LEO PNT Technology & its Applications

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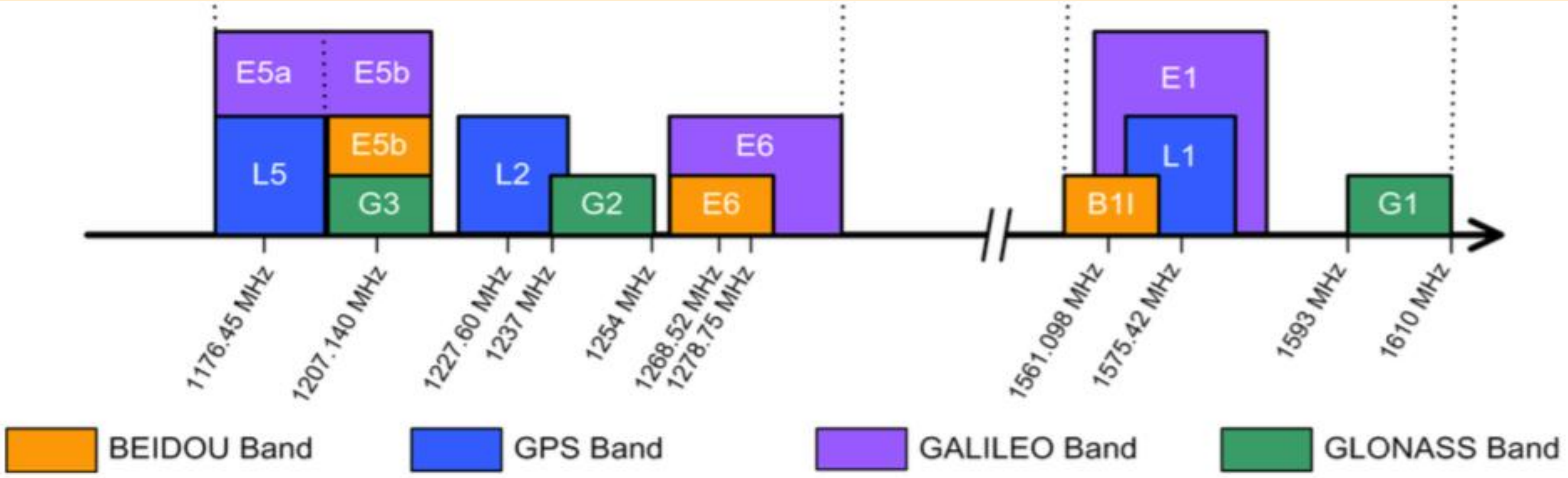
GNSS Signal Characteristics (1/2)

- **Carrier**: Radio frequency sinusoidal signal at a given frequency.
- **Ranging code (PRN)**: Allow the receiver to determine the travel time of radio signal from satellite to receiver.
- **Navigation data**:
  - Satellite ephemeris (Keplerian elements or satellite position and velocity)
  - Clock bias parameters
  - Almanac (with a reduced accuracy ephemeris data set)
  - Satellite health status, and other complementary information.



Source: https://grauonline.de/wordpress/?page_id=1468

GNSS Signal Characteristics (2/2)

- **GNSS Signal Power in the receiver is below the thermal noise**

  - GPS signal power calculation
    - Altitude = 20200 km, f = 1575.42 MHz
    - Satellite transmit power (typical) P_{tx} = +27 dBW

$$FSPL_{dB} = 20\log_{10}(d) + 20\log_{10}(f) + 32.45 \sim 182.5\ \mathrm{dB}$$

$$P_{rx} = P_{tx} - FSPL = -155.5\ \mathrm{dBW}$$

- Free Space Path Loss, FSPL

$$FSPL_{dB} = 20\log_{10}(d) + 20\log_{10}(f) + 32.45$$

d : km, f : MHz

GNSS Principle – Mathematical Foundation: The Observation Model

Original Model

$$\rho_s = \sqrt{(X_s - X_p)^2 + (Y_s - Y_p)^2 + (Z_s - Z_p)^2} + c(dt_r - dr^s) + b$$

PPP Observation Model

Pseudo range

$$P^i = \rho^i + c\delta t_r + T^i + I^i + \epsilon_P^i$$

Carrier Phase

$$\Phi^i = \rho^i + c\delta t_r + T^i - I^i + \lambda N^i + \epsilon_\Phi^i$$

Linearized Observation Equation

$$\boldsymbol{z}_k = \boldsymbol{H}_k \boldsymbol{x} + \boldsymbol{v}_k$$

$$\boldsymbol{x} = [\delta x \;\; \delta y \;\; \delta z \;\; c\delta t_r \;\; T \;\; N^1 \;\; \ldots \;\; N^m]^T$$

$$\boldsymbol{z}_k = \left(\Delta\Phi_k^1 \cdots \Delta\Phi_k^m\right)^T$$

$$\boldsymbol{H}_k = \begin{pmatrix} u_{x,k}^1 & u_{y,k}^1 & u_{z,k}^1 & 1 & 1 & \lambda^1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ u_{x,k}^m & u_{y,k}^m & u_{z,k}^m & 1 & 1 & 0 & \cdots & \lambda^m \end{pmatrix}$$

LOS vector

Integer Ambiguity

$$\left.\begin{aligned} \frac{\partial \rho}{\partial \mathrm{X}} &= -\frac{-X_s - X_0}{\rho} = -u_{x,k}^i \\ \frac{\partial \rho}{\partial Y} &= -\frac{-Y_s - Y_0}{\rho} = -u_{y,k}^i \\ \frac{\partial \rho}{\partial Z} &= -\frac{-Z_s - Z_0}{\rho} = -u_{z,k}^i \end{aligned}\right\} \text{Direction Cosines}$$

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Limitations of Existing MEO GNSS

Single Point of Failure: Heavy reliance on MEO GNSS (GPS, GLONASS, Galileo, BeiDou).

Current Challenges:

- Increasing Jamming & Spoofing incidents
- Signal attenuation in "Urban Canyons" and indoor environments
- Geopolitical risks to space-based infrastructure.

Current Approaches from LEO Constellations (1/2)

Signal of Opportunity

- Repurposing existing communication signals for positioning without new satellite hardware.

Integrated Comm. & PNT

- Hybrid platforms delivering both high-speed data and reliable positioning services.

