

ELLIIT Focus Period - Linköping 2026

# Enabling Technologies for Localization in 5G and Beyond: Terrestrial and Non-Terrestrial Networks

  
**Alda Xhafa**

 [alda.xhafa@uab.cat](mailto:alda.xhafa@uab.cat)

Signal Processing for Communications and Navigation (SPCOMNAV)

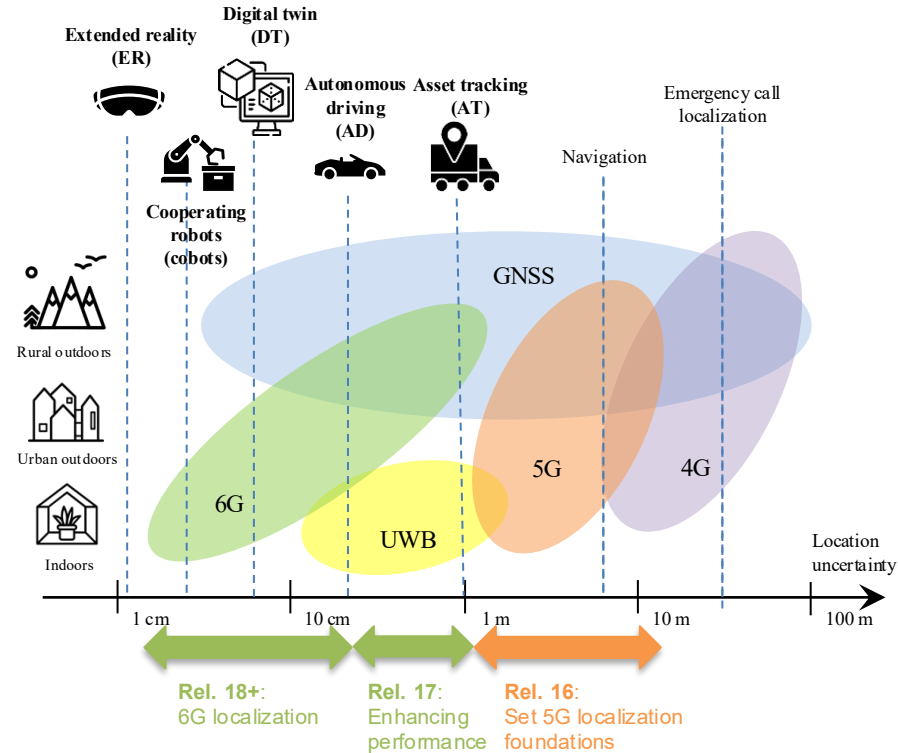
Universitat Autònoma de Barcelona (UAB)

*Joint work with Daniel Egea-Roca, Gonzalo Seco-Granados, José A. López-Salcedo*



# Motivation

- **Growing Demand for High-Accuracy Positioning**
  - 5G and beyond enable **centimetre-level localization** across urban, rural, and indoor environments.
- **Limitations of Traditional Terrestrial Networks (TNs)**
  - Depend on base stations and AoD/ToA-based methods.
  - **Fail under NLoS conditions** due to multipath and signal blockage.
- **Non-Terrestrial Networks (NTNs) Enable Global Coverage**
  - LEO satellite constellations expand reach but **suffer from Doppler, atmospheric attenuation, and limited satellite visibility**.

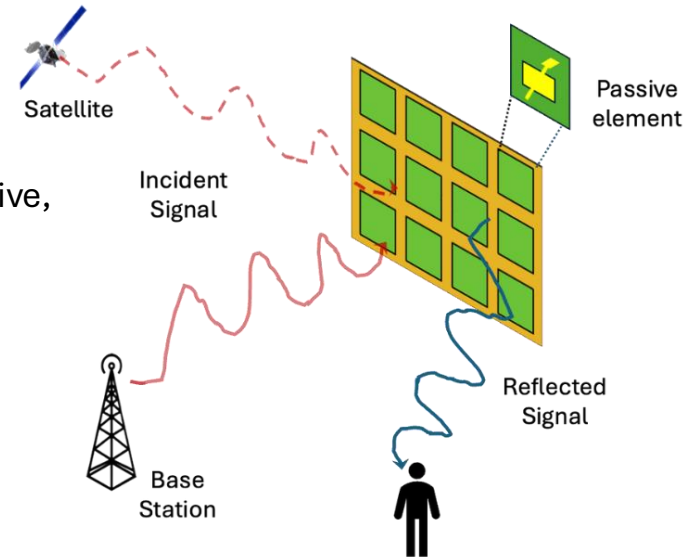


# How RIS solves intractable localization problems?

Composed of passive elements with tunable phase shifts, RIS enables dynamic and programmable signal reflection.

RIS offers two benefits:

- Introduces an extra location reference.
- Provides additional measurements, independent of the passive, uncontrolled multipath.



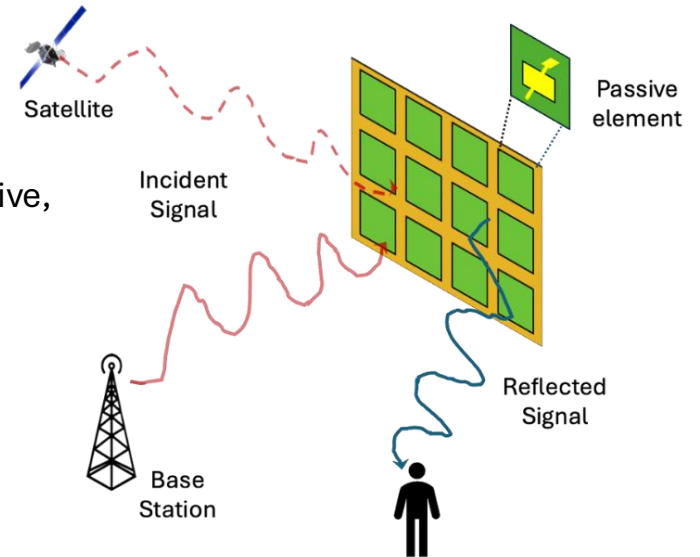
# Reconfigurable Intelligent Surfaces

Composed of passive elements with tunable phase shifts, RIS enables dynamic and programmable signal reflection.

RIS offers two benefits:

- Introduces an extra location reference.
- Provides additional measurements, independent of the passive, uncontrolled multipath.

BS/Sat + RIS needed to localize a user



# RIS-aided Localization: Key Challenges

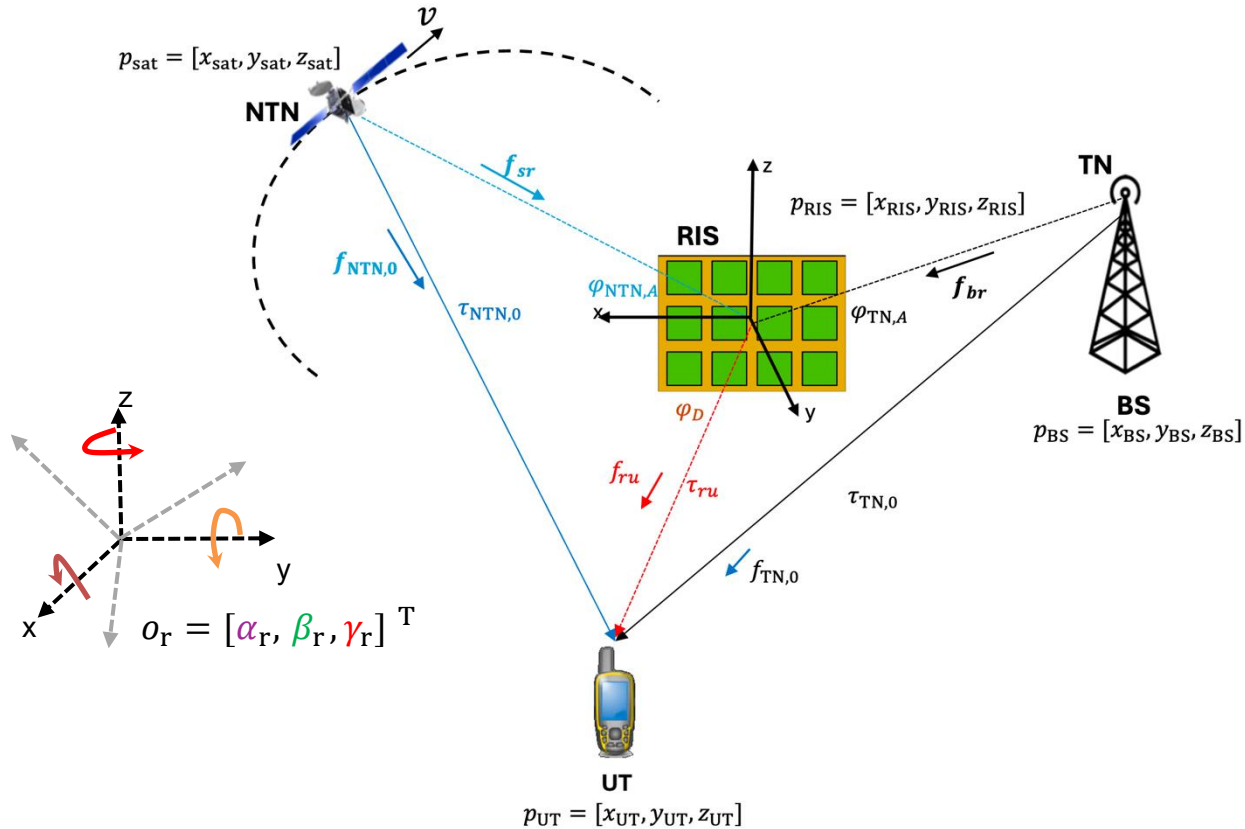
- **RIS-aided TN** localization **extensively** studied (channel modelling and resource allocation). **NTN** implementation **underexplored** due to factors like **orbital dynamics**.
- Integrating **TN** and **NTN** requires **unified** performance metrics.
- Existing KPIs for RIS-based localization (e.g., PEB, RMSE) often neglect NTN impairments, such as **high Doppler shifts**.

