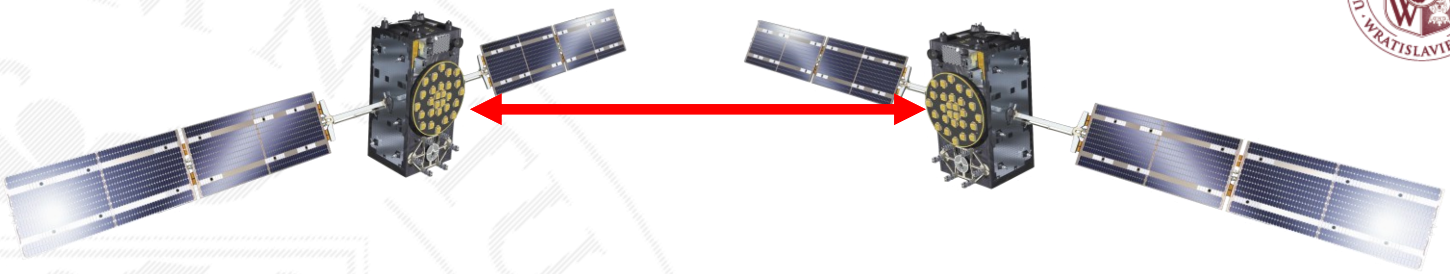

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Inter-Satellite Links in Galileo Second Generation: Strategies and Challenges

Tomasz Kur[1], Krzysztof Sośnica[1], Maciej Kalarus[2]

[1] Wrocław University of Environmental and Life Sciences, Institute of Geodesy and Geoinformatics, Wrocław, Poland

[2] University of Bern, Astronomical Institute, Bern, Switzerland

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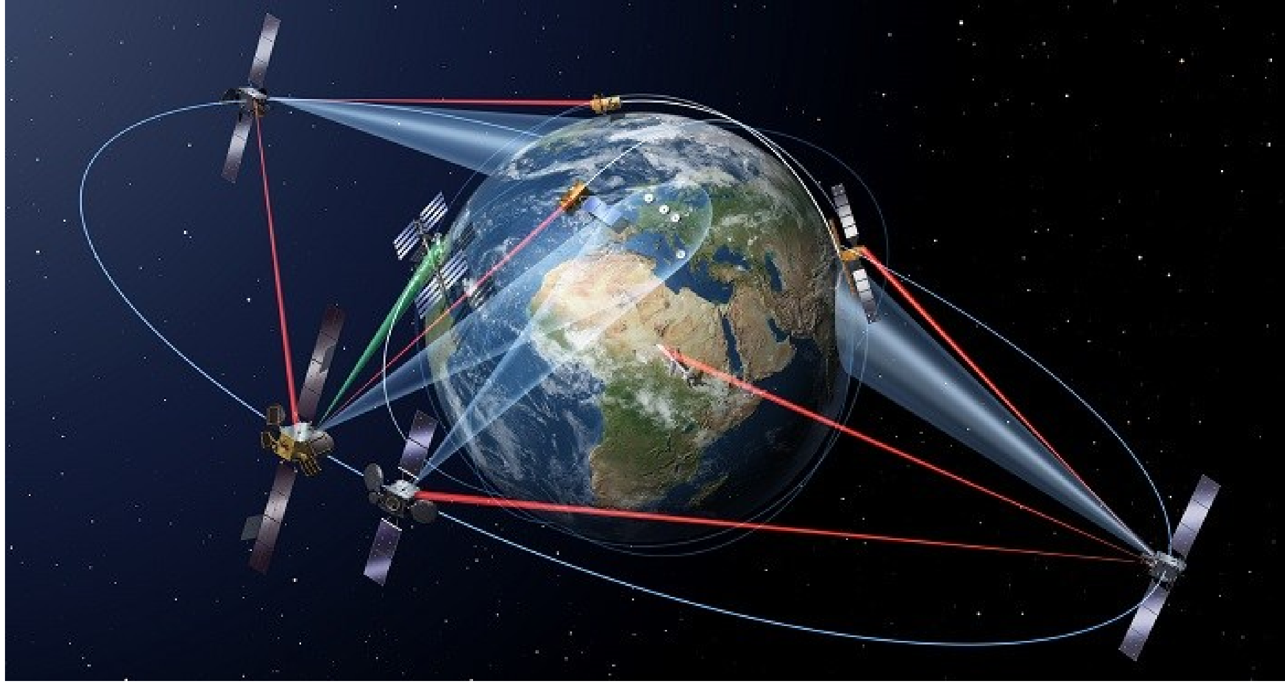
What is an inter-satellite link (ISL)?

An **inter-satellite link (ISL)** is a direct communication channel between two or more satellites, without the need for data to be relayed through ground stations.



<u>What is it used for?</u>

- Real-time data exchange
- Network expansion in space
- Global data coverage
- Low-latency communication
- Ranging

<u>Key Applications</u>

- Global broadband (e.g., Starlink, OneWeb)
- Earth observation and sensor coordination
- Military and defense communication systems
- **<u>GNSS and satellite navigation enhancement</u>**

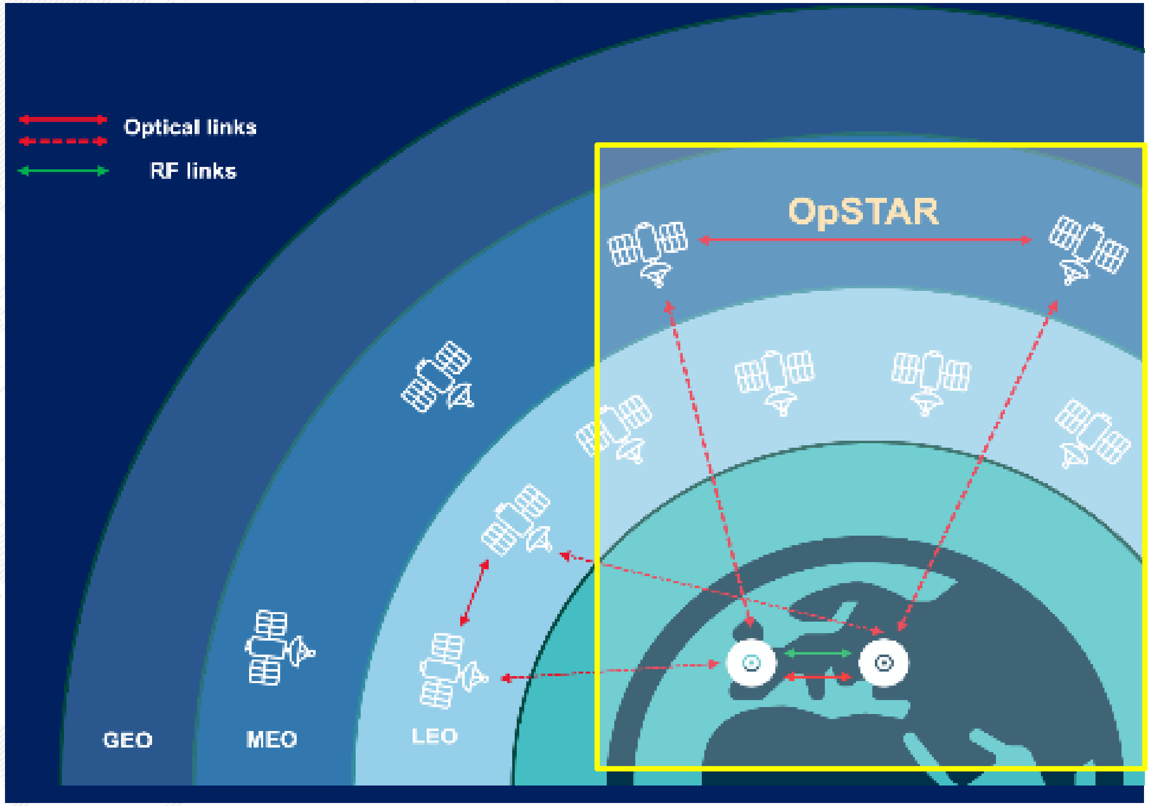
<u>Why it matters:</u> ISLs are the backbone of autonomous satellite networks — enabling faster, more reliable, and globally accessible communication infrastructures.