Dedicated LEO PNT

- Custom satellites offering high-precision, secure, and resilient navigation signals.

Current Approaches from LEO Constellations (2/2)

Category		Representative System / Company	Status
Dedicated PNT	Alternative	Xona Space (Pulsar)	Under deployment & testing
	Augmentation	European Research Proposals, such as: FutureNAV	Research & demonstration phase
Signals of Opportunity		Starlink / OneWeb	Initial navigation testing completed
Integrated Comm. & PNT		Iridium STL	Commercially operational

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LEO PNT Technical Architectures

Constellation

Mega-constellation

Walker / Shell

Dynamic Geometry

Signal

CDMA/OFDM

Multi-frequency

High EIRP

LEO PNT technical architecture

Timing & Sync.

Atomic Clock

Crosslink

Ground Correction

Ground Segment

Multi-sensors fusion

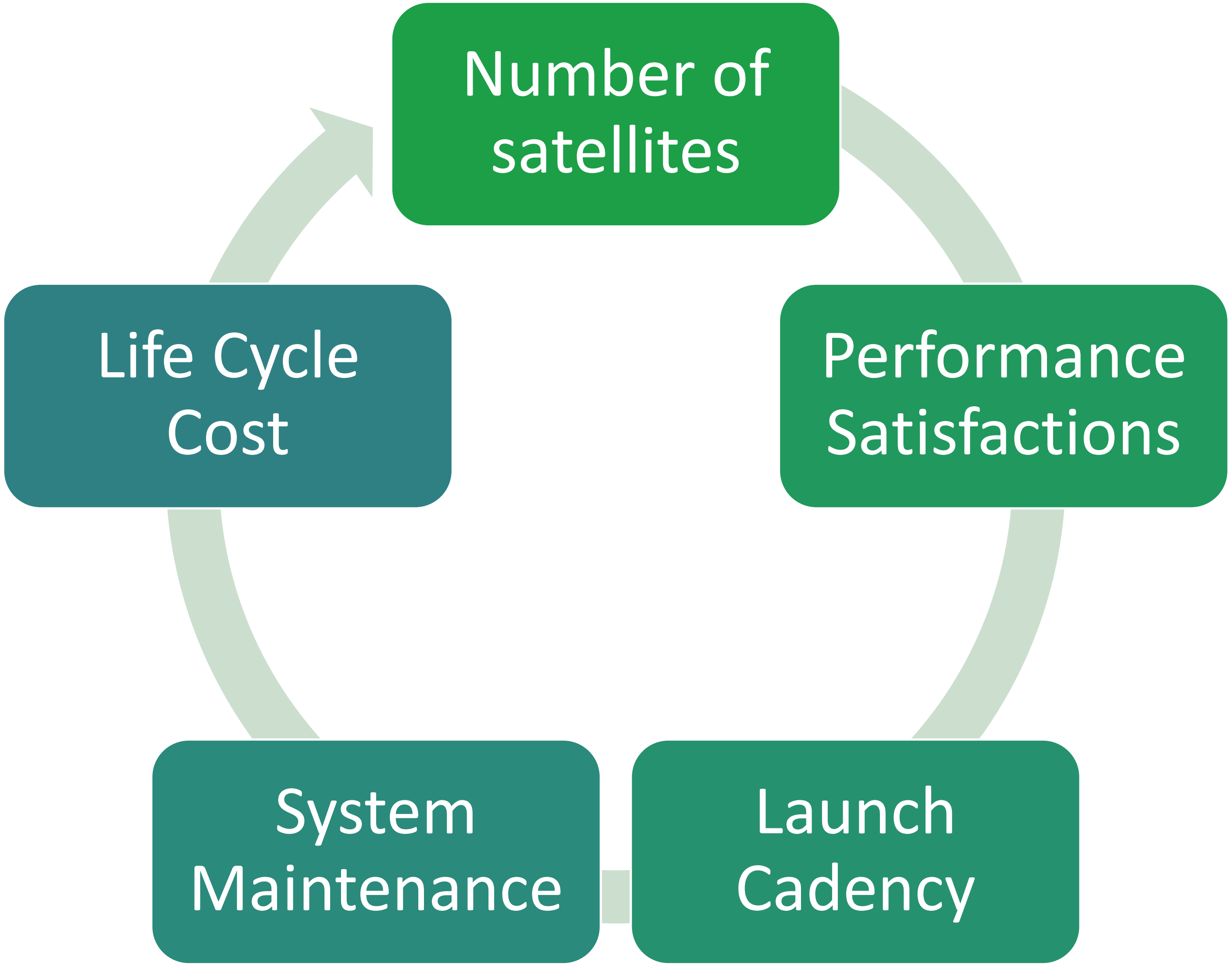
(GNSS + LEO + IMU + Vision)