## Contributions

- **RIS-Aided Localization Framework:** Unified TN/NTN simulation under mobility, far-field effects, and time-varying factors (delays, AoA, gains).
- **Flexible Configurations:** Supports various OFDM setups, RIS sizes, and phase profile designs (random & directional).
- **Comprehensive KPI Analysis:** Comparison using PEB, coverage, and dynamic range.



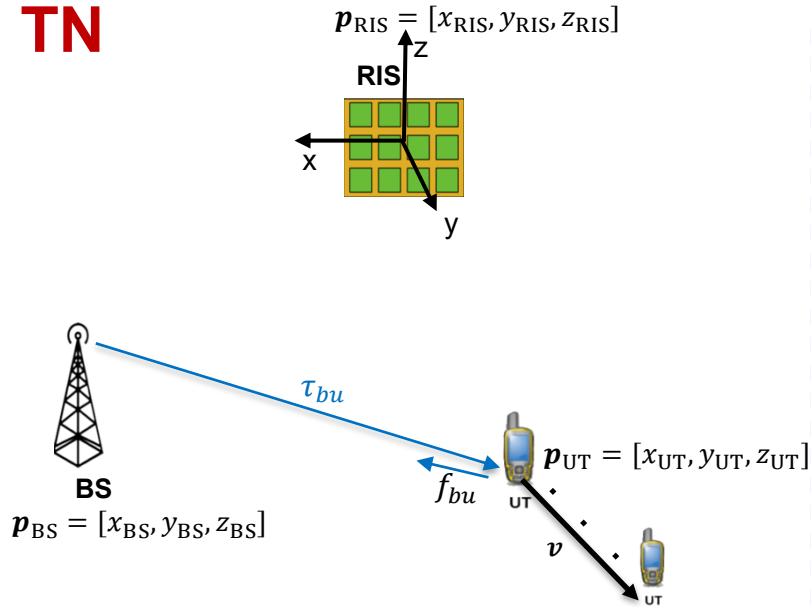
# System Model: Multi-Layer Network (MuLa)



D. Egea-Roca, A. Xhafa, J. A. Lopez-Salcedo, G. Seco-Granados, "First Results on RIS-Enabled Multi-Layer Localization: A Joint Terrestrial and Non-Terrestrial Method", Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), May 2026

# System Model: Geometry setup – Direct channel path

**TN**

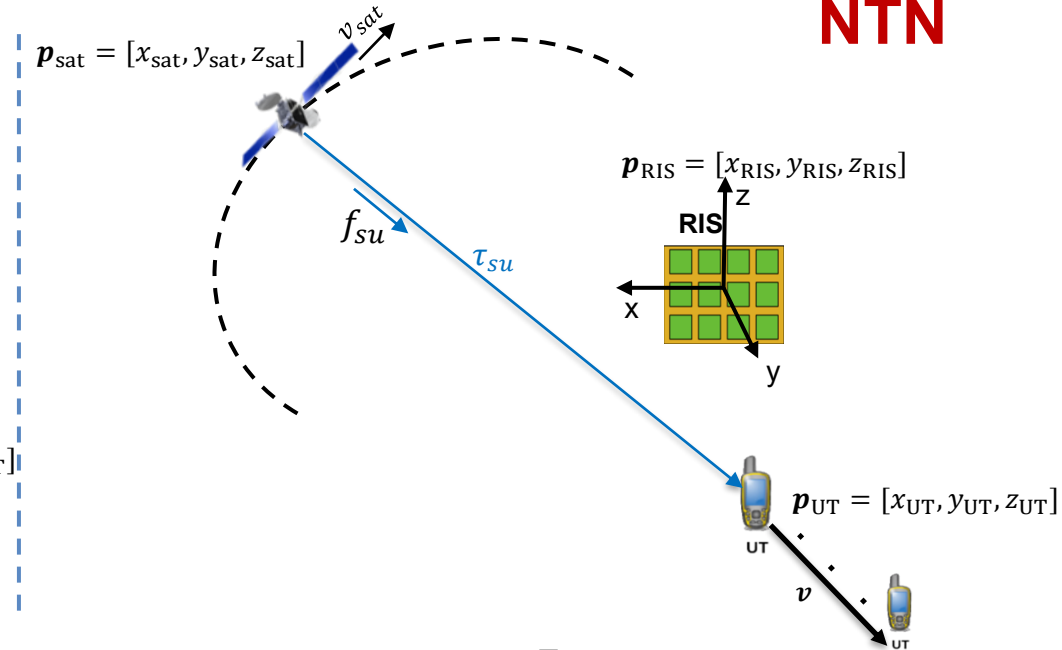


$$\tau_{j,0} \doteq \frac{\|\mathbf{p}_{\text{tx}} - \mathbf{p}\|}{c} + \delta t$$

$$\text{tx} \in \{\text{BS, sat}\} \quad \text{j} \in \{\text{TN, NTN}\}$$

$\delta t$  – clock bias

**NTN**



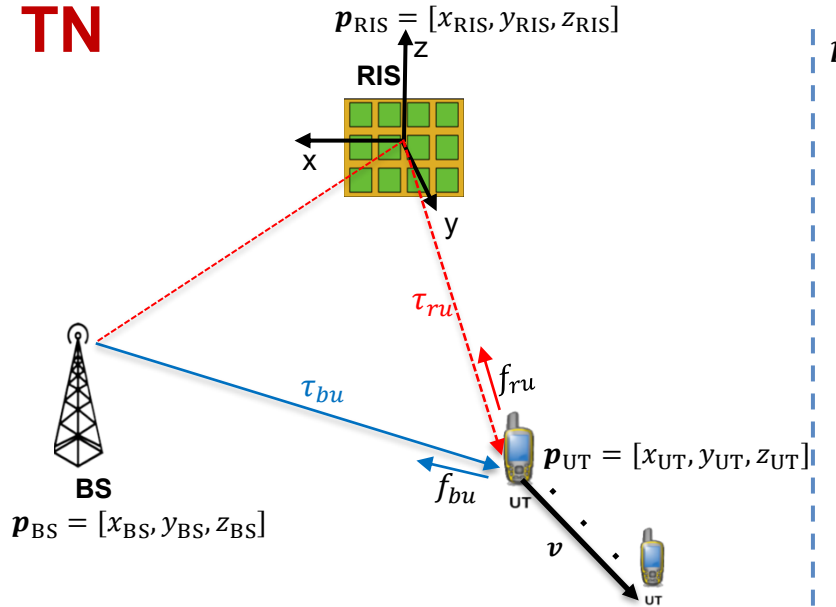
$$f_{j,0} \doteq \frac{(\mathbf{v}_{\text{tx}} - \mathbf{v})^T (\mathbf{p} - \mathbf{p}_{\text{tx}})}{\lambda \|\mathbf{p} - \mathbf{p}_{\text{tx}}\|}$$

TN:  $\mathbf{v}_{\text{tx}} = 0$  (BS static)

