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LEO-PNT as a New System for Satellite-Based Navigation

2023 UNOOSA workshop on the Applications of GNSS

Fabricio S. Prol, Sanna Kaasalainen, Zahidul Bhuiyan, and INCUBATE team

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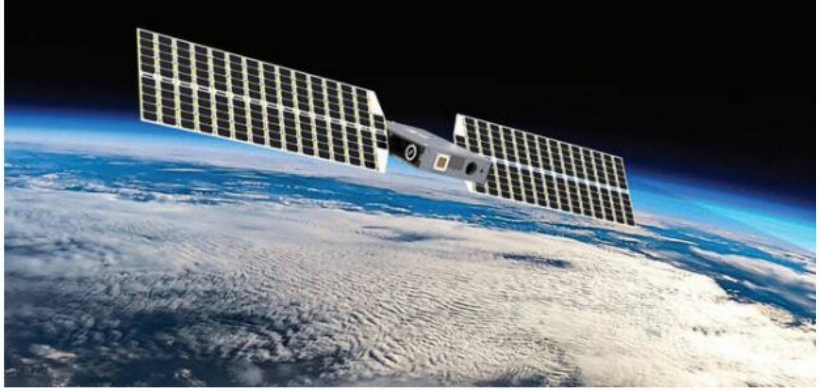
INSTITUTE OF NAVIGATION

Space Weather Lessons Learned in Very Low Earth Orbit Operations

Delores J. Knipp and Vishal Ray

Low Earth orbit (LEO) satellite mega-constellations are providing global phone and internet communications as well as space-based imaging services—and more are on the way. The space community stands to learn much about operating in the LEO environment as these constellations complete their configurations. For example, with an eye toward building a LEO constellation comprised of thousands of spacecrafts, Starlink mission designers use a combination of boosting and electric orbit-raising to elevate constellation spacecraft to operational altitudes. In early February 2022, this seemingly proven approach had a

Is LEO PNT the Next Big Thing?

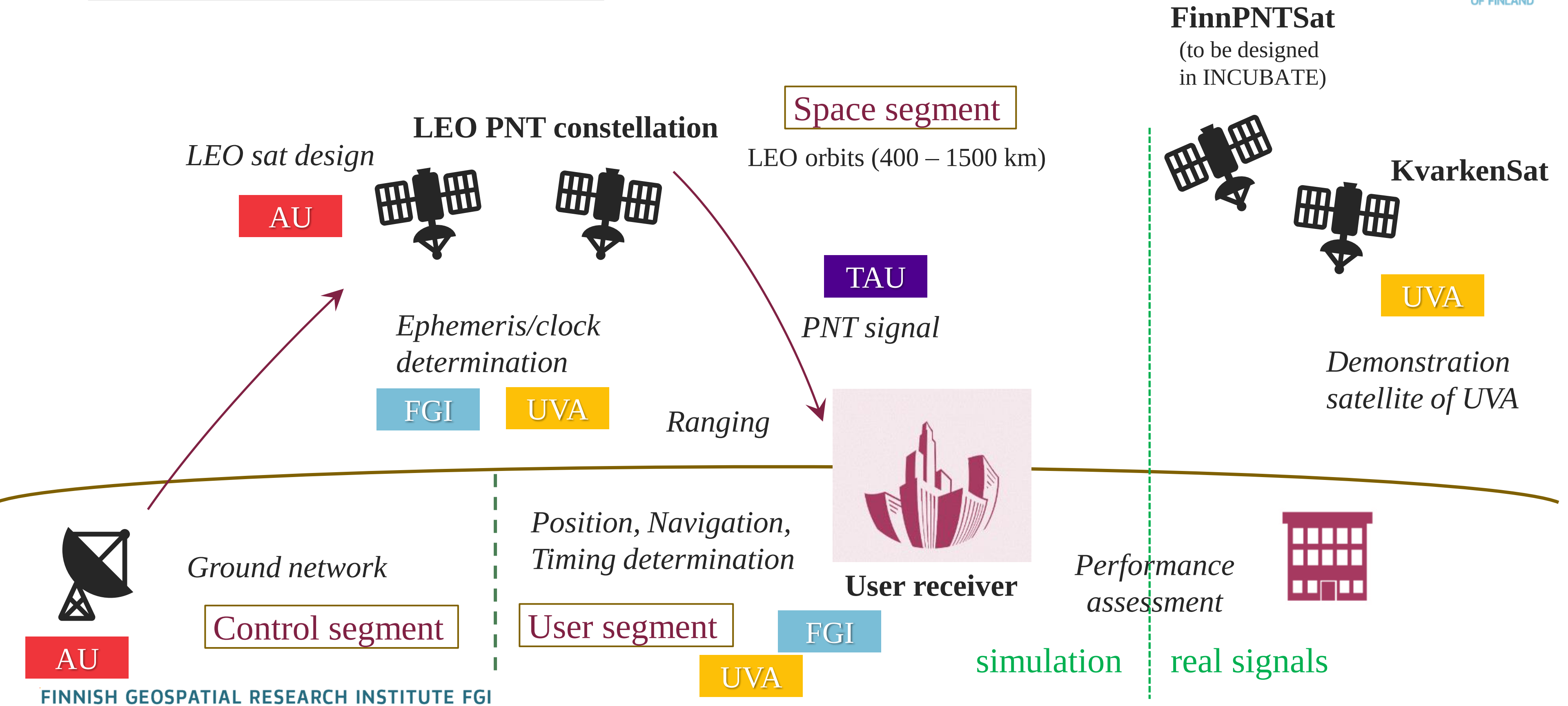


Artist impression of a Xona Space Systems' LEO satellite

Kevin Dennehy

Many companies are developing low Earth orbit (LEO) systems and equipment to augment GPS and other GNSSs for such commercial applications as autonomous vehicles, drone delivery services, critical infrastructure, and other markets. While GNSSs that operate in medium Earth orbit (MEO) are the dominant positioning, navigation, and timing (PNT) satellite constellations, industry experts say their signals are weak, subject to interference, and expensive to augment.

INCUBATE Overview



What does LEO-PNT Entails?

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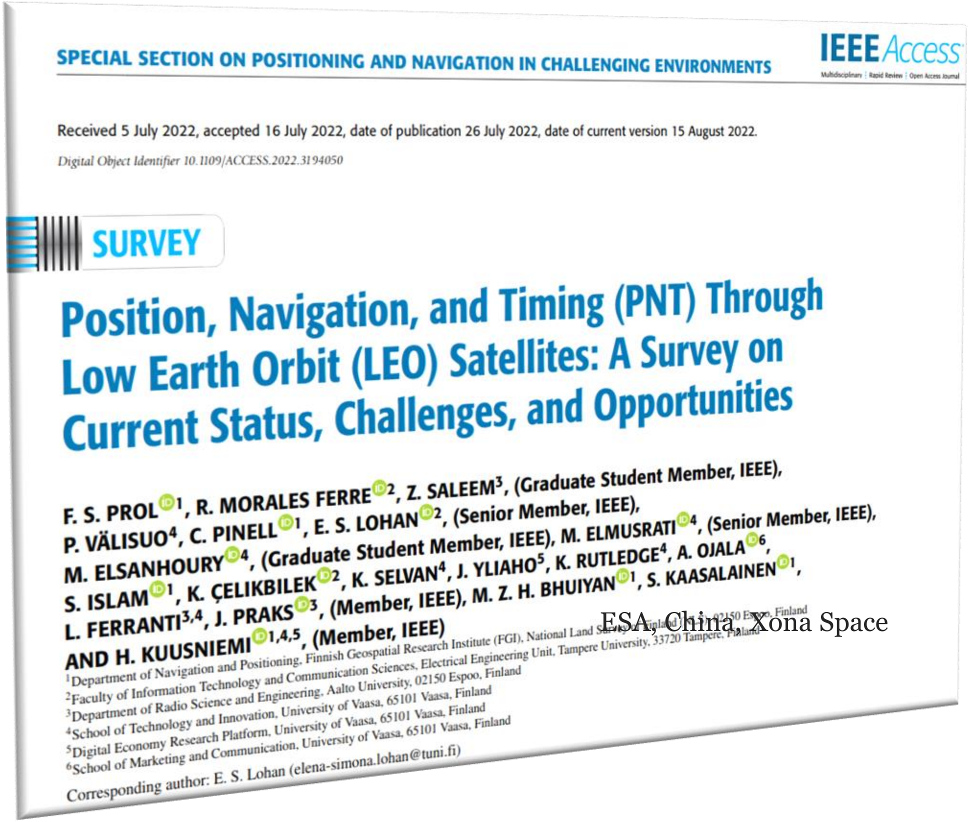
SPECIAL SECTION ON POSITIONING AND NAVIGATION IN CHALLENGING ENVIRONMENTS

IEEE Access

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SURVEY

Position, Navigation, and Timing (PNT) Through Low Earth Orbit (LEO) Satellites: A Survey on Current Status, Challenges, and Opportunities

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ESA, China, Xona Space

Detailed literature review paper about state-of-the-art LEO-PNT challenges and prospects

Dedicated LEO-PNT

- Iannucci et al. ION PLANS, 2020
- Ardito et al., ION ITM, 2019
- Reid et al., NAVIGATI...
- Wang et al., Sensors, ...
- Meng et al., IEEE EN...

