# FaGO | FINAL PRESENTATION

## PROOF-OF-CONCEPT OF ADVANCED NAVIGATION ALGORITHMS BASED ON FACTOR GRAPH OPTIMIZATION

OHB AUSTRIA & TU GRAZ, 04/11/2026

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# AGENDA

1. Project Introduction
2. FGO-Nav Design and Implementation
3. Measurement Campaign and Evaluation Approach
4. Performance Analysis
5. Conclusions and Outlook
6. Questions?

# 1

# PROJECT INTRODUCTION



# FACTOR GRAPH OPTIMIZATION FOR GNSS-BASED PNT DETERMINATION

**FAGO:** PROJECT INTRODUCTION



## CONSORTIUM

**OHB Austria** and **Graz University of Technology**, supported by ESA through the NAVISP programme.

## PROJECT OBJECTIVE

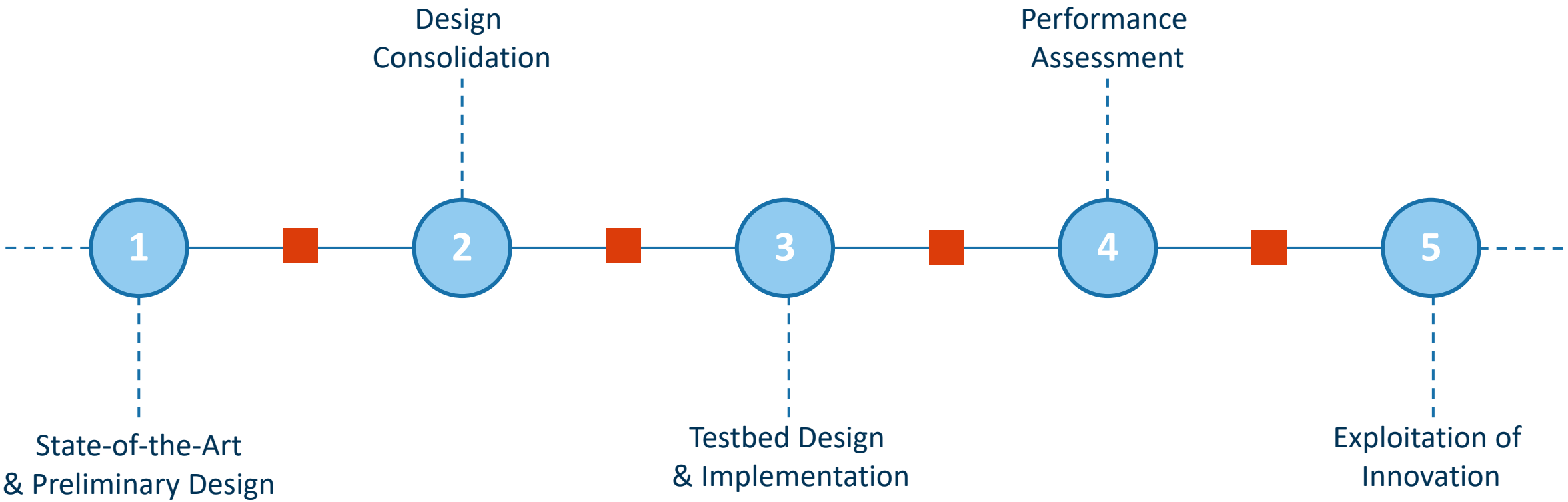
Investigate the applicability of **Factor Graph Optimization** (FGO) for **GNSS-based positioning** and gain a better understanding of its potential benefits and computational requirements.

## OUR APPROACH

Develop a flexible **FGO-based navigation system** and **benchmark its performance** against EKF-based filtering and commercial GNSS/INS solutions using experimental and publicly available datasets.

# PROJECT PHASES

**FAGO:** PROJECT INTRODUCTION



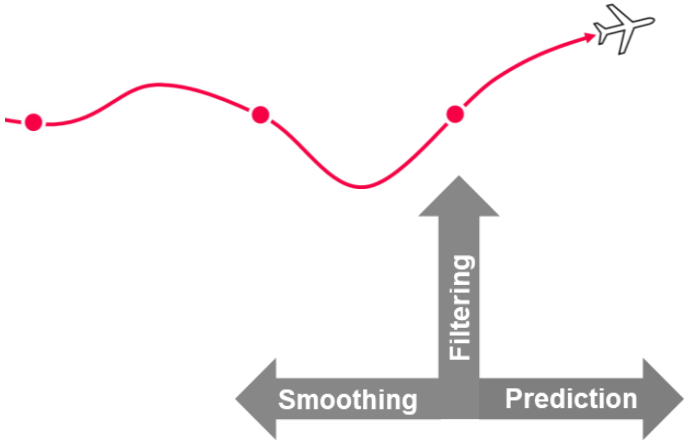
# 2

# FGO-NAV DESIGN AND IMPLEMENTATION



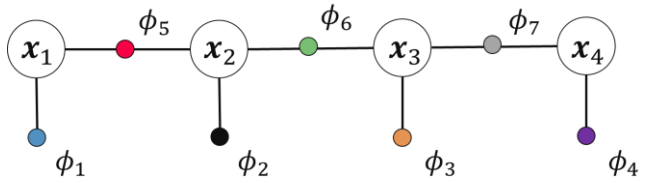
# INTRODUCTION

- Recent trend in the navigation community:
- Smoothing instead of filtering for trajectory determination: convincing results!