NTN:  $\mathbf{v}_{\text{tx}} \neq 0$  (Sat. motion)

# System Model: Geometry setup – Reflected channel path

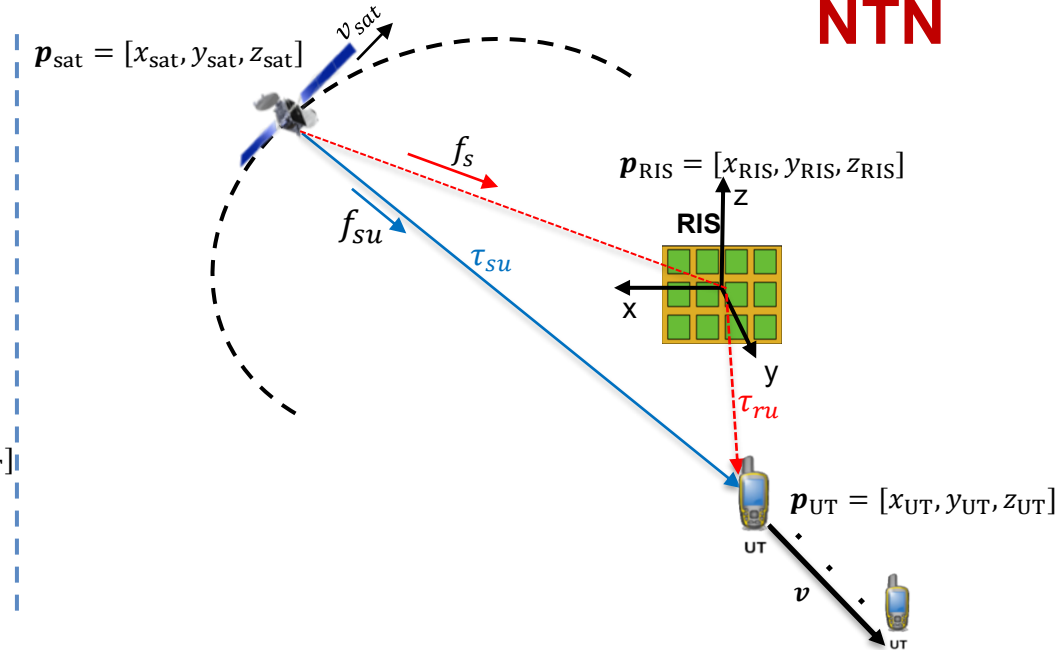
**TN**



$$\tau_{j,1} \doteq \tau_{tr} + \tau_{ru} = \frac{\|\mathbf{p}_{tx} - \mathbf{p}_{RIS}\| + \|(\mathbf{p}_{RIS} - \mathbf{p})\|}{c} + \delta t$$

$$\tau_{tr} \in \{br, sr\}$$

**NTN**

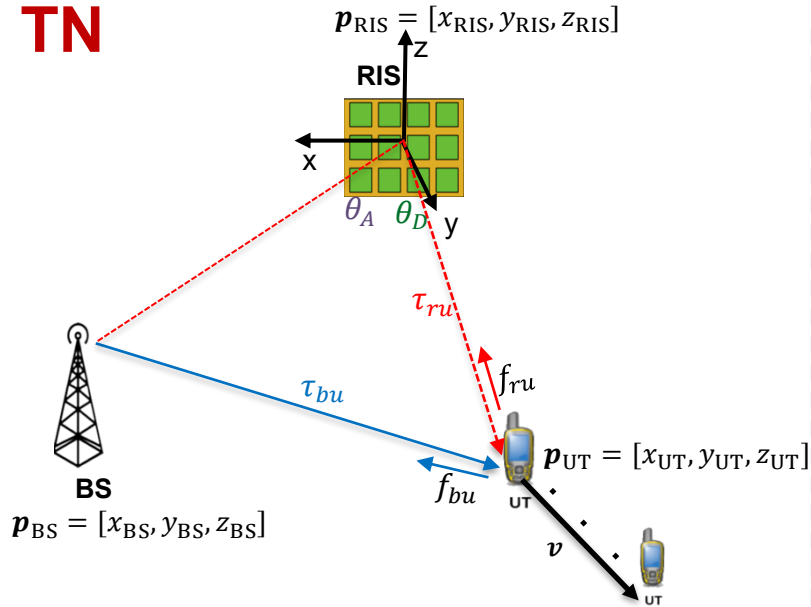


$$f_{j,1} \doteq f_{tr} + f_{ru} = \frac{\mathbf{v}_{tx}^T (\mathbf{p}_{tx} - \mathbf{p}_{RIS})}{\lambda \|\mathbf{p}_{tx} - \mathbf{p}_{RIS}\|} + \frac{\mathbf{v}^T (\mathbf{p}_{RIS} - \mathbf{p})}{\lambda \|\mathbf{p}_{RIS} - \mathbf{p}\|}$$

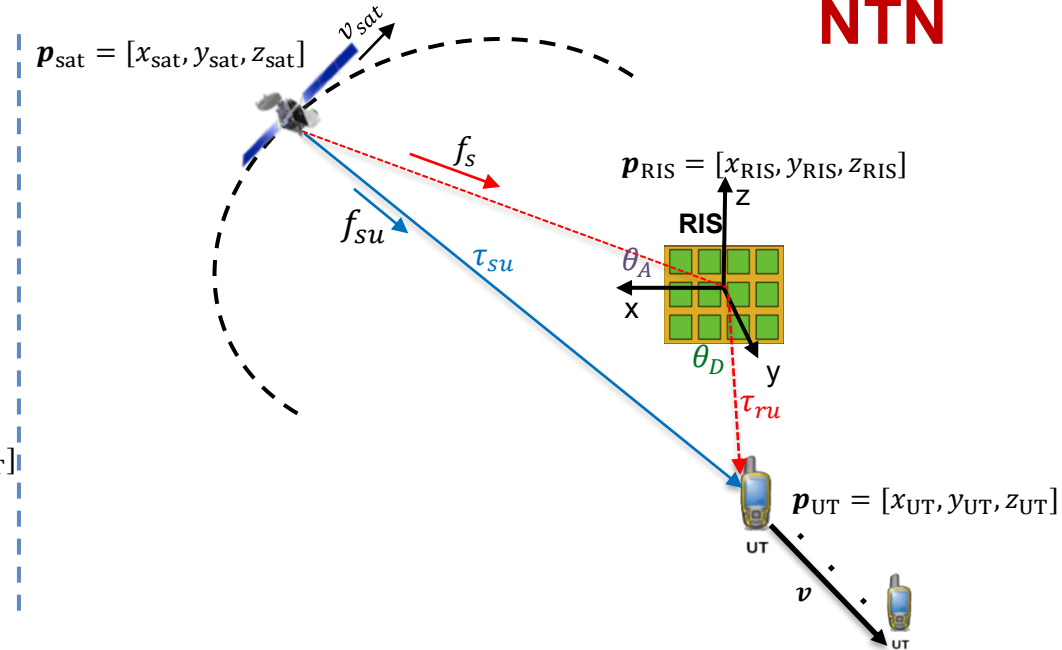
TN:  $f_{tr} = 0$  (BS static)

# System Model: Geometry setup – Reflected channel path

**TN**



**NTN**



**AoA and AoD** ( $g = \{A, D\}$ ): azimuth and elevation angles

Azimuth -  $\phi_g \doteq \text{atan2}([\mathbf{R}^T \Delta \mathbf{p}_g]_2 / [\mathbf{R}^T \Delta \mathbf{p}_g]_1)$

Elevation -  $\theta_g \doteq \arccos([\mathbf{R}^T \Delta \mathbf{p}_g]_3 / \|\Delta \mathbf{p}_g\|)$

Vector from RIS to sat/BS:

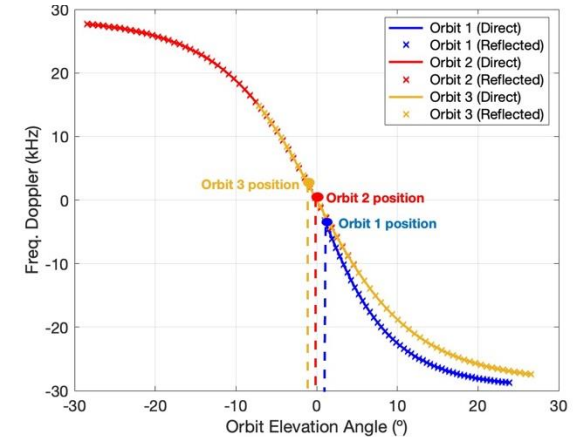
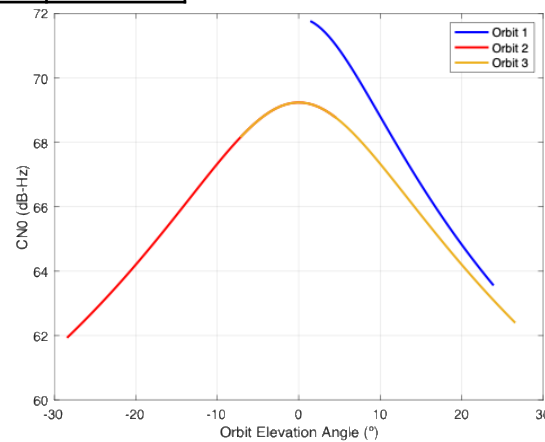
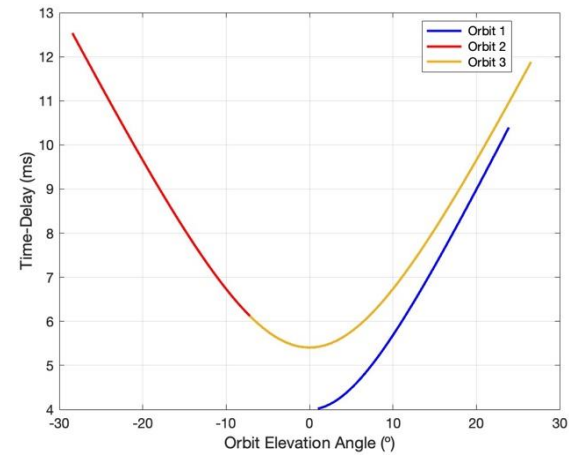
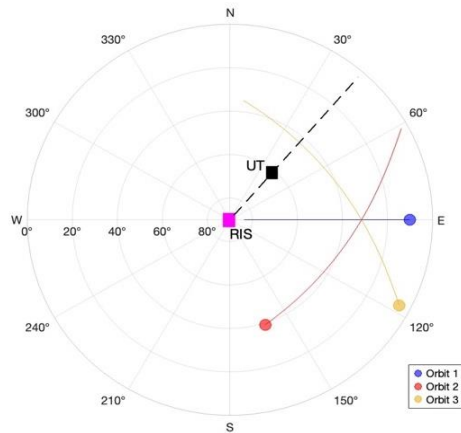
$$\Delta \mathbf{p}_g = \mathbf{p}_g - \mathbf{p}_{\text{RIS}},$$


with  $\mathbf{p}_g \in \{\mathbf{p}_{\text{sat}}, \mathbf{p}_{\text{BS}}, \mathbf{p}\}$

$\mathbf{R}$  - Rotation matrix

# Satellite dynamic conditions

Parameer	Orbit 1	Orbit 2	Orbit 3
Pitch Angle ( $\theta_{PG}$ )	90°	90°	90°
Inclination ( $\theta_I$ )	90°	81°	81°
Ascending Node Angle ( $\theta_{AN}$ )	-90°	45°	-45°
Yaw Angle ( $\psi$ )	1°	10 <sup>-4</sup> °	-1.5°
Orbital Altitude	1200 km	1200 km	1200 km



 A. Xhafa, D. Egea-Roca, J. A. Lopez-Salcedo, G. Seco-Granados, "A Comparative Analysis of Key Performance Indicators for RIS-Enhanced Non-Terrestrial and Terrestrial Localization", Proc. European Signal Processing Conference (EUSIPCO), Sep. 2025

# System Model: Signal Model

$$\text{TX: } s_j(t) = \sqrt{\frac{P_j}{K}} \sum_{k=0}^{K-1} x_{k,l}^{(j)} e^{j2\pi k \Delta_f (t - lT_{\text{sym}})} g(t - lT_{\text{sym}}) \xrightarrow{\text{Passband signal}} s_{\text{PB},j}(t) = \Re \left\{ s_j(t) \exp(j2\pi f_c^{(j)} t) \right\}$$

$P_j$  - transmit signal power of layer  $j$   
 $x_{k,l}^{(j)} \in \mathbb{C}$  -  $l$ -th pilot symbol of layer  $j$   
on the  $k$ -th subcarrier  
 $K$  - Nr. of subcarriers  
 $T_{\text{sym}}$  - total symbol duration  
 $g(t) = \begin{cases} 1 & \text{when } t \in [0, T_{\text{sym}}] \\ 0 & \text{otherwise} \end{cases}$

TN/NTN signal - unified framework

- Operate at different  $f_c$ , but same 3GPP FR1
- Interleaved pilot allocation within the shared bandwidth
- Shared numerology: Aligned OFDM symbol timing and subcarrier spacing

OFDM signals include known pilot sequences, which enable matched filtering and correlation-based estimation at the receiver.



# System Model: Signal Model

$$\text{TX: } s_j(t) = \sqrt{\frac{P_j}{K}} \sum_{k=0}^{K-1} x_{k,l}^{(j)} e^{j2\pi k \Delta_f (t - lT_{\text{sym}})} g(t - lT_{\text{sym}}) \xrightarrow{\text{Passband signal}} s_{\text{PB},j}(t) = \Re \left\{ s_j(t) \exp(j2\pi f_c^{(j)} t) \right\}$$

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- Operate at different  $f_c$ , but same 3GPP FR1
- Interleaved pilot allocation within the shared bandwidth
- Shared numerology: Aligned OFDM symbol timing and subcarrier spacing

$$\text{RX: } r(t) = \sum_{j \in \{\text{TN}, \text{NTN}\}} r_{j,0}(t) + r_{j,1}(t) + w(t)$$

LoS channel
RIS channel
Thermal noise (PSD  $N_o$ )

# System Model: Signal Model

$$\text{RX: } r(t) = \sum_{j \in \{\text{TN}, \text{NTN}\}} r_{j,0}(t) + r_{j,1}(t) + w(t) \xrightarrow[\text{CP removal}]{\text{Sampling}} t = lT_{\text{sym}} + T_{\text{CP}} + nT/K$$

Discrete-time index:  $n=0,1,\dots,K-1$

$$r_{j,0}[n] = \alpha_{j,0} e^{j2\pi f_{j,0}(lT_{\text{sym}} + nT/K)} s(lT_{\text{sym}} + nT/K - \tau_{j,0} + \nu_{j,0}lT_{\text{sym}})$$

$$r_{j,1}[n] = \alpha_{j,1} G_l(\Phi) e^{j2\pi f_{j,1}(lT_{\text{sym}} + nT/K)} s(lT_{\text{sym}} + nT/K - \tau_{j,1} + \nu_{j,1}lT_{\text{sym}})$$

$$G(t; \Phi) = \underbrace{[\mathbf{a}(\varphi_A) \odot \mathbf{a}(\varphi_D)]^T}_{\text{AoA/AoD Steering Vector}} \underbrace{\omega(t)}_{\text{RIS phase Profile: Rnd/Dir}}$$

RIS beamforming Gain

$\omega_l = -\omega_{l+1}$

$$[\mathbf{a}(\varphi)]_m = \exp(-j2\pi f_c \tau_m(\varphi)) \rightarrow \text{Time-shift by the reflection of the signal at the } m\text{-th RIS element.}$$

!  $\nu_i T_{\text{CP}}$  and  $\nu_i nT/K$  are neglected because  $K\Delta_f \nu_i T_{\text{CP}} \ll 1$  and  $K\Delta_f \nu_i T \ll 1$

e.g. for Doppler shift factor  $\approx 1.8 \times 10^{-5}$ ,  $K\Delta_f \nu_i T_{\text{CP}} \approx 2.6 - 3 \ll 1$ ,  $K\Delta_f \nu_i T \approx 0.04 \ll 1$ ,  $K\Delta_f \nu_i lT_{\text{sym}} \approx 10.1 > 1$ ,  $f_c \nu_i lT_{\text{sym}} \approx 675 \gg 1$ , and  $f_c \nu_i T \approx 2.5$ .