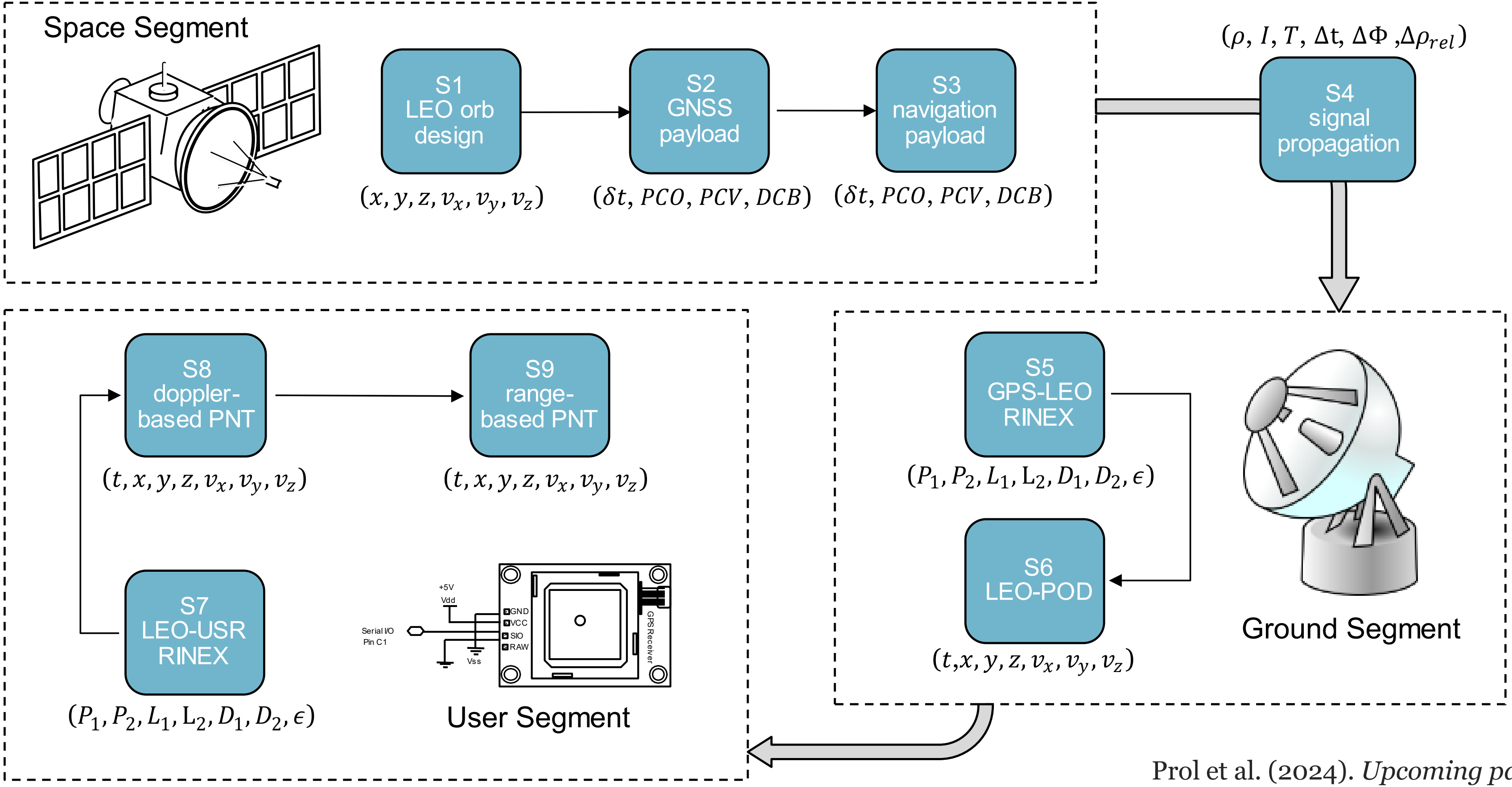
Augmented LEO-PNT

- Oligeri et al., ACM SPWMN, 2020
- Xiao & Lei, J. of Engineering, 2019
- Racelis et al., ION GNSS+, 2019
- Hsu & Jan, IEEE/IO...
- Jorger et al., NAVIG...

SoO

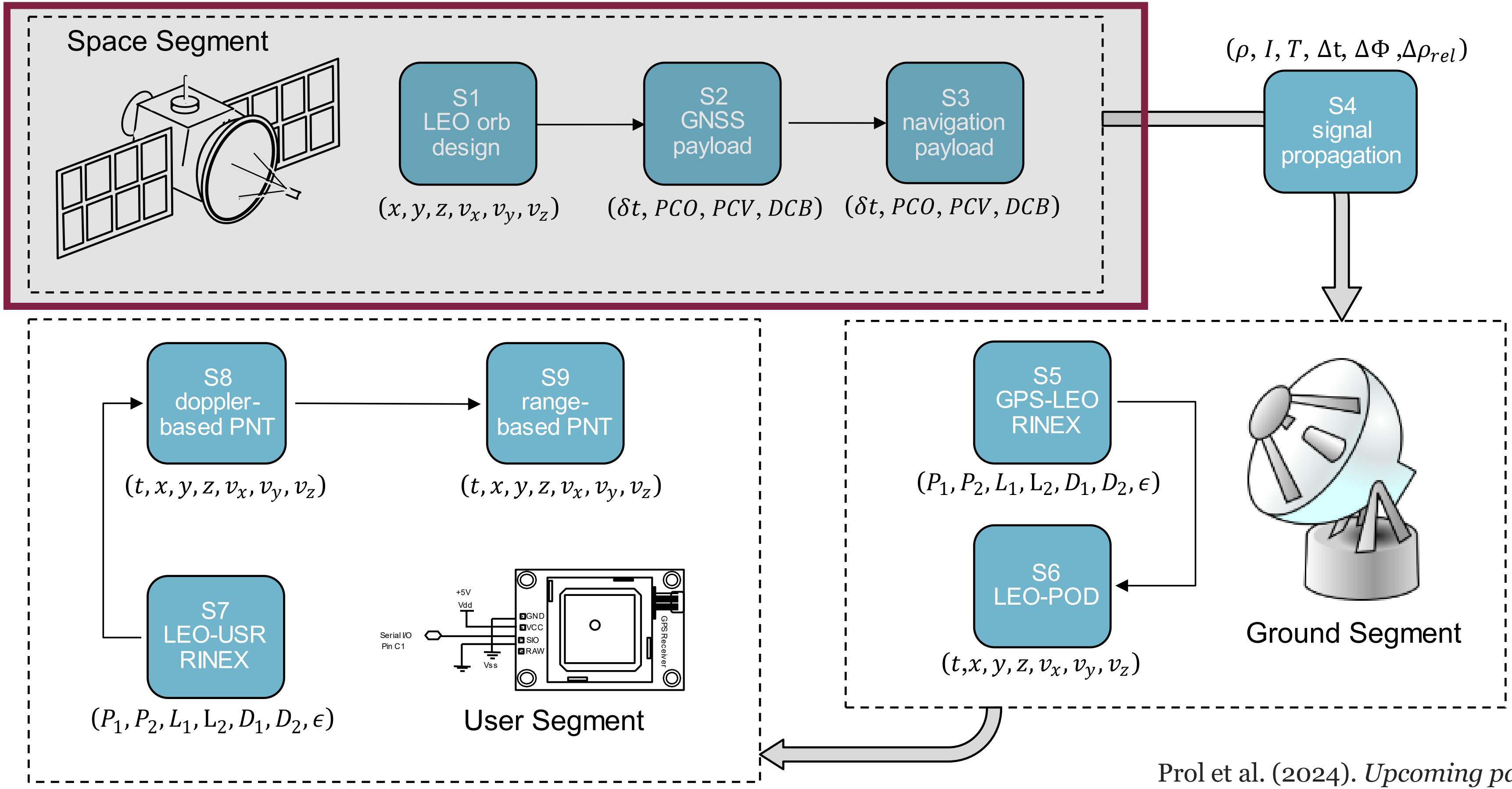
- Kassas et al., Inside GNSS, 2021
- Psiaki, NAVIGATION, 2021
- Farhangian & Landry, Sensors, 2020
- Khalife & Kassas, ION GNSS+, 2019
- Tan et al., IEEE Access, 2019