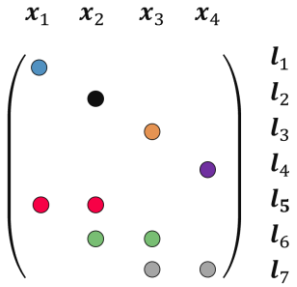

Influenced by an estimation framework from robotics:

Factor Graph Optimization (FGO)

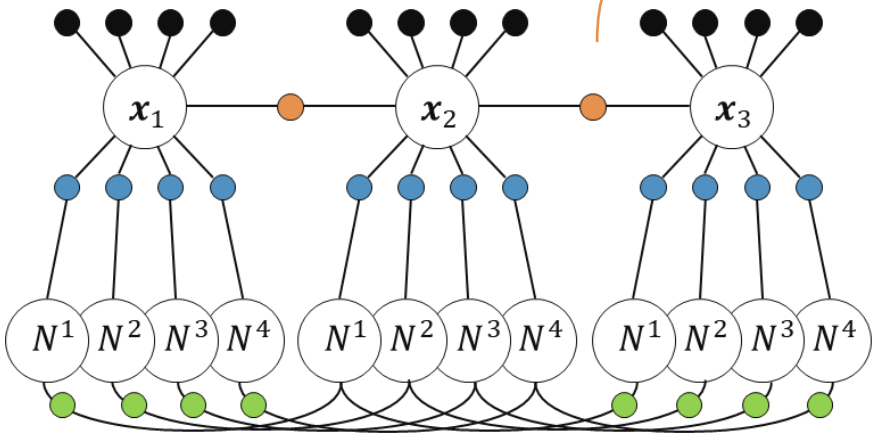



FGO is least-squares supported by graph methods:

Efficient solvers for general, large and sparse problems
(graph ↔ “structure”)



# WHAT IS A FACTOR GRAPH?




Dynamics factors
(motion, ionospheric slant delays, …)

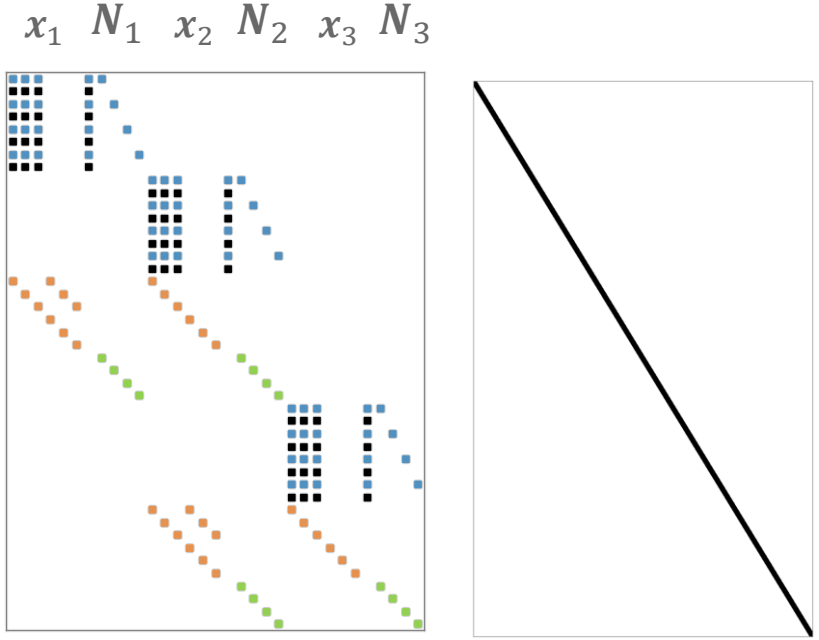
Pseudorange and Doppler Factors

**Epoch variables**
(position, velocity, biases, …)

Carrier Phase Factors

**Ambiguity variables**

Ambiguity Constraints




(3 epochs) (100 epochs)

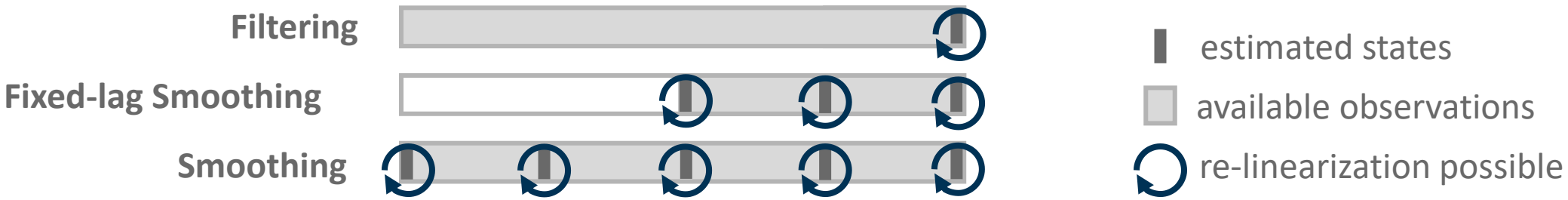
Structure of the corresponding design matrix

