JAXA's Current Activities and Future Perspectives on LEO PNT Systems

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第10回 月測位研究会

2025/6/3

Limitations of GNSS/RNSS

GNSS present vulnerabilities and limitations preventing standalone provision of resilient high-performant PNT

Robustness

Interference

Jamming

Spoofing

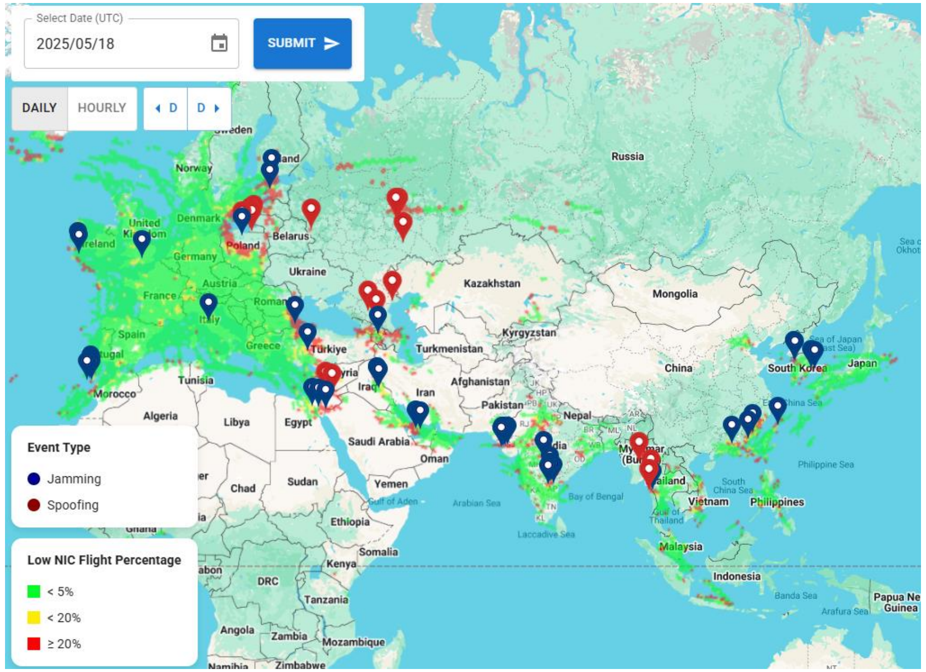
Signal Impairments

Blockages

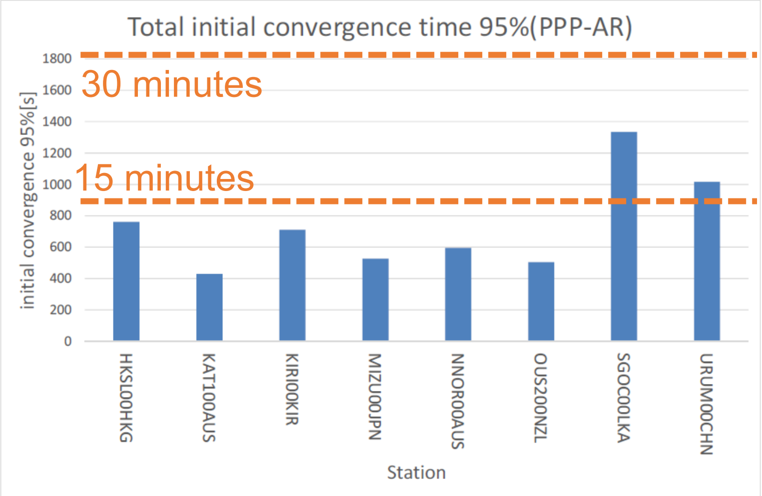
Multipath

Performance

PPP convergence



Source: https://rfi.stanford.edu/ accessed on 2025/05/20

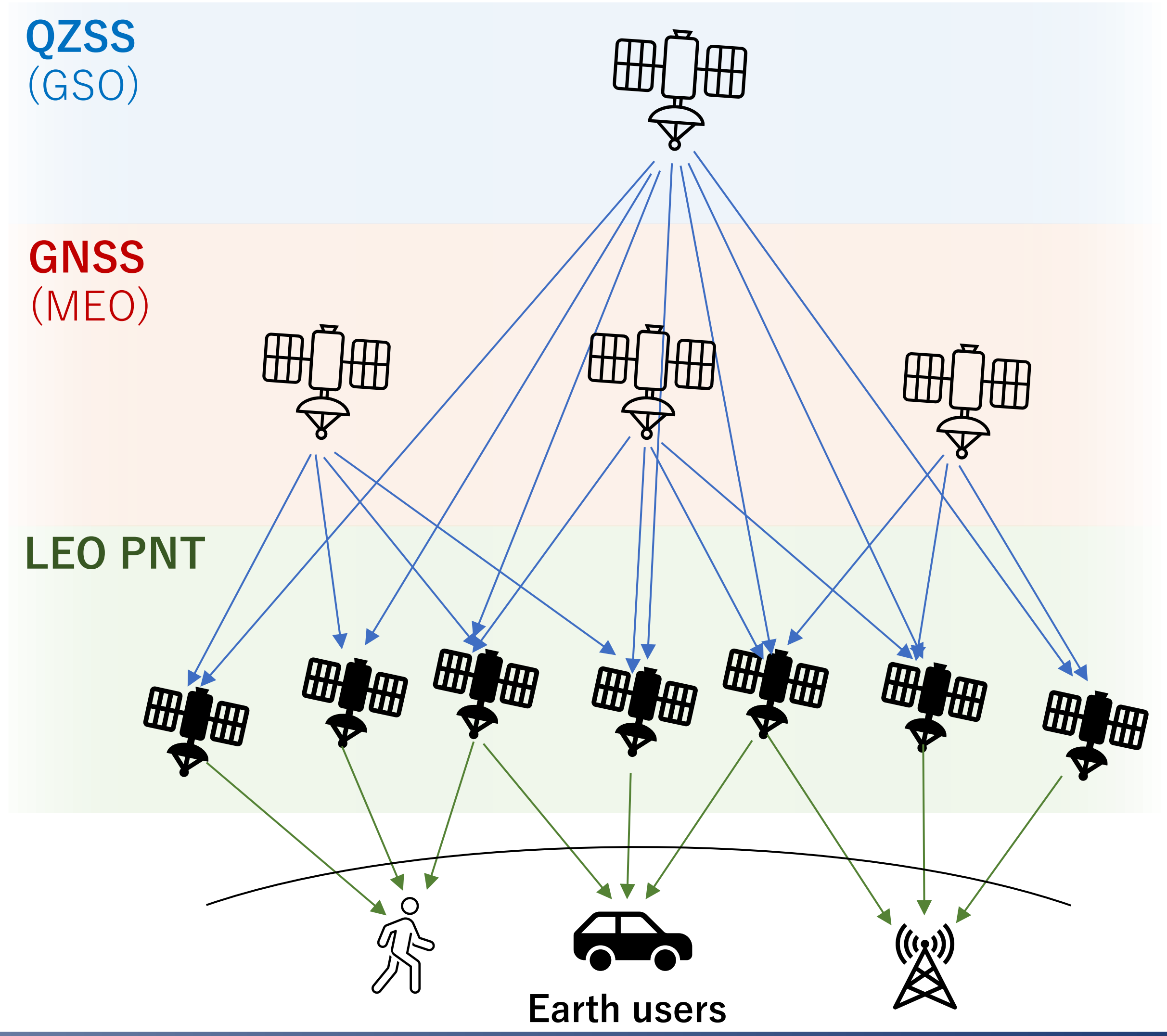


Convergence to 30/50cm (H/V)

