



HYbrid **P**ositioning **E**ngine **R**unning on
5G and **GNSS**

8 May 2024 - Open Attendance Meeting



POLITECNICO
MILANO 1863



algowATT
GREEN TECH SOLUTIONS



Project overview

HYPER-5G aimed at

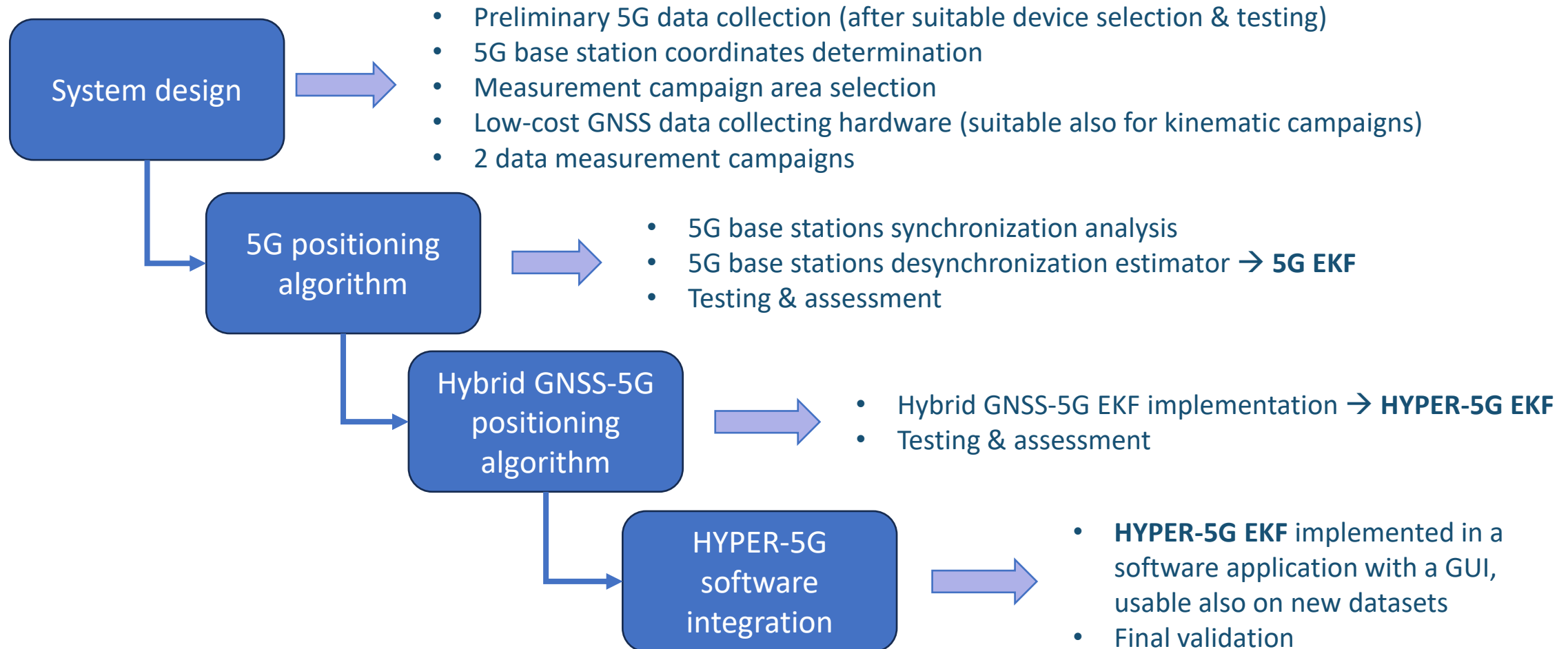
*studying, designing and developing the **algorithms and software** needed to implement a **precise positioning engine** to jointly use multi-constellation **GNSS** and **5G** observations*



*Project activities timeframe:
March 2022 – February 2024*

<http://www.hyper5g-project.eu/>

Project logic



Hybrid GNSS-5G positioning algorithm – obs. equations

GNSS state equation
$$P_{R,t}^{S_i} = \rho_{R,t}^{S_i} - c(dt_{S_i,t-\tau} + dt_{REL,t-\tau}^{S_i}) + cdt_{R,t}^{GNSS} + T_{R,t}^{S_i} + I_{R,t}^{S_i}$$

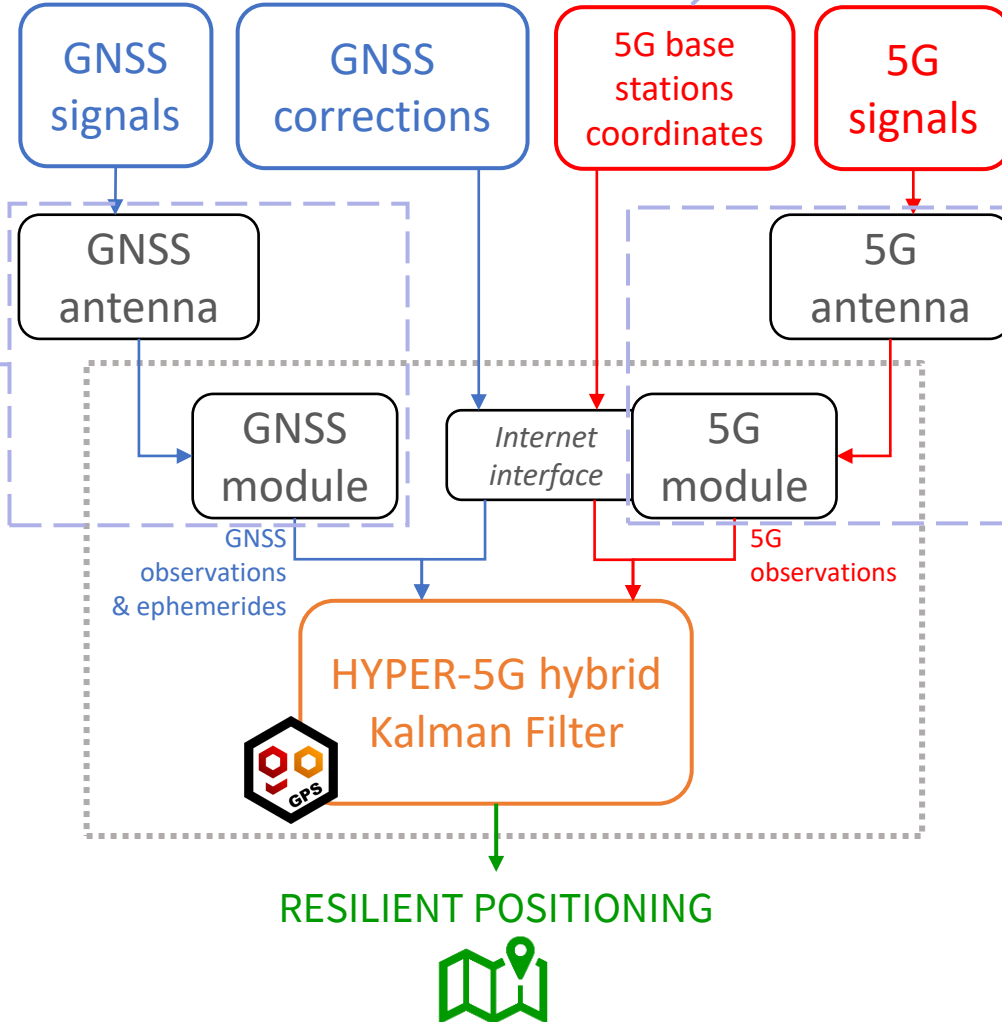
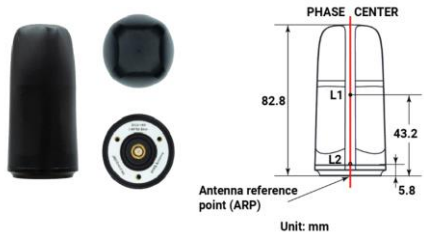
- t = processed epoch, τ = travel time
- $\rho_{R,t}^{S_i}$ = distance between the receiver and satellite at epoch t
- $dt_{S_i,t-\tau}$ = satellite clock offset at transmission time
- $dt_{REL,t-\tau}^{S_i}$ = relativistic clock correction at transmission time
- $cdt_{R,t}^{GNSS}$ = receiver clock offset with respect to different GNSS at epoch t
- $T_{R,t}^{S_i}$ = tropospheric delay at epoch t
- $I_{R,t}^{S_i}$ = ionospheric delay at epoch t

5G state equation
$$ToA_{R,t}^{BS_i} = \rho_{R,t}^{BS_i} + cdt_{BS_i,t}^{5G} + cdt_{R,t}^{5G}$$

- $\rho_{R,t}^{BS_i}$ = distance between the receiver and BS_i at epoch t
- $cdt_{BS_i,t}^{5G}$ = modelled BS_i clock offset at epoch t
- $cdt_{R,t}^{5G}$ = clock offset of the receiver with respect to 5G network

System concept

Technology Readiness Level 5



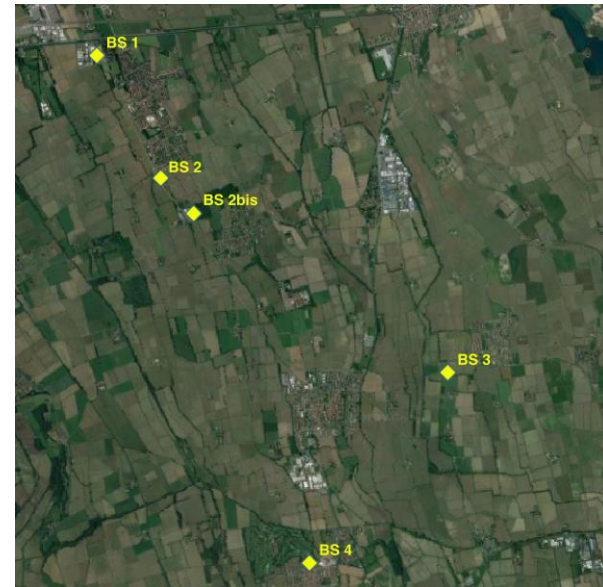
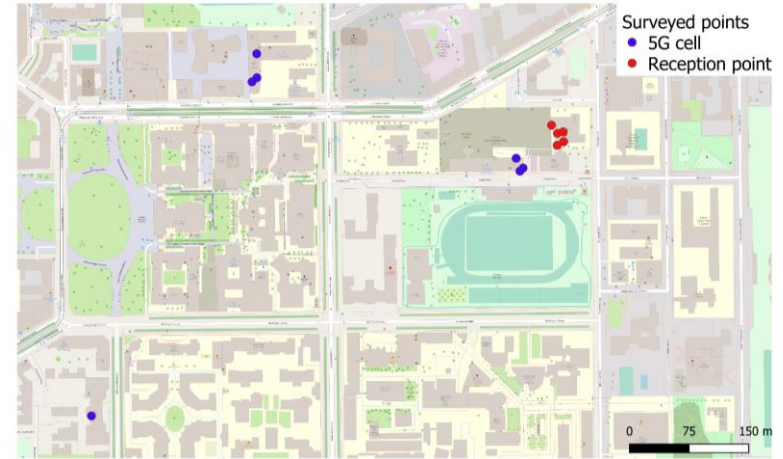
Presentation structure

- System Design (**GReD** – *Eugenio Realini*)
- 5G positioning (**PoliMi IoT Lab** – *Monica Nicoli*)
- Hybrid GNSS-5G positioning (**PoliMi DICA** – *Marianna Alghisi*)
- HYPER-5G software development (**GReD** – *Andrea Gatti*)
- HYPER-5G software validation (**PoliMi DICA** – *Marianna Alghisi*)
- Conclusions (**GReD** – *Eugenio Realini*)