ISLs – status in Galileo

- ISLs are planned on **Galileo 2nd Gen Satellites**

Research on optical technology for enhanced robustness and performance for:

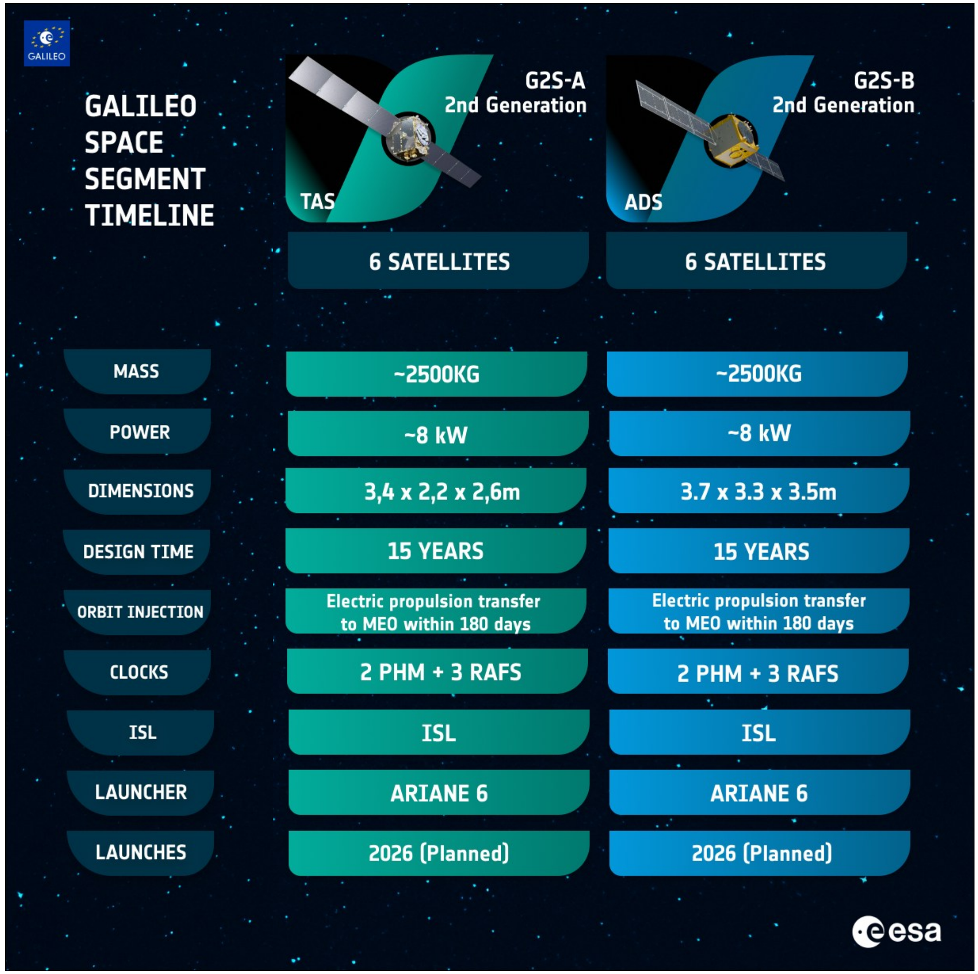
- ✓ Time synchronization & ranging
- ✓ Significant performance improvement at system/user level
- ✓ New system architecture based on optical links
- ✓ Open standards for O-ISL (physical, data link and network layers)



ENABLING & SUPPORT

Optical inter-satellite links are best tech for Galileo

12/07/2019



Challenges of implementing ISLs in Galileo

What are the potential challenges for geodesy then?

and energy-intensive.

- ❖ **The role of the connectivity scheme in orbit determination and clock estimation is important.**

2. Technology readi

- ❖ ISLs require lase in development.
- ❖ Galileo satellites upgrading require

3. Power and size c

- ❖ Laser terminals a challenge for sa

4. Latency vs accur

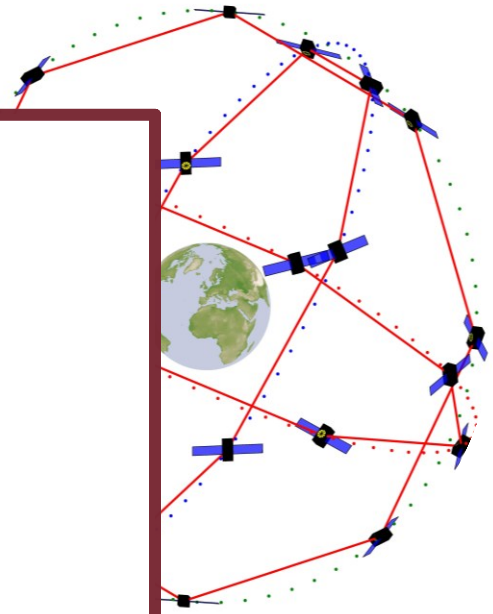
- ❖ ISLs could enabl services.
- ❖ **Clock synchronization, ranging, and navigation message consistency** across ISLs must meet extremely high precision standards.

5. Cost and programmatic risks

- ❖ Adding ISLs increases satellite complexity, cost, and testing requirements.

The objectives of the research are to:

1) preliminary assess the necessity of **on-ground calibrations**,
2) analyze ISL range biases (ISL RB) **estimation strategies**,
3) evaluate the **impact of ISL on orbit and clock determination**.



Simulation properties overview

Primary simulation parameters

Satellite models	
Galileo-like constellation	Galileo FOC box-wing model
Walker definition	56°: 24/3/1
Orbit radius	29 600 km
Numerical integrator	Runge-Kutta 4th order
Satellite surface properties	Box-wing model based on EUSPA metadata https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata
Force models used in orbit propagator	
Earth gravity field	EGM2008 16×16
Gravitational perturbation	Sun, Moon, and nearest planets
Relativistic perturbations	Schwarzschild Term, Lense-Thirring precession, geodetic precession
Solar flux	Constant
Earth's albedo and thermal radiation	Analytical

Simulation of GNSS observations	
GNSS observations for ground stations	
Sampling interval	30 s
Observation noise	1 cm
Zenith wet delays	Harmonic function with horizontal variations
Observation weighting	Observation weight $P_{GNSS} = \frac{cos^2(z)}{\sigma^2_{GNSS}}$, where z is the satellite zenith angle and σ_{GNSS} is GNSS observation noise
Station clock errors - observation noise	1 ns
Satellite clock errors - observation noise	0.1 ns
ISL measurements	
Sampling interval	30 s
Observation noise	0.5 cm
Observation weighting	Observation weight $P_{ISL} = \frac{1}{\sigma^2_{ISL}}$, where σ_{ISL} is ISL observation noise
Satellite clock errors - observation noise	0.1 ns

Estimation
Satellite positions and velocities
ECOM2 – 9 parametr (constants D_0, Y_0, B_0, with periodic terms $D_{2,C}$, $D_{2,S}$, $D_{4,C}$, $D_{4,S}$, $B_{1,C}$, $B_{1,S}$)
Epoch-wise satellite clocks
Epoch-wise station clocks (one reference clock is fixed)
Zenith wet delays – piecewise linear model

Properties evaluated in simulations

Property	Options
(1) Number of ground stations	• 16 (Galileo Ground Segment) • 44
(2) Weighting	• Nominal • Variance component estimation
(3) Connectivity schemes	• Sequential • Nearest General (regarding the orbital plane) • Nearest Inter-Plane (connections only between the adjacent orbital planes) • Intra-Plane Closed** • Intra-Plane Open**
(4) ISL RB estimation approach	• Piecewise constant bias – PCB (3, 6, 12 intervals) • Piecewise linear bias – PLB (3, 6, 12 intervals)
(5) ISL RB calibration constants	• Case 1: calibration constants not included (no a priori bias values are used, bias parameters are estimated) • Case 2: calibration constants included w/o estimation (considered as a priori values and no bias parameters are estimated)

** Intra-Plane Closed and Intra-Plane Open schemes **require ISL RB values to be fixed** for at least one satellite in the orbital plane