Source: Quasi-Zenith Satellite System Service Performance Report MADOCA-PPP (1st half FY2024)

Opportunities of LEO PNT

Multi-layered structure of PNT systems:



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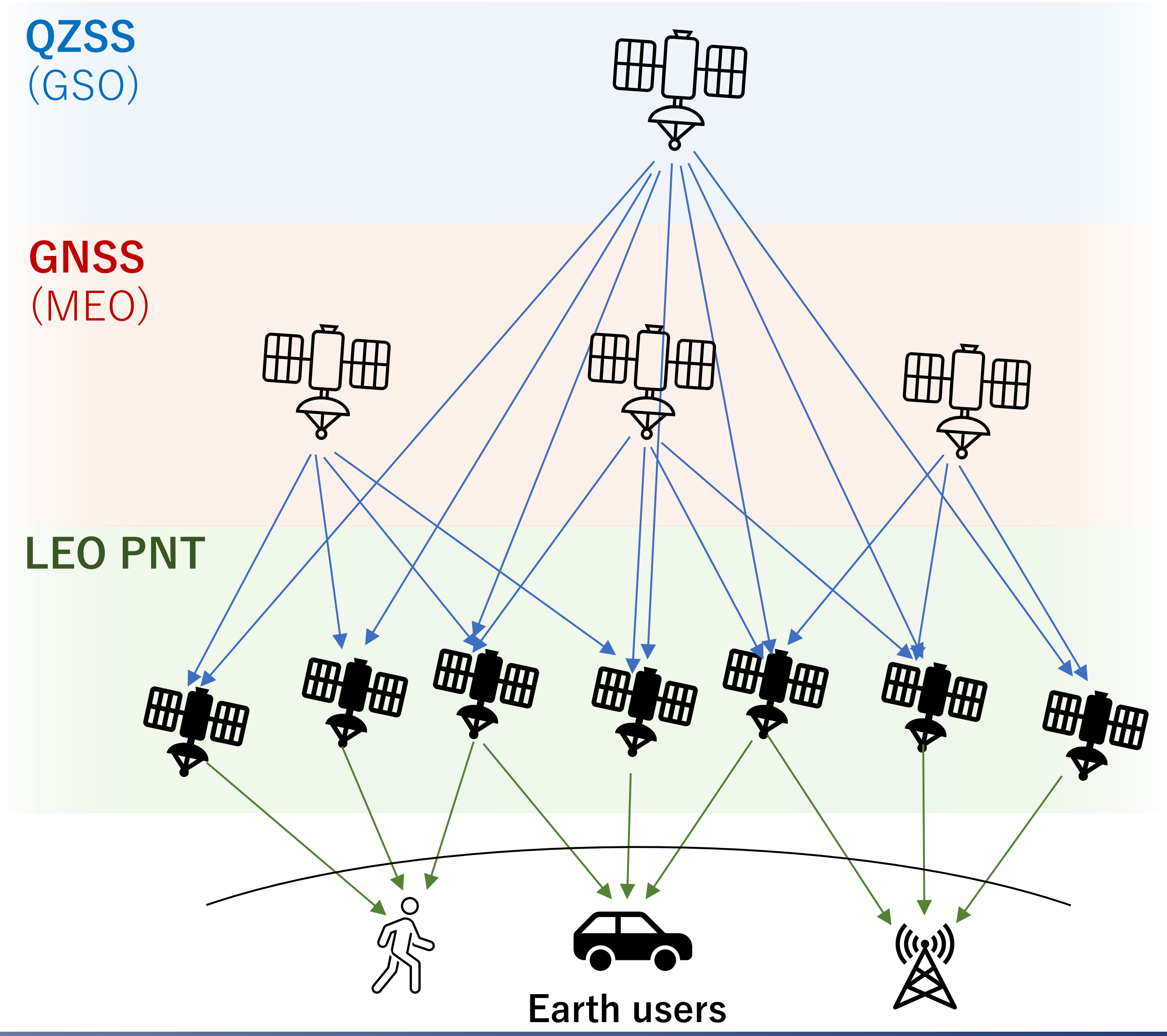

Lower altitude:
→ Lower free space loss
→ Can use of higher frequencies
    → Frequency diversity
    → Less interference
    → More available bandwidth

Opportunities of LEO PNT

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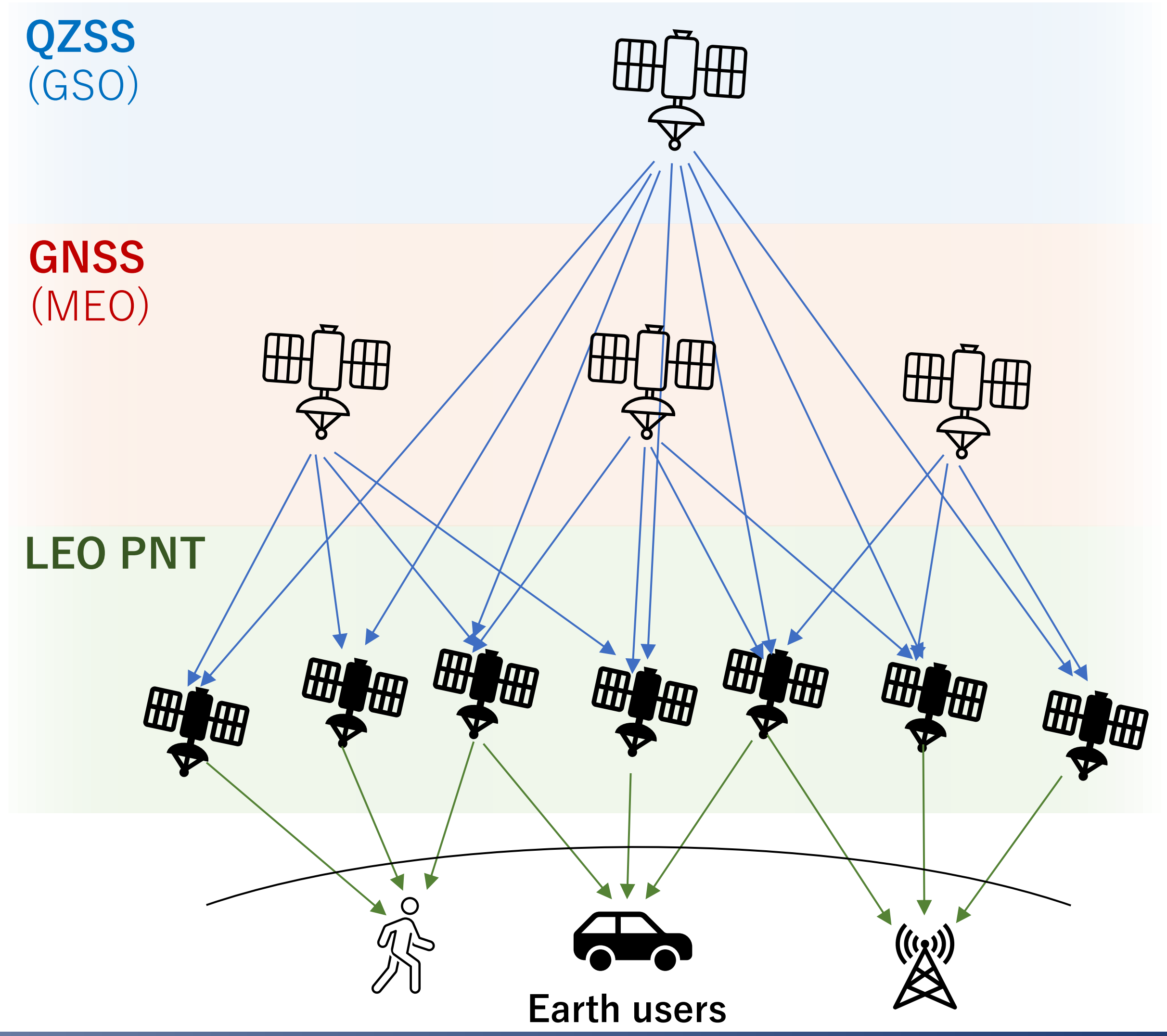