# System Model: Signal Model

$$\text{RX: } r(t) = \sum_{j \in \{\text{TN}, \text{NTN}\}} r_{j,0}(t) + r_{j,1}(t) + w(t) \xrightarrow[\text{CP removal}]{\text{Sampling}} t = lT_{\text{sym}} + T_{\text{CP}} + nT/K$$

Discrete-time index:  $n=0, 1, \dots, K-1$

$$r_{j,0}[n] = \sqrt{\frac{P_j}{K}} \alpha_{j,0} e^{j2\pi f_{j,0}(nT/K)} \sum_{k=0}^{K-1} x_{k,l}^{(j)} e^{j2\pi kn/K} e^{j2\pi f_{j,0} l T_{\text{sym}}} e^{-j2\pi k \Delta_f (\tau_{j,0} - \mathbf{v}_{j,0} l T_{\text{sym}})},$$

Drift term

$$r_{j,1}[n] = \sqrt{\frac{P_j}{K}} \alpha_{j,1} G_l(\Phi) e^{j2\pi f_{j,1}(nT/K)} \sum_{k=0}^{K-1} x_{k,l}^{(j)} e^{j2\pi kn/K} e^{j2\pi f_{j,1} l T_{\text{sym}}} e^{-j2\pi k \Delta_f (\tau_{j,1} - \mathbf{v}_{j,1} l T_{\text{sym}})},$$

**NTN:**  $K \Delta_f v_i L T_{\text{sym}} > 1$  - Keep in the signal model

**TN:**  $K \Delta_f v_i L T_{\text{sym}} \ll 1$  - Can be neglected

# System Model: Signal Model

The frequency-domain received signal is given by  $\mathbf{Y} = \sum_{j \in \{\text{TN}, \text{NTN}\}} \mathbf{Y}_{j,0} + \mathbf{Y}_{j,1} + \mathbf{W}$

- Matrix form  $\{\mathbf{Y}_0, \mathbf{Y}_1\} \in \mathbb{C}^{K \times L}$

$L$ : # of symbols

$K$ : # of subcarriers

$$\mathbf{Y}_0 = \mathbf{A}_0 \mathbf{F} \mathbf{E}(f_0) \mathbf{F}^H (\mathbf{C}(f_0) \odot \mathbf{D}(\tau_0) \odot \mathbf{X})$$

$$\mathbf{Y}_1 = \mathbf{A}_1 \mathbf{F} \mathbf{E}(f_1) \mathbf{F}^H (\mathbf{C}(f_1) \odot \mathbf{D}(\tau_1) \odot \mathbf{G}(\Phi) \odot \mathbf{X})$$

Power + attenuation      FFT matrix      Pilots

↓ varies its rows

→ varies its columns

## TN: Time-Invariant

Fast-Time Doppler      ↓  $[\mathbf{E}(f_i)]_{k,l} = \exp(j2\pi f_i k T / K)$

Slow-Time Doppler      →  $[\mathbf{C}(f_i)]_{k,l} = \exp(j2\pi f_i l T_{\text{sym}})$

Sub-Carrier phase shift      ↓  $[\mathbf{D}(\tau_i)]_{k,l} = \exp(-j2\pi k \Delta_f \tau_i)$

RIS Gain      →  $[\mathbf{G}(\Phi)]_{k,l} = G_l(\Phi)$

## NTN: Time-Variant

↓  $[\mathbf{E}(f_i)]_{k,l} = \exp(j2\pi f_{i,l} (k T / K))$

↓  $[\mathbf{C}(f_i)]_{k,l} = \exp(j2\pi f_{i,l} l T_{\text{sym}})$

↓  $[\mathbf{D}(\tau_i)]_{k,l} = \exp(-j2\pi \Delta_f k (\tau_i - v_{i,l} l T_{\text{sym}}))$

→  $[\mathbf{G}(\tilde{\Phi})]_{k,l} = G_l(\Phi_l)$  with  $\tilde{\Phi} = [\Phi_1, \dots, \Phi_L]$

# RIS profile design

- To avoid **interference** between **paths**.
- Divide in  $L = P \cdot \tilde{L}$ , (L nr. OFDM of symbols,  $P \geq R+1$ , where  $R$  is the number of RISs)
  - Slots ( $\tilde{L}$ ): Slow-Varying

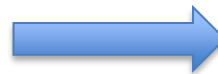
$$\zeta_{r,g}$$

- Intervals ( $P$ ): Fast-Varying

$$\mathbf{B} = [\mathbf{b}_0, \mathbf{b}_1, \dots, \mathbf{b}_R]$$



$$\omega_{r,gP+p} = B_{r,p} \zeta_{r,g}$$



Path  
Separation

$$\mathbf{Z}_r \in \mathbb{C}^{K' \times \tilde{L}}$$

$g$ -th slot



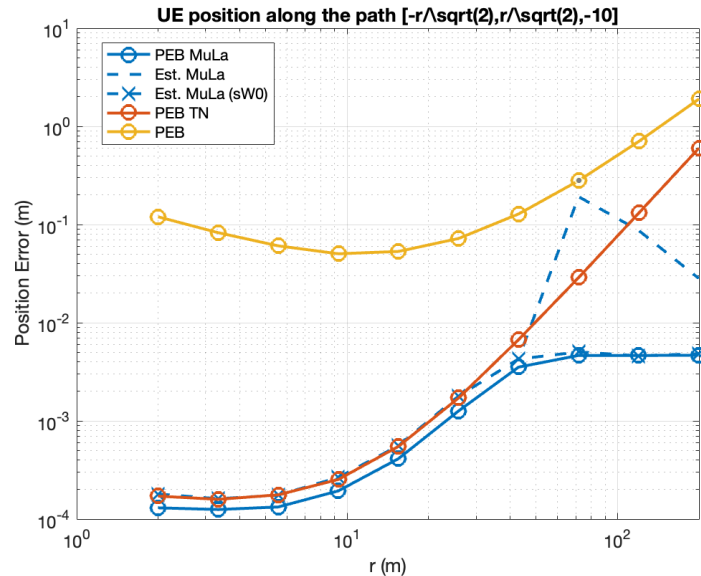
$$[\mathbf{Z}_r]_{:,g} = \frac{1}{P} \left( (\mathbf{X}^{(g)})^* \odot \mathbf{Y}^{(g)} \right) \mathbf{b}_r^*$$



Match  
function



# Performance analysis



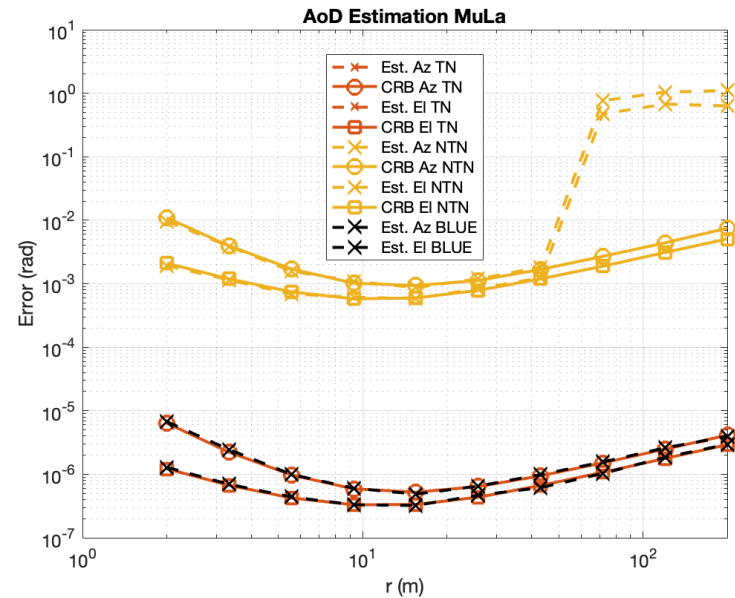
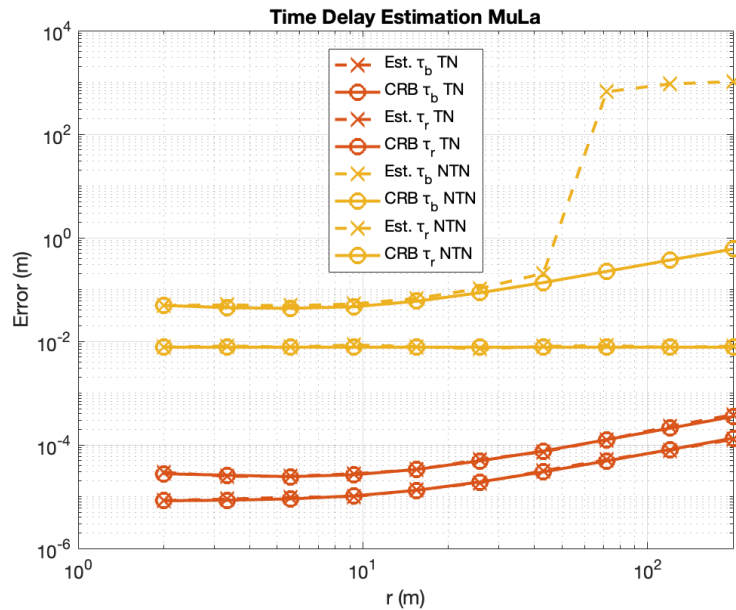
Frequency group	FR1	
Network type	TN	NTN
Operating freq. Band [GHz]	n50 [1.432 – 1.517]	
F <sub>c</sub> [GHz]	1.462	
Duplex mode	TDD	
Δf [kHz]	60	
B [MHz]	80	
N <sub>sc</sub>	1333 <sub>sc</sub>	
L (symbols)	256	
P <sub>tx</sub> [dBm]	23	63
N <sub>0</sub> [dBm/Hz]	-174	
NF [dB]	8	

- MuLa - **sub-cm precision** across all distances.
- RMSE MuLa vs NTN-only reduced by **3 orders of magnitude**.
- RMSE MuLa vs TN-only reduced **2 orders of magnitude**
- **Adaptive range-weighting**: larger distances degraded NTN reflections are filtered.