Weighting approach

Variance component estimation – rescaling NEQ

Step 1.

$$N_{GNSS} = A_{GNSS}^{T} P_{GNSS} A_{GNSS}$$

$$N_{ISL} = A_{ISL}^{T} P_{ISL} A_{ISL}$$

Step 2.

$$k = 0 \rightarrow S_{GNSS}^{(k)} = \sigma_{GNSS},\ S_{ISL}^{(k)} = \sigma_{ISL}$$

$$N^{(k)} = \frac{1}{S_{GNSS}^{2\,(k)}} N_{GNSS} + \frac{1}{S_{ISL}^{2\,(k)}} N_{ISL}$$

$$r_{GNSS}^{(k)} = n_{GNSS} - trace(N_{GNSS} N^{-1})$$

$$r_{ISL}^{(k)} = n_{ISL} - trace(N_{ISL} N^{-1})$$

$$S_{GNSS}^{2\,(k+1)} = \frac{v_{GNSS}^{T} P_{GNSS} v_{GNSS}}{r_{GNSS}^{(k)}}$$

$$S_{ISL}^{2\,(k+1)} = \frac{v_{ISL}^{T} P_{ISL} v_{ISL}}{r_{ISL}^{(k)}}$$

Step 3.

$$S_{GNSS}^{(k+1)} - S_{GNSS}^{(k)} > \varepsilon$$

$$S_{ISL}^{(k+1)} - S_{ISL}^{(k)} > \varepsilon$$

$$k = k + 1$$

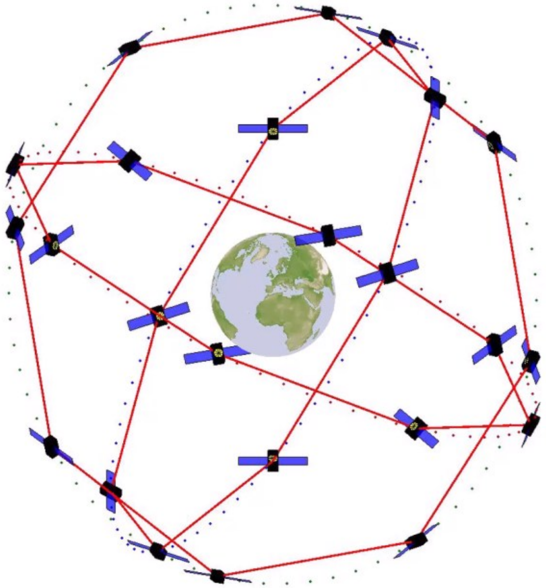
$$N^{(k+1)} = \frac{1}{S_{GNSS}^{2\,(k+1)}} N_{GNSS} + \frac{1}{S_{ISL}^{2\,(k+1)}} N_{ISL}$$

In nominal weighting

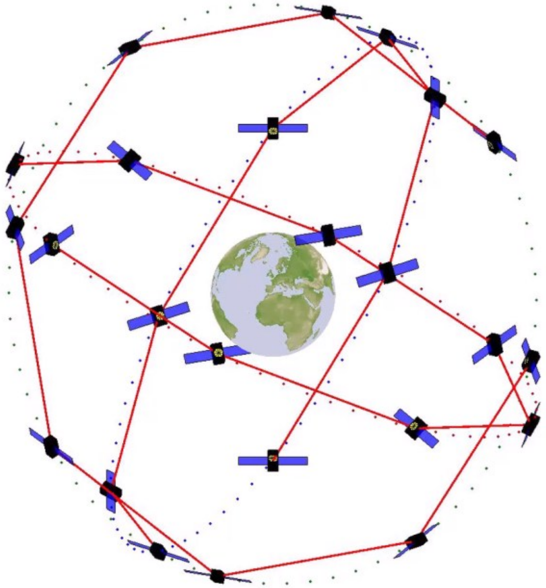
$S_{GNSS} = 1;\ S_{ISL} = 1 \rightarrow$ no NEQ rescaling