Faster geometry change:
- → Faster PPP convergence
- → Shorter outages from blockages
- → Multipath whitening

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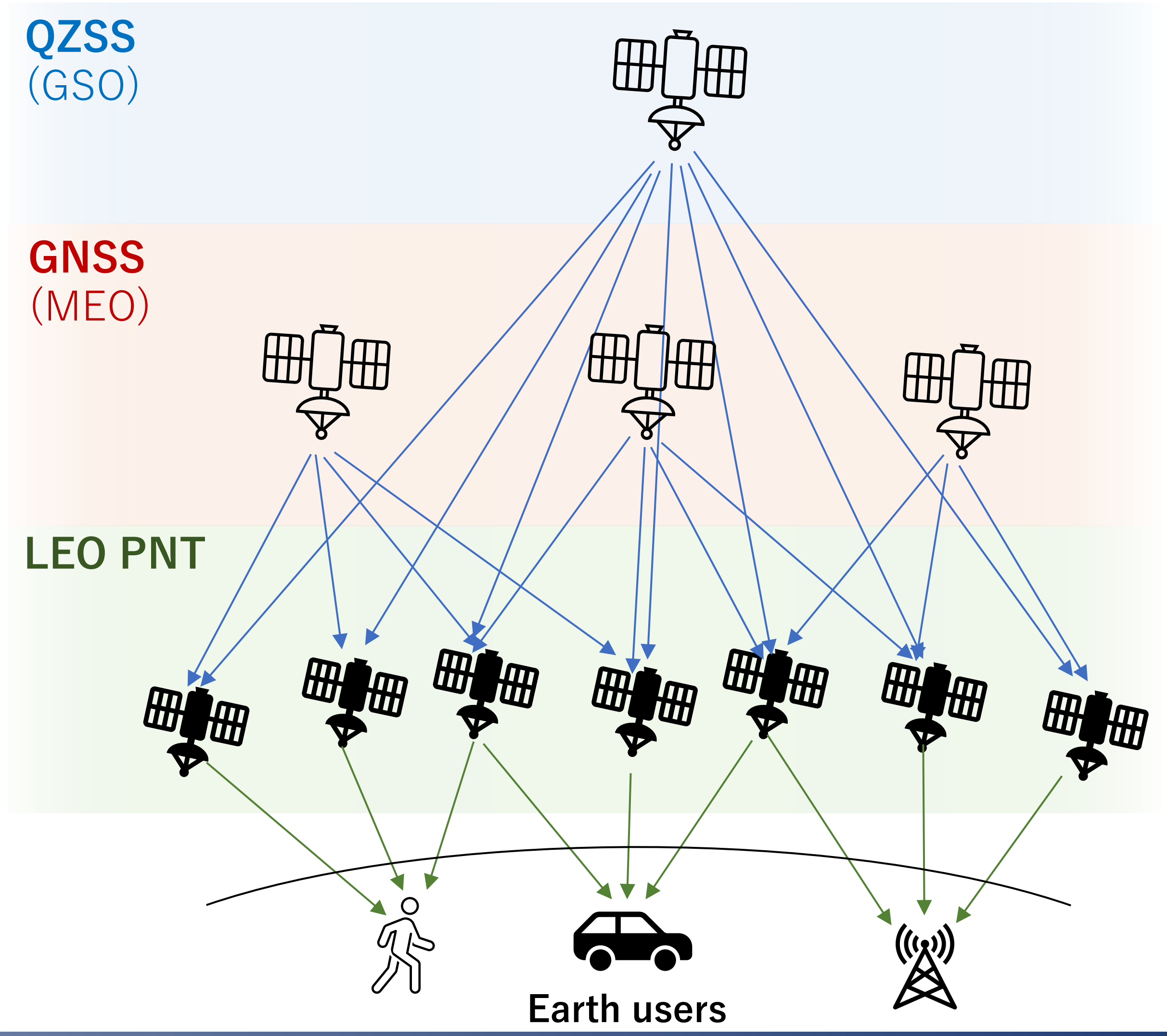
Opportunities of LEO PNT

Multi-layered structure of PNT systems:

Low SWaP satellites:
→ Shorter innovation cycles
→ Lower cost



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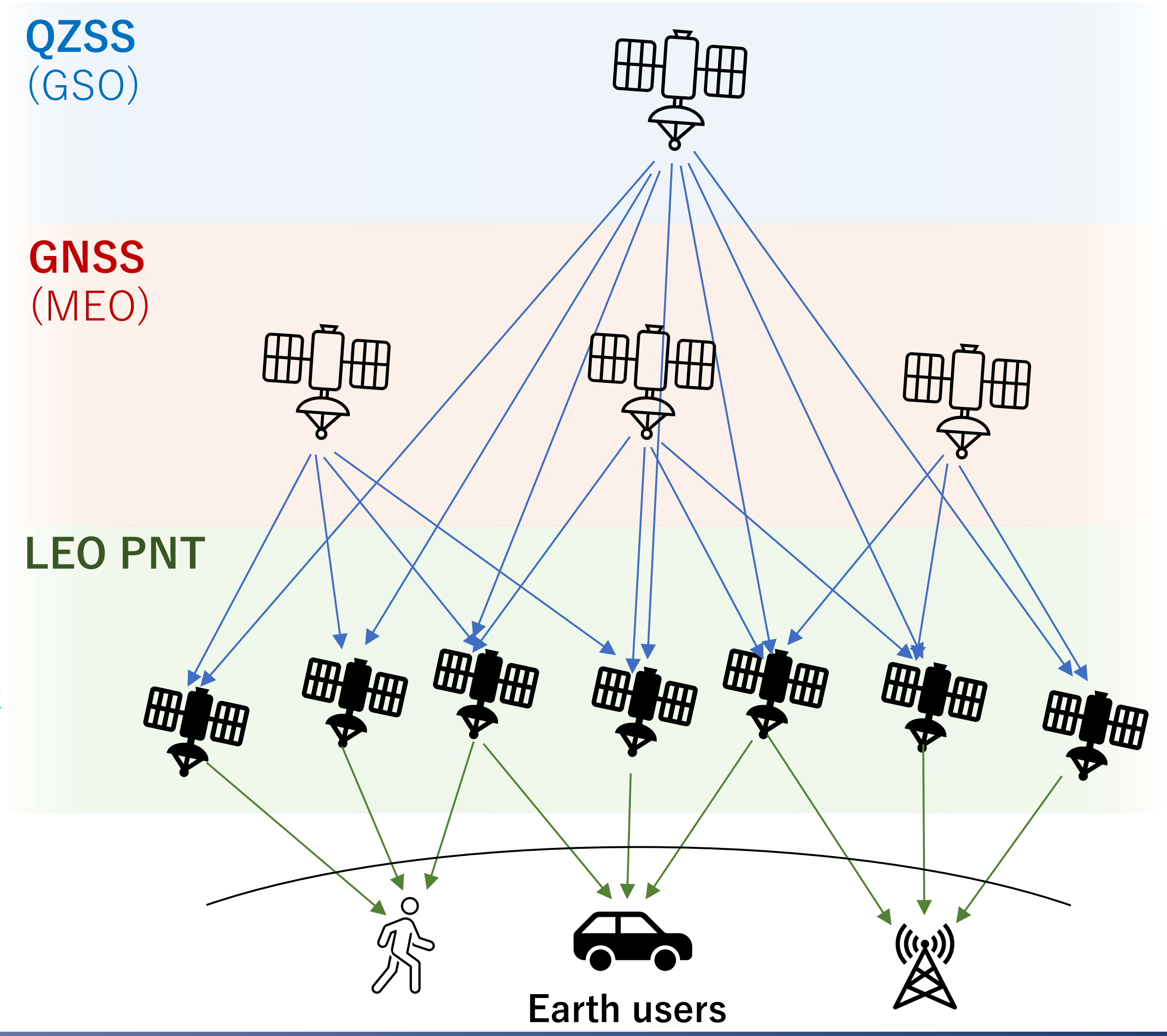
Onboard GNSS receiver on LEO:
→ Real-time accurate position / clock
  → Leaner ground segment
→ Monitoring of GNSS signals