AI-based positioning

LEO PNT Technical Architectures - Comparison of LEO PNT Frequency Bands

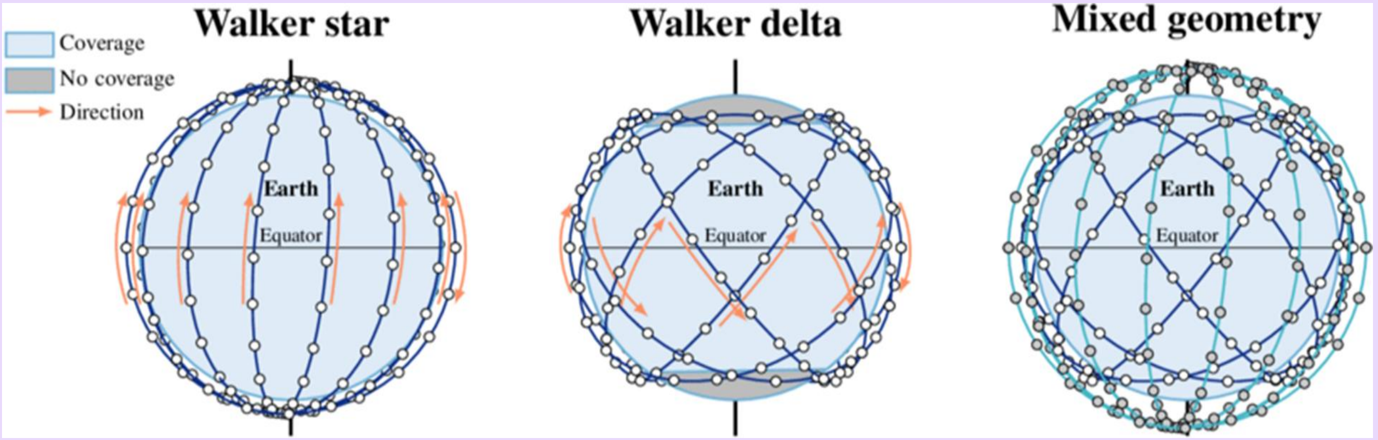
Frequency Band	Range (Approx.)	Pros (Advantages)	Cons (Challenges)	Key Players / Applications
L-Band	1 – 2 GHz	• Highest compatibility with existing GNSS receivers. • Low atmospheric attenuation.	• Extremely congested spectrum. • Limited bandwidth for high-precision data.	GPS, Galileo, Xona Space, Iridium
S-Band	2 – 4 GHz	• Good balance between antenna size and signal propagation. • Less interference than L-Band.	• Requires specific hardware support. • Potential interference with terrestrial 5G/LTE.	Globalstar, some IoT LEO services
C-Band	4 – 8 GHz	• Smaller antenna size (ideal for CubeSats). • High directional gain. • Stronger anti-jamming potential.	• Significant rain fade compared to L-Band. • More complex ground station tracking.	TrustPoint, JAXA (planned)
Ku/Ka-Band	12 – 40 GHz	• Massive available bandwidth. • Supports high-speed data & high-precision ranging.	• Severe rain fade & atmospheric loss. (Ka) • Requires high-precision directional antennas.	Starlink (SOP), OneWeb, Amazon Kuiper

LEO PNT Constellation Design (1/3) - Design Considerations



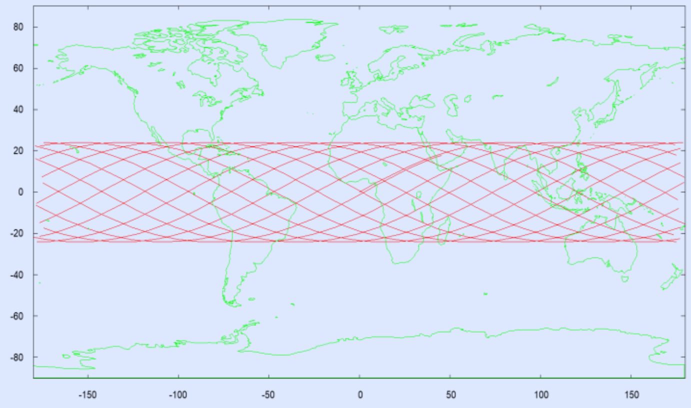
LEO PNT Constellation Design (2/3) - Constellation Orbital Design

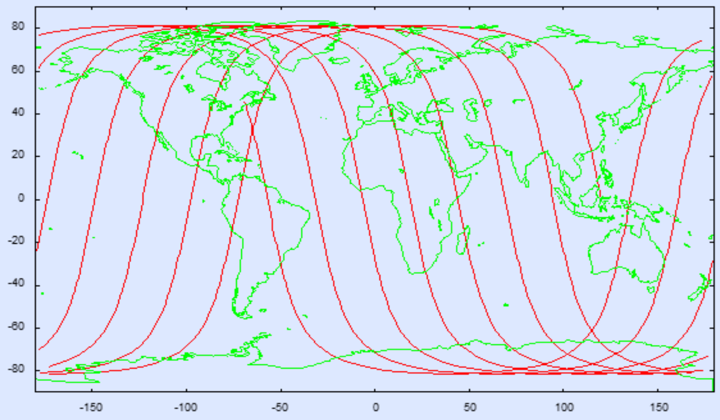
Constellation Topology



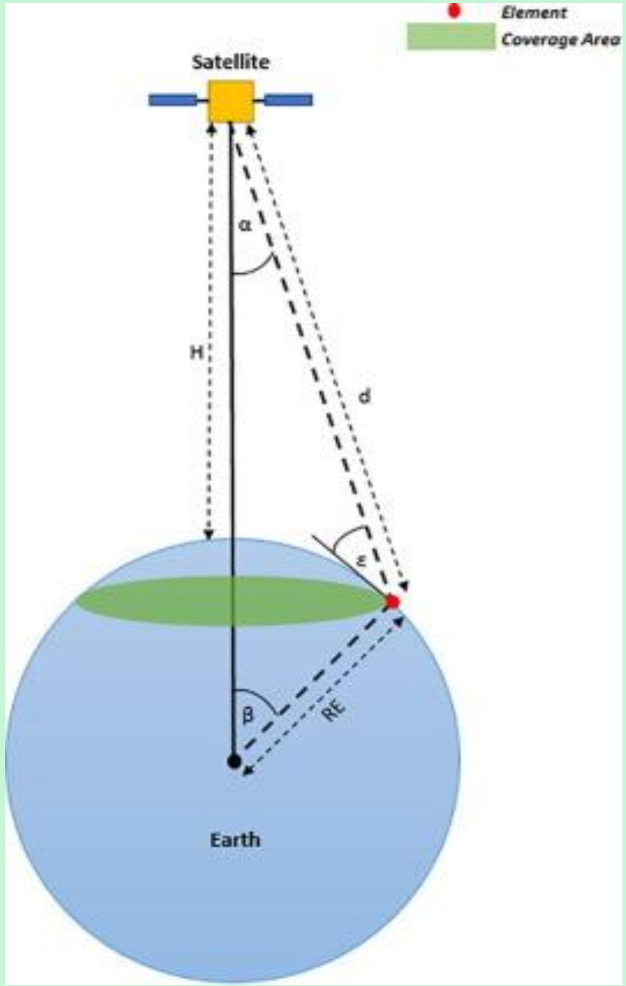
Source：Israel Leyva-Mayorga, et.al., NGSO Constellation Design for Global Connectivity, 0 March 2022

Orbit Inclination





Altitude & Elevation Cut-off



Source: S. Cakaj, B. Kamo, A. Lala, A. Rakipi, The Coverage Analysis for Low Earth Orbiting Satellites at Low Elevation, International Journal of Advanced Computer Science and Applications, 5 (6) (2014), pp. 6-10

LEO PNT Constellation Design (3/3) - Selected Performance Metrics

- Four-fold coverage
- Weighted GDOP
- Carrier-to-noise ratio

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Technical Advantages - the 4 Features of LEO PNT