Connectivity schemes

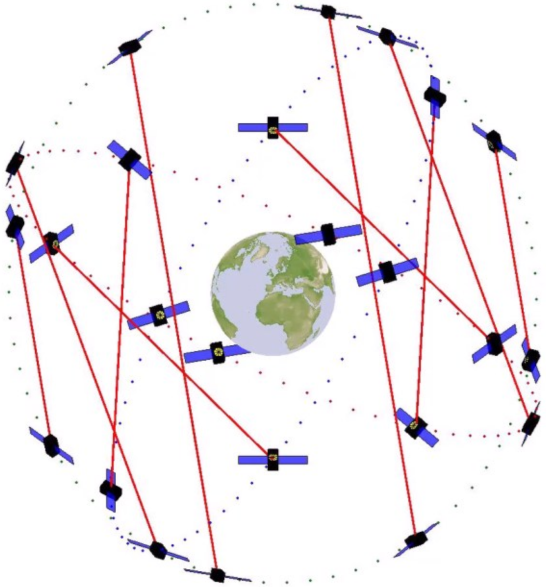
Intra-Plane Closed



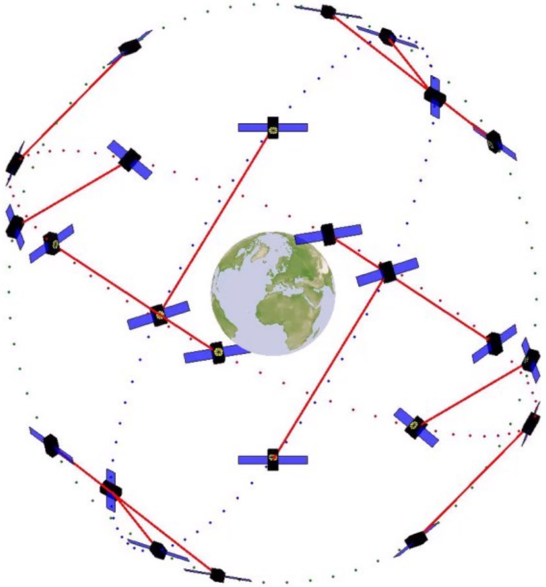
Intra-Plane Open



Sequential



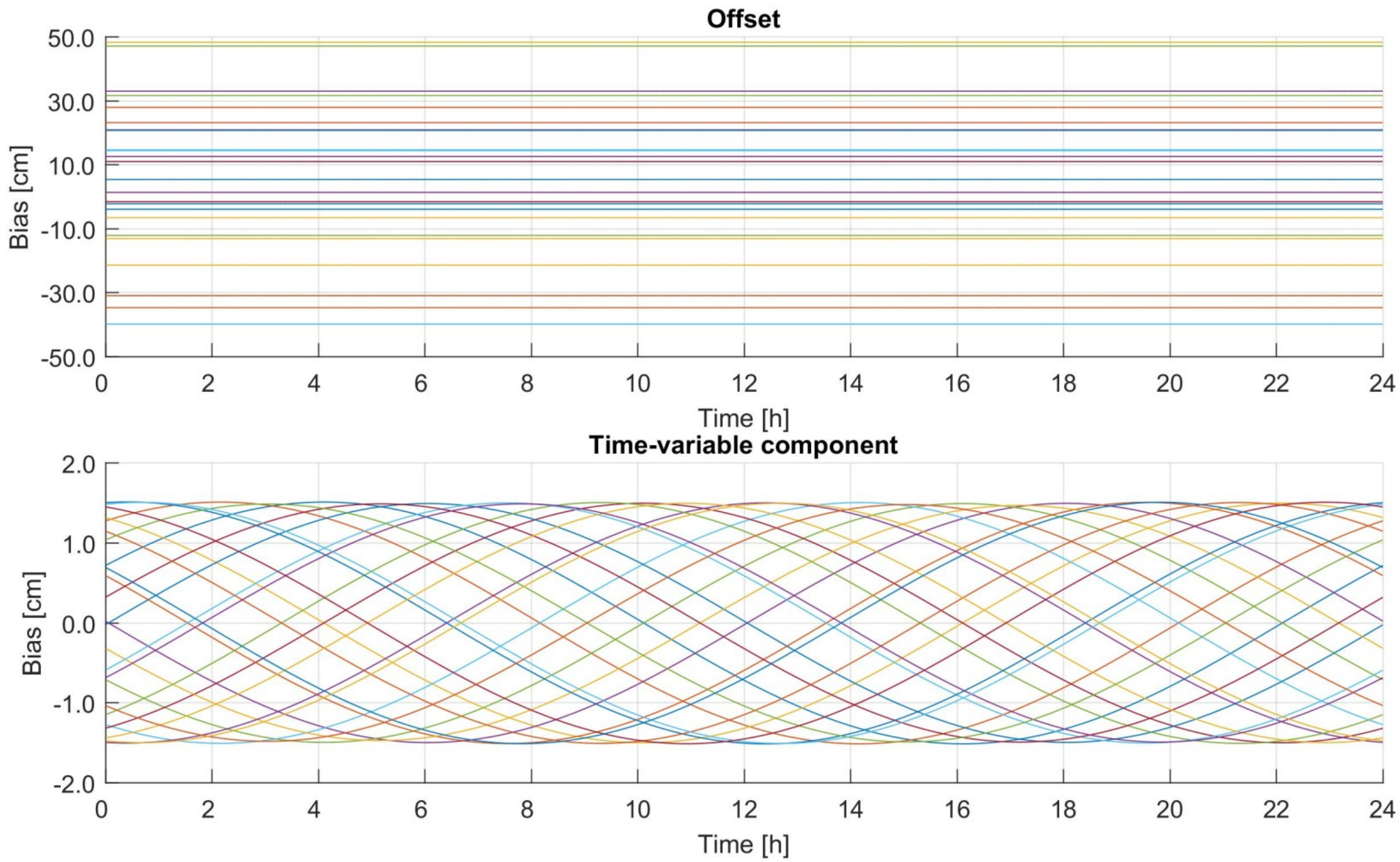
Nearest General
Nearest Inter-Plane



Calibration

ISL RB = offset + time-variable component

Calibration constant = offset + mean(time-variable component)

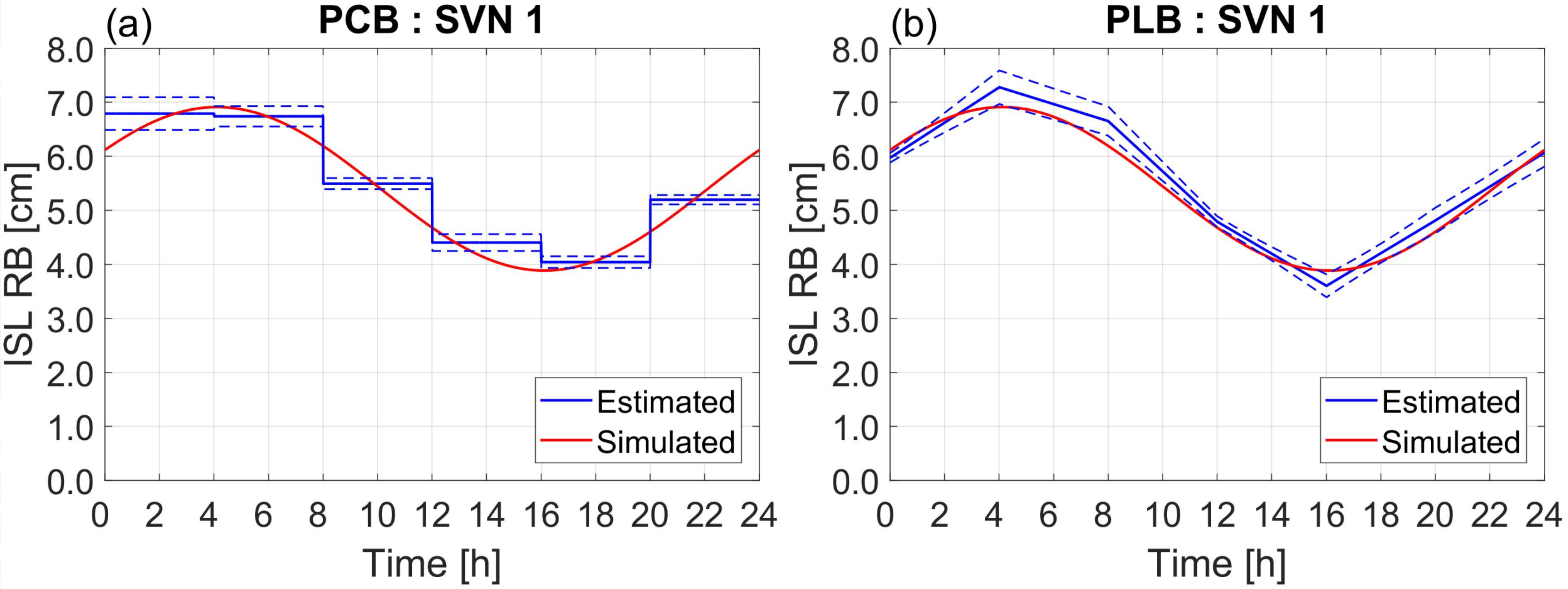


Offset serves as potential input value obtained from on-ground calibration

- **Case 1**: calibration constants not included (no a priori bias values are used, bias parameters are estimated)

- **Case 2**: calibration constants included w/o estimation (considered as a priori values and no bias parameters are estimated)