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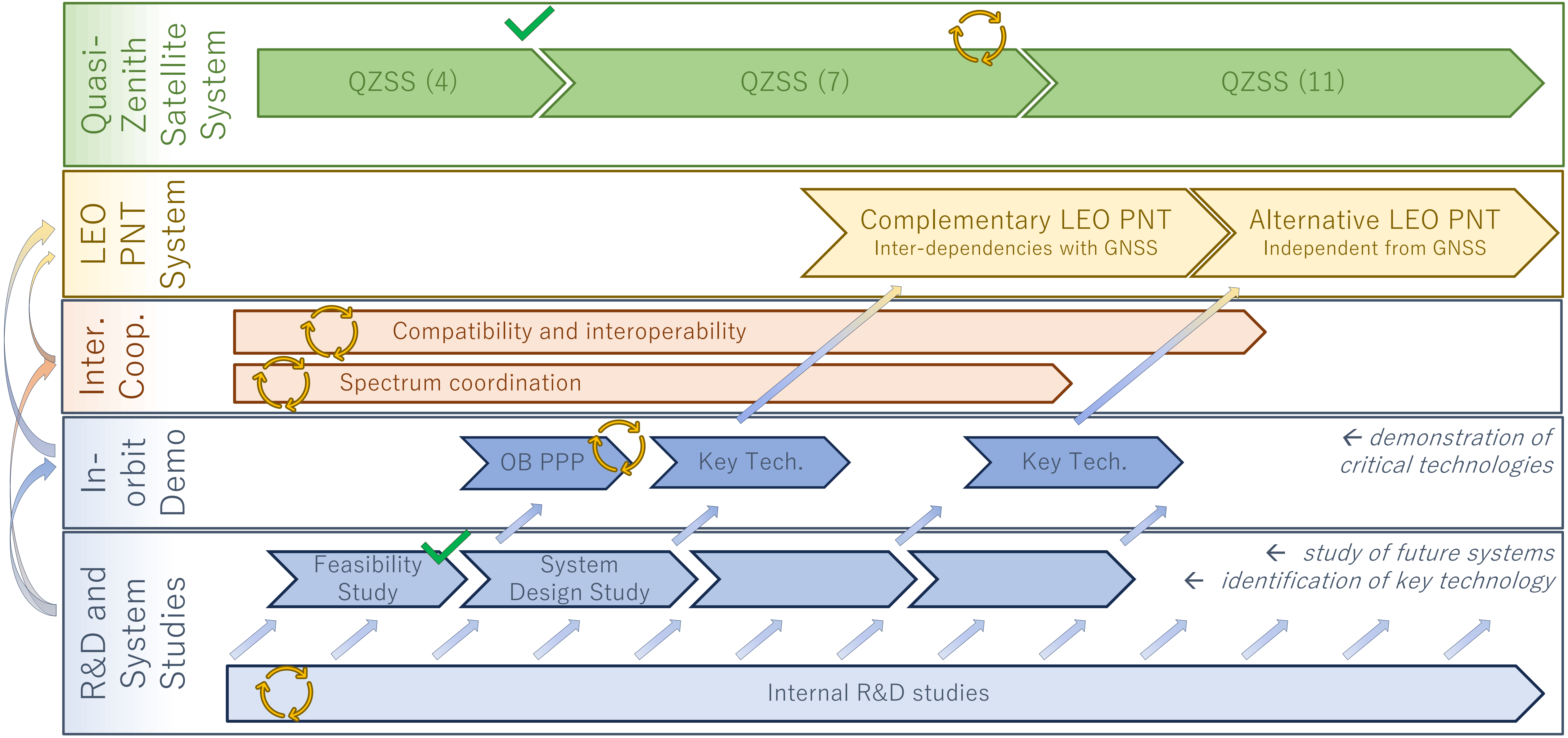
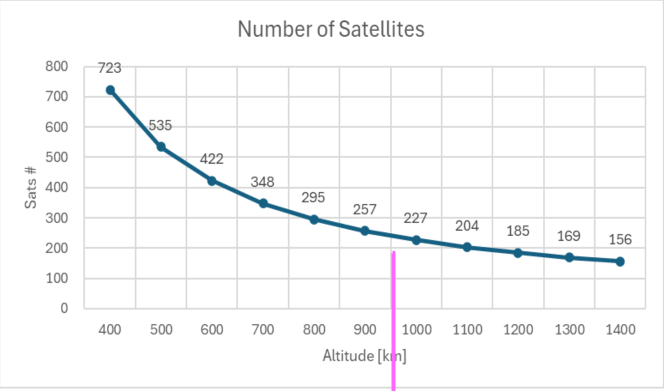
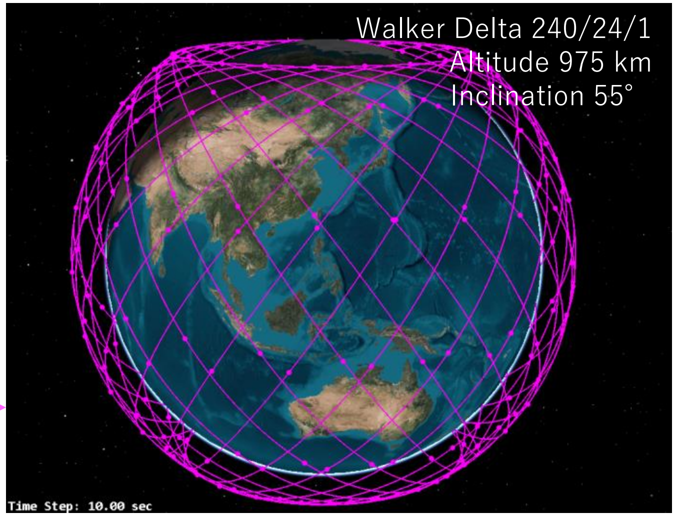
JAXA LEO PNT Roadmap