Superior Signal Power

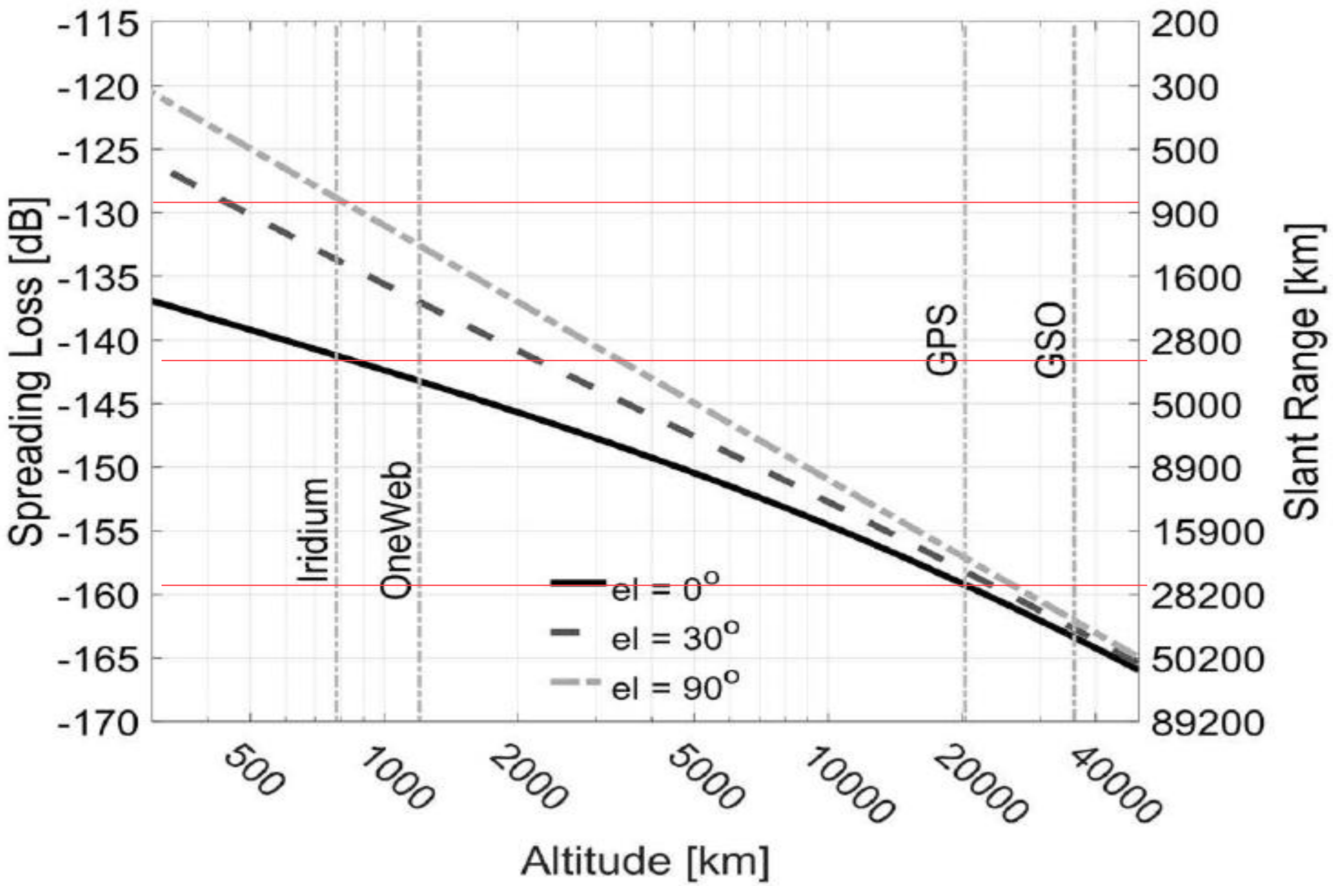
Rapid Geometry Change

Enhanced Doppler effect

Advanced Signal Encryption

Technical Advantages (1/4) - Superior Signal Power

Closer orbits reduce path loss by 30dB, enabling significantly stronger satellite signals.



Source: Satellite Navigation For The Age of Autonomy

- Proximity: 20-40x closer than MEO (500-1200km vs. 20,200km).

- Free Space Path Loss (FSPL)

@ 20200 km ~ 86.11 dB
@ 1200 km ~ 61.58 dB
@ 500 km ~ 53.98 dB

Technical Advantages (2/4) - Rapid Geometry Change

👍 The high-speed orbital motion of LEO satellites accelerates the convergence speed of carrier phase ambiguities.