ISL RB

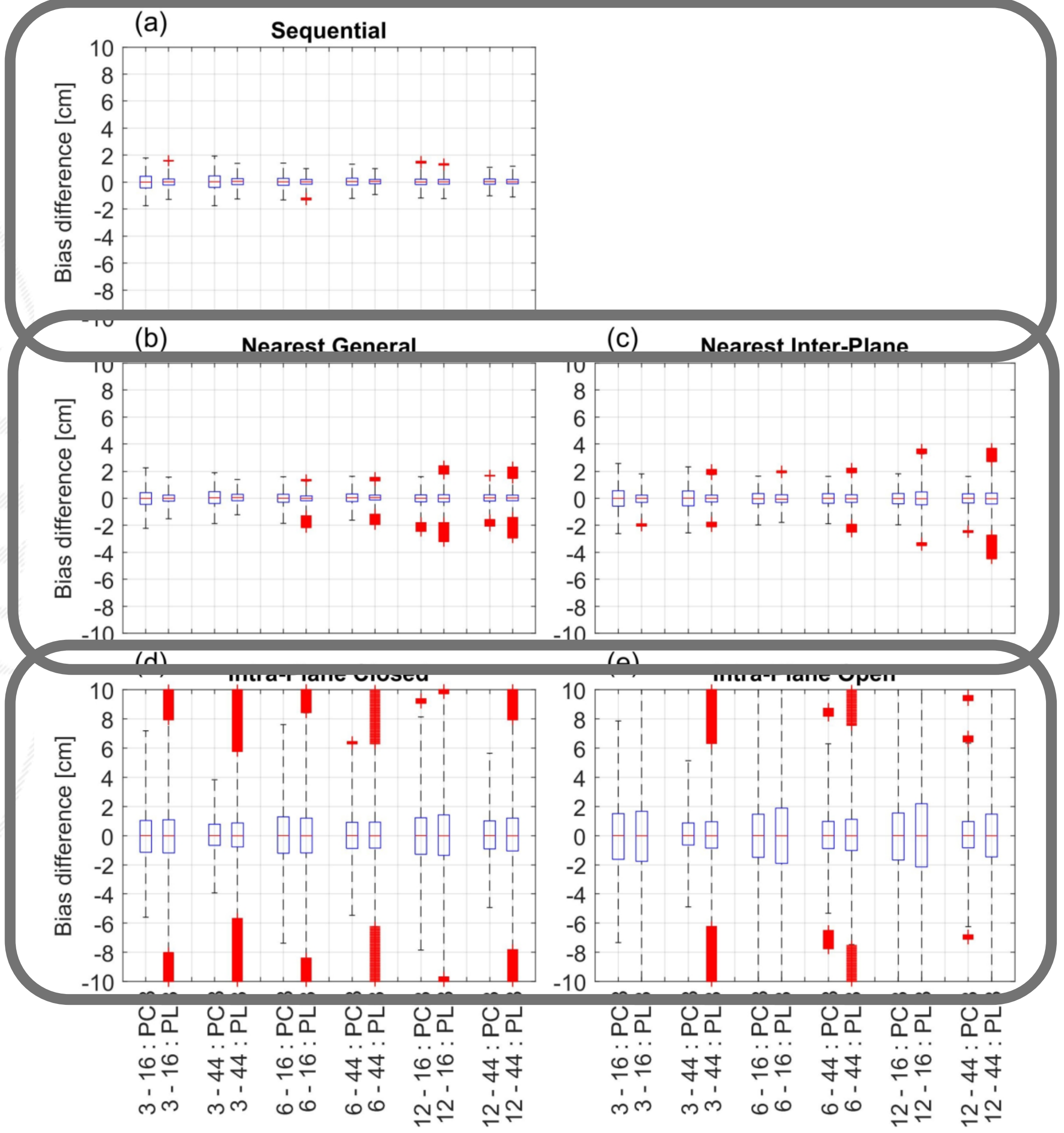


Piecewise constant

Piecewise linear

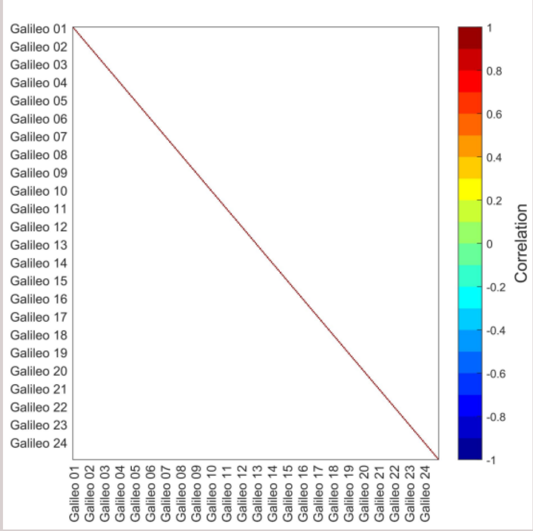
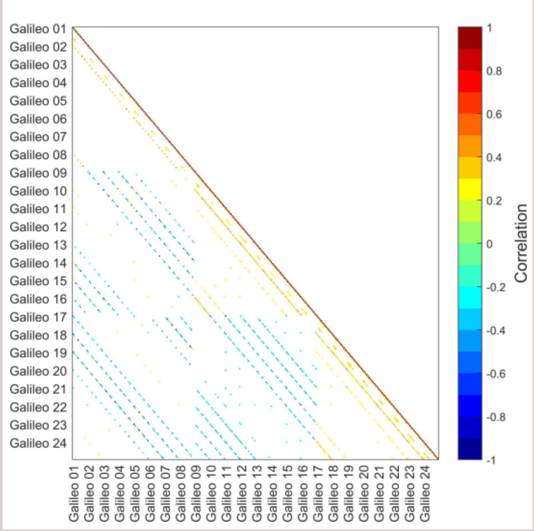
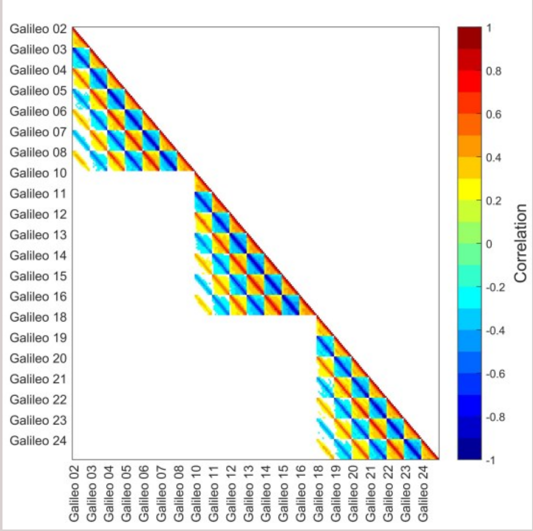
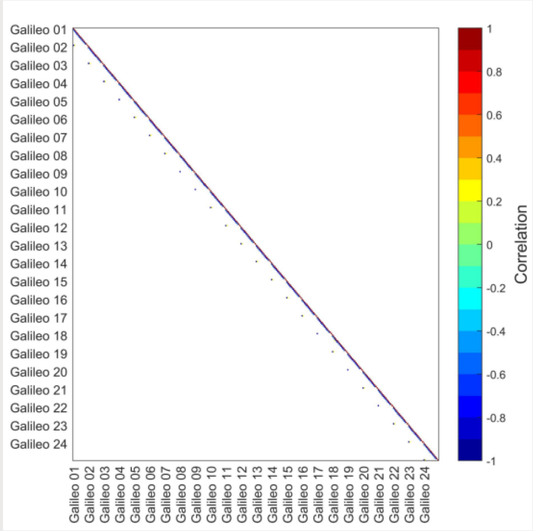
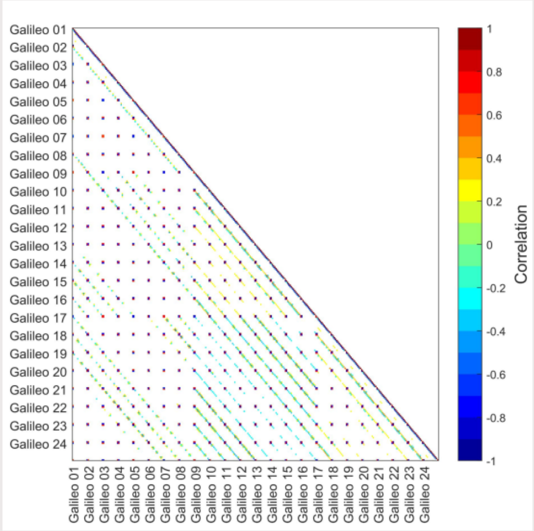
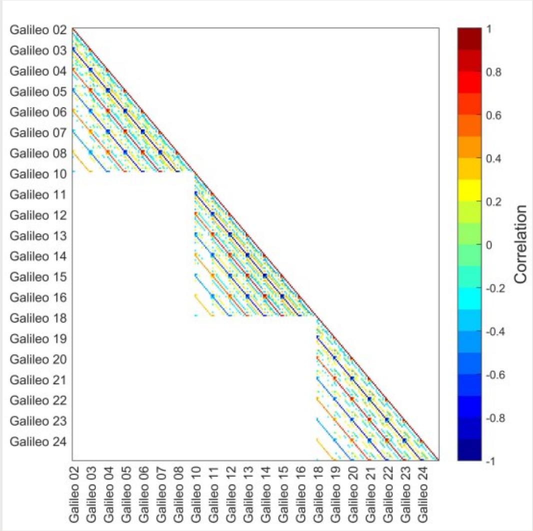
Selected simulation results

ISL RB – observed minus computed

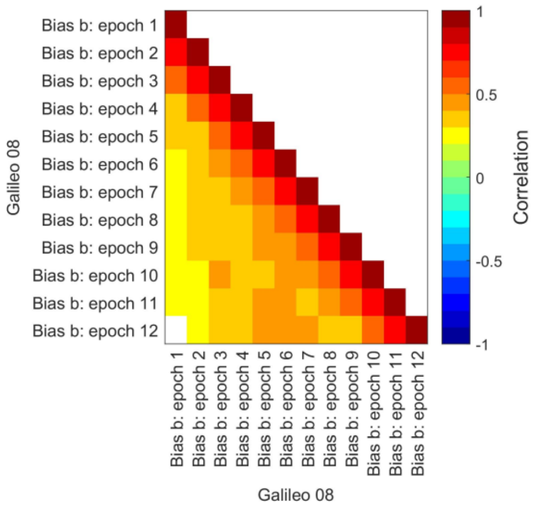


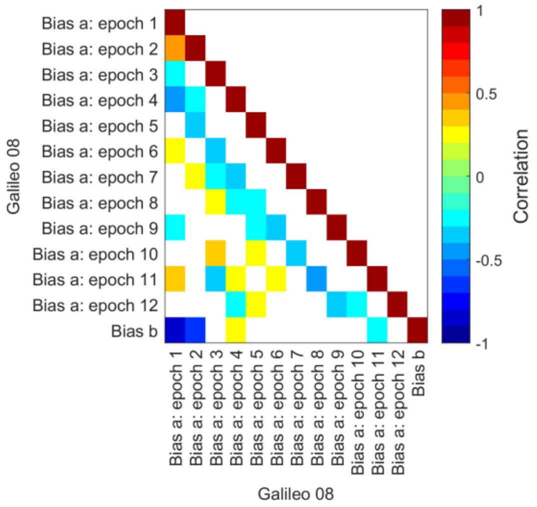
General overview of bias parameters correlation