LEO-S9 - LEO/PNT simulation tool with 9 modules



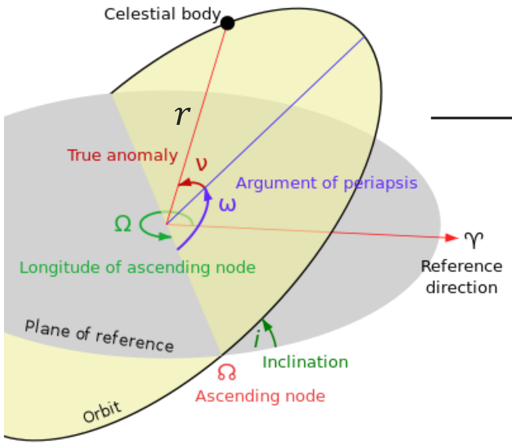
Prol et al. (2024). *Upcoming paper.*

LEO-S9 - LEO/PNT simulation tool with 9 modules



Prol et al. (2024). *Upcoming paper.*

Space Segment: Orbit Design

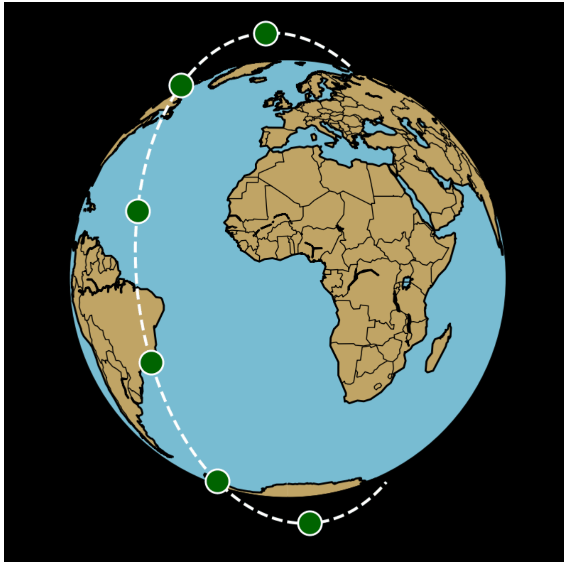


Tab 2. Propagation

Two body effects
Gravity perturbations
Moon attraction
Sun attraction
Solar radiation
Atmospheric Drag

Table 1. Keplerian orbital parameters

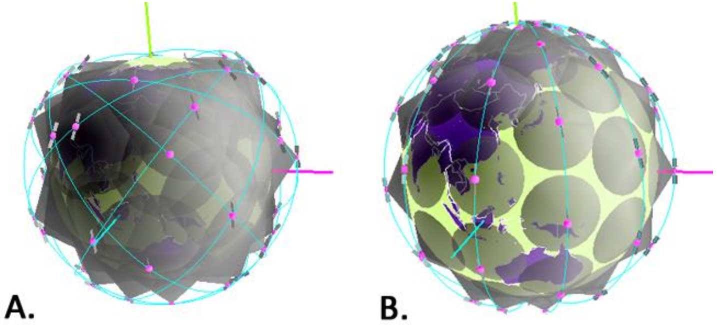
e	Eccentricity
i	Inclination
A	Semi major axis
ω	Argument of periapsis
Ω	Right ascension of ascending node
M_0	Mean anomaly



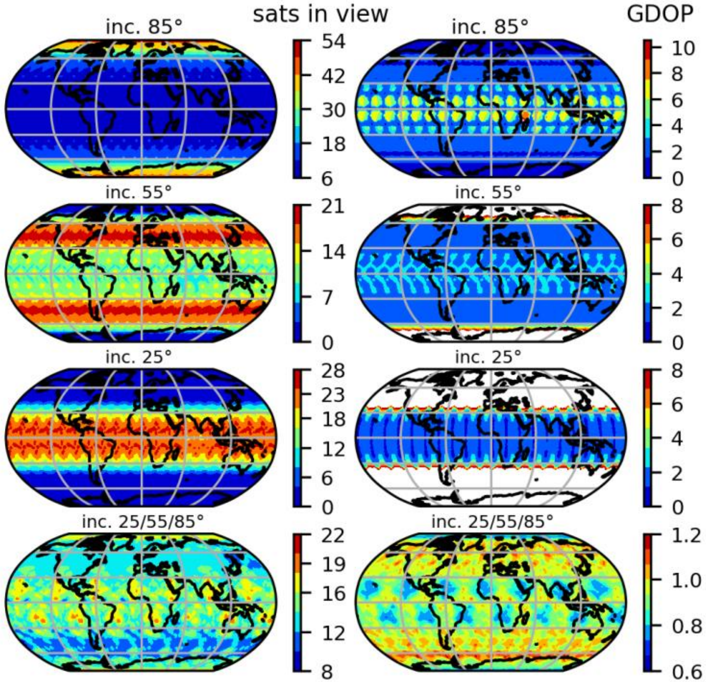
Space Segment: Satellite Constellation

Unknown points for optimization:

- Altitude (550 – 1200 km)
- Inclination (3 planes)
- Eccentricity (0.001 – 0.006)
- Number of orbital planes (~10 - 20)
- Number of satellites per plane (~20)
- Topology (Walker Delta)



Inclination x Satellites in View x GDOP



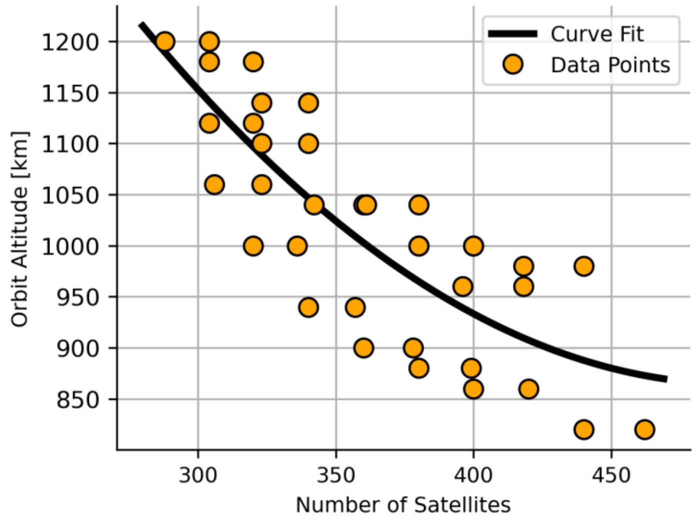
Consistent with Ge et al. [10], which used 240 satellites.