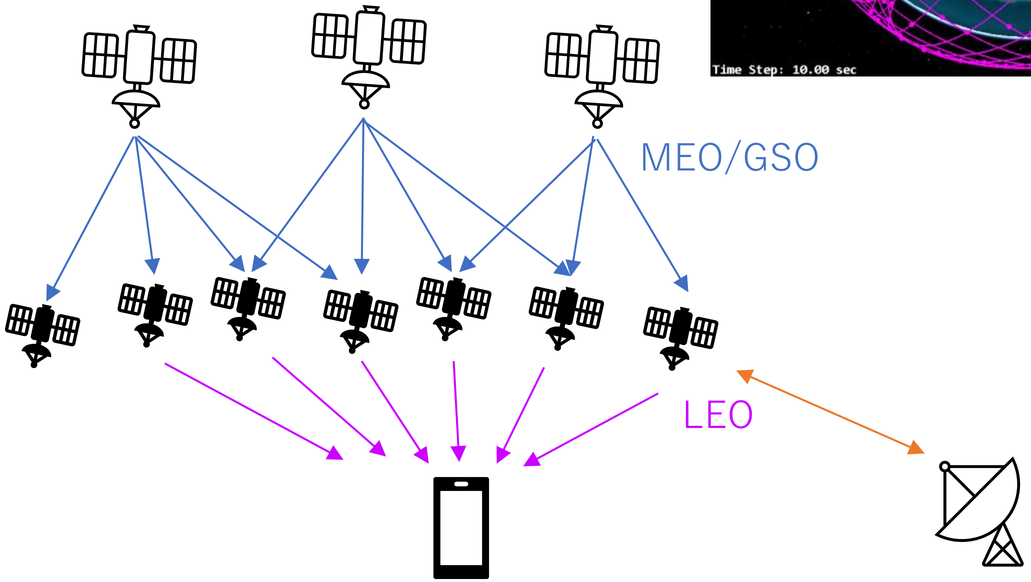
System Architecture

- **Space Segment:**
  - Minimum 4 satellites in view
  - PDOP lower than 2
  - Low SWaP C-band Navigation Payload
  - On-board GNSS Rx
  - Inter-satellite Links





- **Ground Segment:**
  - Sparse control station network
  - Dense monitoring station network



Complementary LEO PNT
Inter-dependencies with GNSS

Alternative LEO PNT
Independent from GNSS

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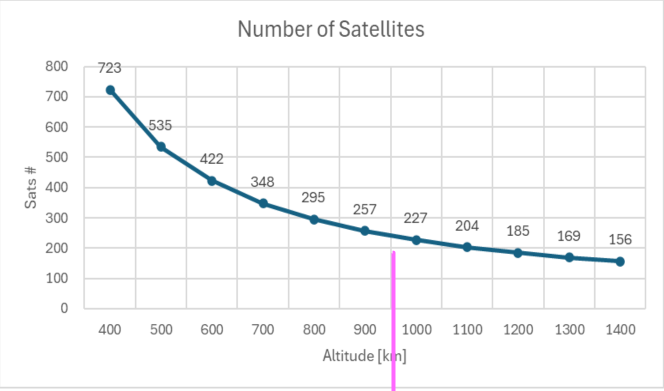

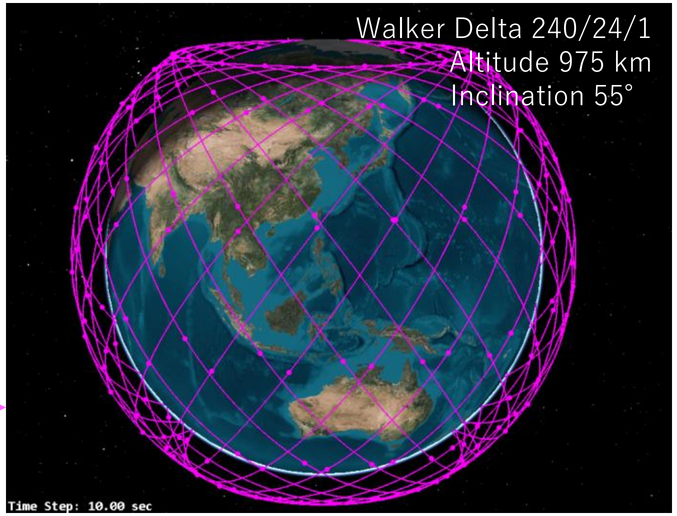

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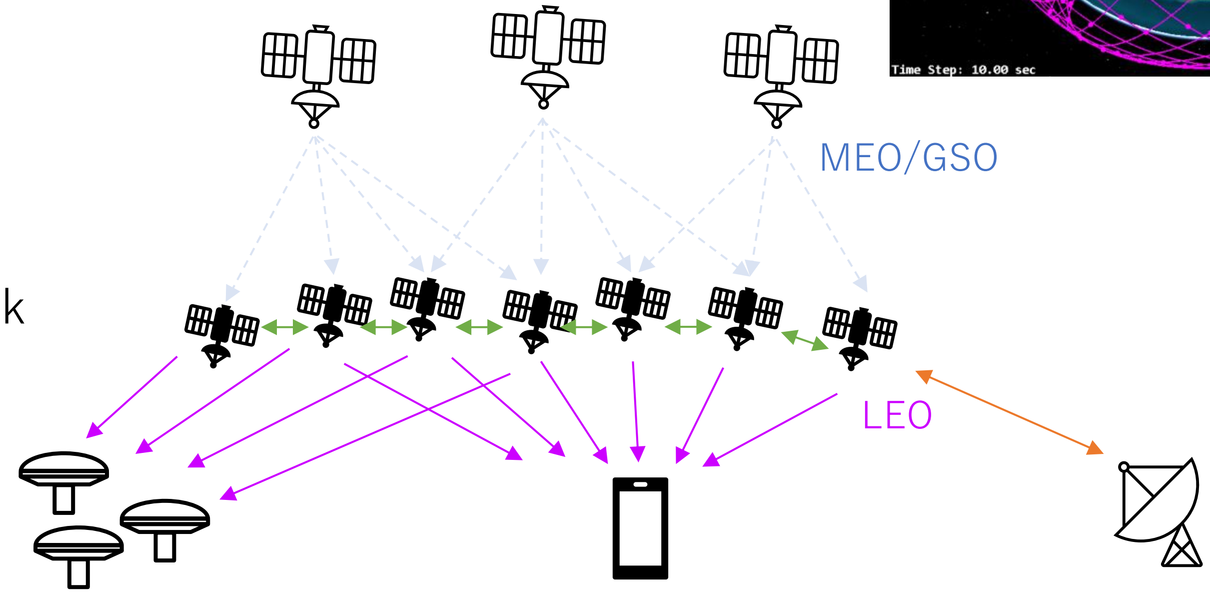

Complementary LEO PNT
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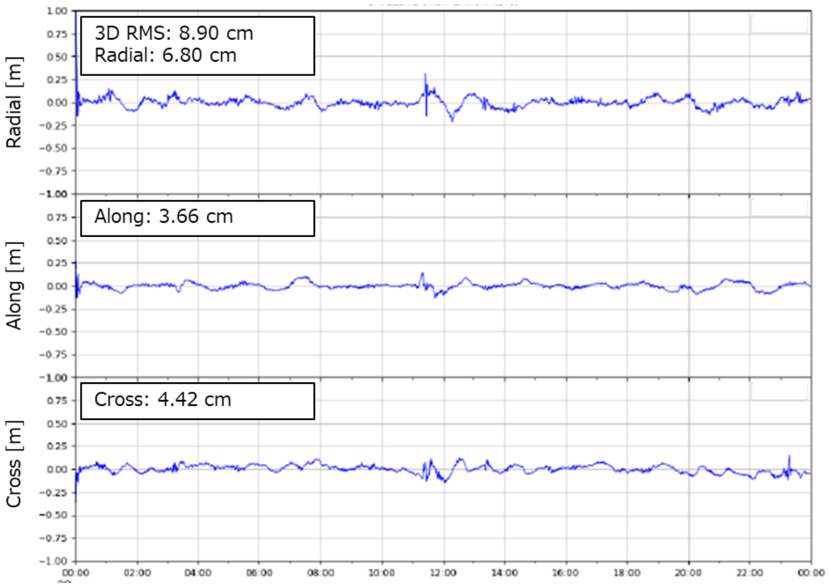
Alternative LEO PNT
Independent from GNSS