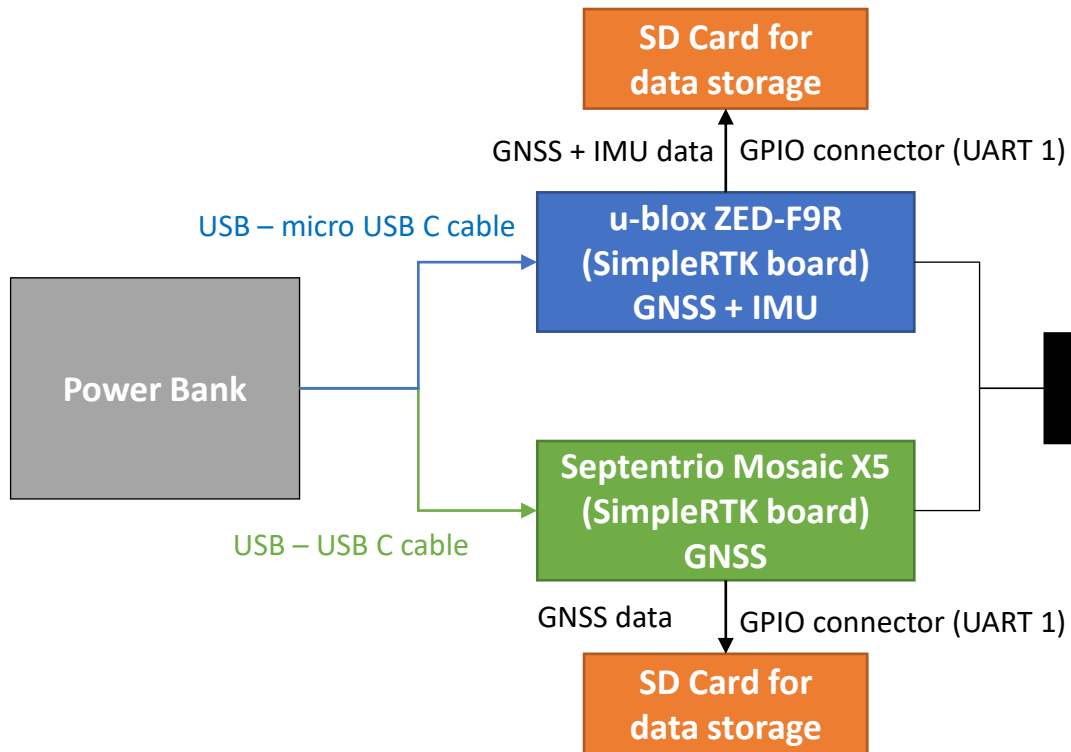
System Design

GReD

Data collection activities – BS coordinates survey



GNSS receiver prototype



GNSS receiver prototype



Data collection activities – 1st campaign

Date: Friday 18 November 2022

Location: South-West of Milan

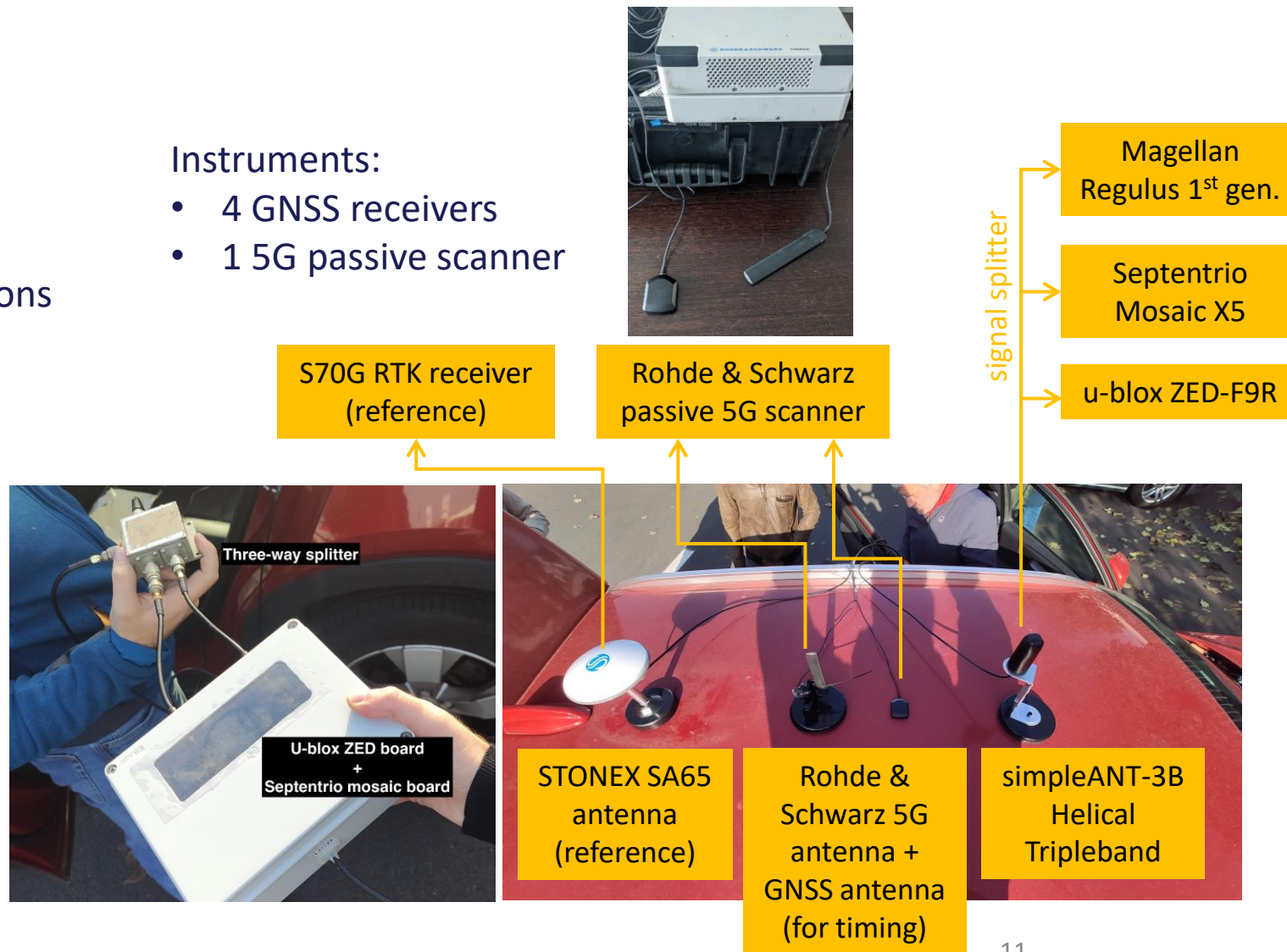
Duration: about 3 hours

Tests: 2 stationary, 3 kinematic

Number of Vodafone 5G base stations
in the area of interest: 5

Instruments:

- 4 GNSS receivers
- 1 5G passive scanner



Data collection activities – 2nd campaign

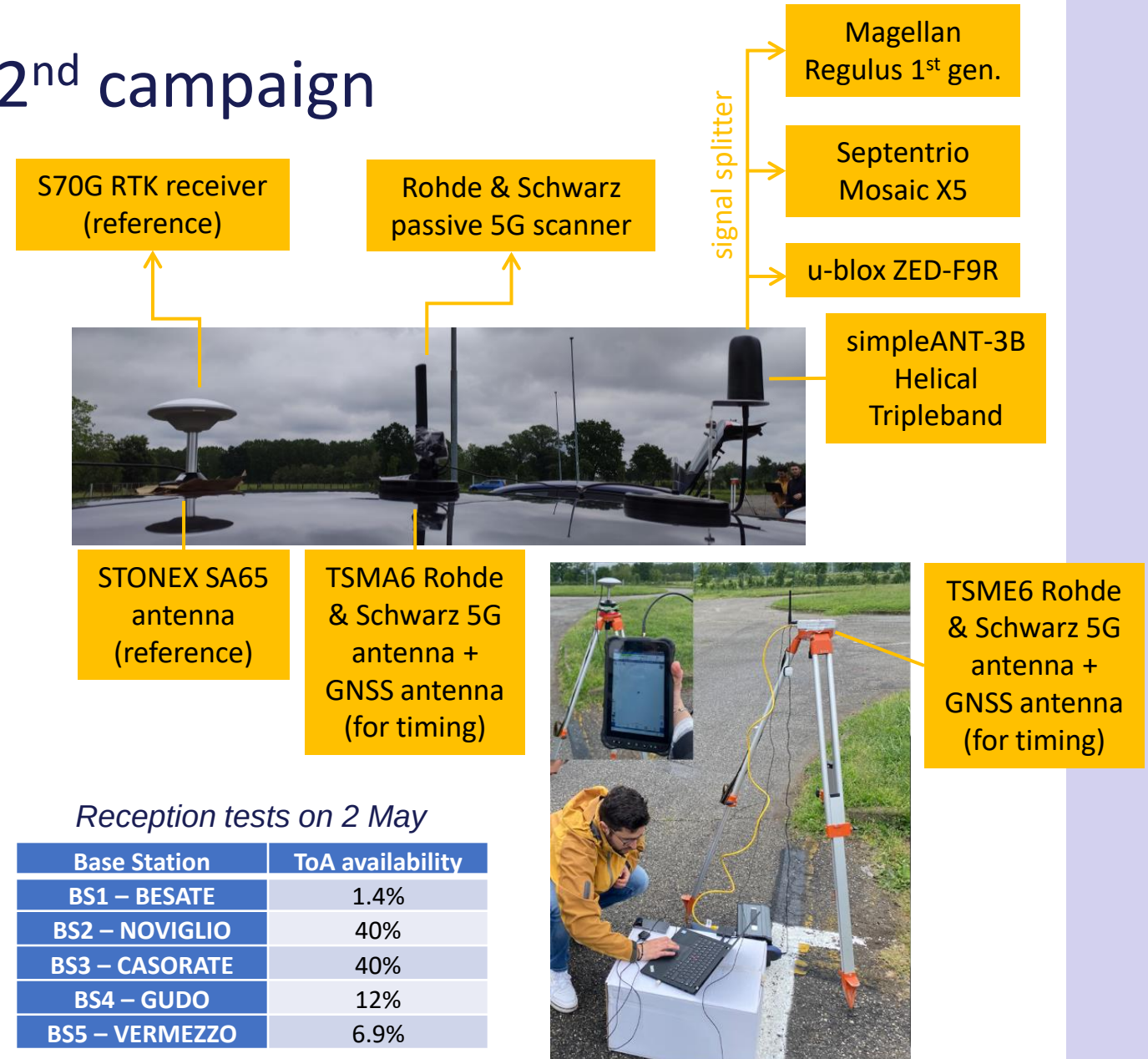
- Second data collection campaign on 10 May 2023, in the rural area southwest of Milan
- 8 consecutive surveys, each one composed by a static acquisition of 5 minutes, then 3 repetitions of the kinematic path



Figure 1



Figure 2



5G positioning design

PoliMi IoT Lab

5G positioning – Overview

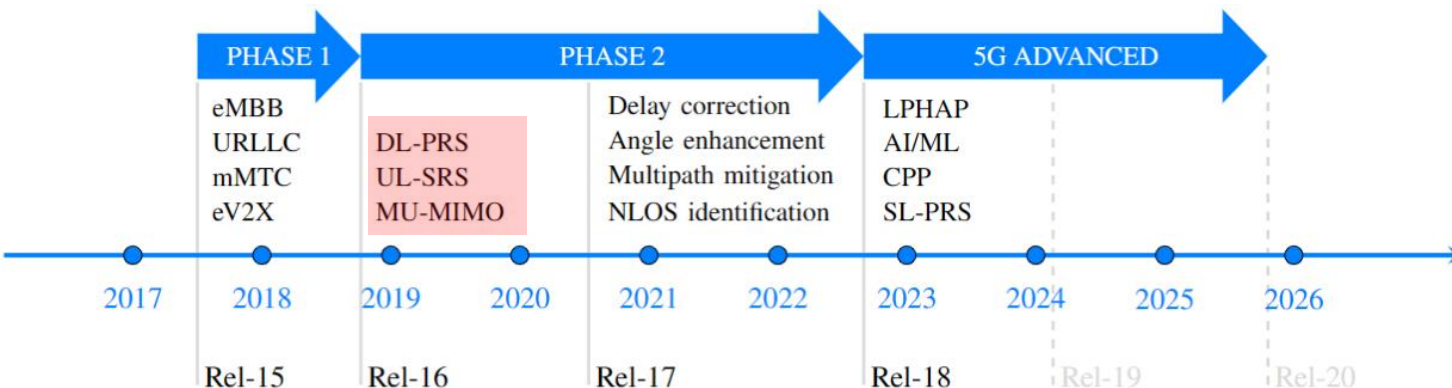
5G nice features for positioning

- **New positioning signals (PRS,SRS)**: improved correlation, simultaneous ranging from multiple BSs
- **Extended bandwidth**: from 50 MHz to 2 GHz (*forthcoming*)
- **mmWave bands**: frequency bands >24 GHz (FR2), up to 71 GHz (Rel.17)
- **Massive MIMO**: multiple antenna for spatial filtering (beamforming)
- **New positioning methods**: OTDOA, RTT, multi-RTT, AoA, AoD

5G base station (BS)
(gNodeB, identified by PCI)



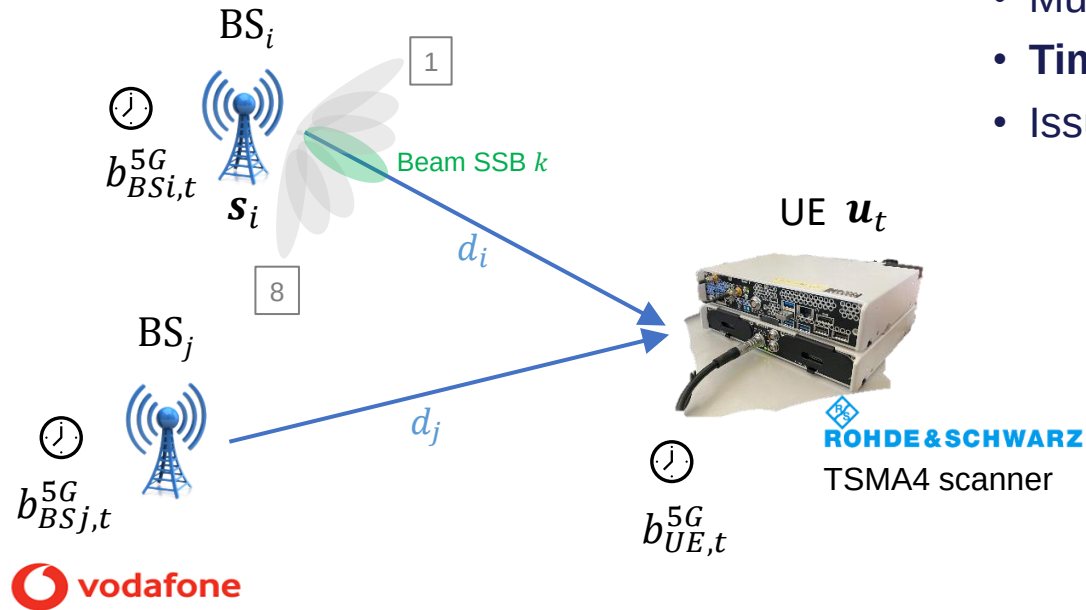
User equipment (UE)



5G physical layer configurations (numerology)

μ	Δf [kHz]	FR	BW [MHz]	Ranging Accuracy $\approx c/BW$ [m]
0	15	1	50	6.00
1	30	1	100	3.00
2	60	1/2	200	1.50
3	120	2	400	0.75
4	240	2	400	-
5	480	2	1600	0.19
6	960	2	2000	0.15