12 epochs
nominal weighting
44 ground stations

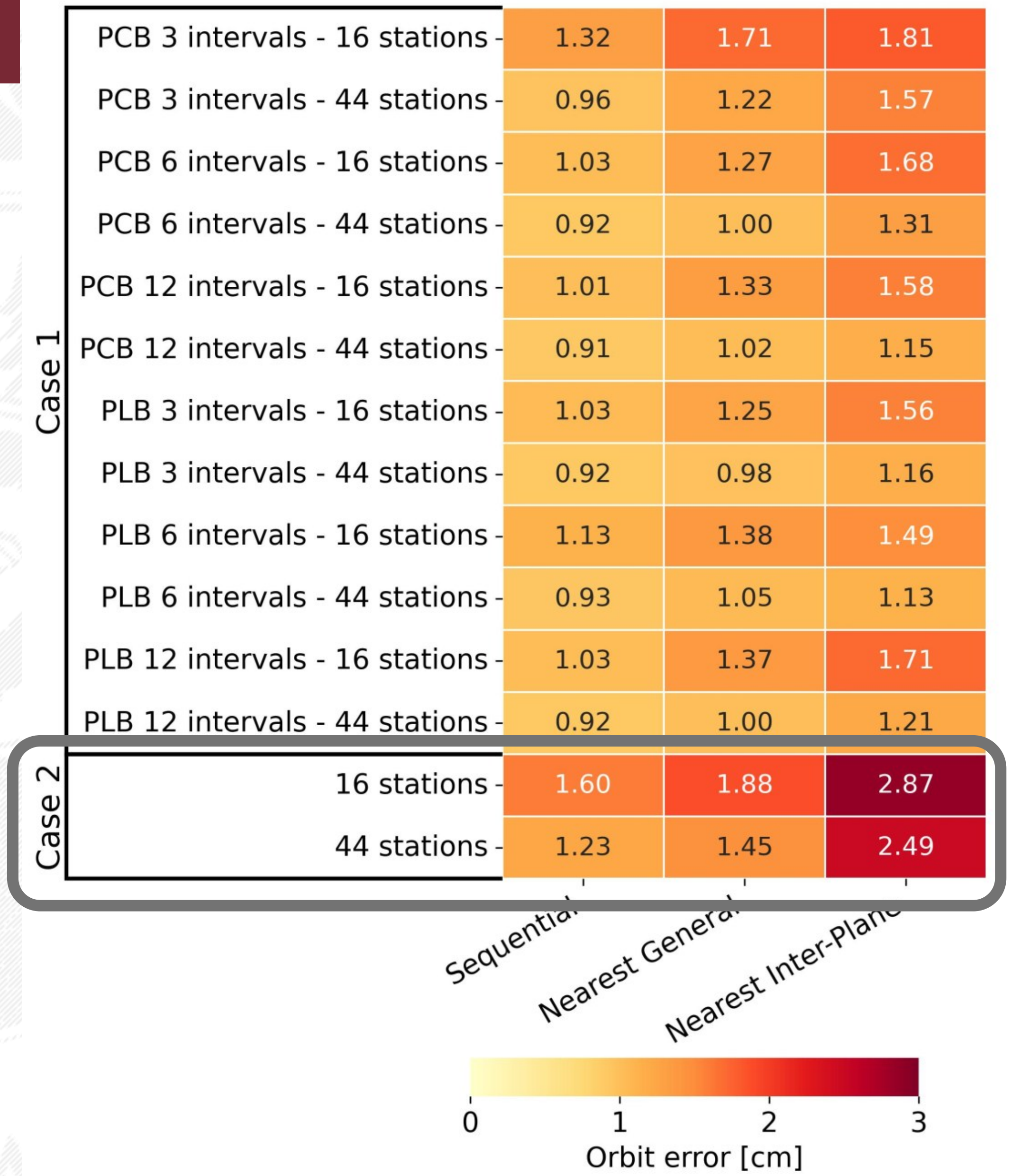
	Sequential	Nearest Inter-Plane	Intra-Plane Open
PCB			
PLB			

Bias parameters for satellite





Considering on-ground calibration



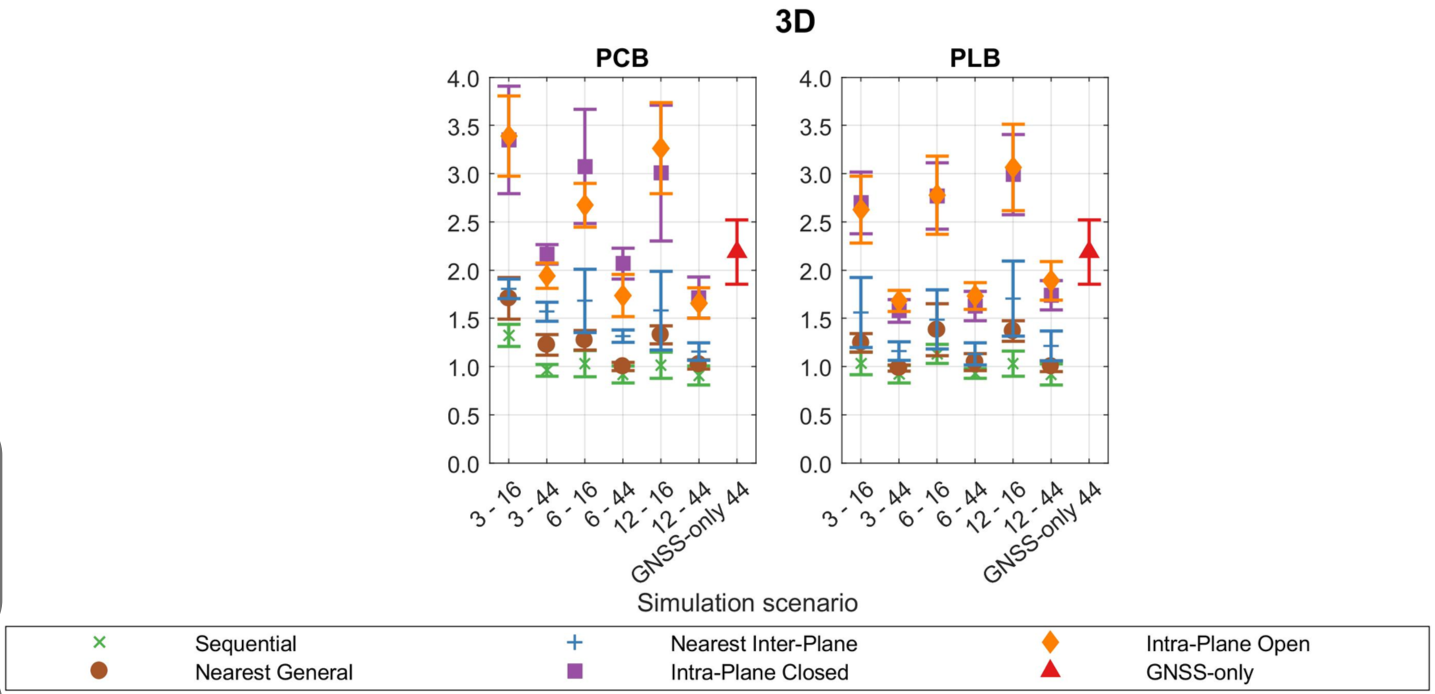
- ***Case 1:*** *calibration constants not included (no a priori bias values are used, bias parameters are estimated)*
- ***Case 2:*** *calibration constants included w/o estimation (considered as a priori values and no bias parameters are estimated)*

- Increasing the number of intervals from 3 to 12 shows mixed effects, but generally helps stabilize or reduce metric values, especially in PLB configurations.
- PLB configurations typically yield slightly lower or comparable values than PCB.
- Estimation of ISL range biases can replace ground calibrations.