Space Segment: Satellite Constellation

12U platforms is planned → Payload cost = 720.000 EUR → Around 400 satellites are required → 400 millions for a 5-year lifetime → Around 1 billion EUR is for 12 years

1U = 10 x 10 x 10 cm

Mayank et al. (upcoming)



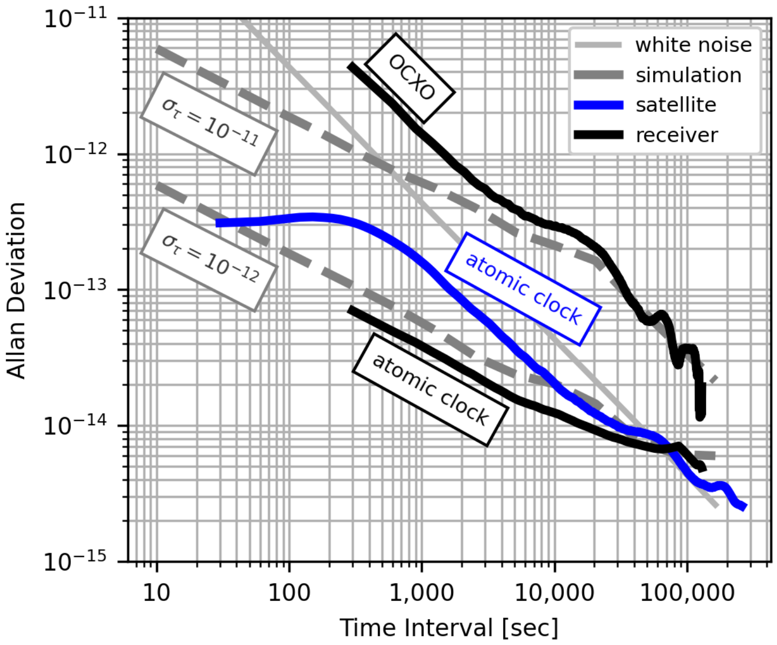
Space Segment: Clock Design

LEO-S9 can describe several clock options:

$$\delta t^{LEO} = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + \psi(\sigma_\tau)$$

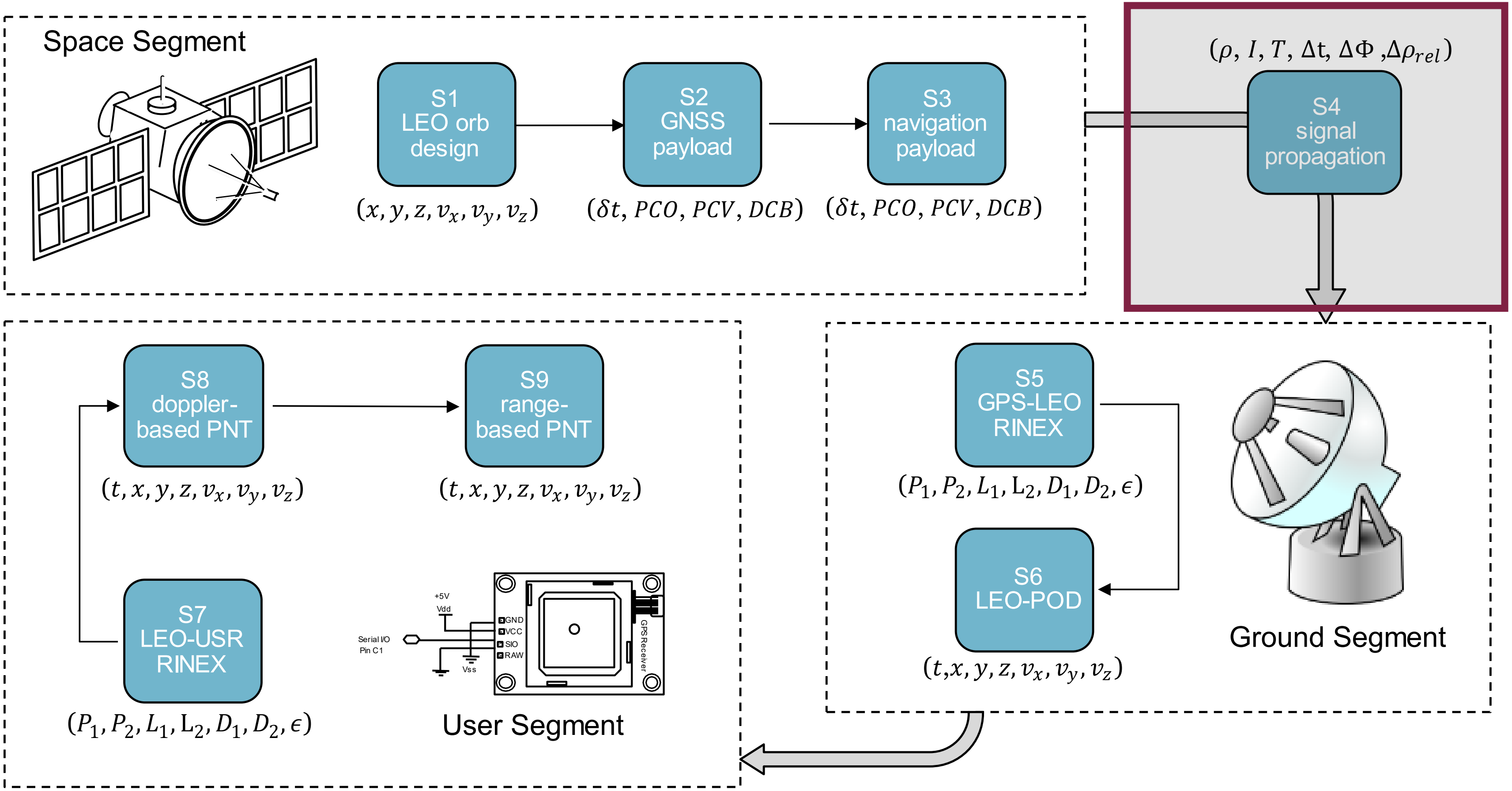
ADOPTED VALUES FOR THE CLOCK SIMULATIONS.

Clock Term	Values
Offset	$-1.00 < a_0 < 1.00$ ms
Drift	$-0.05 < a_1 < 0.05$ ns/s
Drift rate	$a_2 = 0.00$ ns/s^2
Crystal clock stability	$\sigma_\tau = 10^{-11}$ (1s)
Atomic clock stability	$\sigma_\tau = 10^{-12}$ (1s)



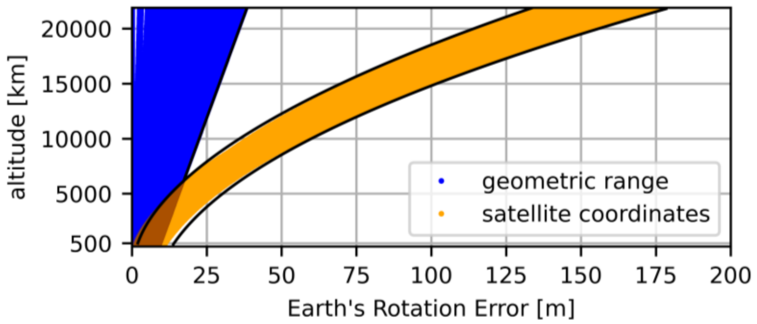
Dashed lines are random-walk distributions
Solid gray lines are Gaussian distributions