5G positioning – Methodology on current network



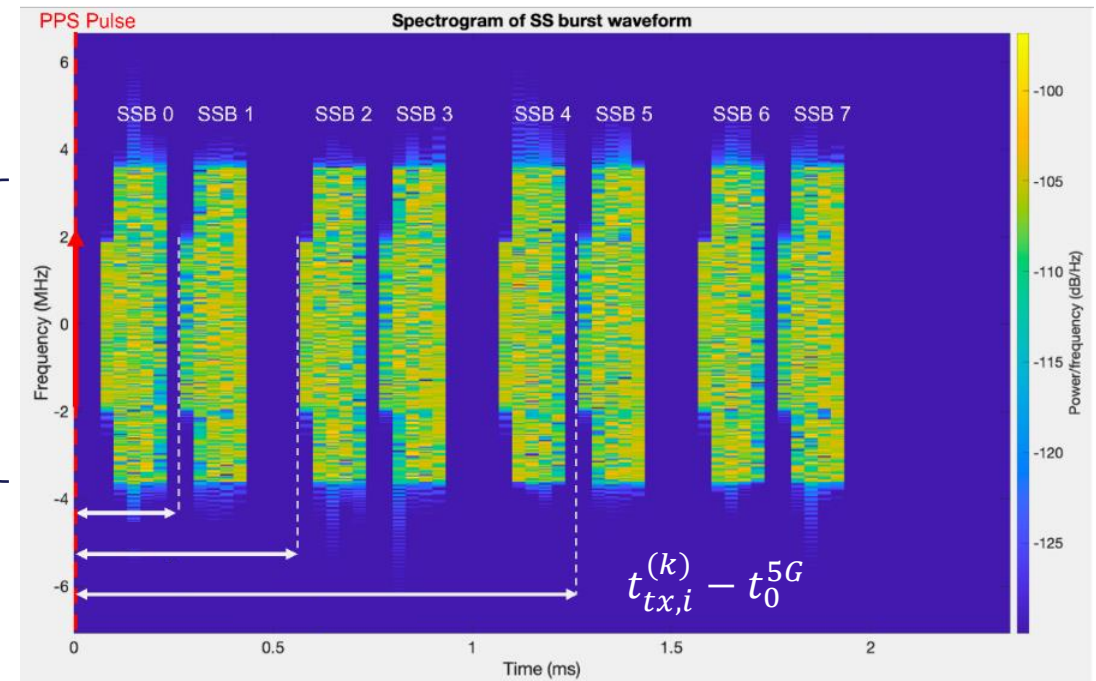
- Multi-lateration from **Synchronization Signal Block (SSB)**
- **Time of Arrival (ToA)** extracted from R&S TSMA4 scanner
- Issues:
 - Limited bandwidth (**7.2 MHz**)
 - Synchronization errors (up to **1.5 μ s** btw BSs)

5G range estimate from ToA:

$$\rho_{i,t}^{5G} = c\hat{\tau}_i = d_i + c \underbrace{(b_{BSi,t}^{5G} - b_{UE,t}^{5G})}_{b_{i,t}^{5G}} + n_{i,t}^{5G}$$

$b_{i,t}^{5G}$
Clock bias
measured by UE

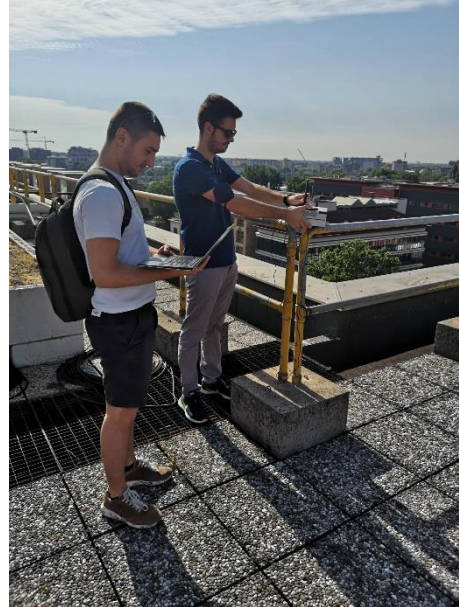
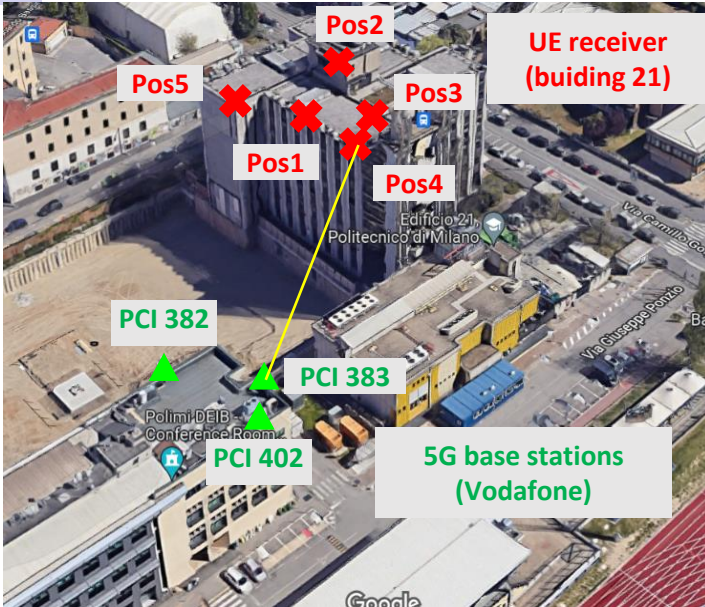
5G SSB signals (Rel-15 SSBs)



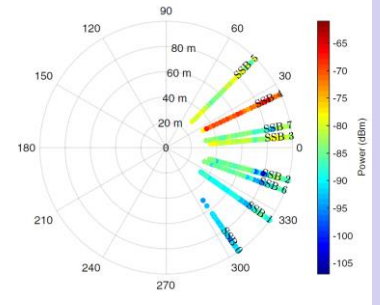
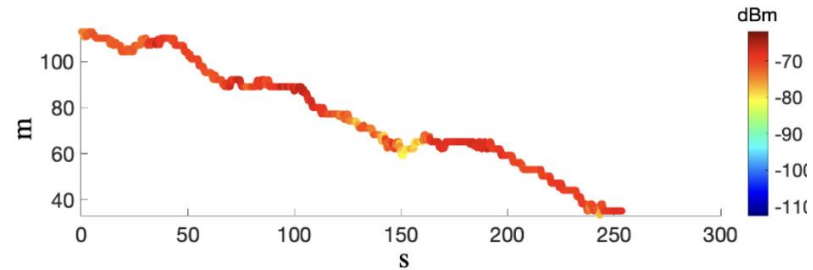
5G positioning – BS synchronization issue

Static tests @POLIMI Leonardo campus, Milan, 18th Oct. 2022

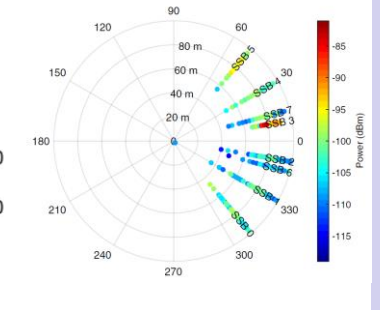
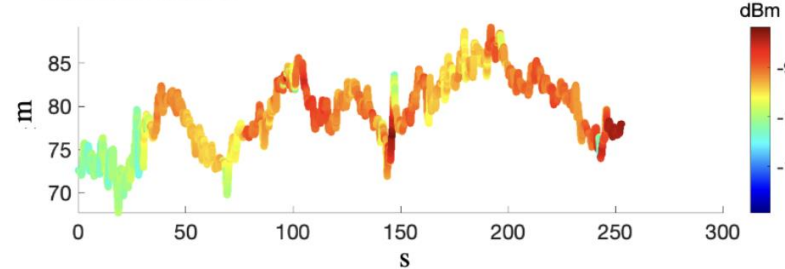
Clock bias vs time and beam



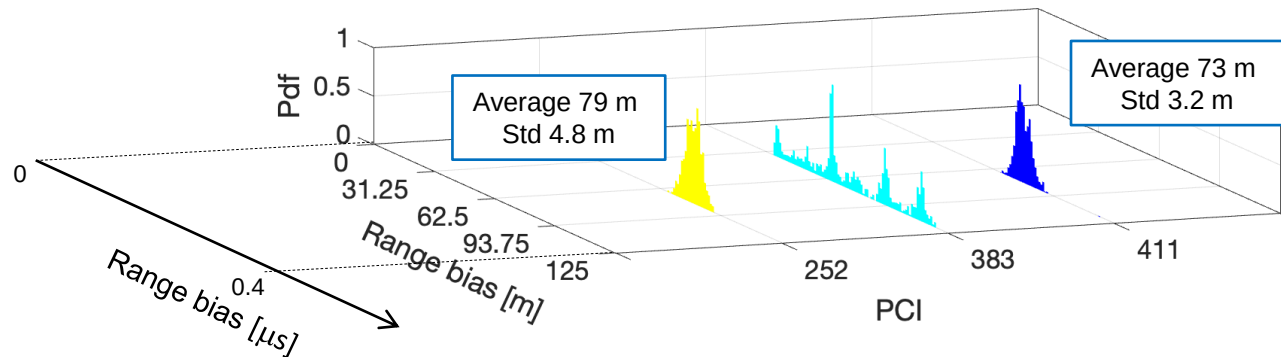
PCI 383 - SSB 4



PCI 252 - SSB 3



Clock bias distribution (SSB 4)



Despite the static condition, the ranging information is unstable due to clock inaccuracy



Need to track and compensate the clock bias

5G positioning – EKF for joint position & clock offset tracking (J-EKF)

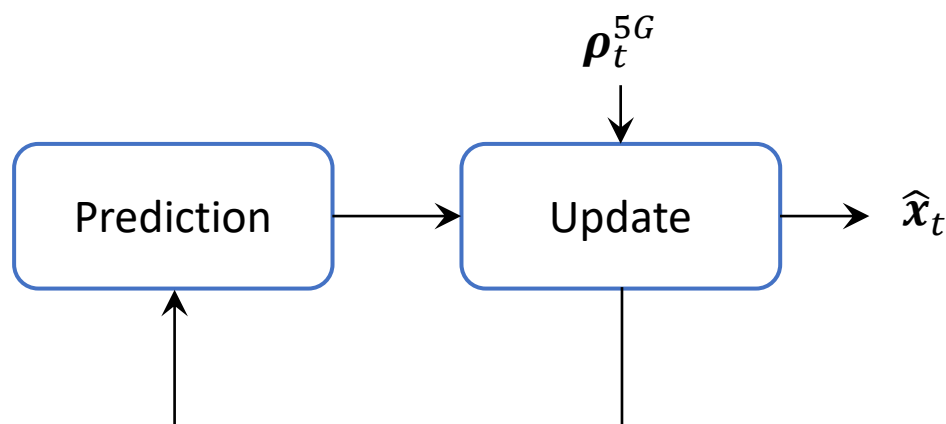
- Dynamic system model:
$$\mathbf{x}_t = \underbrace{\begin{bmatrix} \mathbf{u}_t \end{bmatrix}}_{\text{UE position}}, \underbrace{\begin{bmatrix} \mathbf{b}_{i,t}^{5G} \end{bmatrix}_{i=1}^{N_{BS,t}}}_{\text{BS clock offsets}}^T$$

$$\begin{cases} \mathbf{u}_t^{5G} = f_u(\mathbf{u}_{t-1}^{5G}, \mathbf{w}_{v_{t-1}}) & \text{Random walk} \\ & \text{Nearly constant velocity} \\ \mathbf{b}_t^{5G} = f_b(\mathbf{b}_{t-1}^{5G}, \mathbf{w}_{b_{t-1}}) & \text{Track bias, drift and drift rate} \end{cases}$$

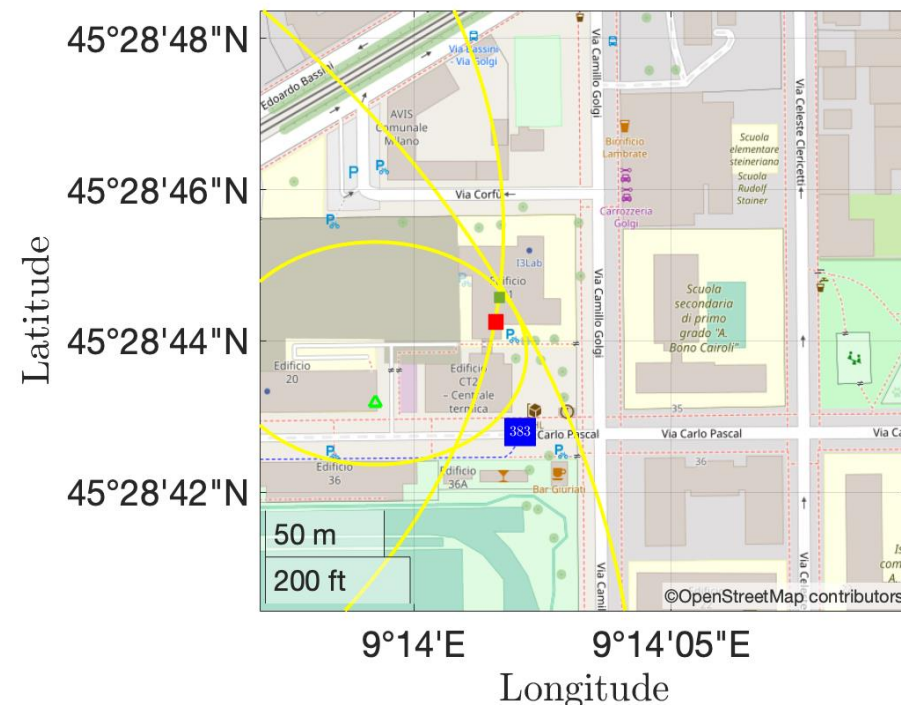
- Measurement model:
$$\boldsymbol{\rho}_t^{5G} = \left[[\rho_{i,t}^{5G}]_{i=1}^{N_{BS,t}} \right]^T$$