Orbit estimation errors

Mean orbit 3D RMS [cm]				
		44 ground stations		
		3 epochs	6 epochs	12 epochs
PCB	Sequential	1.0	0.9	0.9
	Nearest General	1.3	1.0	1.0
	Nearest Inter-Plane	1.5	1.2	1.1
	Intra-Plane Closed	2.2	1.8	1.6
	Intra-Plane Open	1.8	1.6	1.5
PLB	Sequential	1.0	0.9	0.9
	Nearest General	1.0	1.0	1.0
	Nearest Inter-Plane	1.1	1.0	1.1
	Intra-Plane Closed	1.7	1.4	1.6
	Intra-Plane Open	1.6	1.5	1.6

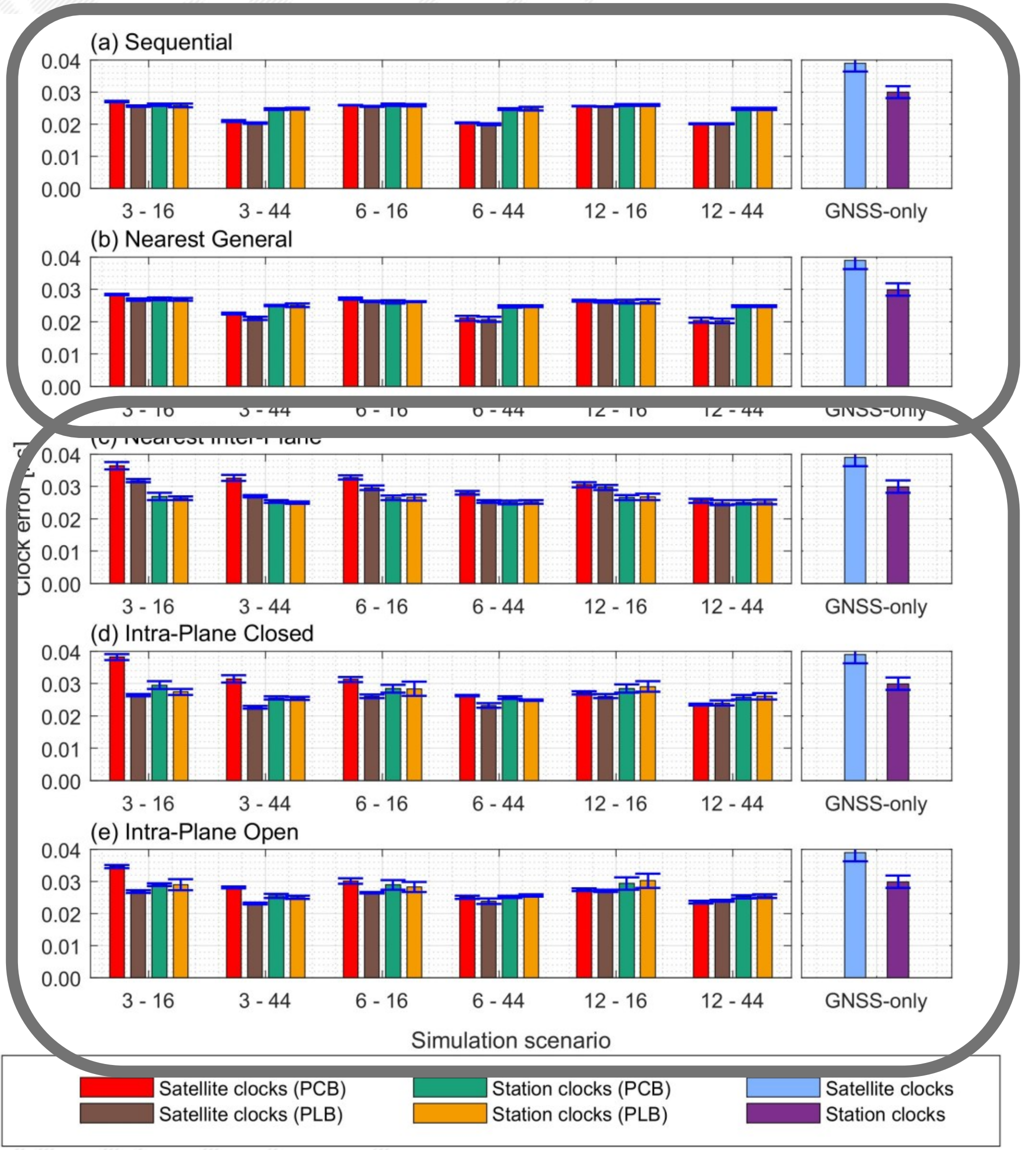
Mean orbit 3D RMS for GNSS-only = **2.3 cm**



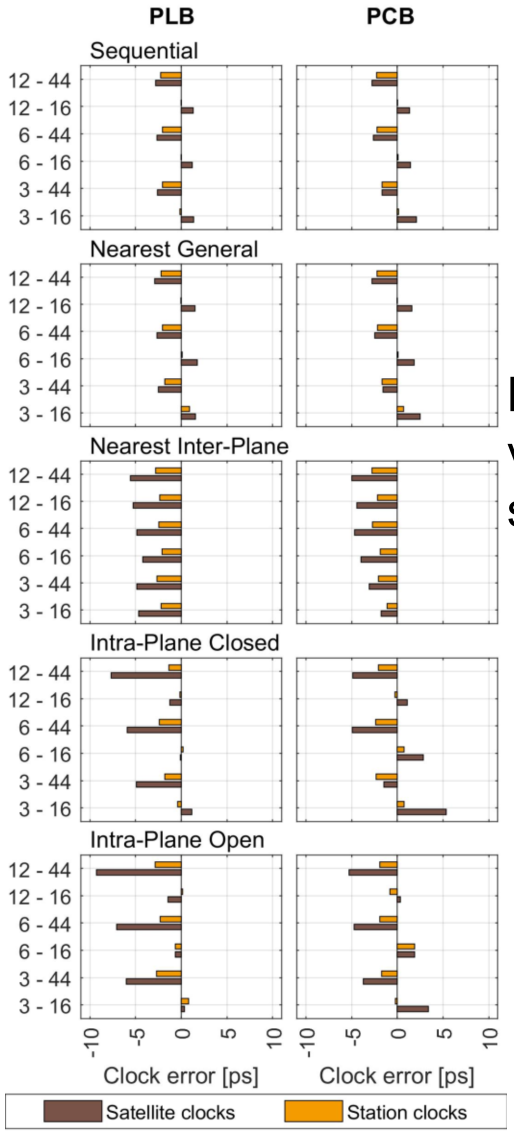
- The Sequential scheme consistently provides the best orbit accuracy across all settings.
- Increasing the number of epochs reduces RMS errors in some cases.
- Intra-Plane methods (Closed and Open) perform the worst.