# FACTOR GRAPH OPTIMIZATION

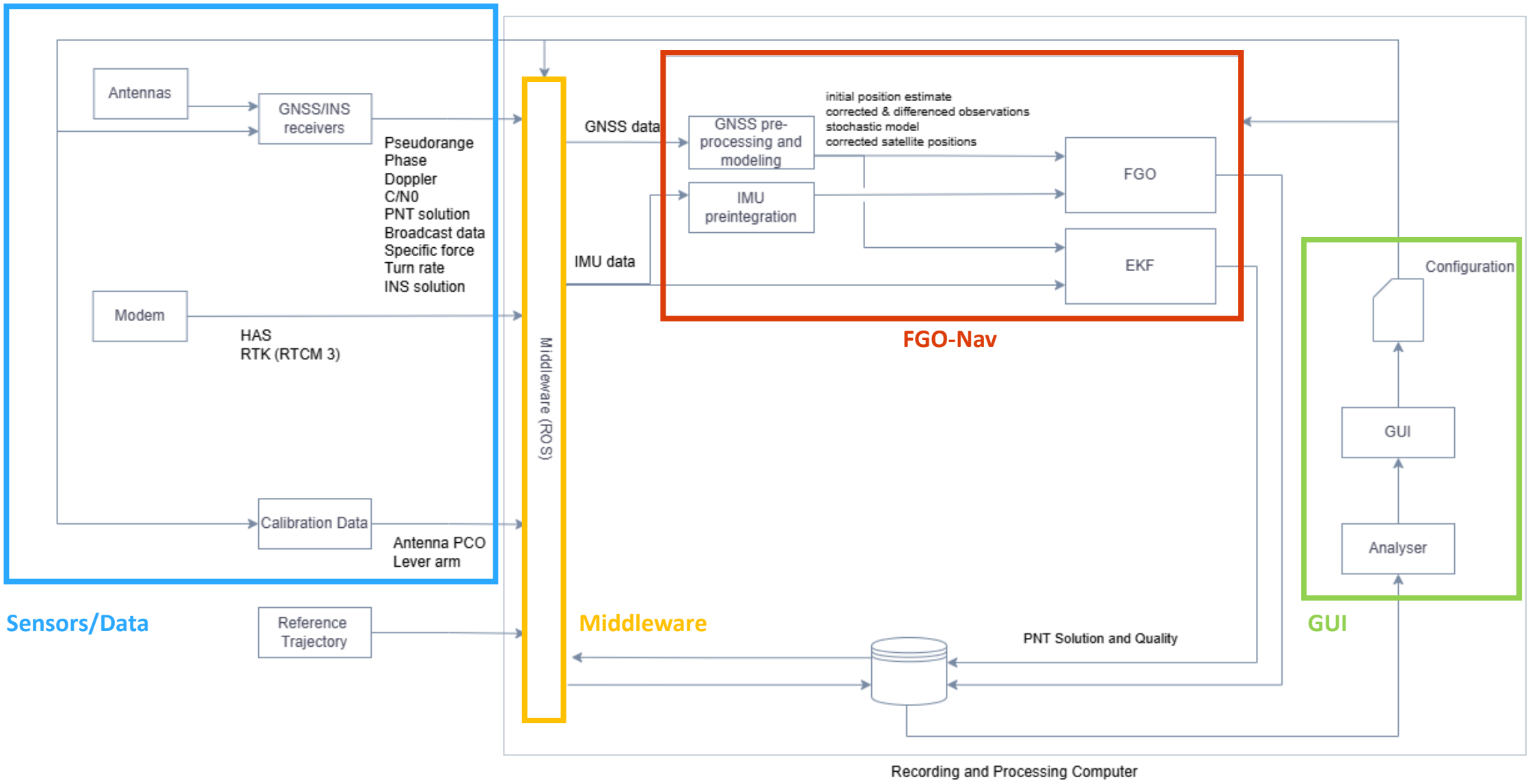
- FGO is used for:
  - smoothing (fixed lag, incremental)
  - batch optimization (fixed interval smoothing)

→ higher computational complexity than filter recursion

- thereby overcoming some of the theoretical disadvantages of the EKF:
  - Markov assumption
  - linearization

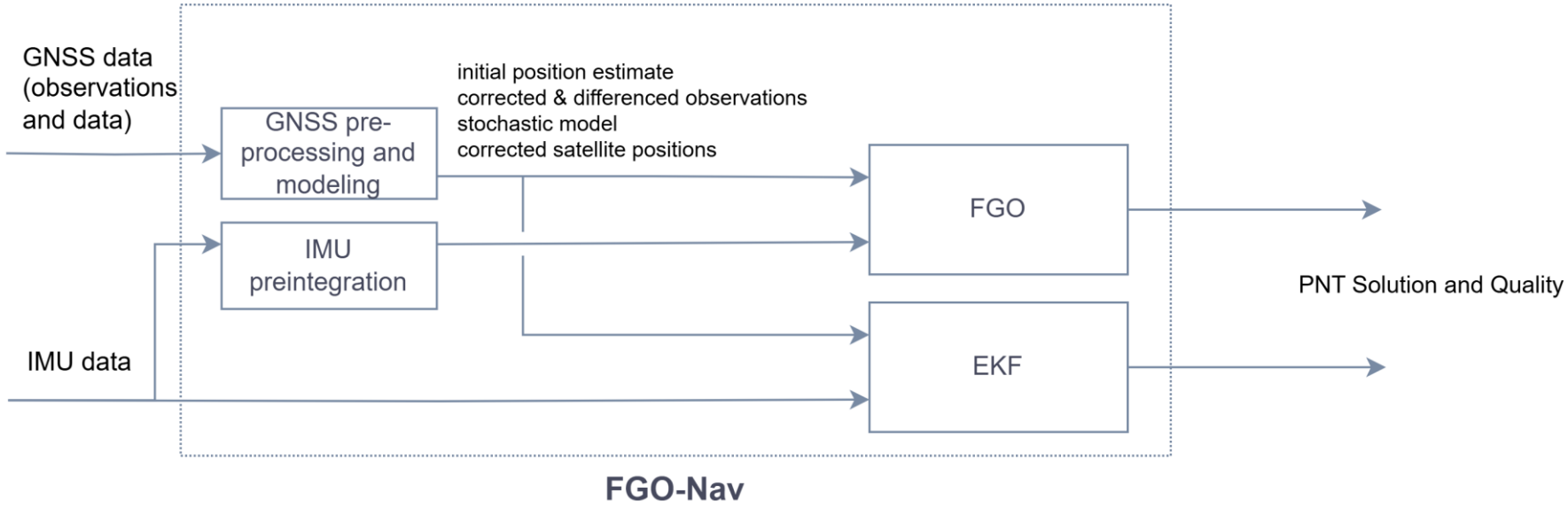


# FAGO TEST PLATFORM



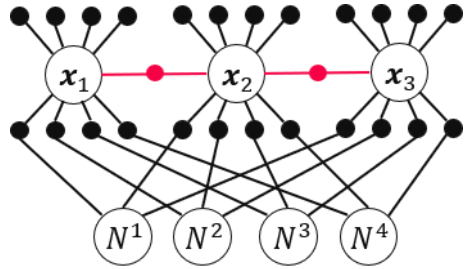
# FGO-NAV SOFTWARE

| | |
|---|---|
| **Input** | Files or from ROS |
| **Positioning models** | SPP, PPP, RTK (single and dual frequency) |
| **Sensor fusion** | IMU (tightly coupled) |
| **Estimators** | IEKF, FGO (incremental, fixed-lag), Batch-FGO with VCE |
| **Robustness** | M-estimation, innovation monitoring |
| **Estimation library** | GTSAM |
| **Programming language** | C++ |