- **LEO PNT:**

Rapid geometry dynamics → fast-changing $\boldsymbol{H}_k$

- **MEO (GNSS):**

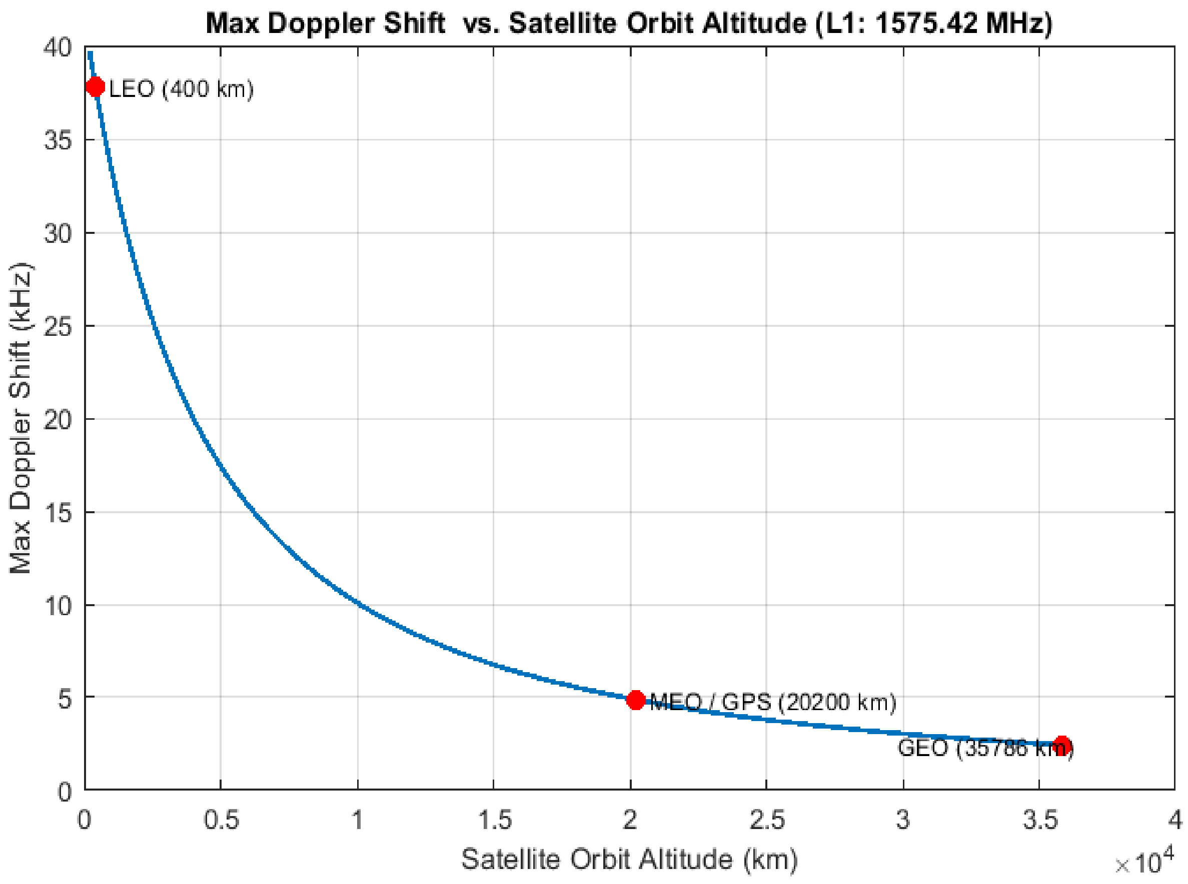
Slow geometry dynamics → quasi-static $\boldsymbol{H}_k$

- Fast variation of $\boldsymbol{H}_k \Rightarrow$ better conditioned $\sum \boldsymbol{H}_k^T \boldsymbol{H}_k \Rightarrow$ faster convergence

- **Impact**: Fast-changing geometry reduces PPP convergence from tens of minutes to seconds (cm-level).

Technical Advantages (3/4) - Enhanced Doppler Shift

Leverages rapid orbital motion to enhance observation precision and accelerate signal locking.



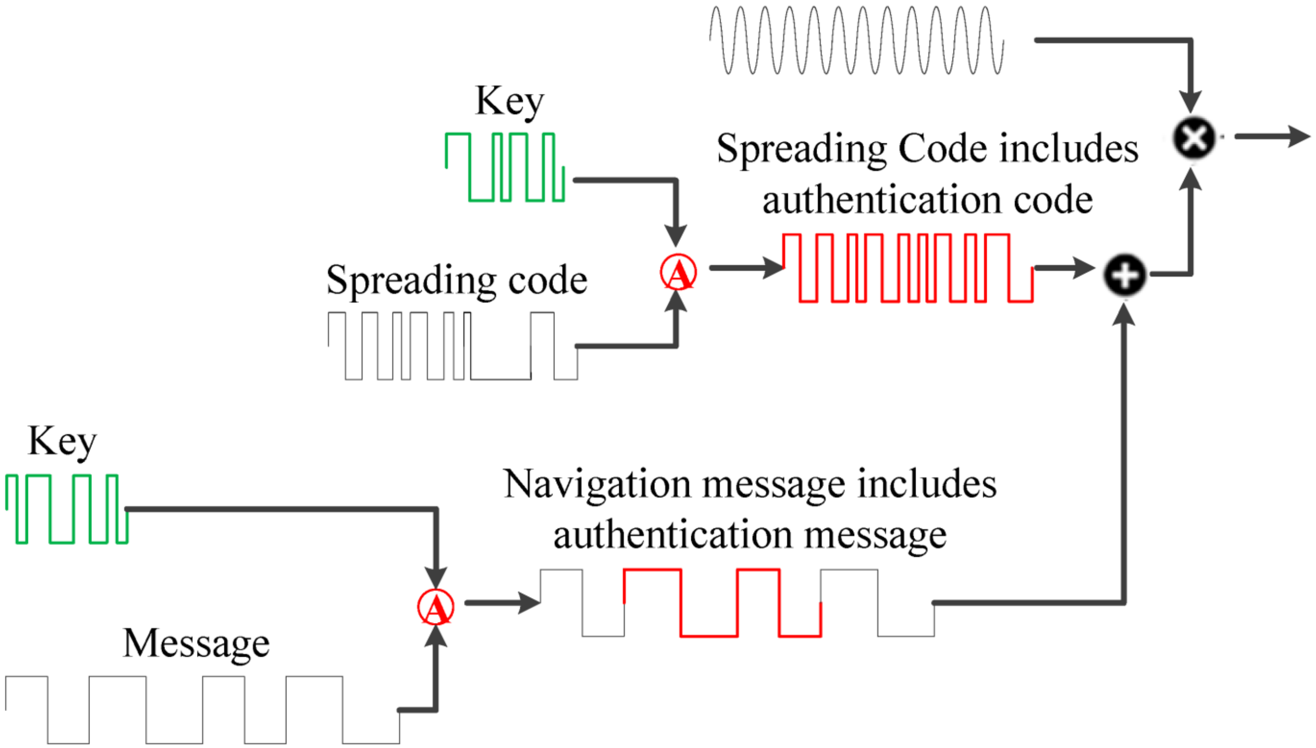
•**Technical Principle:** The high-speed orbital motion of satellites relative to the ground generates significant Doppler frequency shifts.

•**Benefit:** Provides highly precise velocity vector observations.

•**Result:** Facilitates rapid frequency locking for receivers and provides more stable navigation support in dynamic environments.

Technical Advantages (4/4) - Advanced Signal Encryption

Employs integrated encryption and digital signatures to eliminate signal spoofing risks.