5G pseudo-ranges

$$\rho_{i,t}^{5G} = \|\mathbf{s}_i - \mathbf{u}_t\|_2 + c b_{i,t}^{5G} + n_{i,t}^{5G}$$



POLIMI Leonardo campus



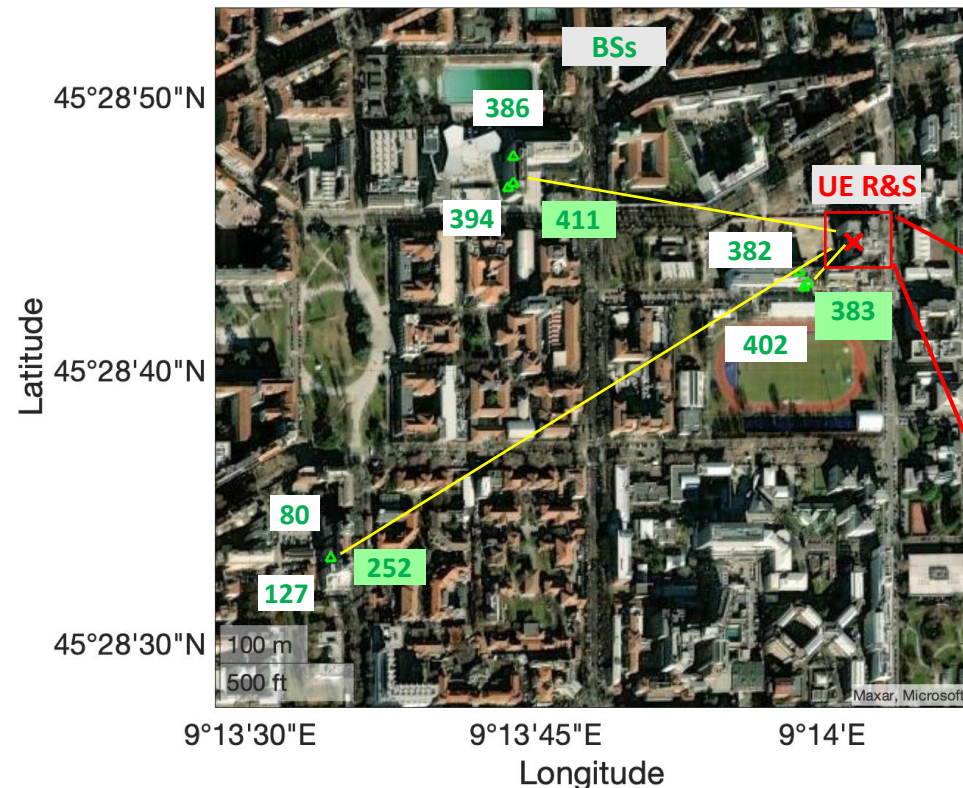
5G positioning assessment

PoliMi IoT Lab

5G positioning – Preliminary assessment in urban scenario

- Static tests @ POLIMI Leonardo campus
- 5 UE locations on the rooftop of building 21
- 3 5G sites (Vodafone Italy), with 3 BSs each
- Selected BSs in line of sight (LOS): PCI # 383, 411, 252

POLIMI Leonardo campus



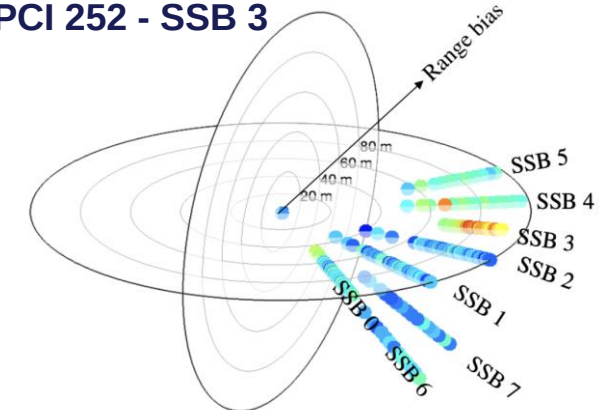
Building 21



POLIMI Leonardo campus



PCI 252 - SSB 3

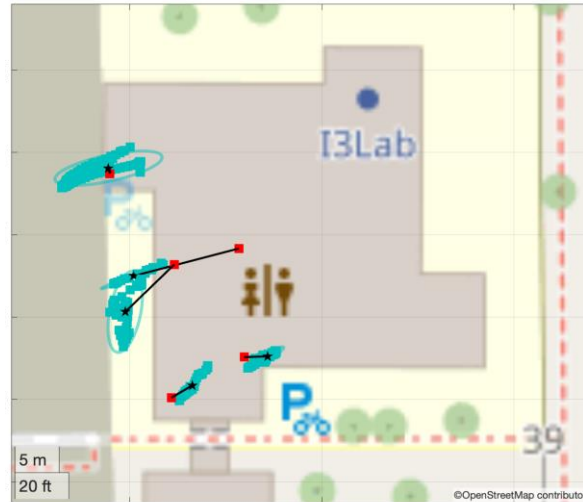


5G positioning – Urban scenario results

Tests in 5 different locations



J-EKF accuracy in 5 tests

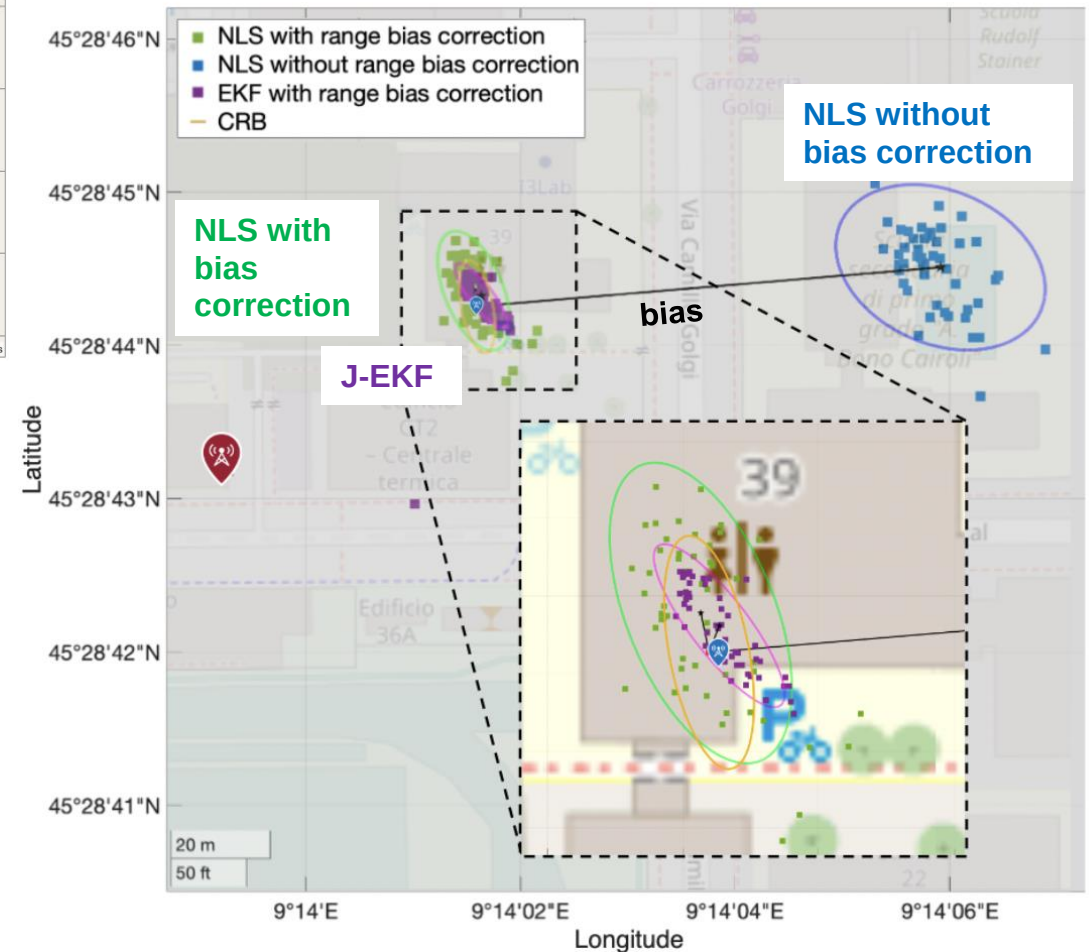


Methods:

- NLS: snapshot non-linear least squares
- J-EKF: tracking with bias correction
- CRB Cramer Rao Bound (CRB)

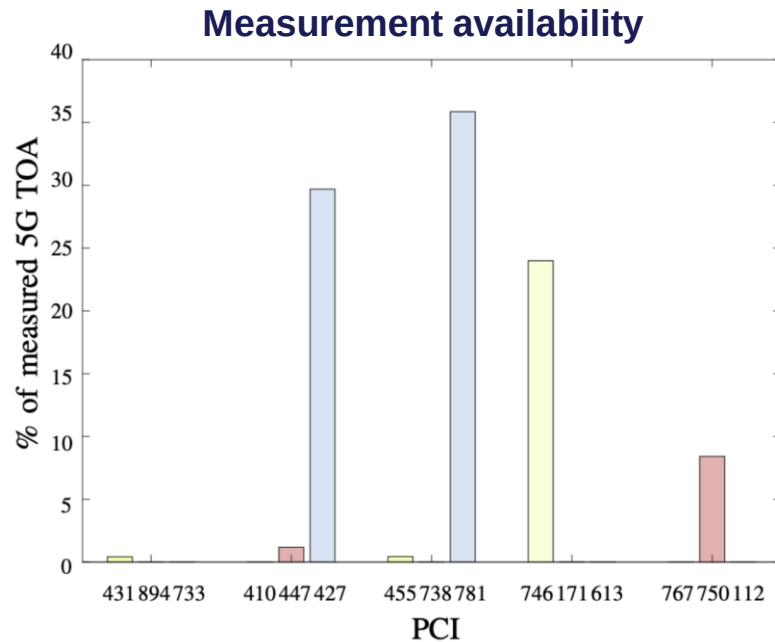
Accuracy averaged over the 5 tests

Positioning method	MAE [m]	CEP95 [m]	Bias [m]
NLS without bias correction	111	134	110
NLS with bias correction	10	16	4
J-EKF with bias correction	5	4	3

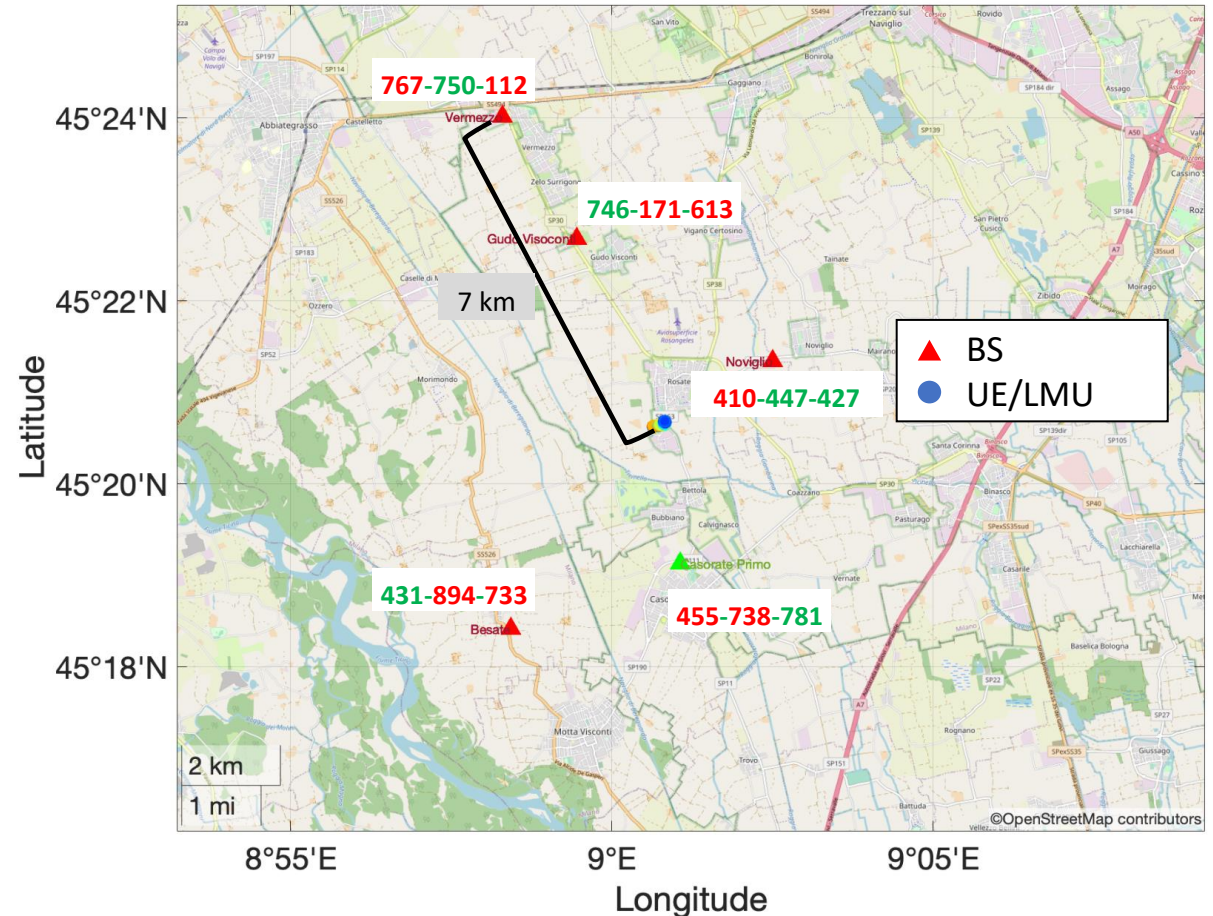


5G positioning – Assessment in rural scenario (2nd campaign)