LEO-S9 - LEO/PNT simulation tool with 9 modules

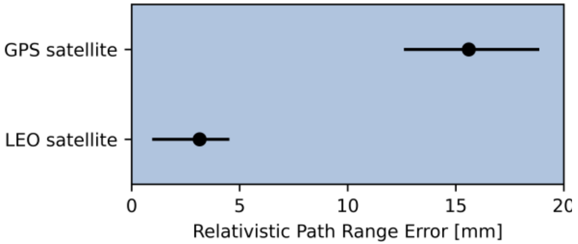


Signal Propagation: Gains

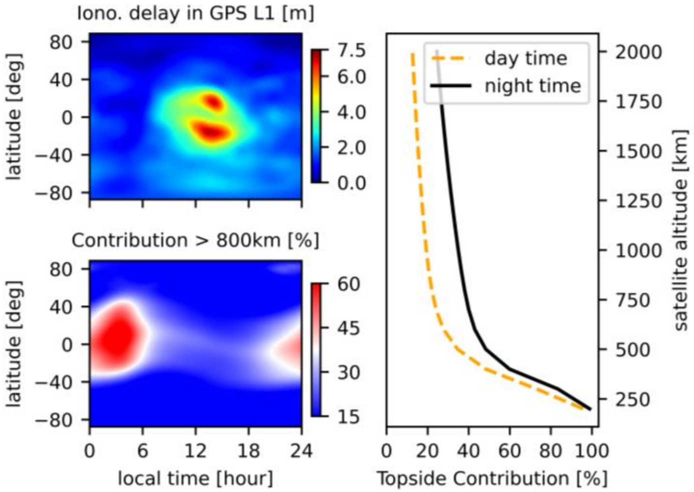
1) EARTH'S ROTATION



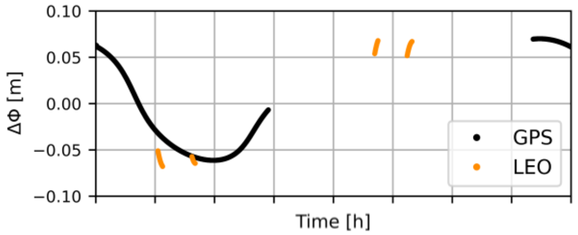
2) SHAPIRO EFFECT



3) IONOSPHERE



4) PHASE WIND-UP



Signal Propagation: Troposphere

RTCA MOPS model

$$ZHD_0 = 10^{-6} k_1 \frac{R_d . p}{g_m}$$

$$ZWD_0 = 10^{-6} k_3 \frac{R_d}{g_m(\lambda+1) - \alpha . R_d} \frac{e}{T}$$

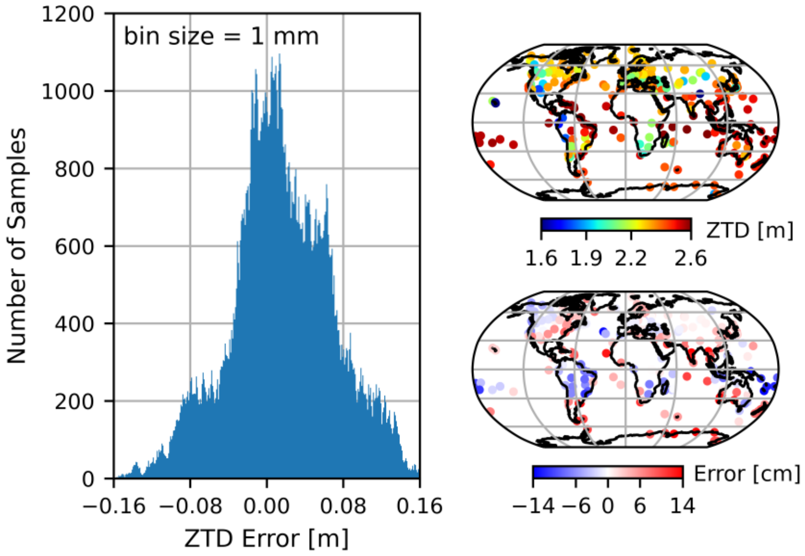
Exponential extrapolation to account the altitudes

$$ZHD = (1 - \frac{\alpha . H}{T})^{\frac{g}{R_d . \alpha}} . ZHD_0$$

$$ZWD = (1 - \frac{\alpha . H}{T})^{\frac{(\lambda+1)g}{R_d . \alpha} - 1} . ZWD_0$$

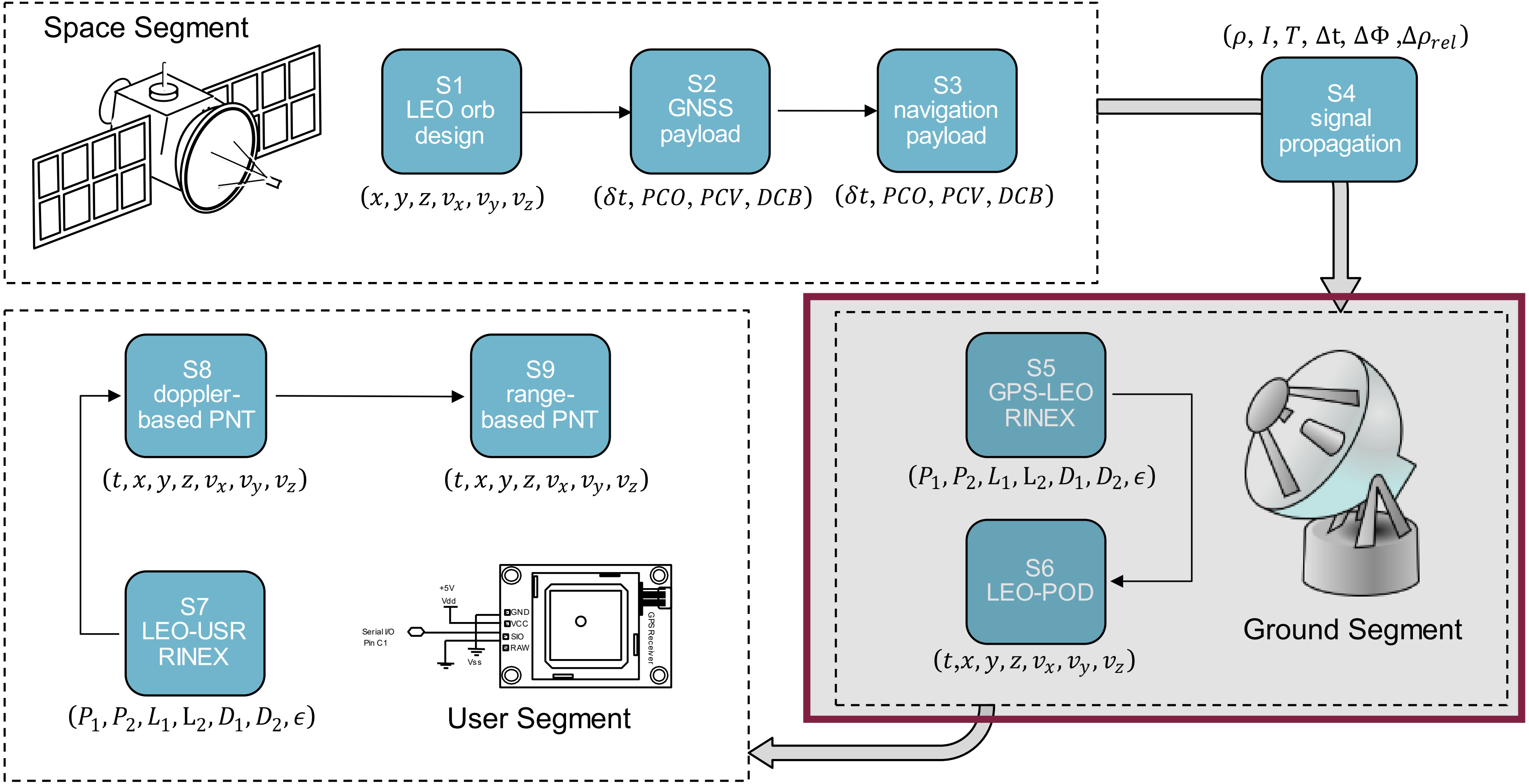
Niell mapping function to convert zenith to slant direction.

Example corresponds to DOY 6, 2021.