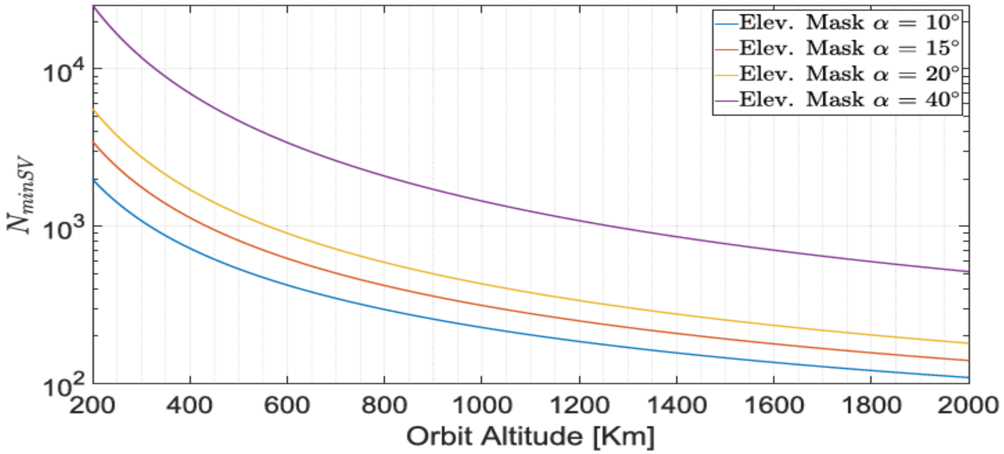
- **Advantages**: Unlike early civilian GPS "cleartext" signals, modern LEO PNT (e.g., Xona) integrates authentication and encryption into its core design.

- **Impact**: This protects against spoofing, ensuring safety-critical applications like autonomous driving receive trusted signals.

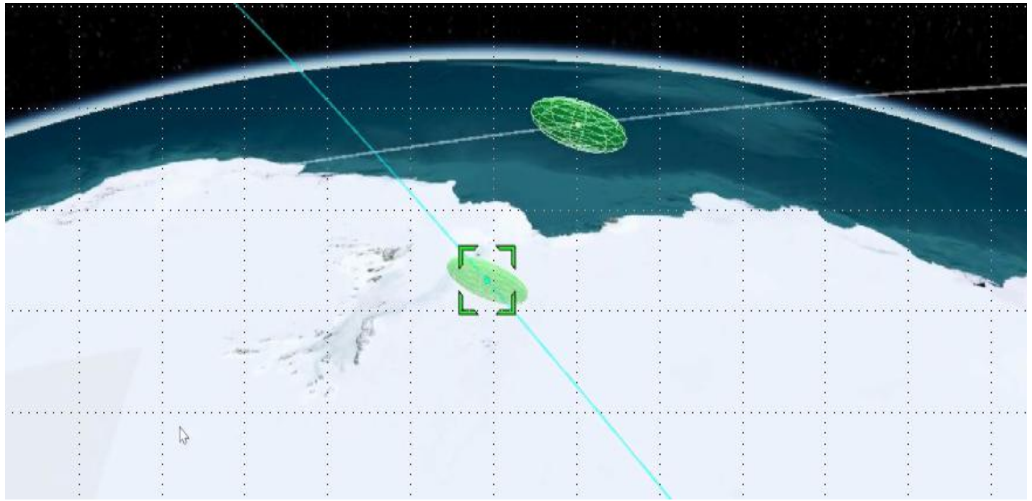
Source: https://encyclopedia.pub/entry/42925?utm_source=chatgpt.com

Technical Challenges (1/4) - Mega-Constellation Management

Minimum number of satellites required for a 4-fold global coverage



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



Key Points

- Hundreds ~ thousands of satellites
- Deployment & replenishment cost
- Launch cadence dependency
- Lifecycle management complexity

Engineering Issues

- Constellation optimization
  - 4-fold coverage
  - GDOP
  - Carrier-to-Noise Ratio (C/N)
- Availability vs cost trade-off
- Collision avoidance

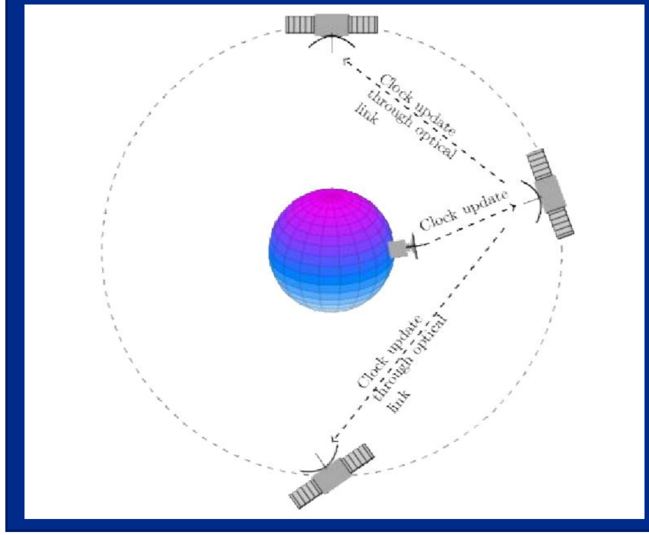
Technical Challenges (2/4) - Timing Synchronous

Clock	Stability at update (s/s)	Update Interval	Uncertainty (ns)
GPS	$\sim 3 \times 10^{-14}$	> 1/day	2.5
CSAC*	$\sim 1 \times 10^{-12}$	> 1/orbit	6.0

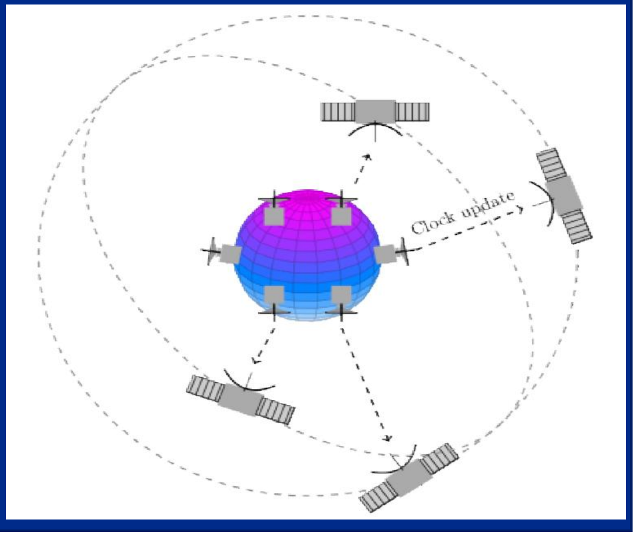
CSAC=Chip-Scale Atomic Clock

Source: Tyler G. R. Reid, Leveraging Commercial Broadband LEO Constellations for Navigation