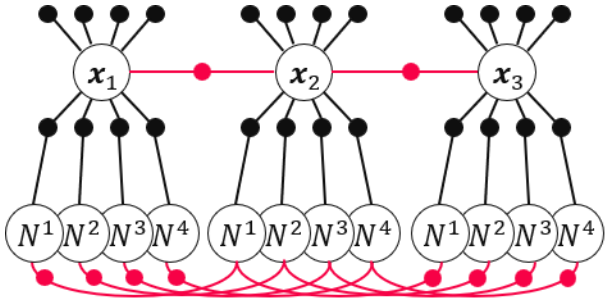


# GNSS MODELS AND GRAPH STRUCTURES

| Setting | SPP1F | SPP2F | PPP1F | PPP2F | RTK |
|---|---|---|---|---|---|
| **Signals** | E1,<br>L1 C/A | E1, E5b,<br>L1 C/A, L2C | E1,<br>L1 C/A | E1, E5b,<br>L1 C/A, L2C | E1, E5b,<br>L1 C/A, L2C |
| **Observables** | pseudorange,<br>Doppler | pseudorange,<br>Doppler | pseudorange,<br>carrier phase,<br>Doppler | pseudorange,<br>carrier phase,<br>Doppler | pseudorange (DD),<br>carrier phase (DD),<br>Doppler (SD) |
| **Orbit** | broadcast | broadcast | broadcast +<br>Galileo HAS | broadcast +<br>Galileo HAS | broadcast |
| **Sat. clock & code bias** | broadcast | broadcast | broadcast +<br>Galileo HAS | broadcast +<br>Galileo HAS | eliminated by DD |
| **Rec. clock** | estimated | estimated | estimated | estimated | eliminated by DD |
| **Ionospheric delays** | corrected | estimated | corrected | estimated | eliminated by DD |
| **Tropospheric delays** | corrected | corrected | corrected | corrected | eliminated by DD |
| **Ambiguities** | n/a | n/a | PER_EPOCH,<br>no IAR | PER_TRACK,<br>no IAR | PER_TRACK,<br>IAR by PAR |




ambiguities „per track“




ambiguities „per epoch“

# 3

# MEASUREMENT CAMPAIGN AND EVALUATION APPROACH



# EVALUATION METHODOLOGY

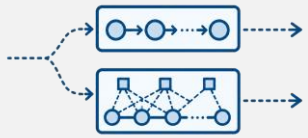
APPROACH

## DATA COLLECTION



Establish a representative test basis using data collected during a dedicated **measurement campaign** as well as selected **open datasets**, covering different receiver classes and GNSS environments.

## DATA PROCESSING



Using identical measurement preprocessing and observation models, process the same datasets with an **FGO** and **EKF** estimator.