D. Egea-Roca, A. Xhafa, J. A. Lopez-Salcedo, G. Seco-Granados, "First Results on RIS-Enabled Multi-Layer Localization: A Joint Terrestrial and Non-Terrestrial Method", Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), May 2026

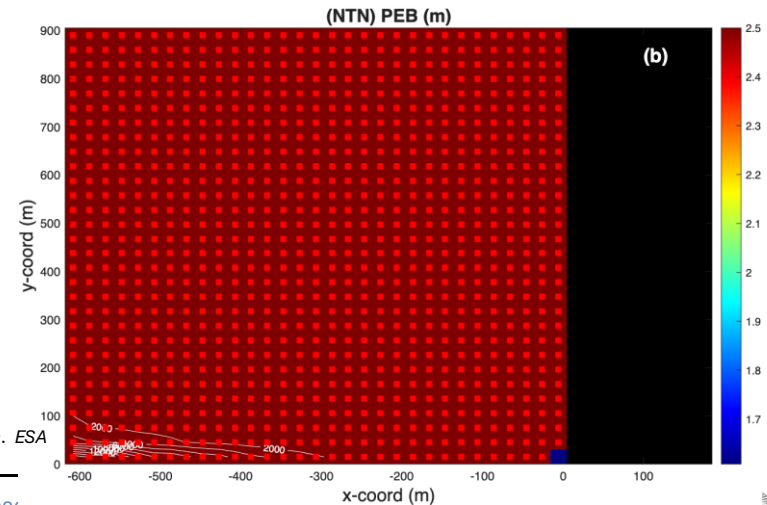
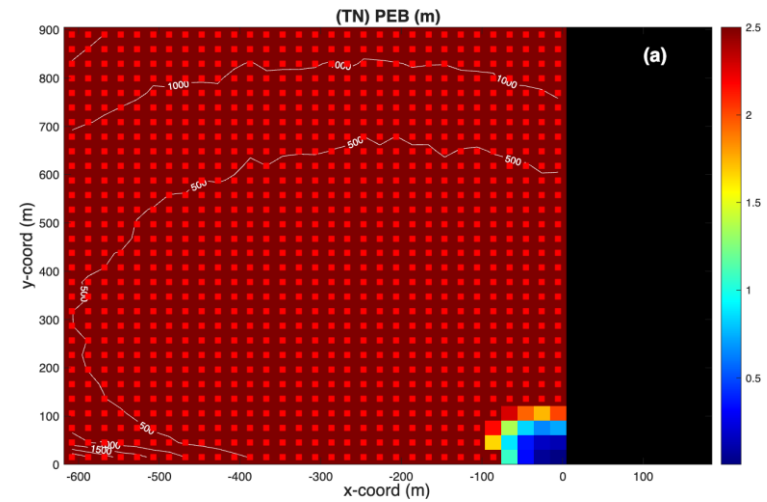
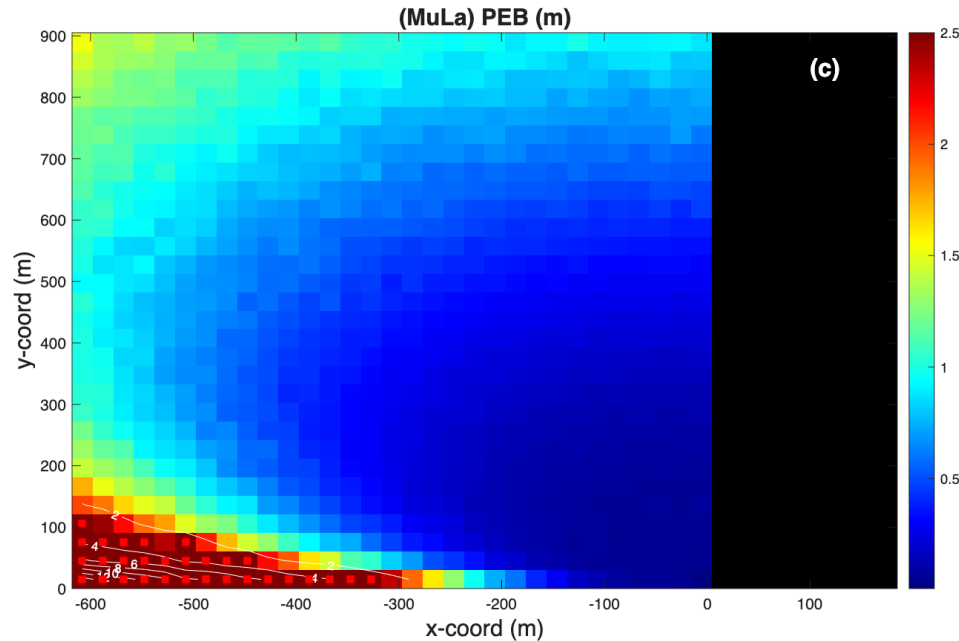
# Performance analysis




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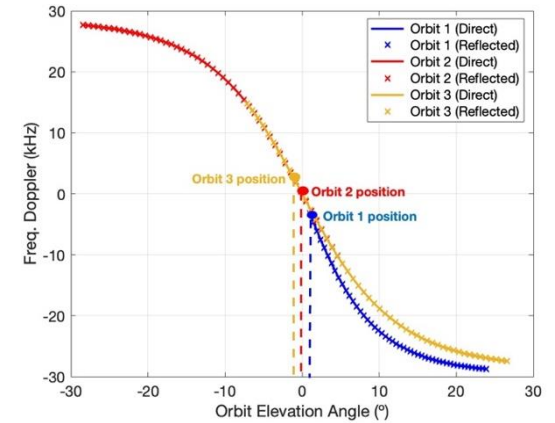
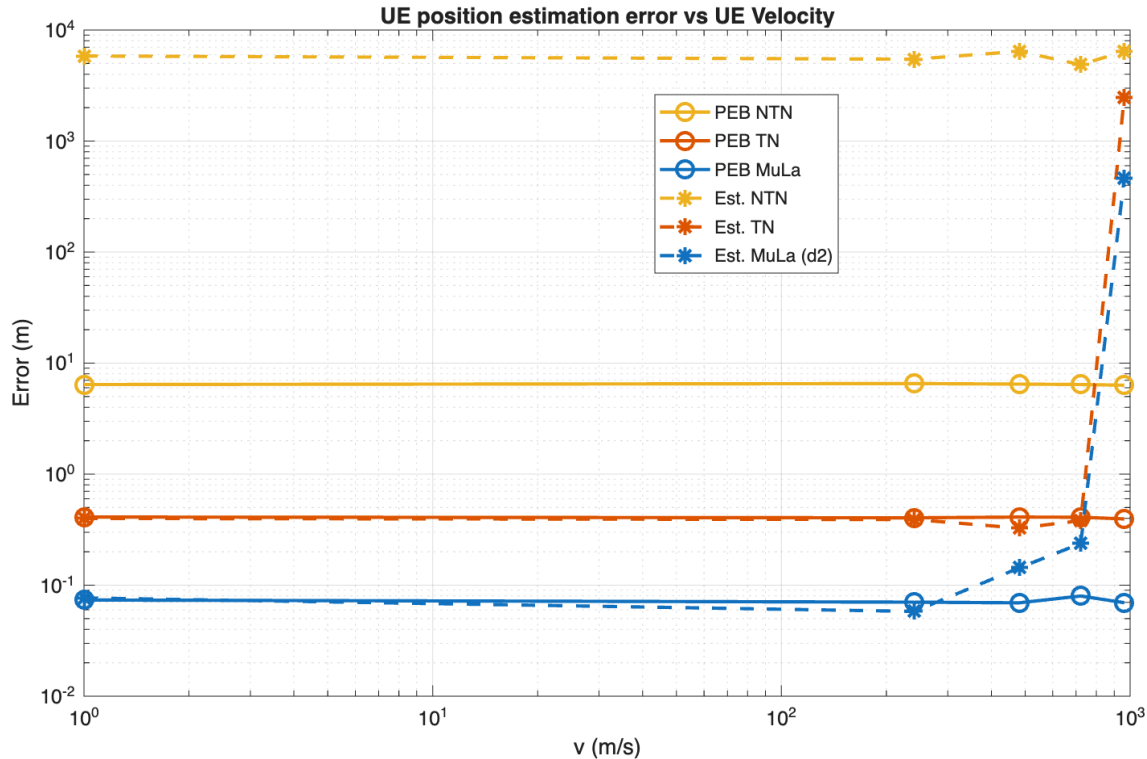
# Coverage analysis