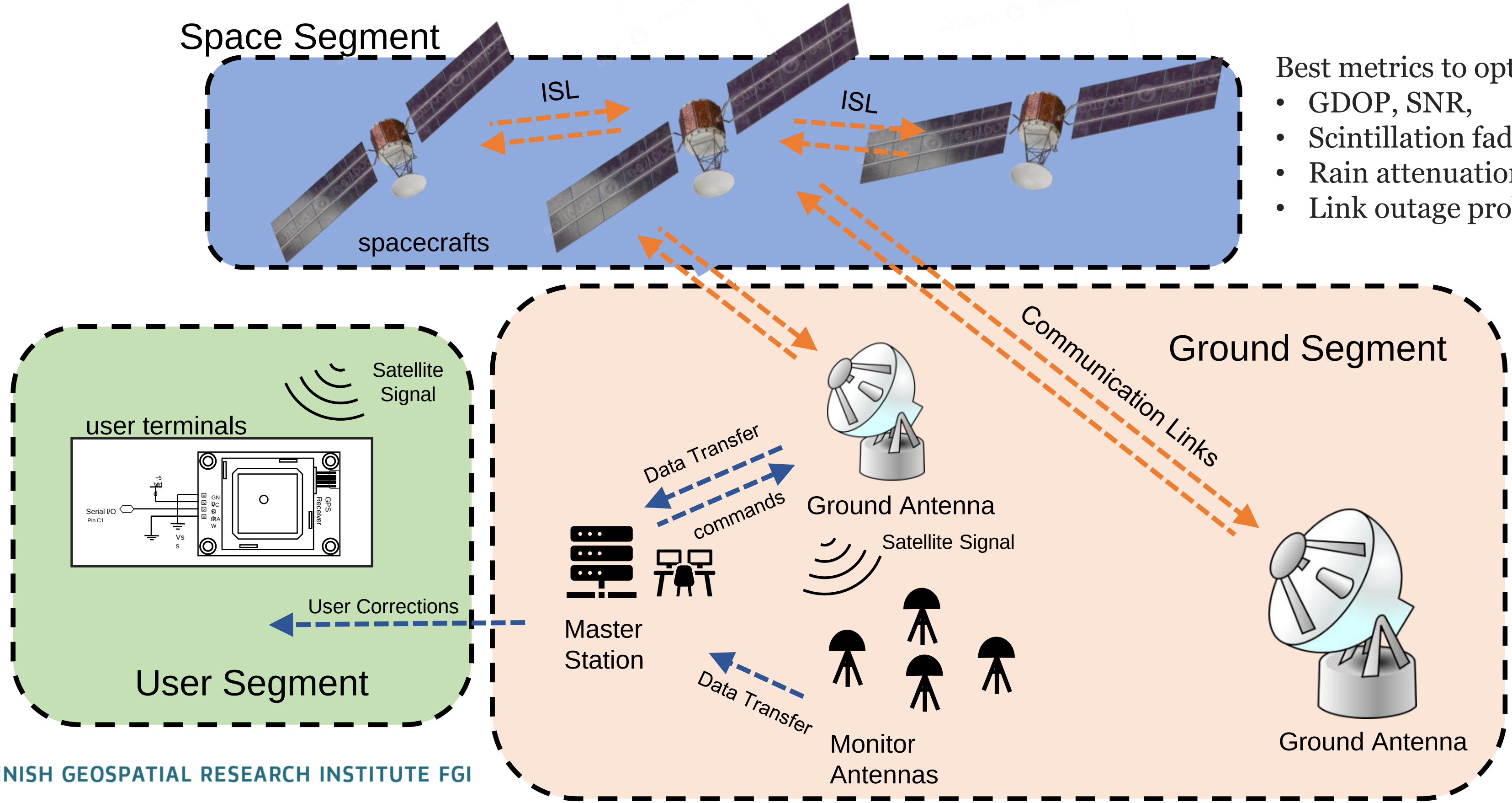


Reference values: IGS final products of the troposphere.

LEO-S9 - LEO/PNT simulation tool with 9 modules



Ground Segment: Ground Infrastructure



Best metrics to optimize are:

- GDOP, SNR,
- Scintillation fade depth,
- Rain attenuation,
- Link outage probability.

Ground Segment: Precise Orbit Determination

Processing STRATEGY

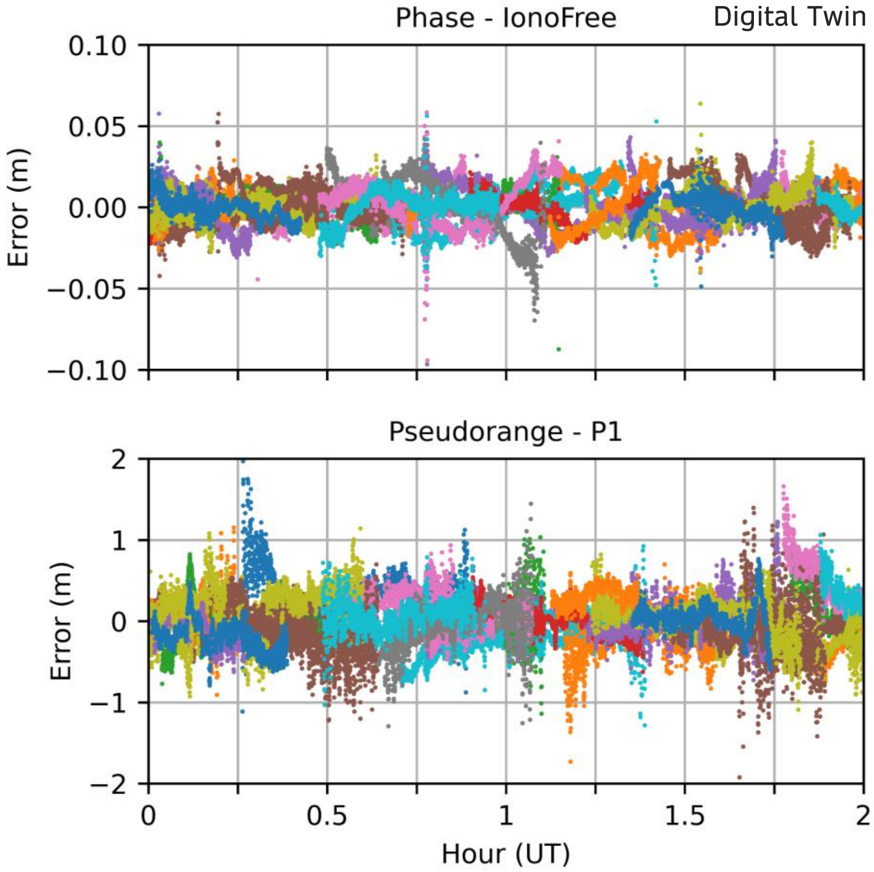
- Date: Jan.6.2020
- Satellite: SWARM-A
- Estimator: Least-squares
- Signals: GPS Dual-frequency (DF)
- Observations: Undifferenced (UD)
- Filter: Kinematic PPP
- El. Mask: Cutoff angle of 10°
- Ionosphere: global tomography in P1
- Files: IGS SP3, ANTEX, and 5s clocks
- Ambiguity: not fixed

Average POD accuracy in literature: **1-10 cm**

POD Accuracy of our model IF: **1-5 cm**

POD Accuracy of our model P1: **0.5 - 1 m**

Ionosphere: Prol et al. (2021) Global-scale ionospheric tomography. Space Weather. doi: 10.1029/2021SW002889.