- Tests in Milan's southwest suburbs: 8 dynamic + 8 static
- 5G receiver: R&S TSMA6
- 5G sites: 5 with 3 BSs each (**non LOS**)
- Selected BSs: PCI n. 750, 746, 447, 427, 431, 781

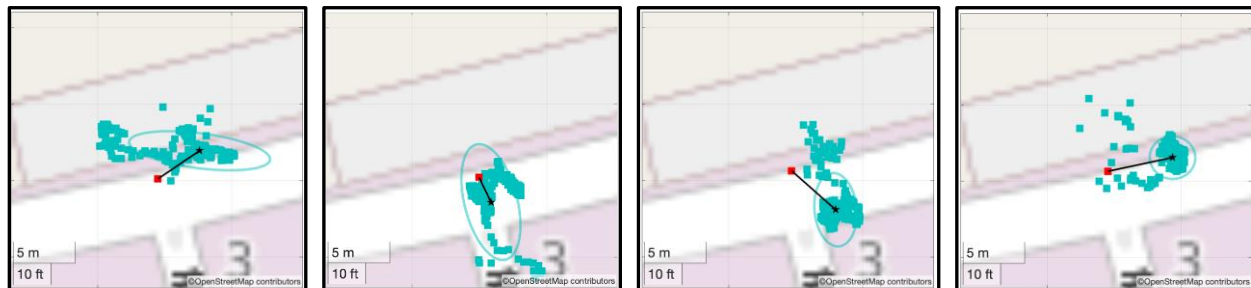


Static tests @ Milano suburbs, 10th May 2023



5G positioning – Rural scenario: results in static case

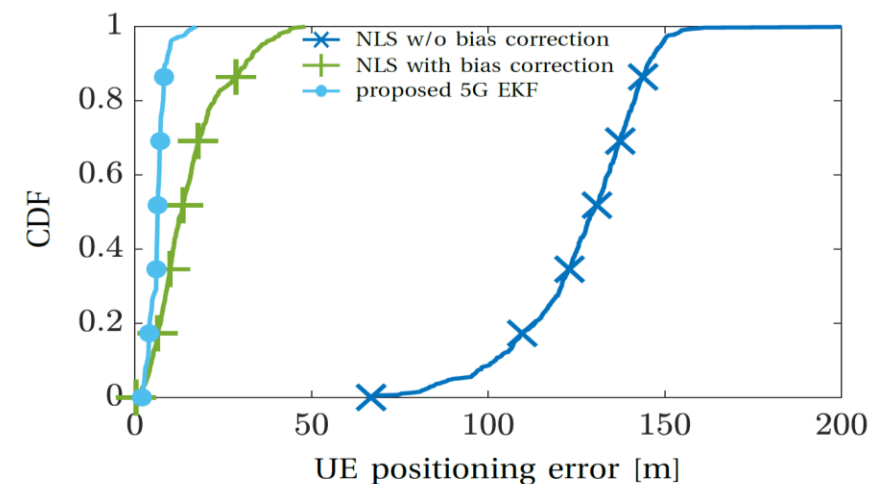
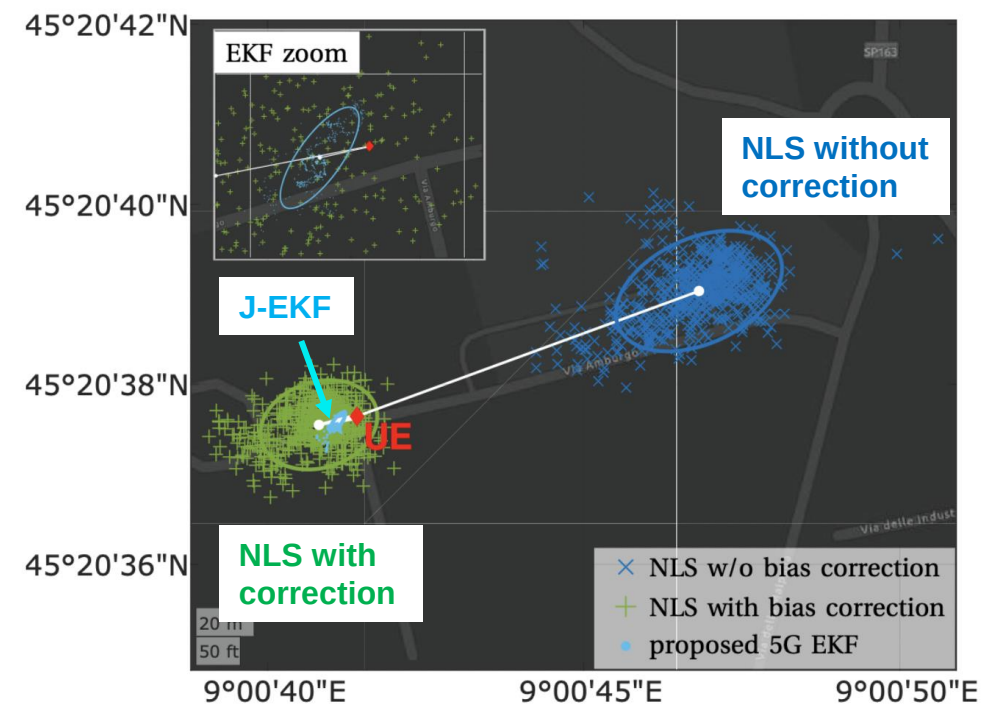
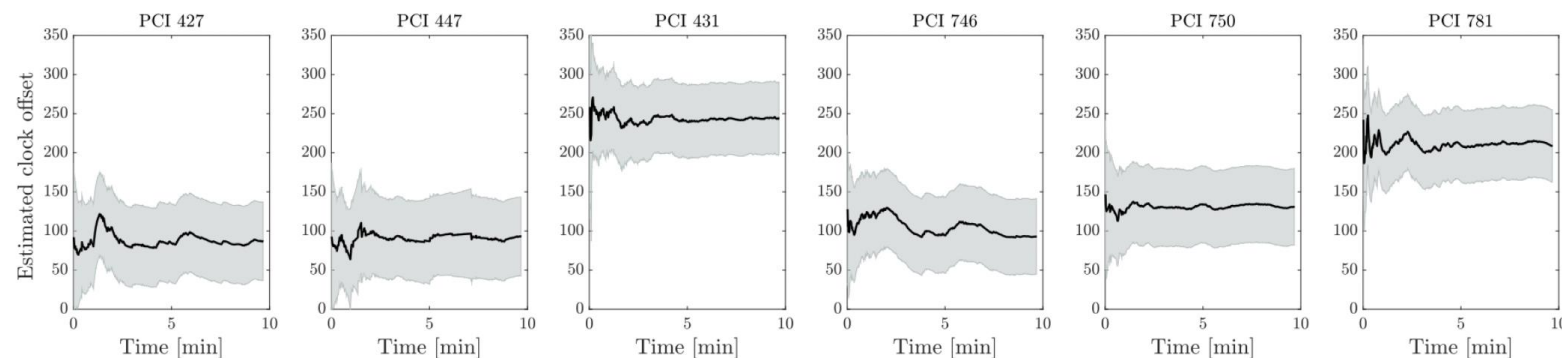
J-EKF accuracy in 4 tests



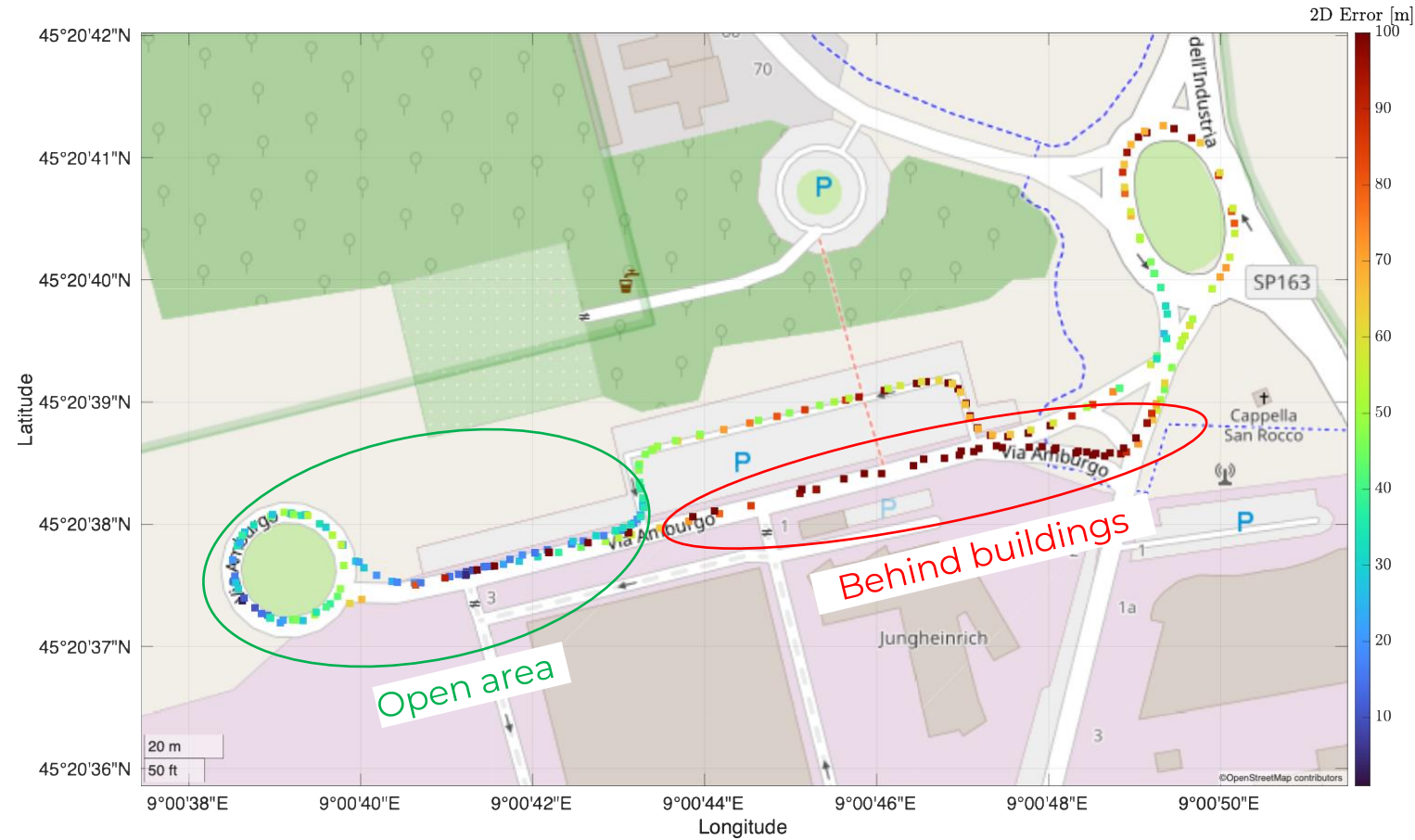
Accuracy averaged over 4 tests

Positioning method	MAE [m]	CEP95 [m]	Bias [m]
NLS without range bias correction	136	23	136
NLS with range bias correction	16	24	11
J-EKF with range bias correction	4	4	3

Range bias estimate [m]



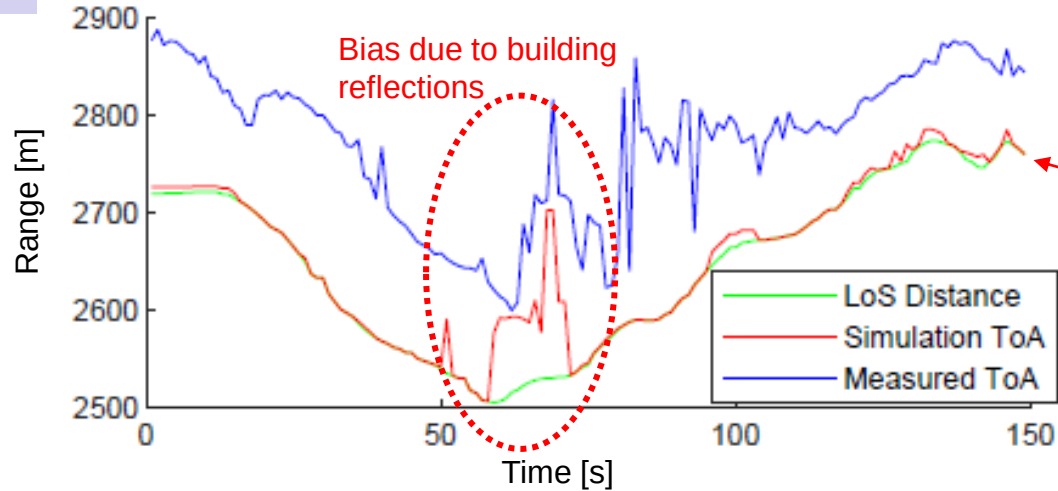
5G positioning – Rural scenario: results in dynamic case



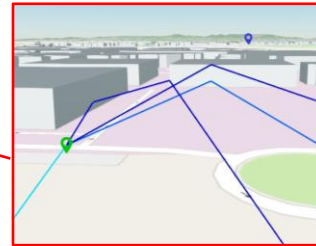
- Mean error over the whole area: **MAE = 30 m**
- The range bias increases in presence of buildings
- In open areas, the error reduced to **MAE = 20 m**