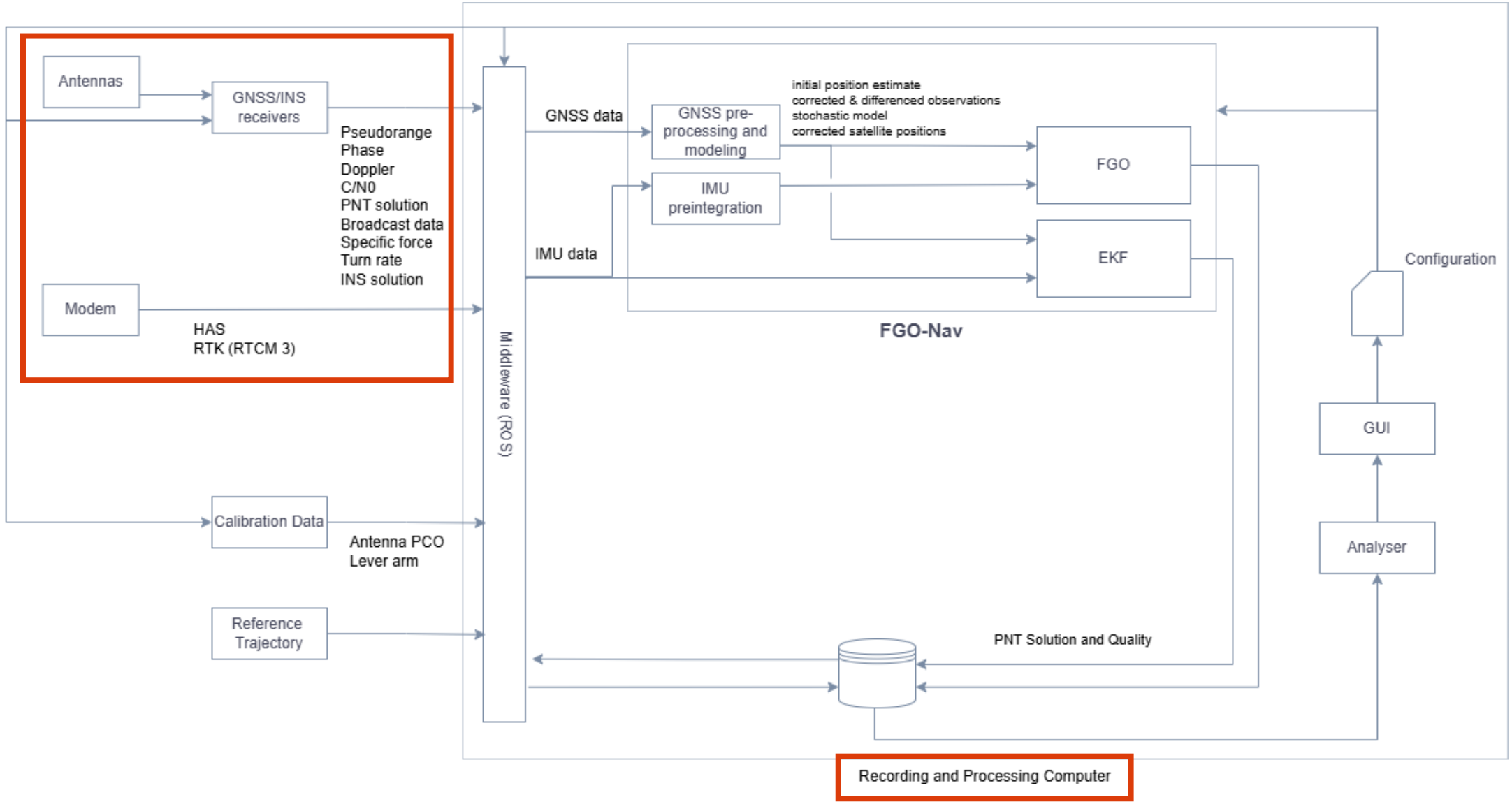
## PERFORMANCE ANALYSIS



Evaluate and compare the **positioning performance** and **computational requirements** of both estimators across different test conditions and processing configurations.