Inter-satellite links (ISL)



Ground synchronization



Source: FrontierSI (2024), State of the Market Report, Low Earth Orbit Positioning Navigation and Timing –2024 Edition

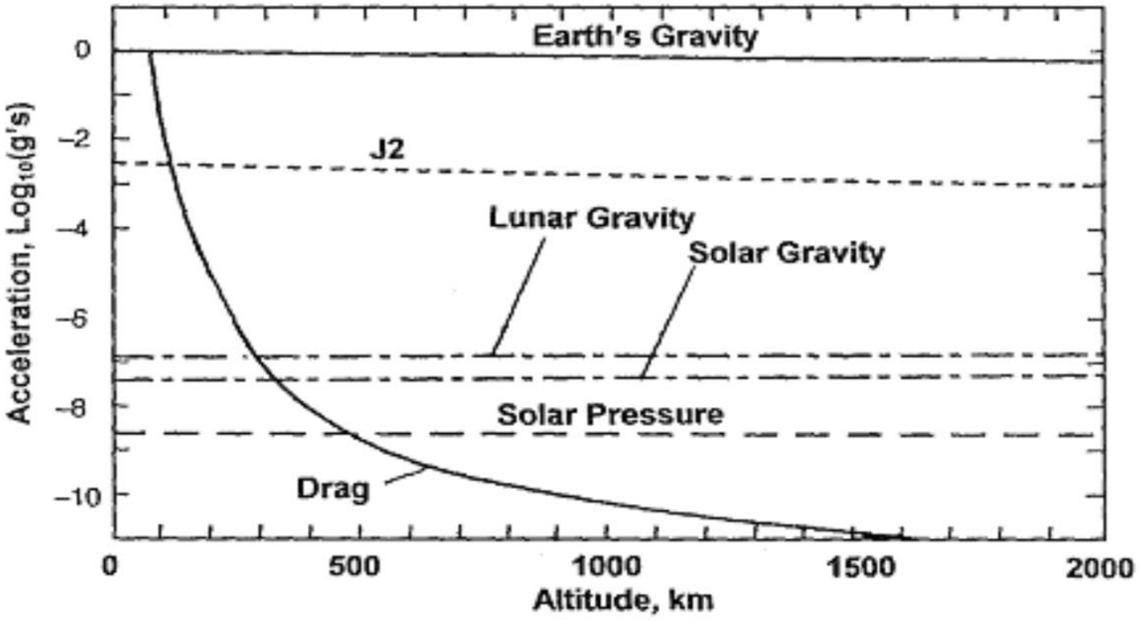
Key Points

- Need ns-level synchronization
- Limited onboard atomic clocks
- Clock drift accumulation

Solutions (but challenging)

- Inter-satellite links (ISL)
- Ground synchronization
- Network timing

Technical Challenges (3/4) - Precise Orbit Determination



Source: Spacecraft Systems Engineering, Fortescue & Stark

Key Points

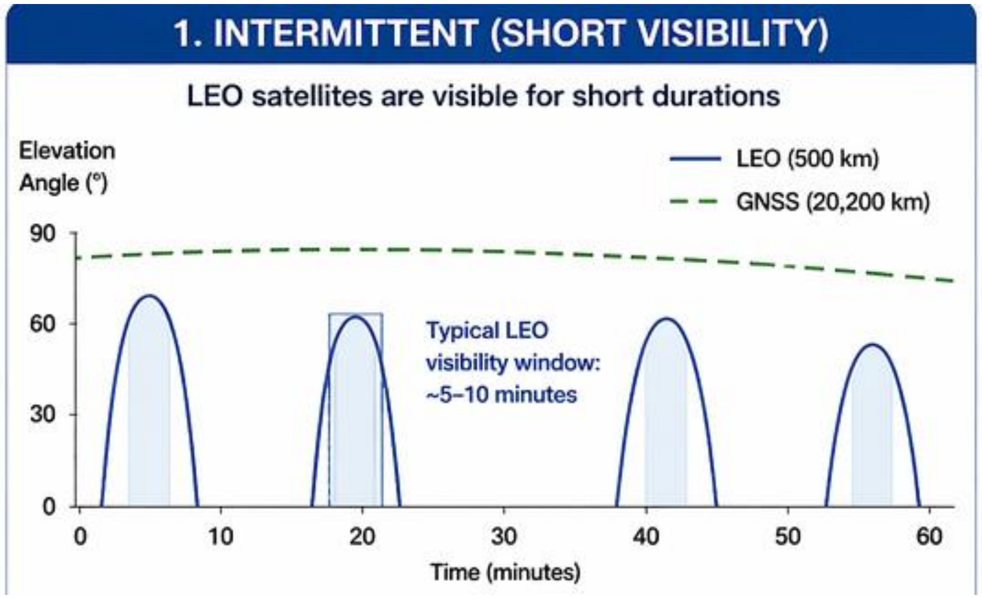
- Orbit error directly impacts positioning error
- LEO perturbations are significant:
  - Atmospheric drag
  - J2 effect
  - Solar radiation

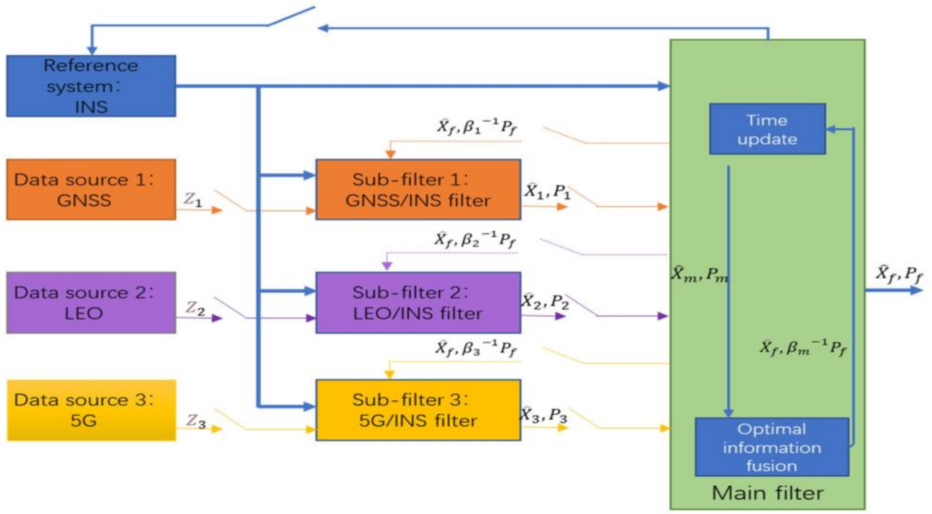
Approach	Accuracy	Latency	Complexity
Ground OD	High	High	Medium
Onboard OD	Medium	Low	High
Hybrid	High	Low	Very High