GNSS-based ODTS for LEO PNT

Achievable positioning accuracy for LEO satellites using GNSS: ~10cm (3D RMS)

Demonstration by analysis

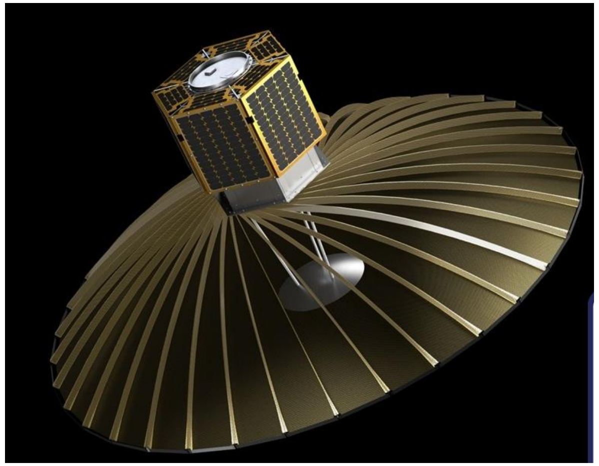
with real in-orbit data post-processed on ground

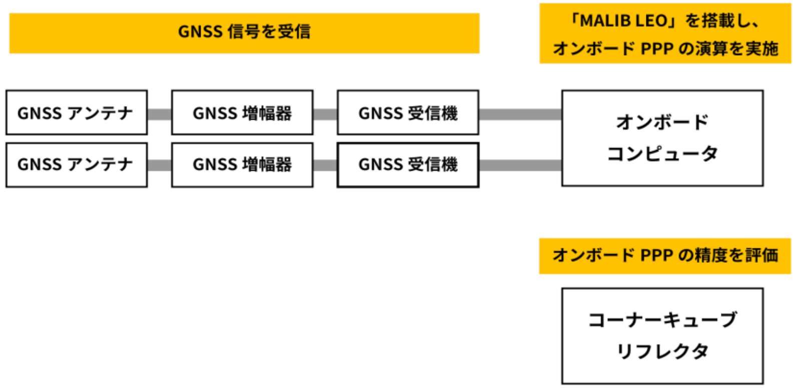


SW used: MALIB LEO
Data used: Sentinel-6A
Configuration: Galileo+GPS, dual-frequency, L6E data

In-orbit demonstration (ongoing)

with onboard PPP equipment flying on QPS-SAR-10 satellite





Credits: iQPS

打ち上げ: 2025/05/17
機器:

- GNSS :多周波（L1、L2、L5信号), QZSSのL6E信号に対応
- オンボードコンピュータ:ソフトウェア「MALIB LEO」を搭載
- コーナナキューブリフレクタ「Mt.FUJI」: 精度評価のために

詳細はこちら： https://www.satnavi.jaxa.jp/ja/project/on-board-ppp/

Carrier Based Positioning

Faster PPP convergence is enabled by the fast geometry changes of the LEO constellation

- With GNSS:
  - typical PPP convergence is 15-30 mins
- With GNSS + LEO constellation:
  - less than 5 mins can be achieved
- With GNSS + large LEO constellation:
  - 1-3 mins can be achieved

Bigger constellation

	120-satellite constellation, SISE=20cm	240-satellite constellation, SISE=20cm	480-satellite constellation, SISE=20cm
< 1 min	0%	1%	13%
< 1 mins 30 secs	3%	22%	63%
< 2 mins	23%	67%	93%
< 2 mins 30 secs	57%	96%	100%
< 3 mins	78%	99%	100%
< 3 mins 30 secs	90%	100%	100%
< 4 mins	96%	100%	100%
< 4 mins 30 secs	99%	100%	100%
< 5 mins	100%	100%	100%

Lower SISE

	120-satellite constellation, SISE=10cm	240-satellite constellation, SISE=10cm	480-satellite constellation, SISE=10cm
< 1 min	8%	33%	77%
< 1 mins 30 secs	58%	90%	99%
< 2 mins	89%	99%	100%
< 2 mins 30 secs	98%	100%	100%
< 3 mins	99%	100%	100%
< 3 mins 30 secs	100%	100%	100%
< 4 mins	100%	100%	100%
< 4 mins 30 secs	100%	100%	100%
< 5 mins	100%	100%	100%

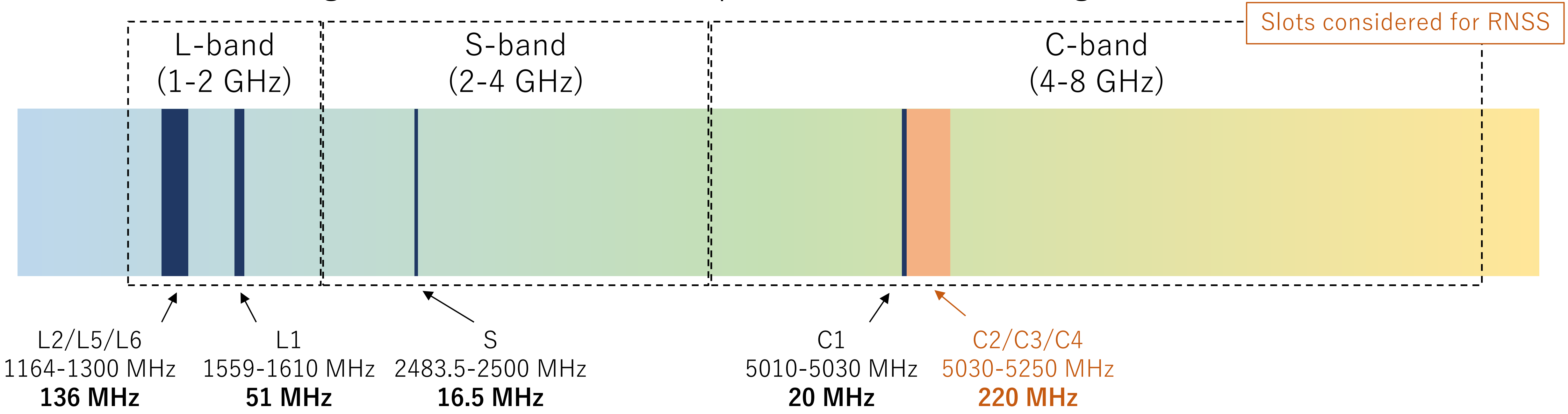
Convergence to horizontal accuracy of less than 10 cm is considered

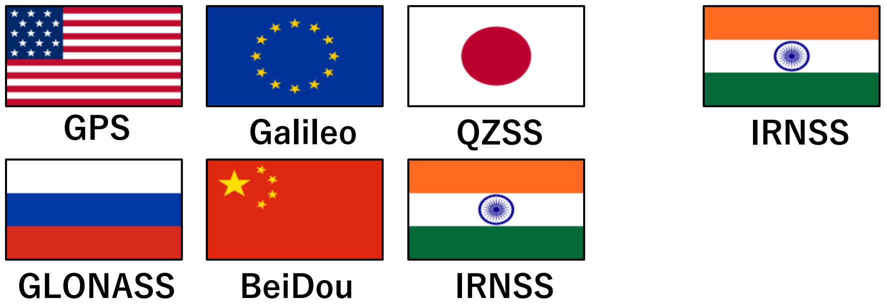
Source: Impact of Signal-In-Space Error on LEO PNT Augmented PPP Convergence, Murata, 2024