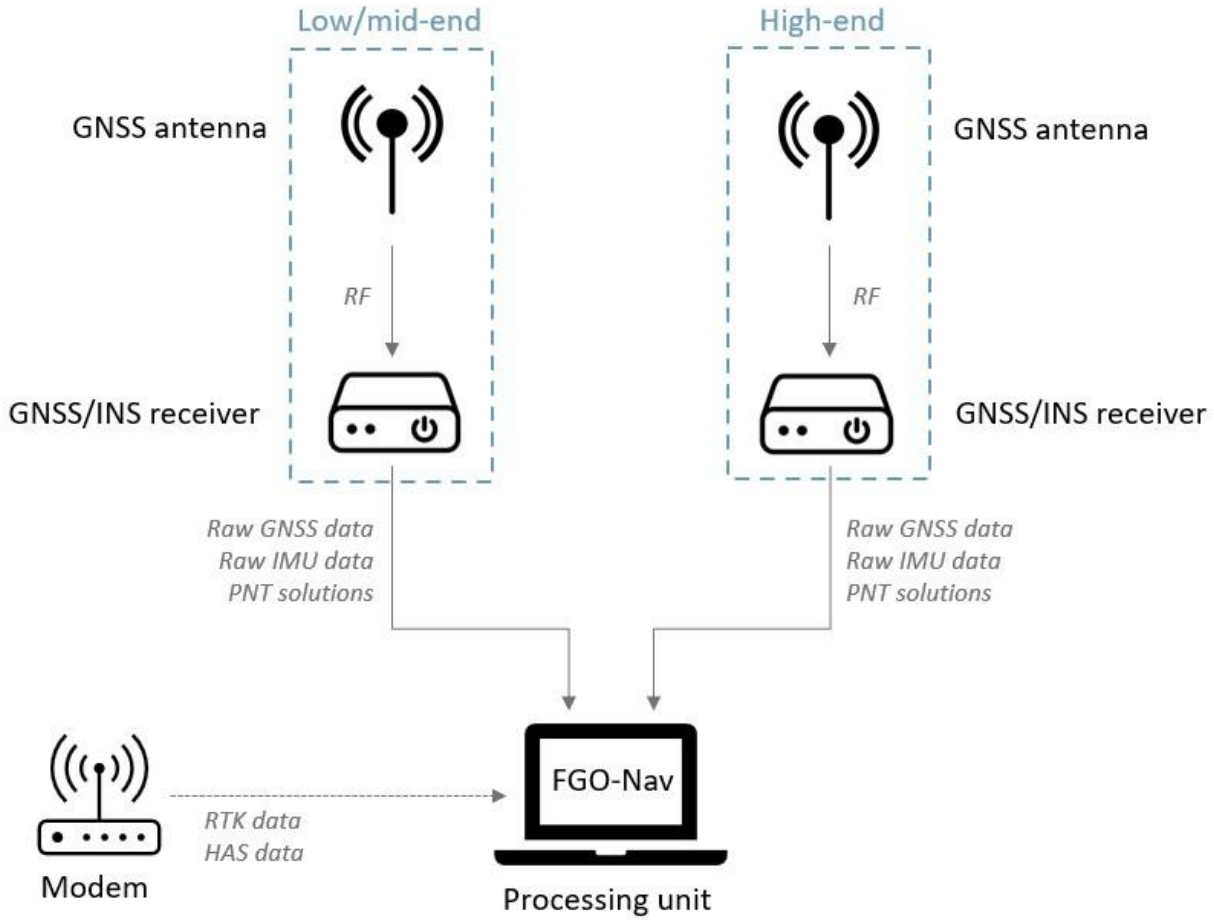
# MEASUREMENT CAMPAIGN

## TESTBED DESIGN



# MEASUREMENT CAMPAIGN

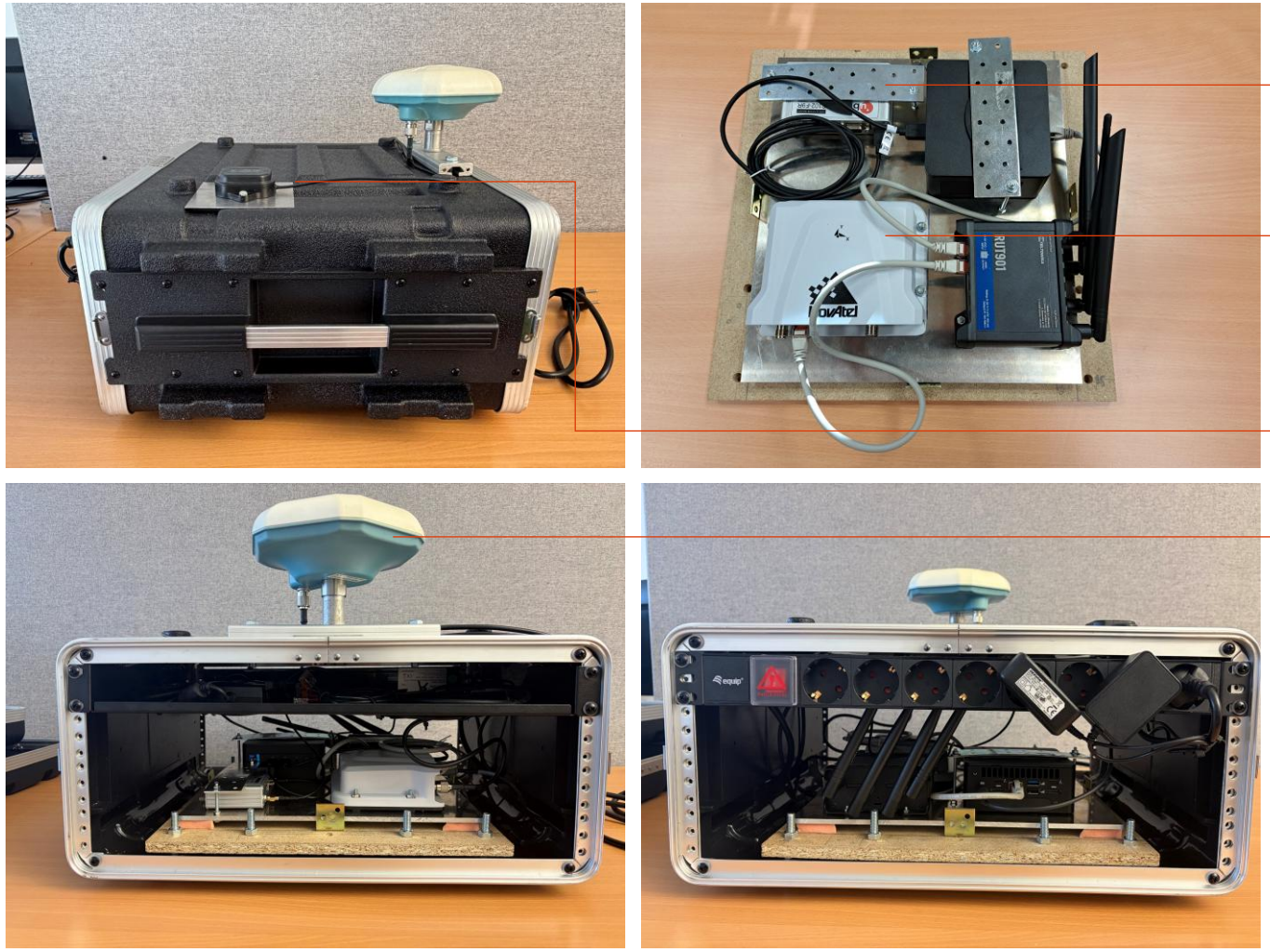
## TESTBED DESIGN




- **Two GNSS receiver classes** were selected to investigate the influence of measurement quality on FGO positioning performance.
- **Two independent sensor paths** were established, each combining a GNSS/INS receiver with an antenna of a corresponding performance class.
- **Integrated inertial sensors** in both receivers provide raw IMU measurements and internal INS solutions.
- **External correction data** are received via an LTE modem, providing access to RTK corrections from EPOSA and PPP corrections from Galileo HAS (IDD).

# MEASUREMENT CAMPAIGN

## TESTBED IMPLEMENTATION



u-blox C102-F9R EVK

NovAtel PwrPak7-E1

u-blox ANN-MB2

NavXperience 3G+C Mobile

Figure 1: FaGO testbed hardware.



Figure 2: Testbed installation on the car.