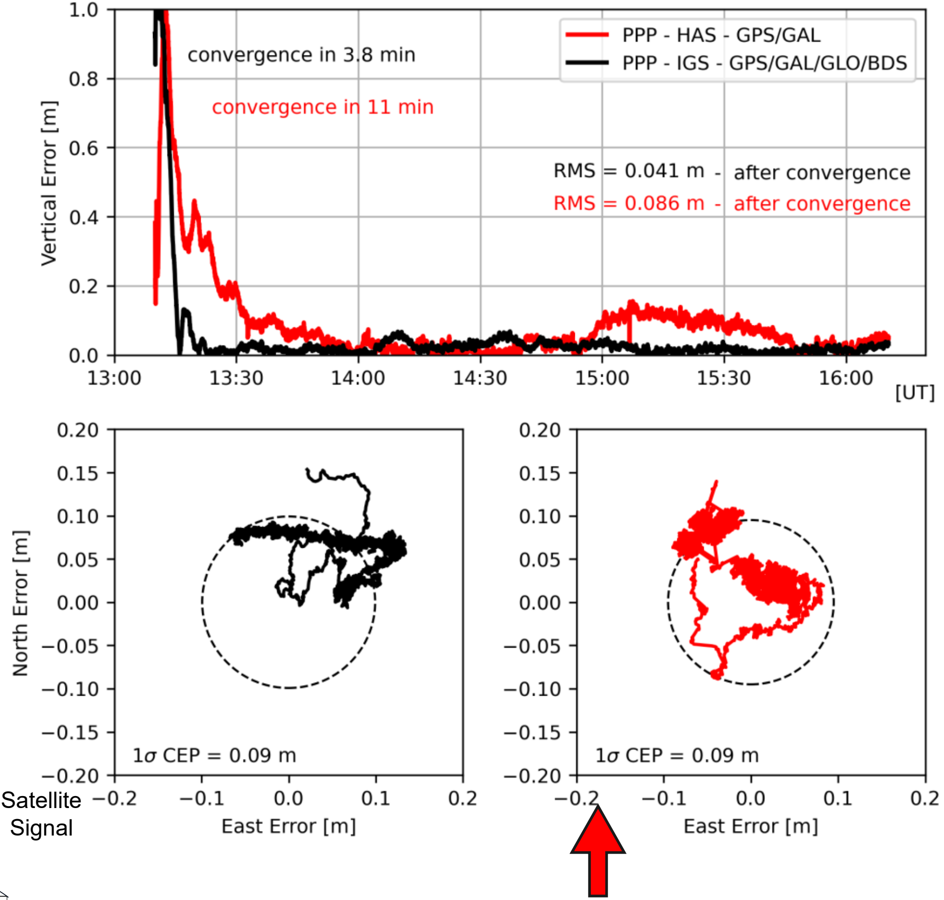


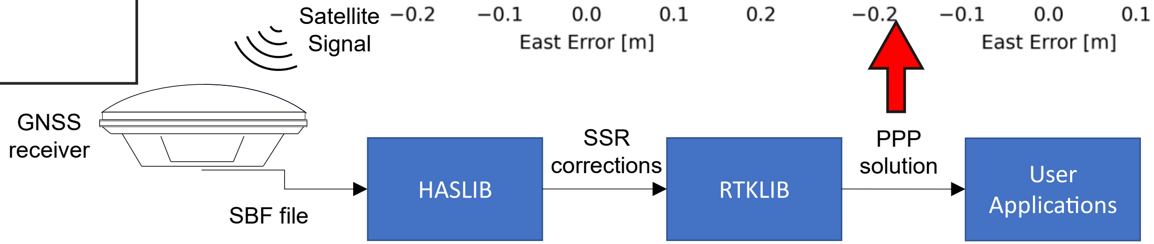
POD = precise orbit determination

Galileo HAS

Processing STRATEGY

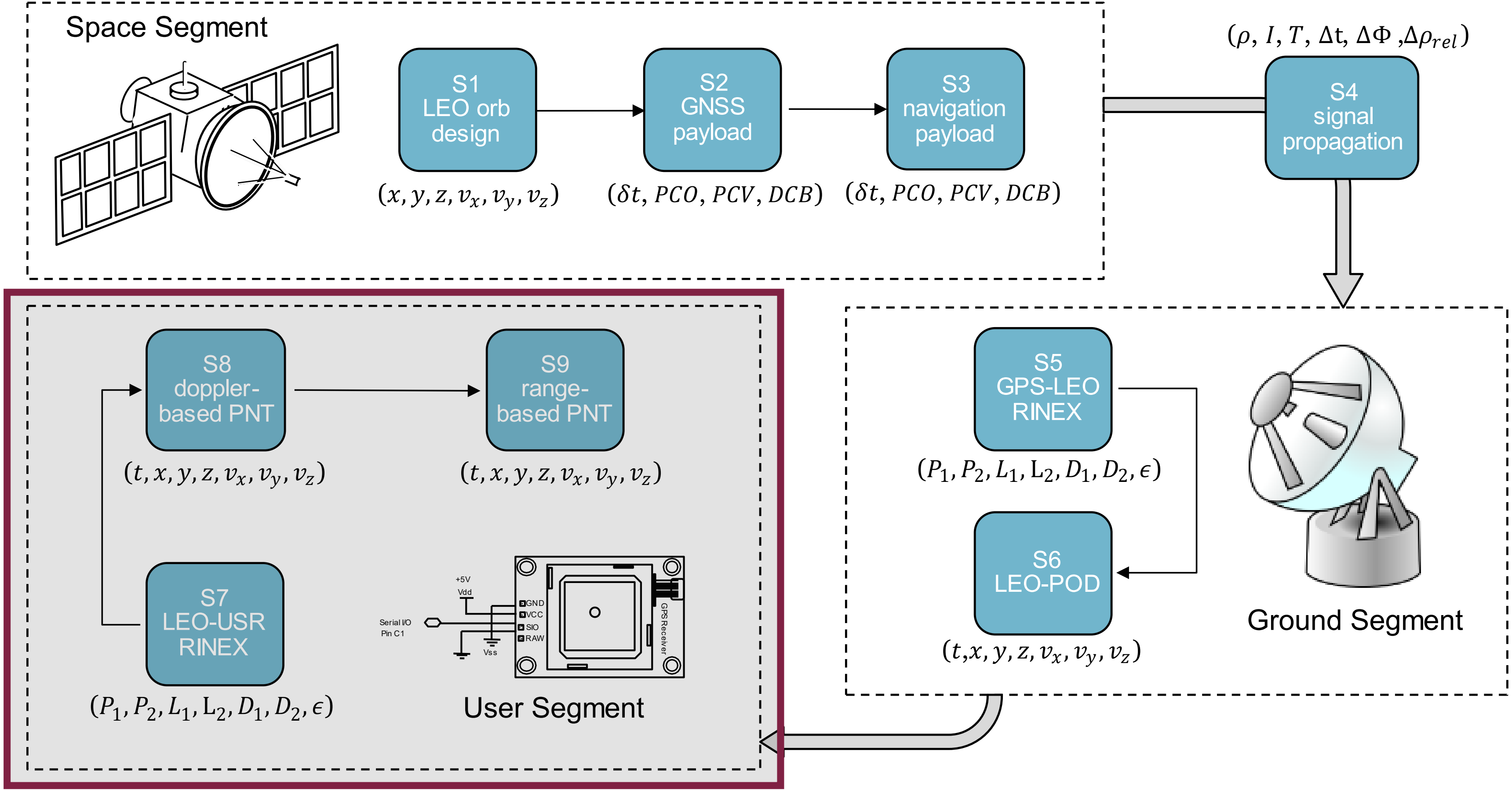
- FGI has developed **HASLIB**.
- It allows the conversion of HAS corrections to RTCM.
- We have integrated the HASLIB output to RTKLIB.
- Accuracy is orders of magnitude better than other real-time solutions using only GNSS communications.





Prol et al. (2024) Upcoming.

LEO-S9 - LEO/PNT simulation tool with 9 modules



User Segment: Receiver Architecture

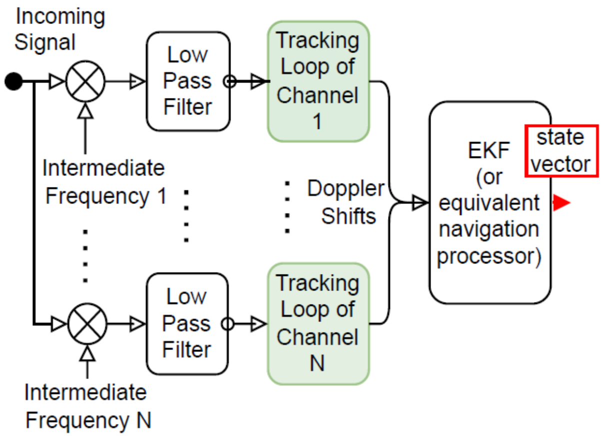
Dedicated System

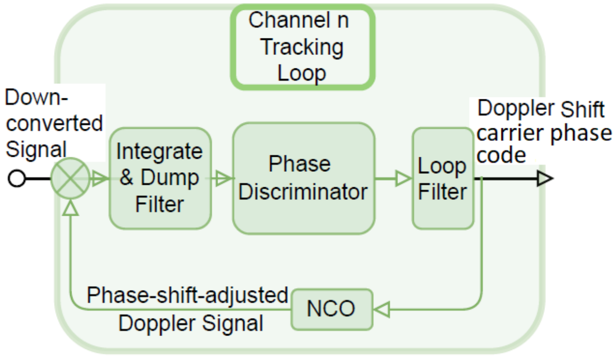
Assuming GNSS-like signals in the L band, the receiver design show in the right panel gives an idea of the main components.

Main Points:

1) Navigation message still need to be defined.

2) High number of LEO satellites will demand faster algorithms for acquisition.





Pinell et al. (2023) Receiver architectures for positioning with low earth orbit satellite signals: a survey. *EURASIP JASP*.

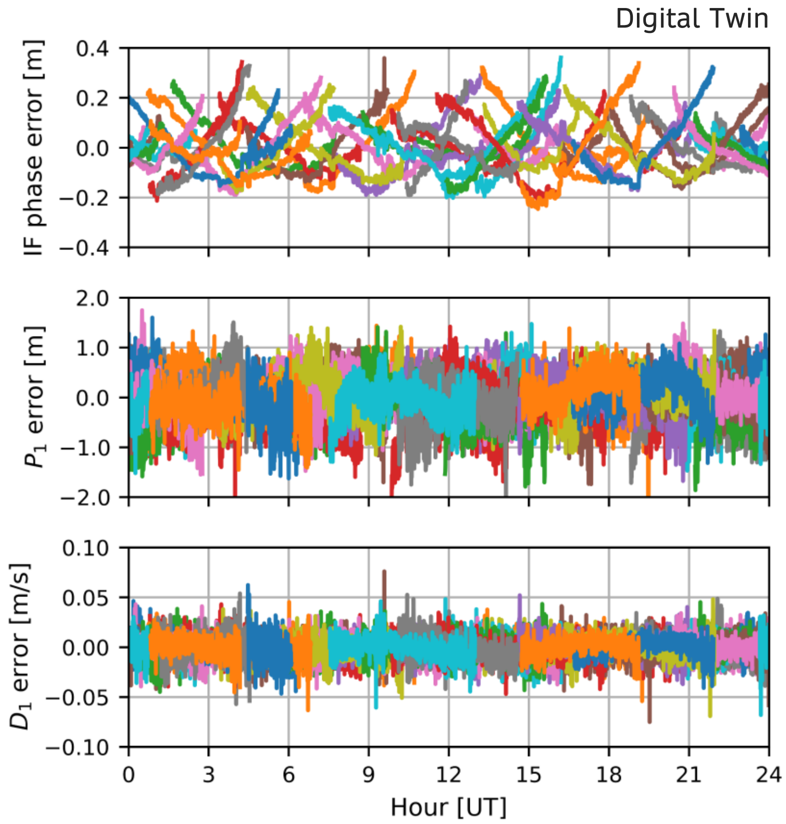
User Segment: PPP

Processing STRATEGY

- Date: Jan.6.2020
- Station: BRST, France
- Estimator: Least-squares
- Signals: GPS Dual-frequency (DF)
- Observations: Undifferenced (UD)
- Filter: Kinematic PPP
- El. Mask: Cutoff angle of 10°
- Ionosphere: global tomography in P1
- Troposphere: RTCA MOPS and NMF
- Files: IGS SP3, ANTEX, and 5s clocks
- Ambiguity: not fixed

Accuracy of our model: **5 - 40 cm**

Our PPP accuracy: **< 10 cm**



Ionosphere: Prol et al. (2021) Global-scale ionospheric tomography. Space Weather. doi: 10.1029/2021SW002889.