5G positioning – Rural scenario: range bias repeatability

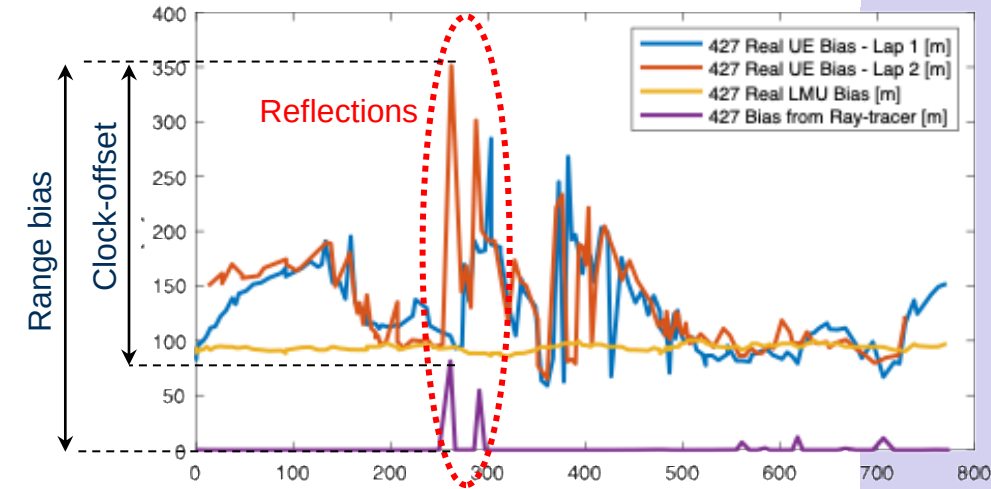
Range estimate - PCI 427



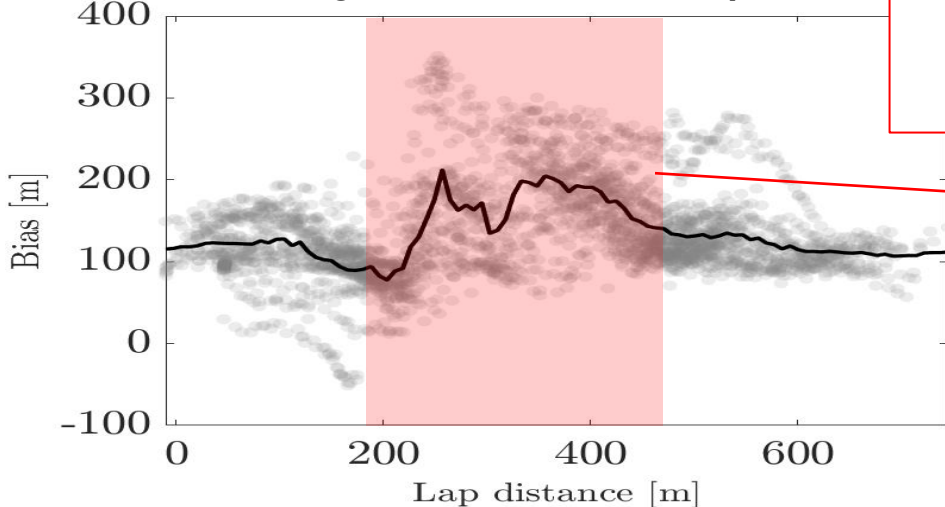
Ray tracing simulation



Range estimate over 2 laps

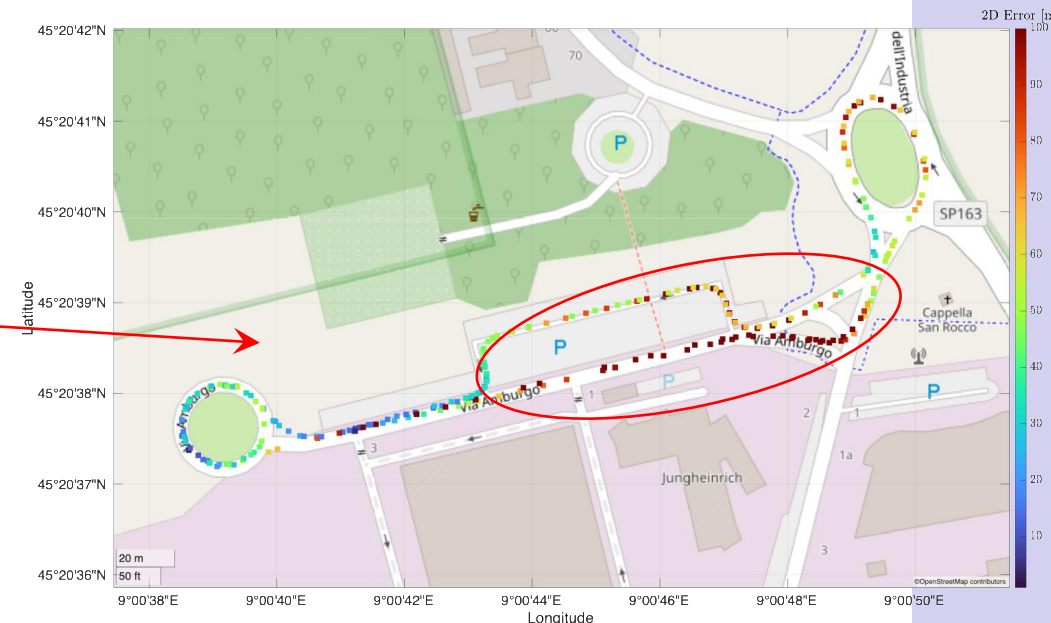


Range statistics over 25 laps



Static multipath
is location-
dependent and
predictable

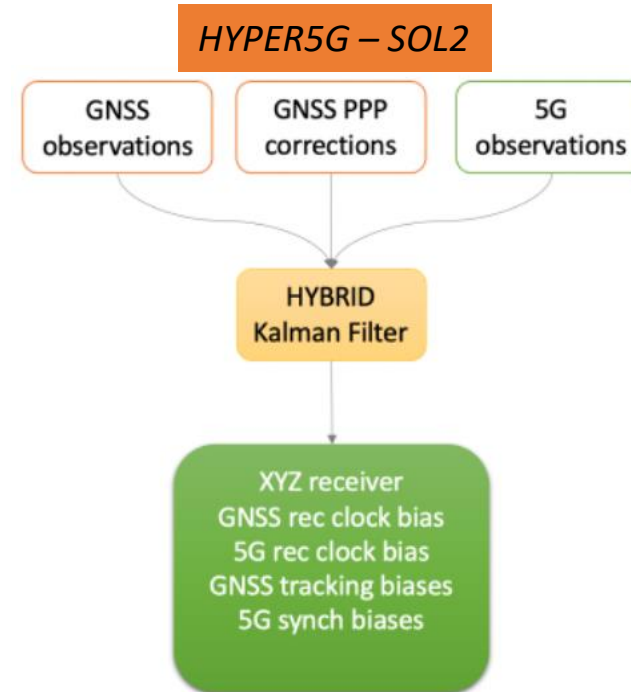
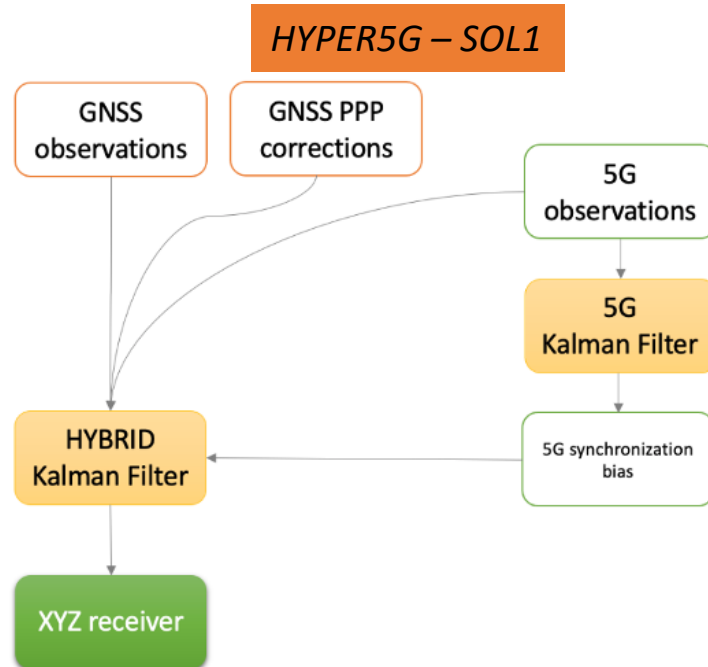
Higher bias and variability
due to multipath



Hybrid GNSS-5G positioning

PoliMi DICA

Hybrid positioning algorithm design & implementation



- ✓ 5G and GNSS raw data management
- ✓ 5G and GNSS pre-processing
- ✓ Multi-receiver, multi-antenna systems.
- ✓ Multi-frequency and multi-constellation.
- ✓ Uncombined/iono-free GNSS processing

- ✓ GNSS standalone static/kinematic positioning.
- ✓ Hybrid static/kinematic positioning
- ✓ Support receivers with different rate/gaps in data.
- ✓ Prepared to work with carrier-phases, cycle-slips detection.

Hybrid positioning algorithm

State variables

Static	Kinematic	Description	Numerosity	Model
$\begin{bmatrix} x_R \\ y_R \\ z_R \end{bmatrix}$	$\begin{bmatrix} x_R \\ y_R \\ z_R \end{bmatrix}$	Receiver's position	[3 x ant]	Random walk
	$\begin{bmatrix} \dot{x}_R \\ \dot{y}_R \\ \dot{z}_R \end{bmatrix}$	Receiver's velocity	[3 x ant]	Random walk slow varying
	$\begin{bmatrix} \ddot{x}_R \\ \ddot{y}_R \\ \ddot{z}_R \end{bmatrix}$	Receiver's acceleration	[3 x ant]	Random walk slow varying
dt_R^{GNSS}	dt_R^{GNSS}	Receiver's clock offset wrt GNSS	[1 x rec]	Random walk
dt_R^{5G}	dt_R^{5G}	Receiver's clock offset wrt 5G	[1 x rec]	Random walk
δt_R^{GNSS}	δt_R^{GNSS}	GNSS clock tracking bias	[1 x <u>trk</u>]	Random walk slow varying
dt_{BS}^{5G}	dt_{BS}^{5G}	5G network clock synchronization bias. (Only IF HYPER sol2)	[1 x #BS]	Random walk static/slow varying
dT	dT	Residual Tropospheric delay	[1 x rec]	Random walk slow varying

EKF solution

State propagation, according to the dynamic model:

$$\hat{\underline{x}}_{r,t} = D \hat{\underline{x}}_{t-1}$$

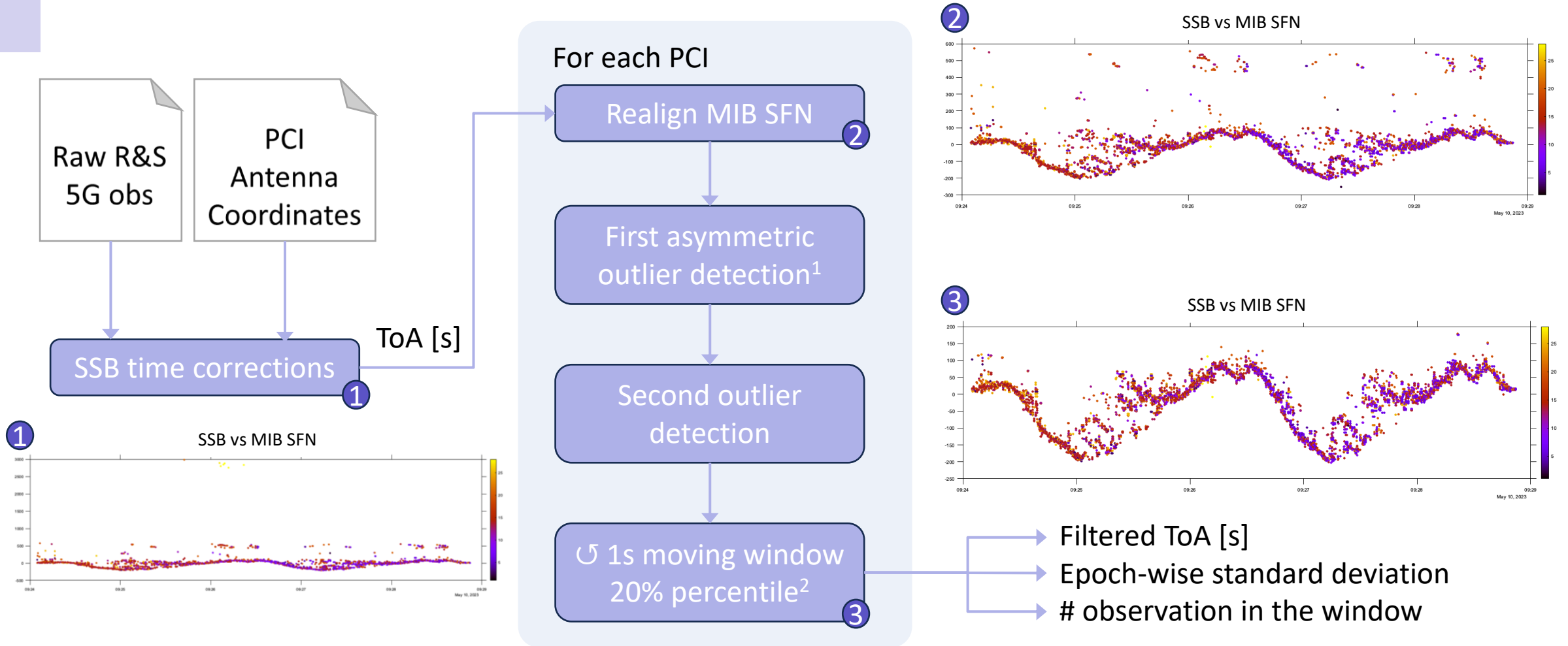
The predicted state is corrected according to the available observations:

$$\begin{aligned}
 K_t &= D C_{e,t-1} D' + C_{e,t} \\
 G_t &= K_t A_t' (A_t K_t A_t' + C_{v,t})^{-1} \\
 \hat{\underline{x}}_t &= (I - G_t A_t) \hat{\underline{x}}_{r,t} + G_t \underline{y}_{0,t} \\
 C_{e,t} &= (I - G_t A_t) K
 \end{aligned}$$