Clock estimation – impact of weighting method

Nominal

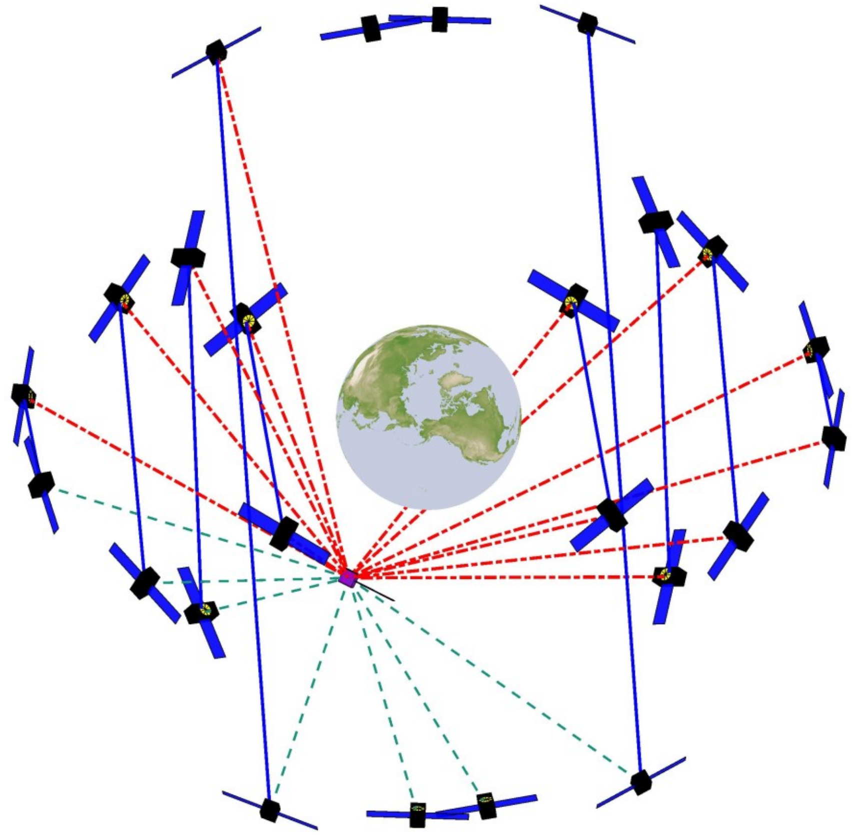


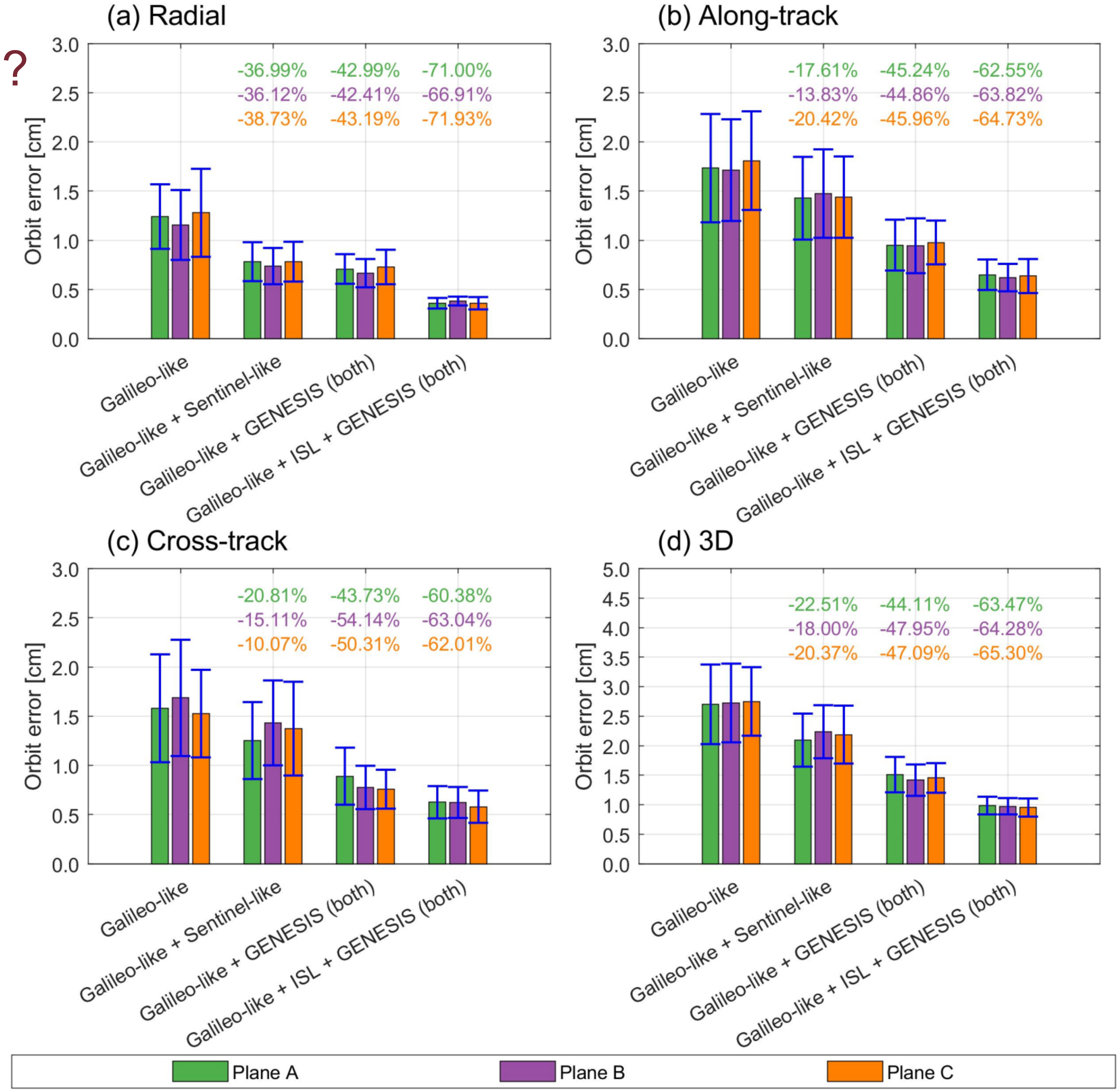
Difference VCE - Nominal



Both weighting approaches, i.e., nominal and variance component estimation, provide small differences in the estimation results.

Alternatives – MEO + LEO satellites? (Sentinel 6-like / Genesis)





Genesis – zenith and nadir GNSS antenna

Sentinel 6 – zenith GNSS antenna

Summary and conclusions

1. **Connectivity schemes**
   - Sequential schemes give the best results for ISL RB, orbit, and clock accuracy.
   - Ring schemes perform poorly due to limited ISL geometry - cross-plane links are essential to reduce systematic errors.
2. **Calibration and parameterization**
   - ISL RB estimation can replace on-ground calibration.
3. **Ground stations and weighting**
   - Ring schemes should be avoided when using a few ground stations.
   - Weighting methods have minimal impact on the orbit and clock estimation (but still!).
4. **Recommendations**
   - Use schemes with diverse ISL geometry, especially cross-plane links as intra-plane schemes are less reliable.
   - Sequential schemes can maintain orbit accuracy even with fewer stations.
   - Joint MEO – LEO satellites orbit estimation → multilayer concept → zenith and nadir GNSS antennas on new LEO?

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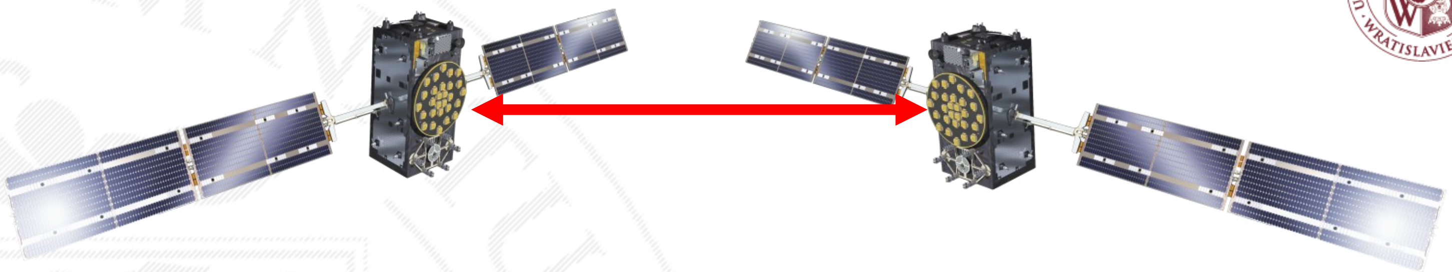

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Thank you for your attention

Tomasz Kur[1], Krzysztof Sośnica[1], Maciej Kalarus[2]

[1] Wrocław University of Environmental and Life Sciences, Institute of Geodesy and Geoinformatics, Wrocław, Poland

[2] University of Bern, Astronomical Institute, Bern, Switzerland

tomasz.kur@upwr.edu.pl

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