- The RIS (1m<sup>2</sup>) is located at [0,0,0]<sup>T</sup> m.
- The TN transmitter is positioned near the RIS with diagonal direction relative to the RIS.
- The NTN transmitter follows a LEO orbit 2 configuration.



 J. A. del Peral-Rosado et al. "Technology Enablers Towards Unified PNT with GNSS, 5G and 6G Solutions", Proc. ESA Workshop on Satellite Navigation User Equipment Technologies (NAVITEC), May 2026.

# Dynamic range analysis

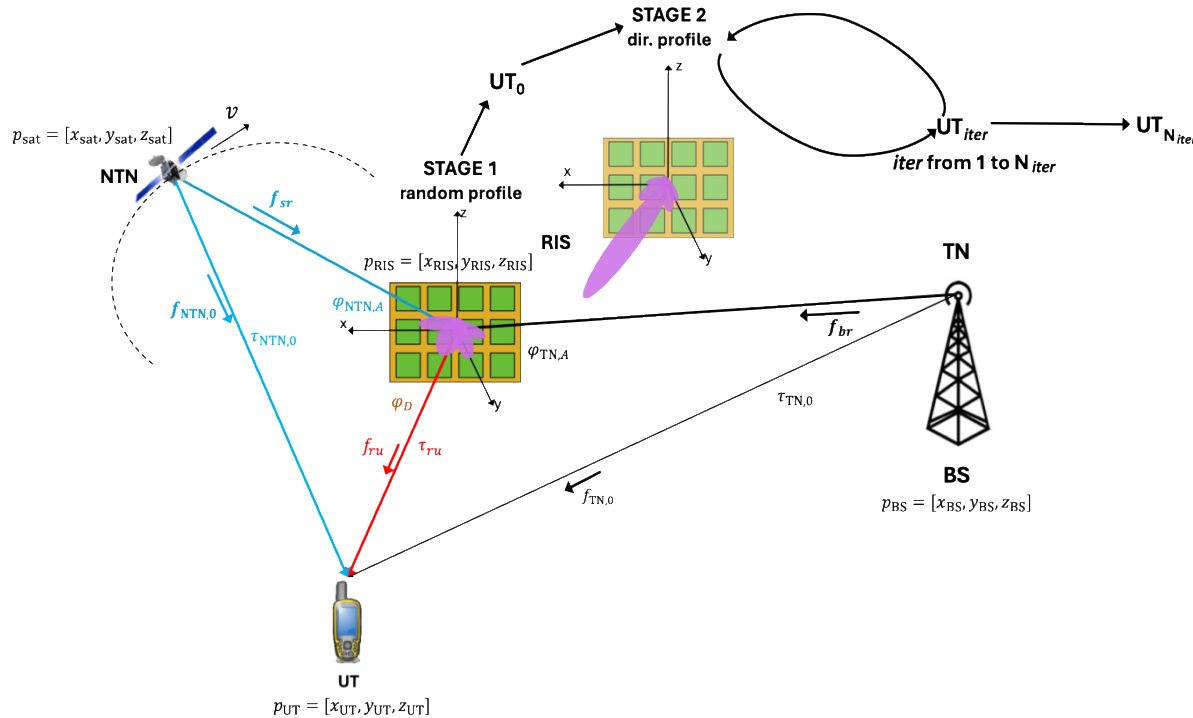


Pre-compensating for the dominant satellite Doppler ( $f_{sr}$ ).



The equivalent baseband channel becomes **"approximately time-invariant"** over the observation window.

# Hybrid Random-DIR RIS profile

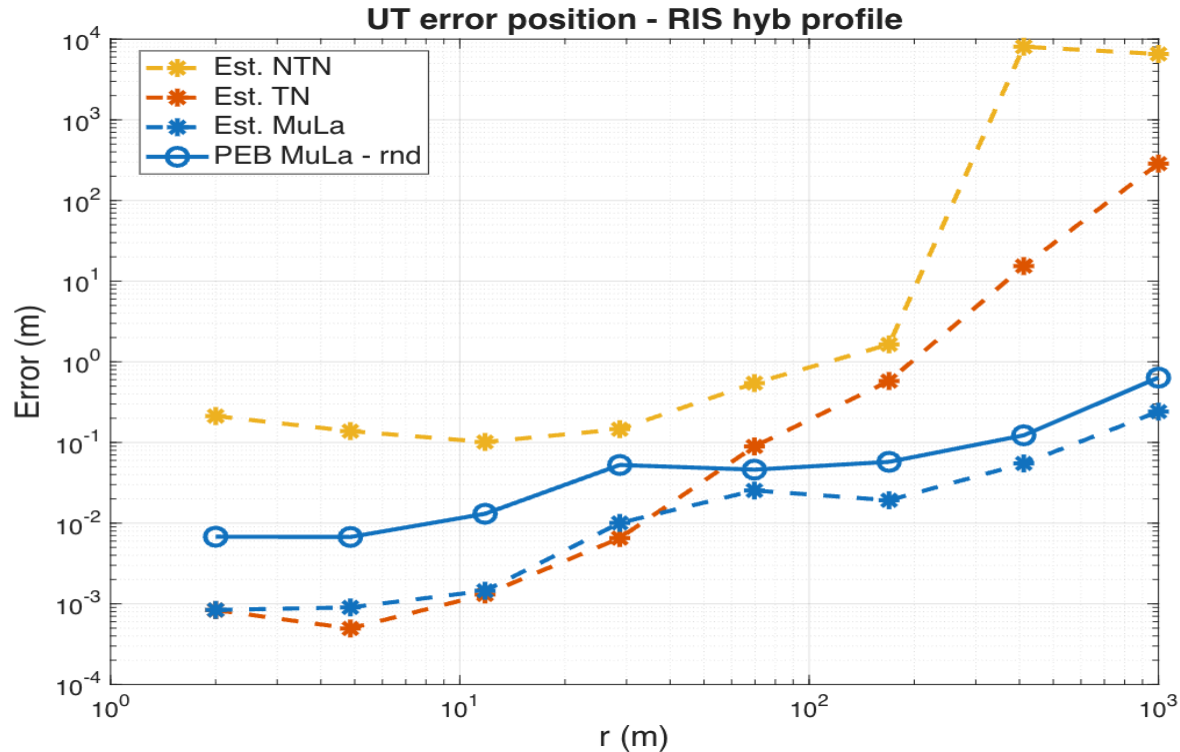


Frequency group	FR1	
Network type	TN	NTN
Operating freq. Band [GHz]	n1 [2.11 – 2.17]	n256 [2.17 – 2.2]
F_c [GHz]	2.13	2.185
Duplex mode	FDD	FDD
$\Delta f$ [kHz]	30	
B [MHz]	10	
Nsc	24 RB (288 sc)	
L (symbols)	280	
Ptx [dBm]	23	63
N0 [dBm/Hz]	-174	
NF [dB]	8	



A. Khafa, D. Egea-Roca, J. A. Lopez-Salcedo, S. Schlötzer, J. A. del Peral-Rosado, F. Abel, G. Seco-Granados, "Hybrid Random-Directional RIS Phase Profile Design for Multi-Layer TN/NTN Positioning", Proc. ESA Workshop on Satellite Navigation User Equipment Technologies (NAVITEC), May 2026.