Hybrid positioning algorithm – integration of 5G observations

- The 5G module is considered as an **additional receiver**
- Observations are assimilated considering them as **pseudo-ranges** of a new 5G “constellation”
- 5G **base stations** can be considered as **satellites** of the 5G “constellation”, their position is known from RTK
- As a GNSS receiver, **one** electronic **clock** error will be estimated
- **5G observations** are affected by **network synchronization error**, each 5G base station has its own correction
- **Observations** are injected into the Kalman filter after a pre-processing that will get rid of **outliers** and perform a robust **merge** of consecutive observations (to also decrease the computational effort of the processing)

Hybrid positioning algorithm – 5G pre-processing



1. Robust above average, robust below average (multipath is additive)
2. 20th percentile to mitigate for multipath

HYPER-5G software development

GReD

HYPER-5G software development

goGPS

Open source GNSS positioning software developed by GReD staff since 2007 for precision positioning

- Post-processing
- Batch joint least squares
- PPP and Network solutions

Limits of goGPS:

- Only support static solutions, no kinematic solutions (no KF)
- No epoch wise function for corrections
- No support for real-time positioning



HYPER-5G software development

HYPER-5G EKF

Based on goGPS

Incorporates functions updated to support the epoch-wise processing

For GNSS:

- Tropospheric corrections and mapping functions
- Ionospheric corrections and mapping functions
- Orbits interpolation
- Clock interpolation
- Phase wind up

For 5G:

- Reads R&S csv format and applies pre-processing



HYPER-5G software development

HYPER-5G EKF

- Supports multiple GNSS receiver, multi-antenna systems
- Supports one 5G receiver
- Stand-alone processing
- Static mode and kinematic mode
- Uses GNSS pseudoranges – uncombined or iono-free
- GNSS multi-frequency
- GNSS multi constellation support (including Galileo)
- Pre-processed 5G observations can be passed to the filter



Software integration

Graphical User Interface

go5G

Base goGPS config: /Users/andrea/Repositories/goGPS_H5G/data/project/H5G_2023May/co... Edit in goGPS

GNSS RINEX file: /Users/andrea/Repositories/goGPS_H5G/data/project/H5G_2023May/RINEX/MAGELLAN/...

5G UE obs. file: /Users/andrea/Repositories/goGPS_H5G/data/project/H5G_2023May/5Gdata/UE/Dynamic/...

5G PCI coordinates: ...data/project/H5G_2023May/5Gdata/PCIs.csv

Log

- 2024/03/15 17:29:51 Welcome to Hyper5G goGPS!
This software is brought to you by GReD s.r.l.
for any problem contact us at <http://bit.ly/goGPS>
- 2024/03/15 17:29:58 Building settings object...
- 2024/03/15 17:30:00 File
"/Users/andrea/Repositories/goGPS_H5G/data/project/H5G_2023May/config/configDynamic.ini"
found, settings imported!
- 2024/03/15 17:30:21 "Dynamic_03_3laps_01s.obs" appears to be a valid RINEX
- 2024/03/15 17:30:21 first epoch found at: 2023/05/10 09:47:28.2000000 GPS
- 2024/03/15 17:30:21 last epoch found at: 2023/05/10 09:54:41.6500000 GPS
- 2024/03/15 17:30:22 Importing 5G antenna positions
- 2024/03/15 17:30:23 Importing UE data
- 2024/03/15 17:30:31 * realign mib_sfn
- 2024/03/15 17:30:31 * remove big outliers mib_sfn
- 2024/03/15 17:30:46 * remove big outliers pci
- 2024/03/15 17:30:46 Start processing:
- 2024/03/15 17:30:46 - starting loop
- 2024/03/15 17:30:49 Export results at "export/Results_dynamic2.mat"

Clear Show figures Adaptive Order 0 Options Process

Output directory: /Users/andrea/Repositories/goGPS_H5G/data/project/H5G_2023May/out



H5G KF Options

Initial sigma Regularization Advanced

Initial error sigma

xyz	100	100	100	[m]
velocity xyz	0.1	0.1	0.1	[m/s]
acceleration xyz	0.1	0.1	0.1	[m/s ²]
GNSS receiver clock	100000			[m]
GNSS tracking bias	10			[m]
5G clock	100000			[m]
5G PCI bias	100			[m]
tropospheric delay	0.03			[m]

Cancel Apply

H5G KF Options

Initial sigma Regularization Advanced

Time regularisation

GNSS receiver clock	100000	[m/sqrt(h)]
GNSS tracking bias	0.001	[m/sqrt(h)]
5G clock	100000	[m/sqrt(h)]
5G PCI bias	0.1	[m/sqrt(h)]
tropospheric delay	0.03	[m/sqrt(h)]

Cancel Apply

H5G KF Options

Initial sigma Regularization Advanced

Dynamic

	along-track	cross-track	up	
Order 2	0.8	1.1	0.002	[m/s ³]
Order 1	1.5	1.5	0.15	[m/s ²]
Adaptive order 0	10	3	0.05	[m/s]

Scale function:

$$f(v, s, m) = \left(0.01 + 0.99 \left(\frac{1}{1 + e^{-s_1(v-m_1)}}\right)\right) \cdot \left(0.4 + \left(1 - \frac{1}{1 + e^{-s_2(v-m_2)}}\right) \cdot 0.6\right)$$

Steepness (s₁, s₂) 3 0.3

Mid point (m₁, m₂) 1.4 10

Weights

Weight 5g 0.25

Cancel Apply

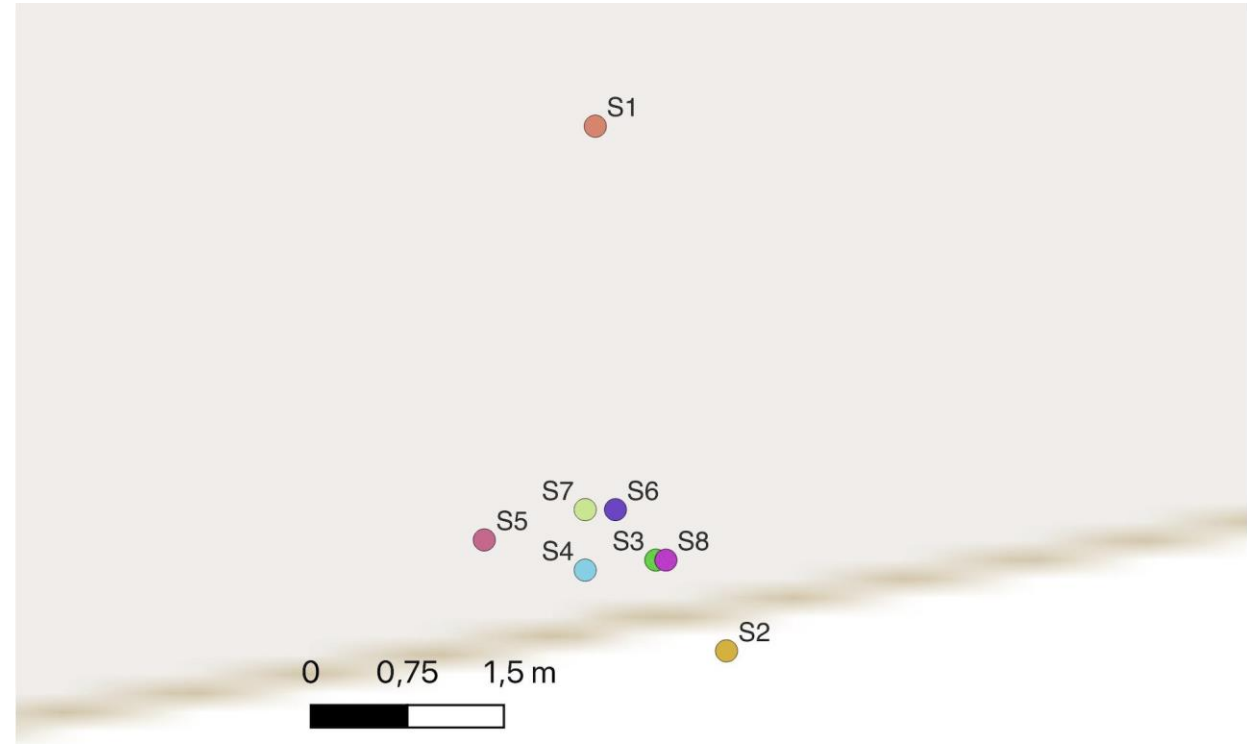
HYPER-5G software validation

PoliMi DICA

Hybrid 5G-GNSS positioning results

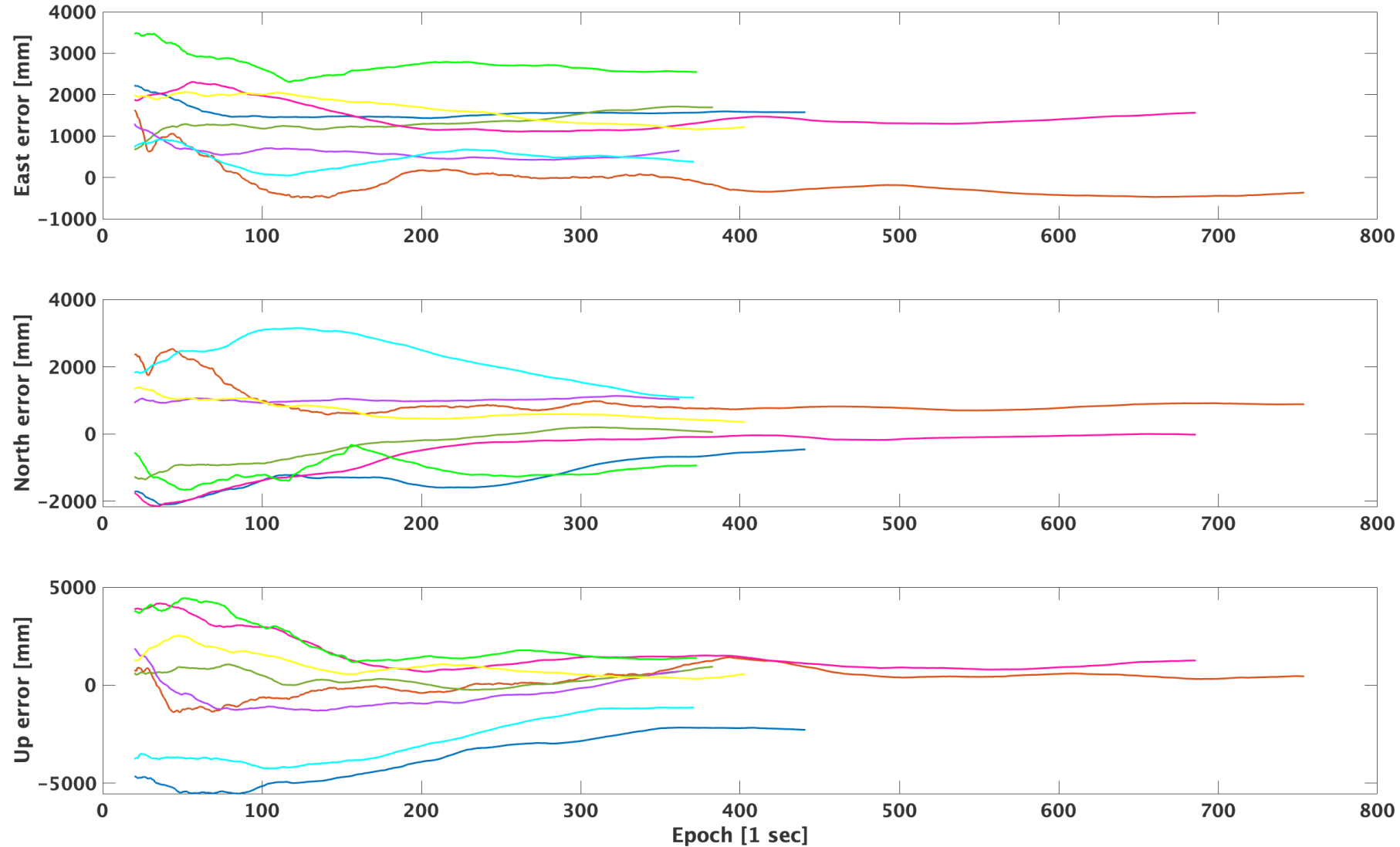
STATIC RESULTS

- ✓ Tested receivers: Magellan, u-blox, Septentrio
- ✓ Configurations:
 1. HYBRID-5G – SOL 1 – GNSS IONOFREE
 2. HYBRID-5G – SOL 1 – GNSS UNCOMBINED
 3. HYBRID-5G – SOL 2 – GNSS IONOFREE
 4. HYBRID-5G – SOL 2 – GNSS UNCOMBINED
- ✓ 8 static sessions of measurements