Space Weather Application

LEO-PNT can help **3D ionospheric imaging**.

TEC observations allow **tomography**.

Main question: Can LEO overcome current problems in GNSS geometry for ionospheric imaging?

Answer: Prol et al. (2023) IEEE JSTARS. The potential of LEO-PNT mega-constellations for ionospheric 3D imaging: A simulation study.

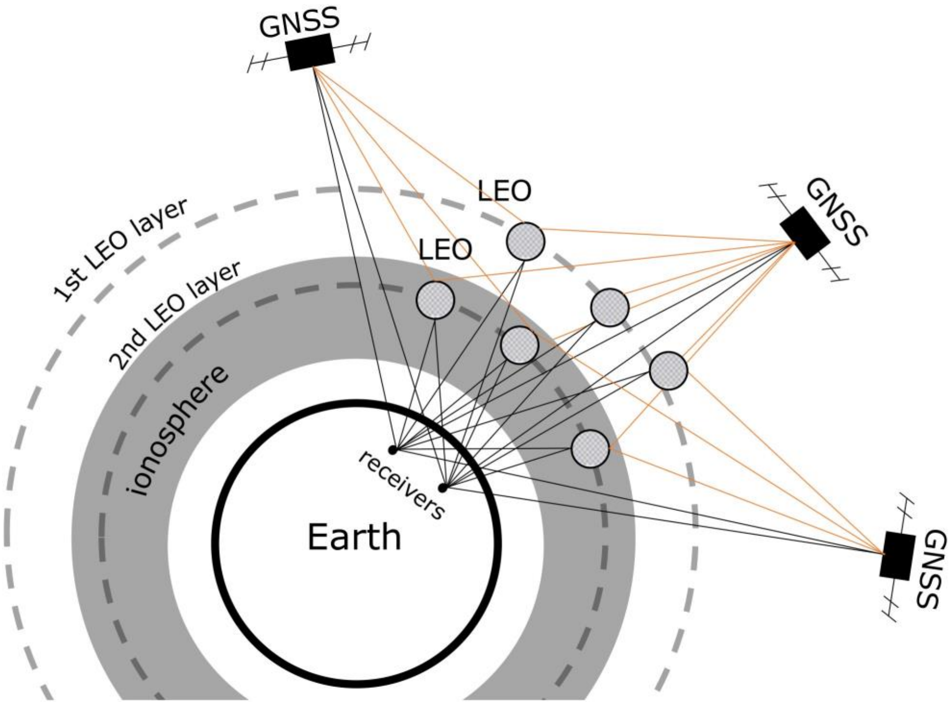
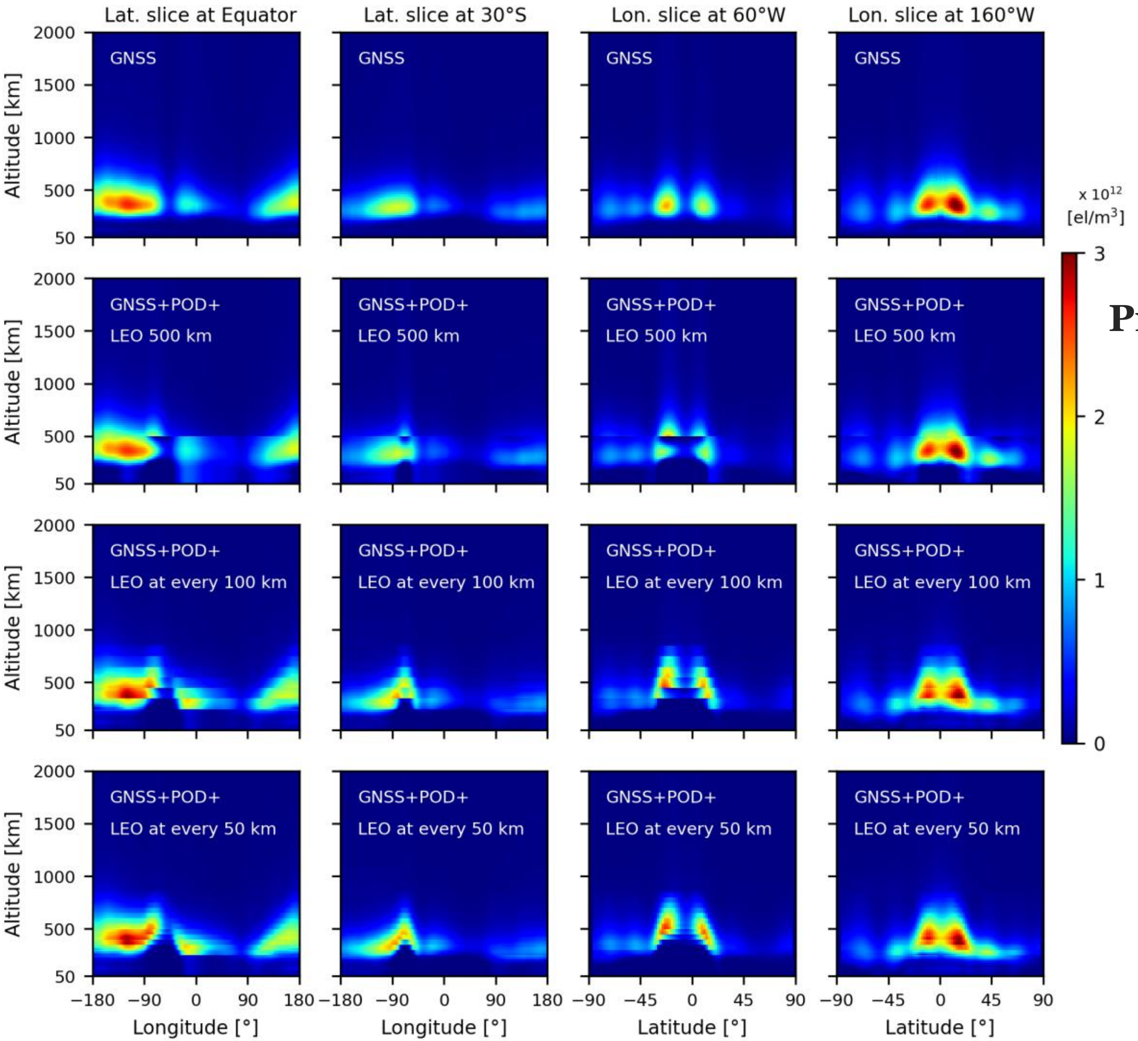


Fig. Ray path geometries provided by GNSS satellites and dedicated LEO satellites to PNT.



Processing STRATEGY

- GNSS constellation: 113 satellites
- LEO constellation: 400 per layer
- GNSS Files: IGS SP3
- El. Mask: Cutoff angle of 10°
- Background: NEDM model (DLR)
- Observations: Slant TEC
- Estimator: Tomography

Tomography: Prol et al. (2021) Space Weather. Global-Scale Ionospheric Tomography During the March 17, 2015 Geomagnetic Storm.

Future Work

- Challenges for the future:
  - Further improvement is required to bind all the LEO-PNT segments in the simulations
  - More points other than geometry needs to be simulated, like noise, orbit errors, and clock errors.
  - I/Q simulated data would benefit the understanding of the receiver designs.
  - Satellite design is still unsure: clocks, frequency, antenna design are to be investigated.

Teknologiateollisuuden 100-vuotissäätiö

INCUBATE

Advancing together

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