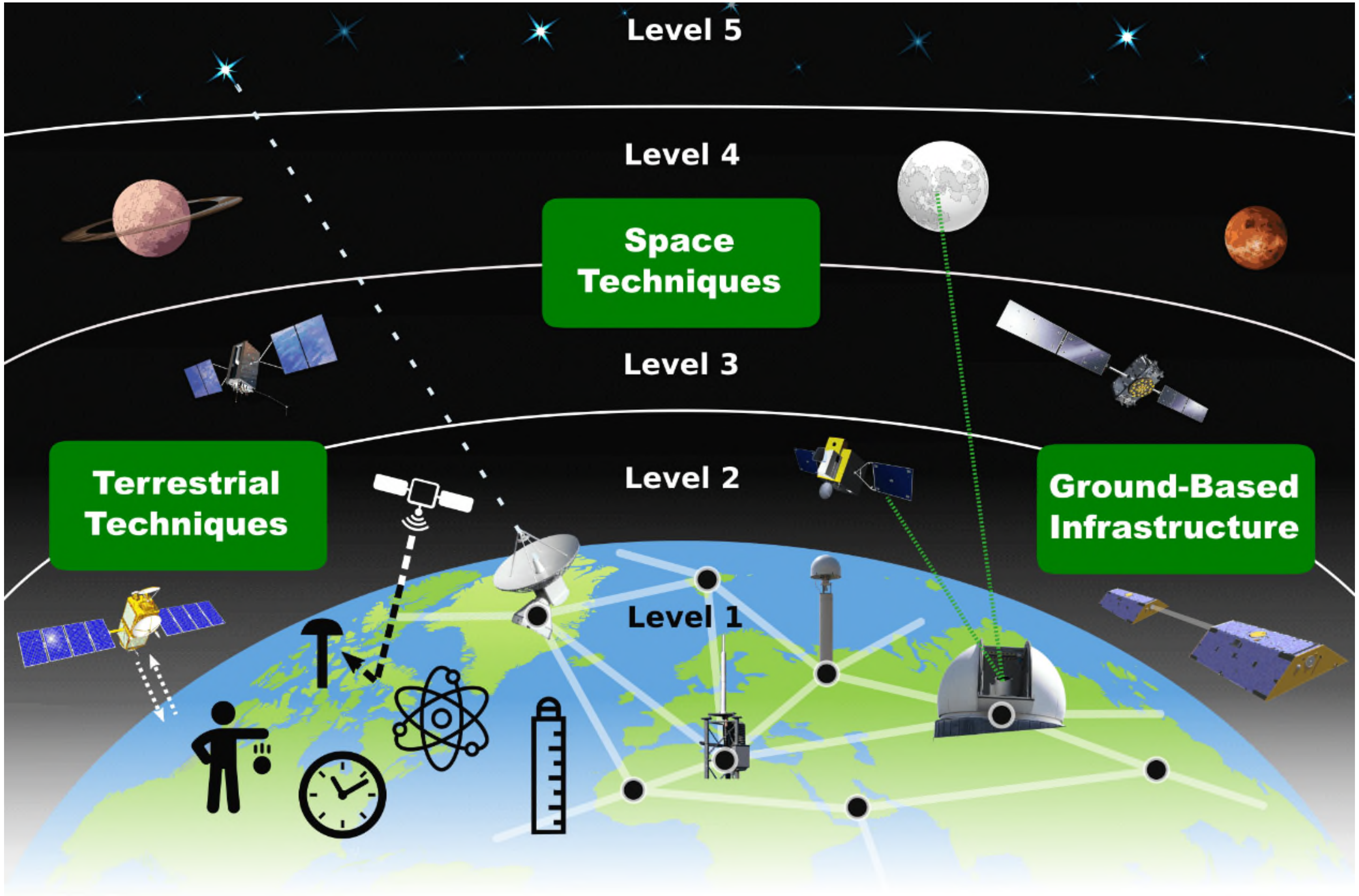
Conclusions

- We need more sophisticated orbit determination
- We need dedicated signals from VLBI transmitters to confirm readiness of processing chain
  - Even more so for the time-of-flight signals



FWF Der Wissenschaftsfonds.

Thanks for your attention



Connecting the levels!

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