Technical Challenge

- Real-time POD (cm-level)
- Frequent orbit updates
- Ground vs onboard OD trade-off

Technical Challenges (4/4) - Adaptive Multi-Sensor Fusion





Source: https://www.e-education.psu.edu/geog862/node/1786

Key Points

- **Spectrum Coexistence**: Managing multi-band signals and GNSS interference.
- **High-Dynamic Observability**: Leveraging rapid geometry and high Doppler shifts.
- **Intermittent Link Management**: Solving short orbital passes with robust tracking.

Engineering Impact

- **Advanced Waveform Engineering**: Using hybrid waveforms and RF Doppler compensation.
- **Non-Linear State Estimation**: Deploying EKF/UKF for complex navigation problems.
- **Integrated PNT Fusion**: Implementing multi-sensor architectures (GNSS, LEO, INS).

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Future Application Scenarios

Urban Autonomy & Level 4/5 Driving

- **Centimeter-Level Accuracy**: Real-time positioning with cm-level accuracy.
- **Rapid Convergence**: Faster TTFF (Time to First Fix) for RTK services.
- **Integrity Monitoring**: Guaranteed safety-of-life for Level 4/5 autonomous driving.

Indoor Positioning & Industrial IoT

- **Deep Signal Penetration**: Up to 30 dB higher signal strength than MEO GNSS.
- **Warehouse Automation:** Seamless indoor-outdoor transition for AGVs
- **Infrastructure Synergy:** Integration with 5G/6G terrestrial networks for positioning.

Critical Infrastructure & Power Grids

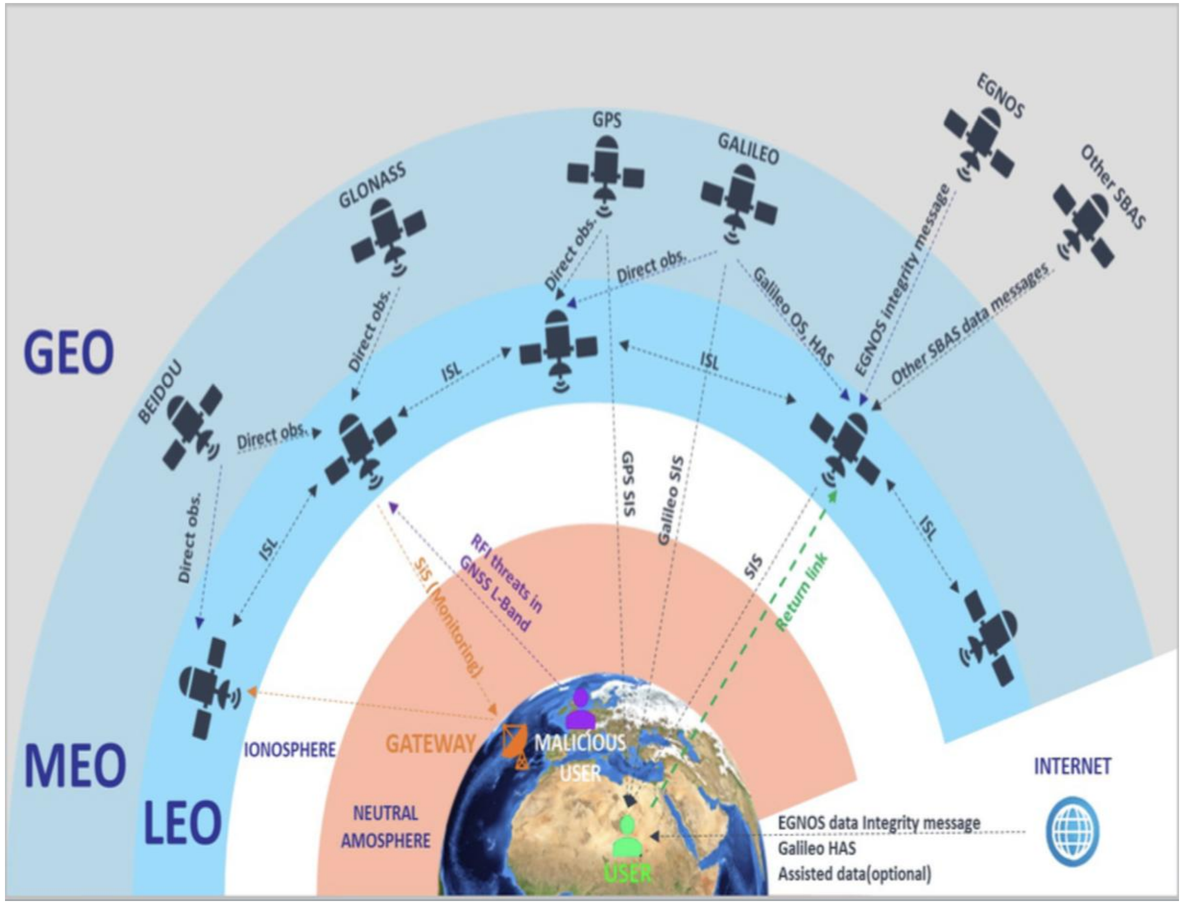
- **Resilient Timing**: Ns-level synchronization for 5G base stations and power grids.
- **Anti-Jamming/Spoofing**: Robust authentication to counter signal interference.
- **Redundant Backup**: Independent PNT source as a fallback for GPS/Galileo outages..

Contents

Conclusions

- **Multi-layer PNT**
  - GNSS(MEO) + LEO + terrestrial(5G / Wi-Fi / sensors）
  - Cross-layer integration

- **Resilient PNT architecture**
  - Navigation signals embedded in comm signals
  - Software-Defined Architecture
  - Adaptive waveform



Source: https://www.esa.int/ESA_Multimedia/Images/2023/06/LEO-PNT_within_a_multi-layer_satnav_architecture

Thank you for your attention