# MEASUREMENT CAMPAIGN

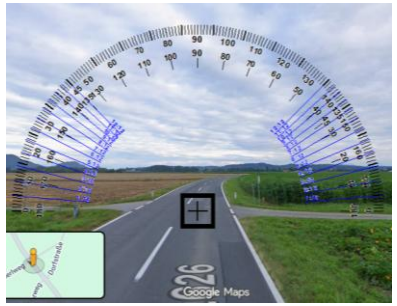
## ENVIRONMENT SELECTION

**Suburban:**

Masking angles less than 15°

Low buildings, trees

Level of multipath medium



**Light urban:**

Masking angles between 15° and 60°

Obstruction, non-line-of-sight

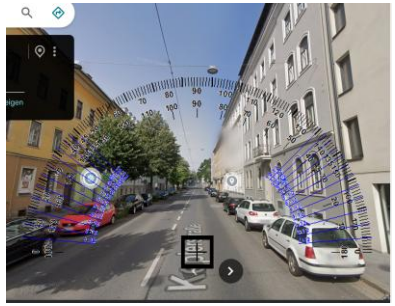
Multipath receptions



**Deep urban:**

Masking angles higher than 60°

Longer, more frequent tracking interruptions



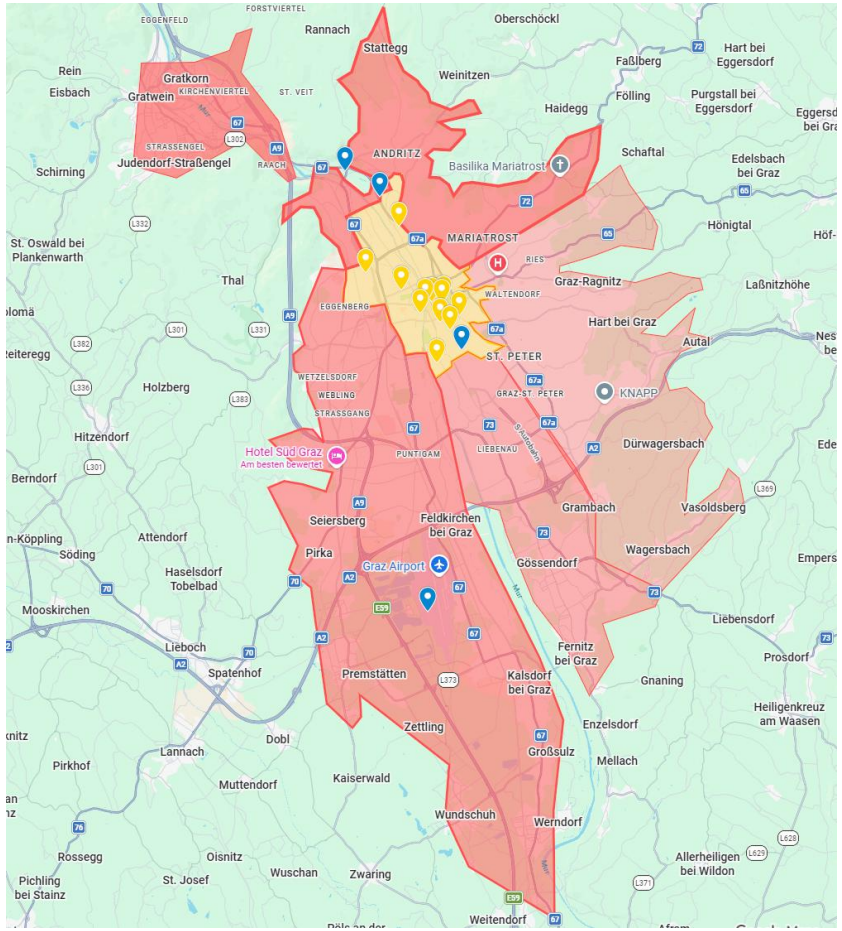



**Figure 3: Environment definitions in and around Graz, Austria: Yellow = deep urban; red = light urban; other area = suburban**

# MEASUREMENT CAMPAIGN

## FIELD TEST DEFINITION

- **Six different sensor configurations (scenarios) within three different environments = 18 field tests**
- **Sensor configuration differences:**
  - Used signals
  - IMU usage
  - Internal PVT
- **Duration:**
  - 6x two hours (FT 01-03, FT 10-12)
  - 12x one hour

**Correction data:**

- NTRIP client for RTK corrections from Austrian EPOSA
- NTRIP client for PPP corrections from Galileo HAS IDD

**Reference trajectory:**

- Navigation-grade INS (iMAR iNAV-RQH)
- Javad Sigma G3T GNSS receiver
- Tightly coupled post-processing using NovAtel Waypoint Inertial Explorer

| Receiver and IMU configurations | | | | Environment | | |
|---|---|---|---|---|---|---|
| GNSS signals | IMU | internal PVT | | sub-urban | deep urban | light urban |
| | | *u-blox* | *NovAtel* | | | |
| E1, E5b, L1 C/A, L2C | No | RTK | RTK | **FT-01** | **FT-02** | **FT-03** |
| E1, E5b, L1 C/A, L2C | No | SPP2F | SPP2F | **FT-04** | **FT-05** | **FT-06** |
| E1, L1 C/A | Yes | RTK + IMU | RTK + IMU | **FT-07** | **FT-08** | **FT-09** |
| E1, E5b, L1 C/A, L2C | Yes | RTK + IMU | RTK + IMU | **FT-10** | **FT-11** | **FT-12** |
| E1, E5b, L1 C/A, L2C | Yes | SPP2F + IMU | SPP2F + IMU | **FT-13** | **FT-14** | **FT-15** |
| E1, E5 (AltBOC), L1, L5 | Yes | - | RTK + IMU | **FT-16** | **FT-17** | **FT-18** |

**Table 1: Field test definitions.** Combination of receiver configuration and environment.

# GRAPHICAL USER INTERFACE

## TESTBED UI

- **Connects to FaGO testbed for an easy use of the testbed to collect data**

- **Features**:
  - Start docker container on the testbed
  - Configure NTRIP clients
  - Select and start scenario
  - Download recorded data

- **Status monitor**:
  - Receiver status + data rates
  - NTRIP client information
  - Recording status