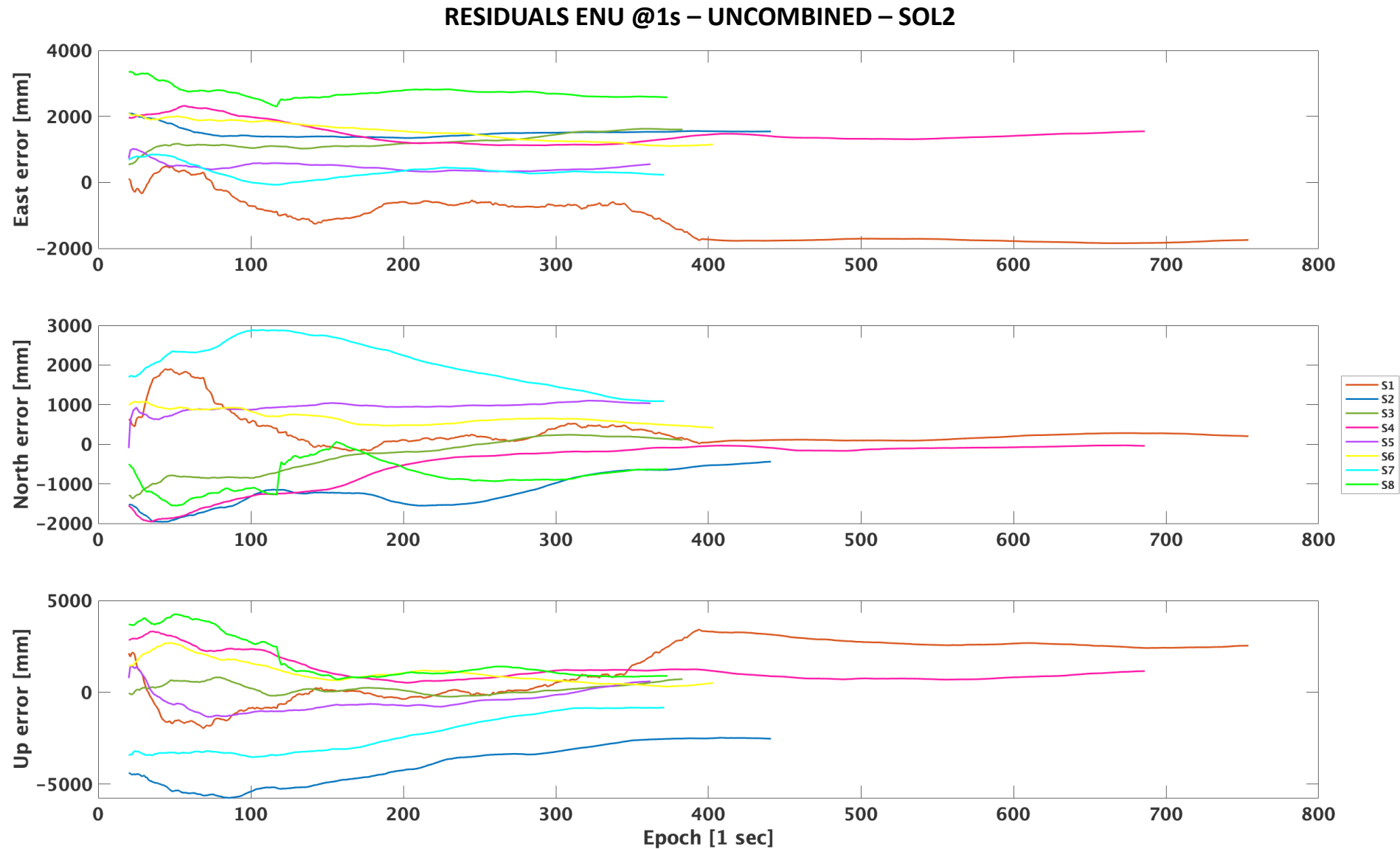


Static results: HYPER5G – SOL2 – IONOFREE

RESIDUALS ENU @1s – IONOFREE – SOL2



Static results: HYPER5G – SOL2 – UNCOMBINED



Static results: HYPER5G – SOL2 – IONOFREE

HYPER5G-SOL2-IONOFREE

RECEIVER 1	MEAN		2D ERROR	3D ERROR	SIGMA			MAX			MIN		
	E	N			H	E	N	H	E	N	H	E	N
1,2	1,0	1,5	1,6	2,2	0,3	0,5	0,9	2,3	2,4	4,6	0,1	0,2	0,4
RECEIVER 2	MEAN		2D ERROR	3D ERROR	SIGMA			MAX			MIN		
	E	N			H	E	N	H	E	N	H	E	N
1,2	1,3	2,4	1,8	2,4	0,6	0,5	0,8	3,5	2,3	4,3	0,0	0,1	0,1
RECEIVER 3	MEAN		2D ERROR	3D ERROR	SIGMA			MAX			MIN		
	E	N			H	E	N	H	E	N	H	E	N
1,3	0,9	1,1	1,6	1,9	0,2	0,4	0,7	1,5	1,9	3,7	0,2	0,3	0,9

Kinematic results: HYPER5G – SOL2 – IONOFREE

Case study:

Kinematic test 7

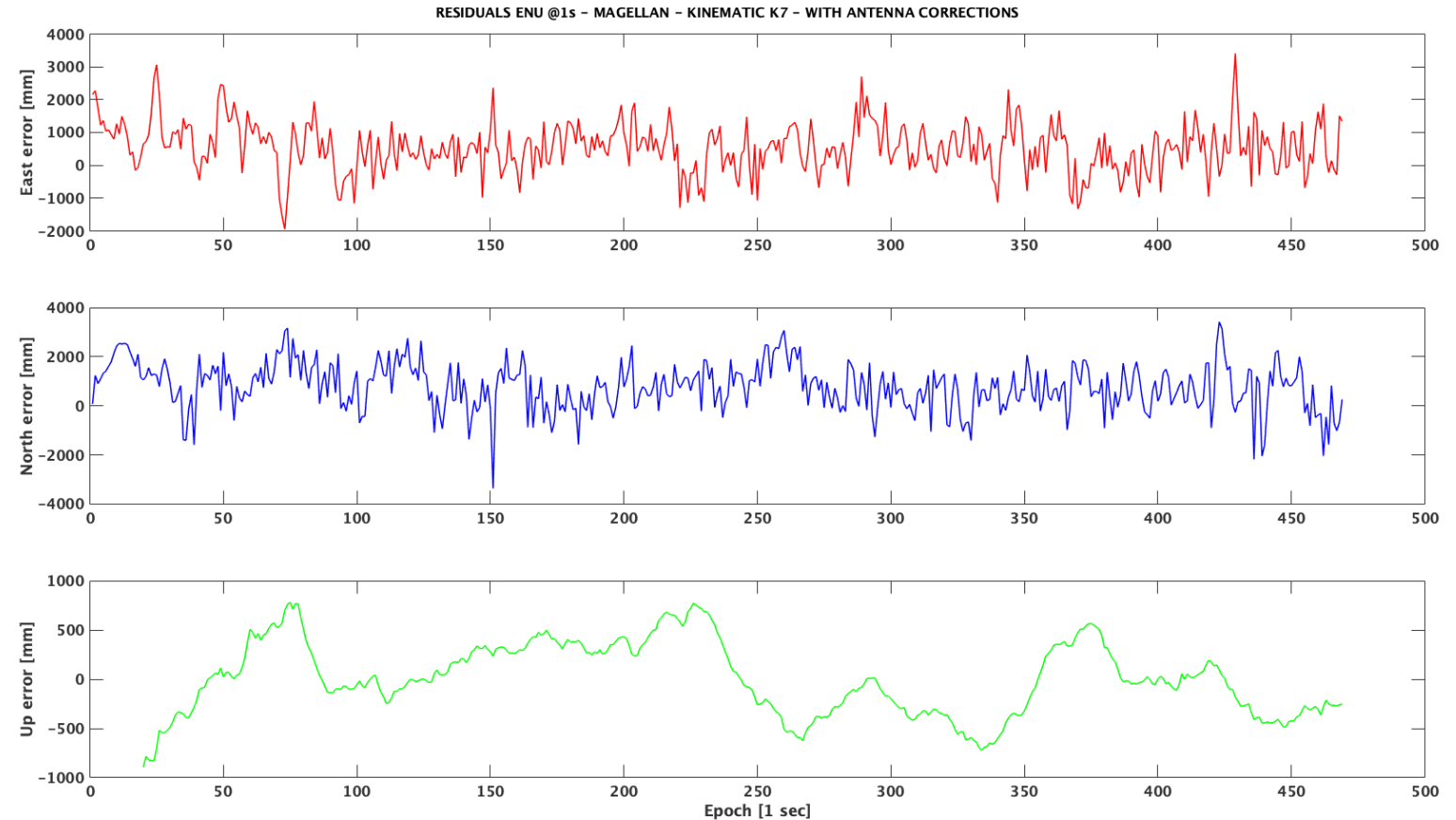
Time:

11:05:12 - 11:13:00

Number of epochs:

470 (~ 8 min)

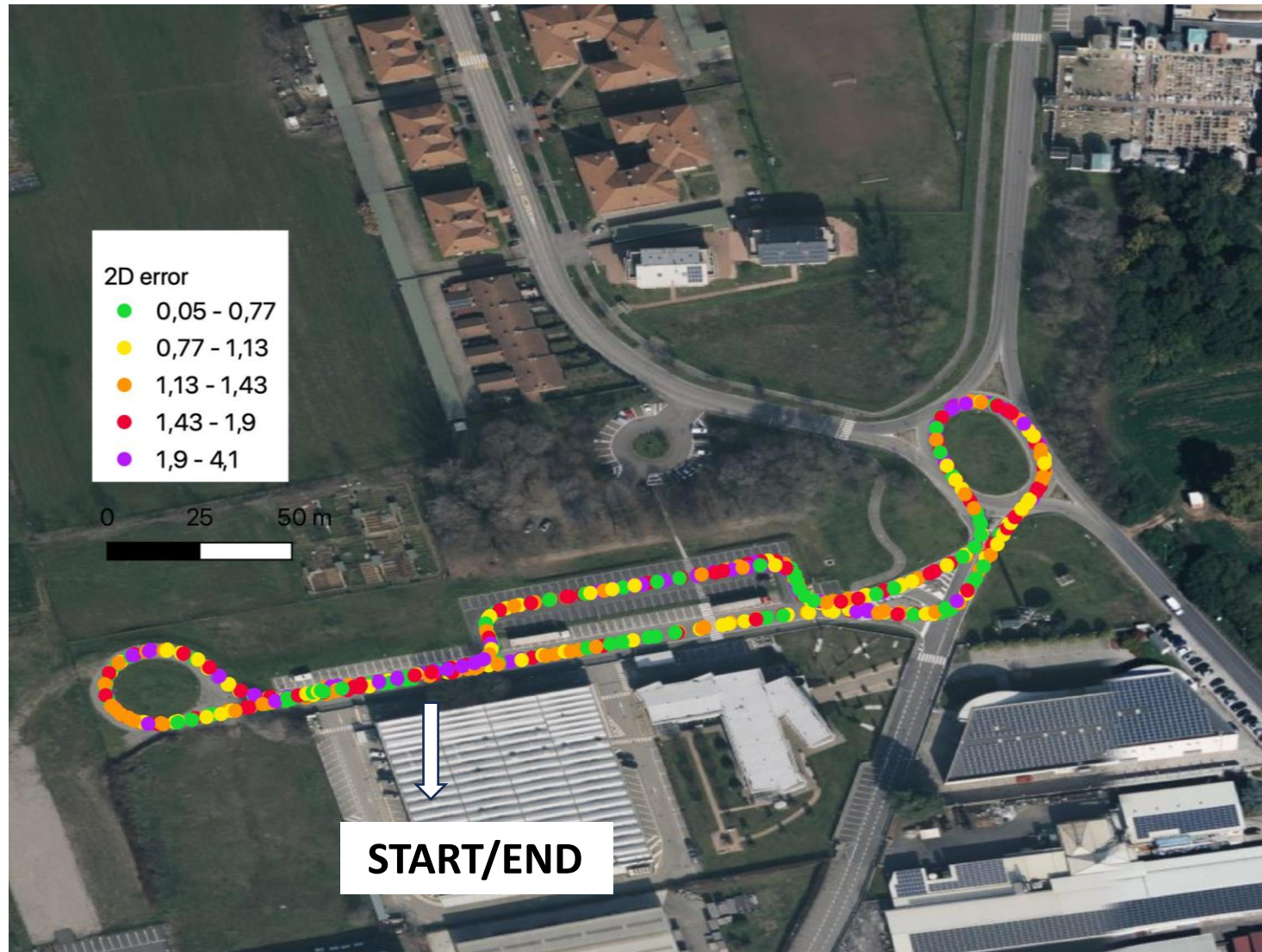
- ✓ Residuals computed wrt RTK
- ✓ Applied horizontal corrections to align Stonex antenna to **ANT3B-HEL5**



KINEMATIC RESULTS

Test	MEAN			STD			MAX			MIN		
	EAST	NORTH	UP	EAST	NORTH	UP	EAST	NORTH	UP	EAST	NORTH	UP
K7	0,5	0,8	0,0	0,8	1,0	0,4	3,4	3,4	2,8	0,0	0,0	0,0

Kinematic results: HYPER5G – SOL2 – IONOFREE



Conclusions

- **Addressed problem**: positioning with the 5G cellular network and hybridization with GNSS
- **Experimental approach**: real data collected on the field for both 5G and GNSS
- **Main product of the project**: algorithms and software capable of jointly processing 5G ToAs and GNSS pseudorange observations in a hybrid approach
- **Achieved positioning accuracy**:
 - Static:
 - 5G-only: ~4 m (2D error)
 - Hybrid 5G-GNSS: ~1-3 m (2D error)
 - Kinematic:
 - 5G-only: ~20 m (2D error)
 - Hybrid 5G-GNSS: ~1-4 m (2D error)



HYbrid P ositioning E ngine R unning on
5 G and G NSS



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