# Hybrid Random-DIR RIS profile

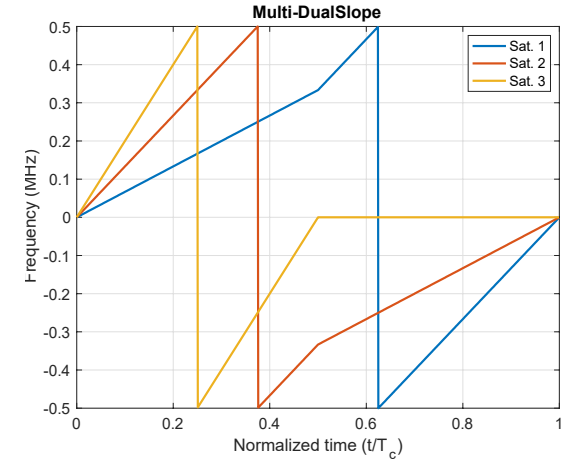
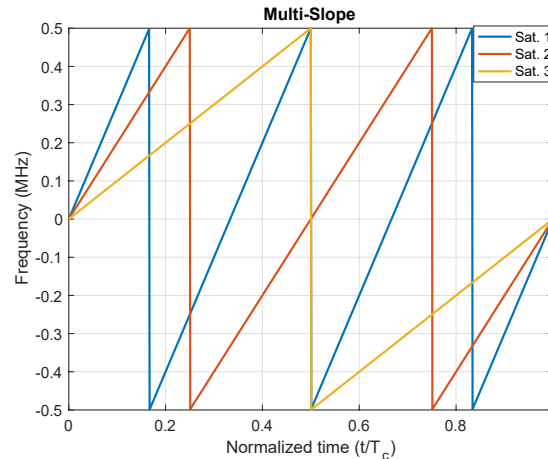
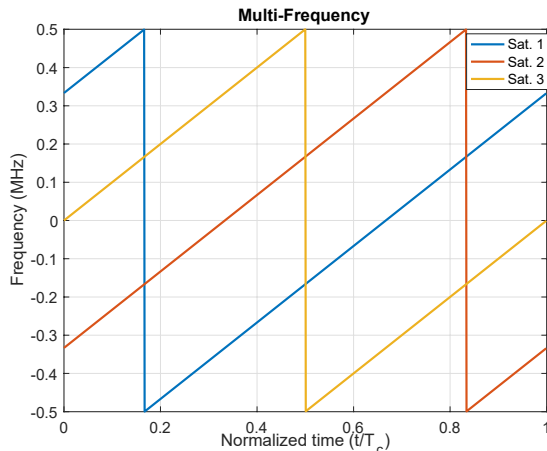


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# Signals for LEO-PNT

## Chirp Spread Spectrum

- Traditionally used in radar for range and velocity (Doppler) sensing
- Also used in communications: LoRaWAN networks (wide area and low power)
- LEO-PNT: Lower complexity (from 1 up to 2 orders of magnitude) than DSSS (GNSS-like)
- Three different strategies to achieve orthogonality between satellites:

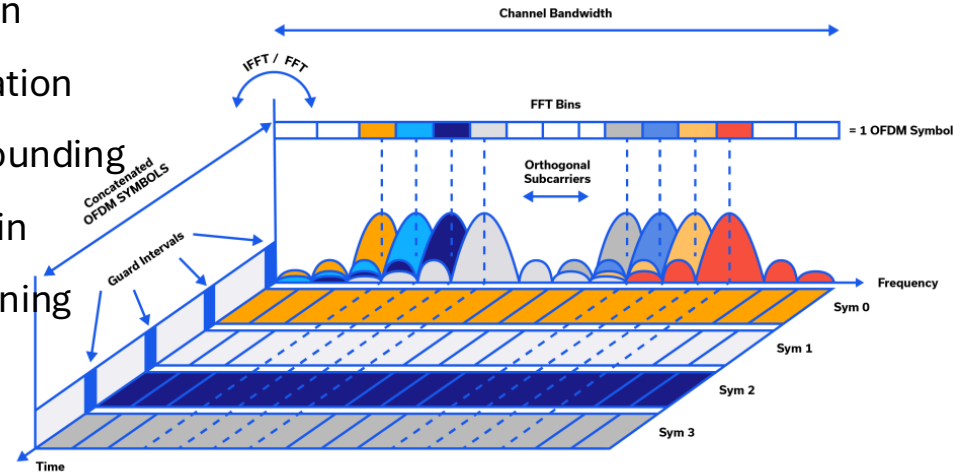


ESA-funded LEGION - LEO-PNT End-to-End In-Orbit-Demonstration. @Fran Fabra, FranciscoJose.Fabra@uab.cat

# Signals for LEO-PNT

## 5G Non-Terrestrial Networks

- 5G: waveform structure based on orthogonal frequency division multiplexing (OFDM)
- 3GPP includes NTN for 5G and it is working on optimizing 5G signals for NTN-based localization
- The positioning reference signal (PRS) and sounding reference signal (SRS) are dedicated signals in downlink and uplink, respectively, for positioning purposes based on time-delay estimation

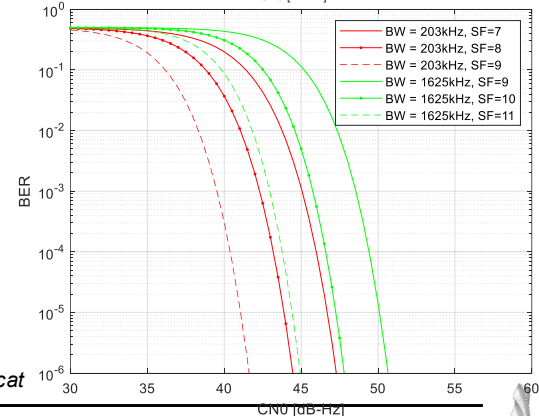
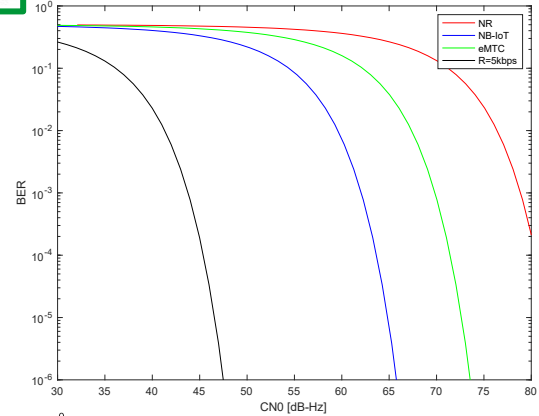
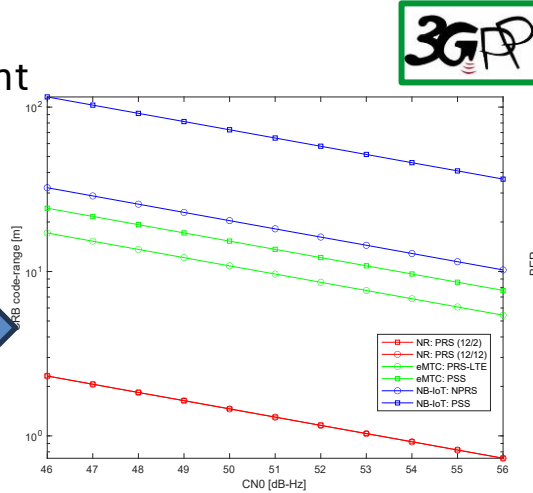
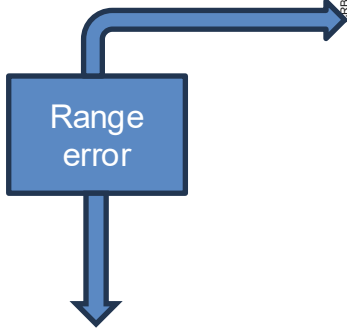


ESA-funded LEGION - LEO-PNT End-to-End In-Orbit-Demonstration. @Fran Fabra, FranciscoJose.Fabra@uab.cat



# Analysis of range accuracy with communication signals

- CRB computations done for different configurations
- BER computations allow to also evaluate the communication performance



CRB (Tc) [m]	SF						
	7	8	9	10	11	12	
BW [kHz]	203	110.2	78.0	55.1	39.0	27.6	19.5
	406	78.0	55.1	39.0	27.6	19.5	13.8
	812	55.1	39.0	27.6	19.5	13.8	9.7
	1625	39.0	27.6	19.5	13.8	9.7	6.9

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## Further Work

Handling high mobility and motion effects: Development of improved algorithms that can effectively manage satellite-induced motion effects.

Exploring multiple RIS units for the integrated TN/NTN scenario.

Improve the hybrid phase profile design using constrained optimization

**Thank you for your attention !**