Radio Navigation Spectrum

Current GNSS signals are in L-band, except for IRNSS S-band signal

Slots allocated to RNSS/RDSS





Opportunity for C-band signals

- Wide bandwidth available
- Less spectrum congestion
- Low ionospheric delay
- Compact array antennas

L-band: congested and interfered

Frequency Band Selection

Each of the candidate frequency bands presents pros and cons:

Frequency Band	**L-band**	**S-band**	**C-band**
Available bandwidth	**136 MHz (1164-1300 MHz)** **51 MHz (1559-1610 MHz)**	**16.5 MHz (2483.5-2500 MHz)**	**20 MHz (5010-5030 MHz)** **[240 MHz (5010-5250 MHz)]**
Spectrum outlook	**Crowded**	**Promising**	**Promising**
Free Space Loss* (@975km)	**153 – 168 dB**	**160 – 172 dB**	**166 – 178 dB**
Other propagation losses** (troposphere, rainfall, clouds)	**<1 dB**	**1-2dB**	**5-6 dB**
Ionospheric delay [residual after correction***]	**up to ~30m** **[3-12m]**	**up to ~14m** **[1.3-5m]**	**up to ~3m** **[0.3-1.1m]**
Technology Readiness (transmitter and receiver)	**Very mature**	**Partially available**	**Low maturity**
Antenna array size (16-element, $\lambda/2$ spacing, 10dBi@90°)	**(28-38) x (28-38) cm**	**18 x 18 cm**	**9 x 9 cm**

*FSL values range accounts for user elevation range 0-90 degrees and center frequency allowed range in each frequency band.

**References: ITU-R P.676-12, P.618-13, P.838-3, P.837-7, P.840-8

A Role for C-band? https://www.insidegnss.com/auto/mayjune07_064-073.pdf

The case for LEO GNSS at C-band https://insidegnss.com/the-case-for-leo-gnss-at-c-band/

A Search for Spectrum: GNSS Signals in S-band Part 1 Part 2

***Assuming correction via a-priori model with 20 TECU model accuracy (equivalent to NeQuick G model)

Ranging Error Budget

Ranging error improvement thanks to low ionospheric delay in C-band

Frequency Band	L-band				C-band			
Centre frequency [MHz]	1575.42				5020.00			
Elevation [deg]	10	30	60	90	10	30	60	90
Orbit [m] Clock [m] HW Bias [m]	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Ionosphere [m]	34.42	22.29	13.35	9.74	3.39	2.20	1.31	0.96
Ionosphere (after correction) [m]	*11.47*	*7.43*	*4.45*	*3.25*	*1.13*	*0.73*	*0.44*	*0.32*
Troposphere [m]	0.03	0.01	0.01	0.01	0.03	0.01	0.01	0.01
Channel (code) [m]	0.25	0.10	0.08	0.06	0.25	0.10	0.08	0.06
Total [m]	**34.43**	**22.29**	**13.35**	**9.74**	**3.41**	**2.21**	**1.33**	**0.98**
Total (after iono correction) [m]	***11.48***	***7.43***	***4.45***	***3.25***	***1.17***	***0.77***	***0.49***	***0.38***

Opportunity for accurate single-frequency code-based positioning

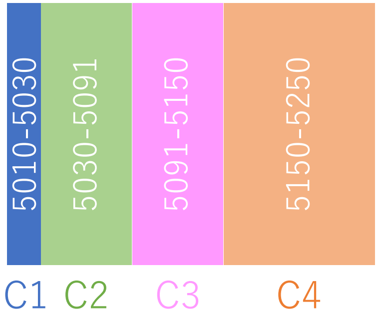
Underlying assumptions:
- BPSK(5) signal for both frequency bands
- Ionospheric model with 20 TECU accuracy*
- GNSS-based ODTS errors
- Multipath contribution, which is expected to be lower in C-band, is not reflected in this table

* Equivalent to NeQuick G model: https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_Ionospheric_Model.pdf

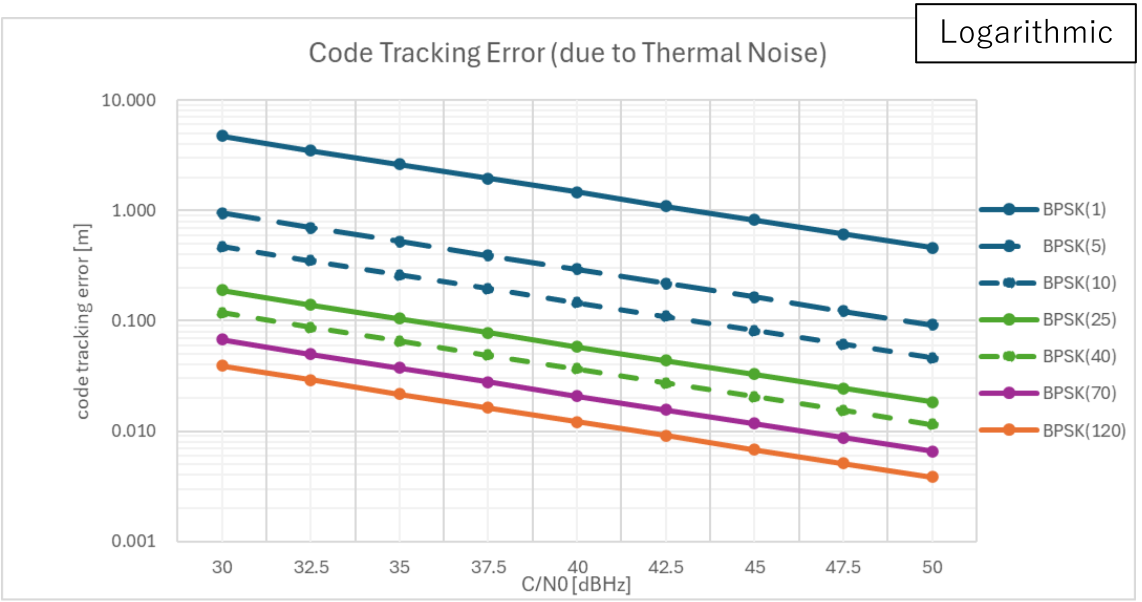
Code Tracking Error

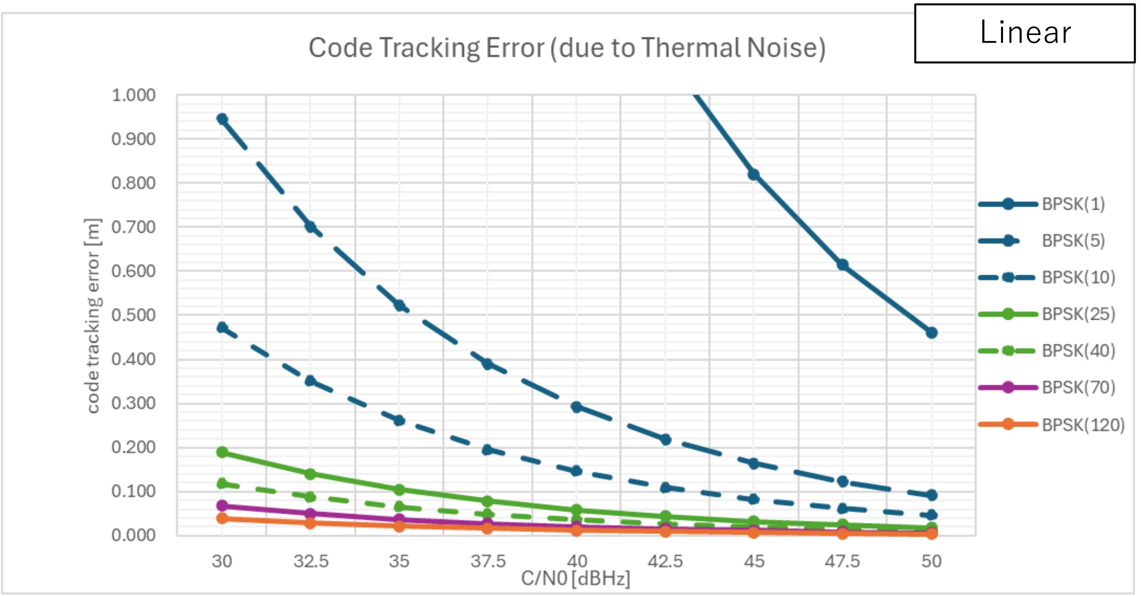
The tracking error due to thermal noise (DLL jitter) is lower for larger bandwidths:

- The potential new allocation in C-band enables reducing DLL jitter by 4-12 times
- Accurate single frequency code measurements are possible



Compatible with C1 | Compatible with C1-C2 | Compatible with C1-C3 | Compatible with C1-C4





A required bandwidth equal to twice the chip rate is considered.

Code Based Positioning

For many applications, achieving the ultimate precision is less relevant than:

- Robust PVT solution available in challenging environments (such as urban canyons)
- Fast convergence and recovery from environmental changes
- Short outages

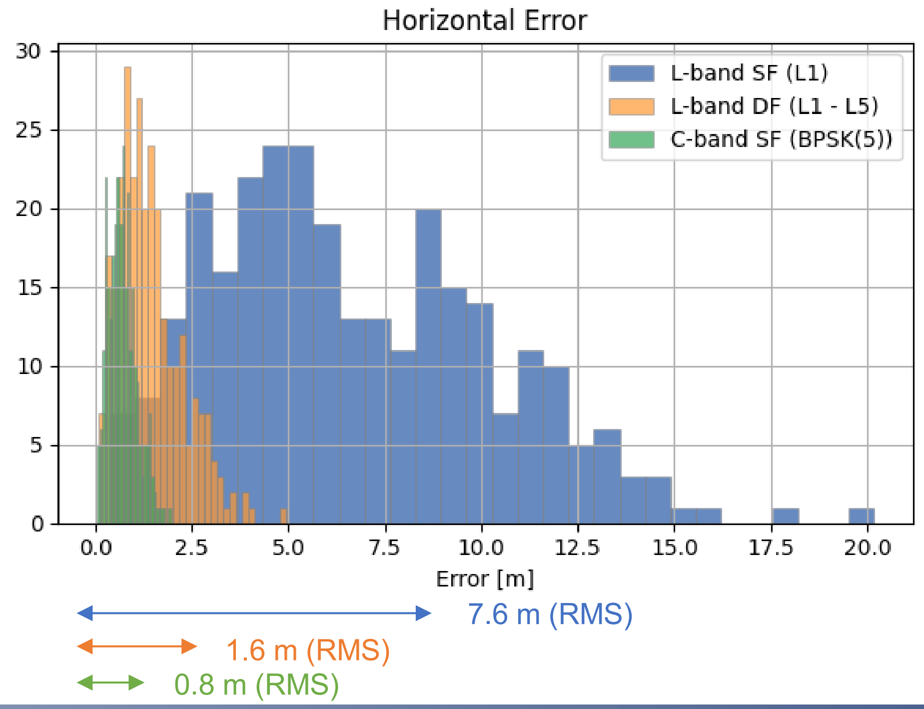
Single frequency reduces the receiver complexity / cost

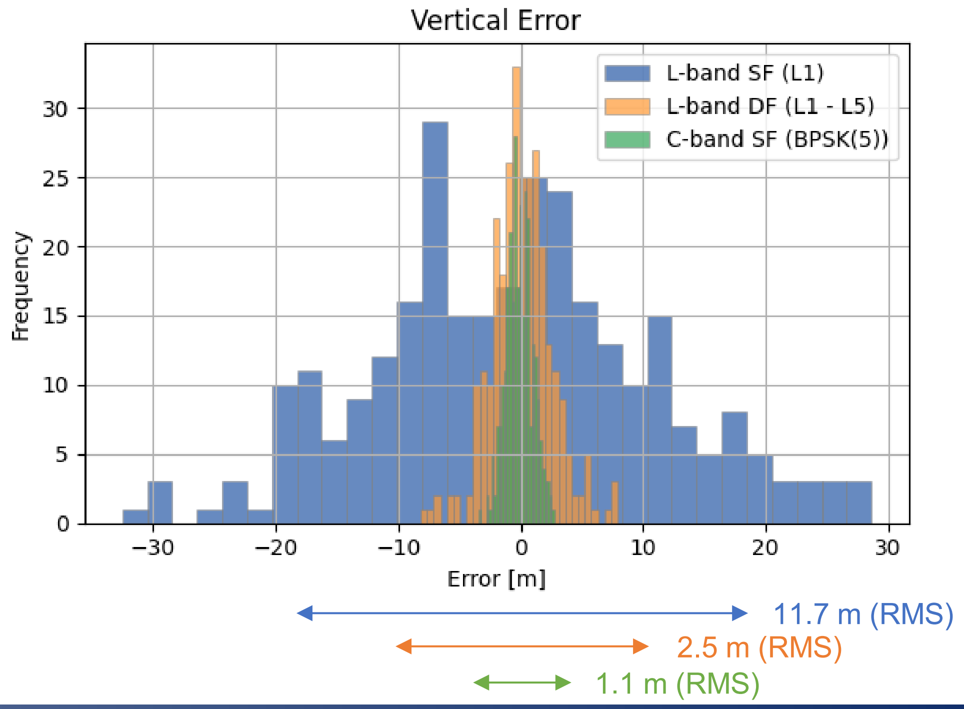
Accurate code-based positioning

Accurate single-frequency measurements

Example of code-based positioning errors improvement:

- Based on simulated data for one user location in Japan (36° N, 140° E) in open-sky conditions





International Coordination

We are coordinating with international GNSS and LEO PNT providers:

- **Spectrum aspects:**
  - Frequency coordination and spectrum usage
  - Allocation of new bands to RNSS (5030-5250MHz)
- **Compatibility** *(use separately or together without interfering):*
- **Interoperability** *(use together for better user performance)*:

	GNSS	LEO PNT
– System Interoperability		
• Reference frame and time aligned to standard • Transmission of time offset (if needed)	✓	✓
– Signal interoperability:	✓	
• Center frequencies • Signal structure, waveform, codes, data	✗	🔄

International Committee on Global Navigation Satellite Systems

An approach similar to GNSS is needed

Trade-off between:
- similarity to enable simple receiver technology
- diversity to enhance frequency/signal diversity and reduce vulnerability of combined solution

Key Messages

- JAXA is actively researching LEO PNT systems that can complement GNSS, and the related enabling technologies
- Progressive development of a GNSS-independent LEO layer is envisioned to contribute to resilient multi-layer PNT services
- Navigation signals in higher frequencies (C-band) are being studied to exploit low ionospheric delays and opportunity for wideband signals
- Coordination efforts are underway for radio compatibility and spectrum aspects (ITU) and system / signal interoperability aspects (ICG)

Thank you for the attention!

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