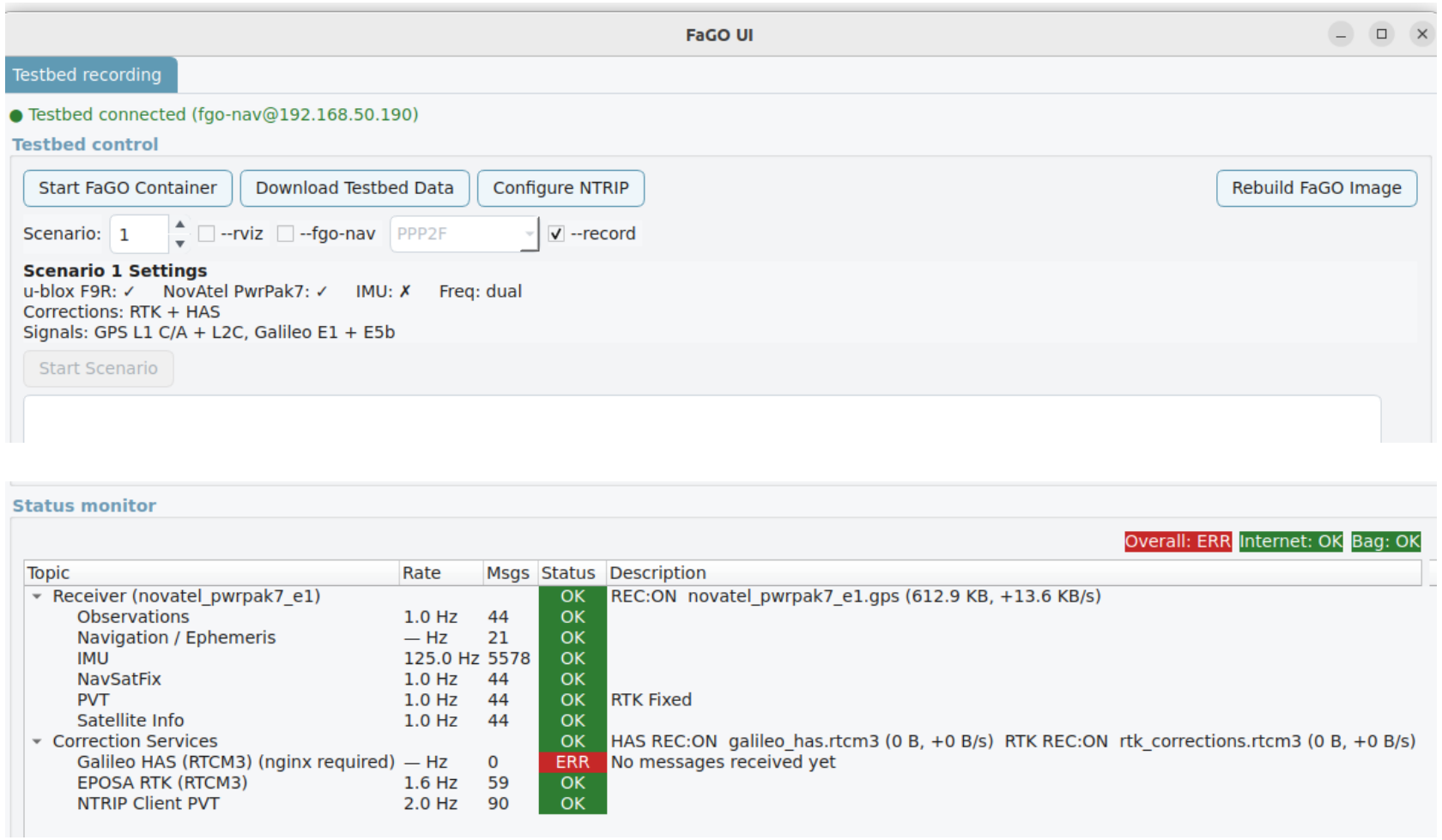
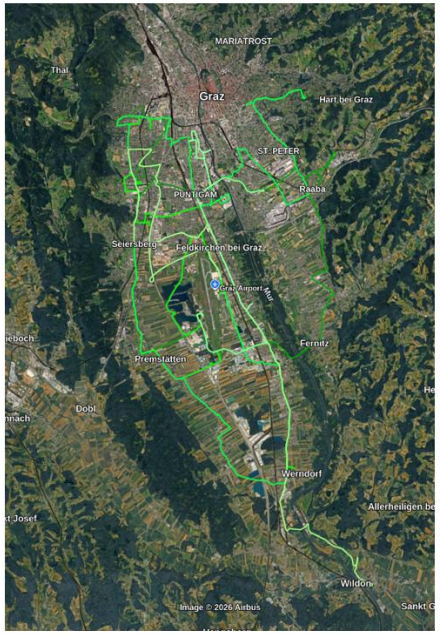



**Figure 4 : Testbed UI**
Top: Main window allowing scenario selection and start
Bottom: Status monitor showing status of NovAtel receiver

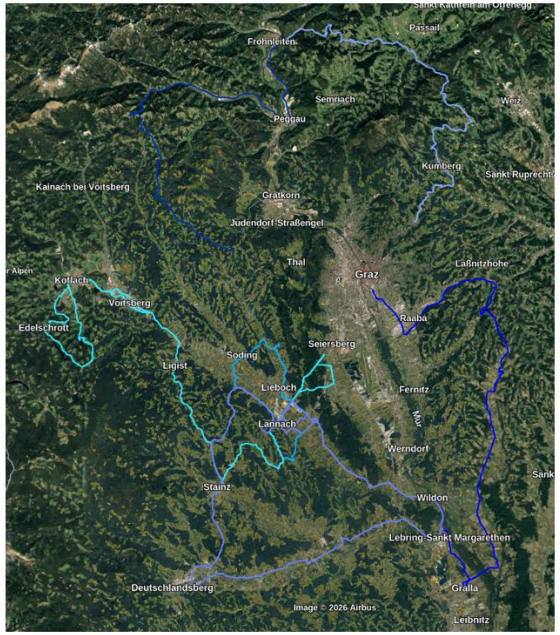
# USED DATASETS




Deep urban




Light urban




Suburban



**Figure 5:**
**Left: Field test trajectories per environment**
**Right: Measurement campaign vehicle setup**

## 1. Measurement campaign

- Data recorded with the **FaGO testbed**.
- **ROS2 bags** + **receiver proprietary data**
- 18 field tests across six sensor configurations in suburban, light urban and deep urban environments (Graz, Austria). Duration recorded data: **24h 54 min.**
- 17 field tests were included in the performance analysis; FT-14 excluded due to an unreliable reference trajectory.

## 2. Open datasets

- **UrbanNav:**
  - UrbanNav-HK-Medium-Urban-1 (Hong Kong)
  - u-blox ZED-F9P + Xsens MTi-10 IMU
- **Google Smartphone Decimeter Challenge:**
  - 2023-05-26-18-51-us-ca-sjc-ge2 (San Jose, California)
  - Google Pixel 5 and 7 Pro smartphone

# EVALUATION APPROACH

## GENERAL

**Comparison principle:** All datasets were processed with the **FGO-based fixed-lag smoother** and the **EKF-like filtering estimator**. Identical GNSS preprocessing, observation models and stochastic models were used for both estimators, allowing the influence of the estimation approach to be assessed directly.

| Category | Setting used | |
|---|---|---|
| **Estimator** | FGO [FIXED-LAG], lag length = 10 s<br>EKF [FILTERING] | |
| **Dynamic models** | Receiver<br>Clock<br>Ionosphere | constant velocity / IMU<br>constant drift<br>random walk |
| **Stochastic model** | $C/N_0$ | |

**Table 2: Common processing settings.**

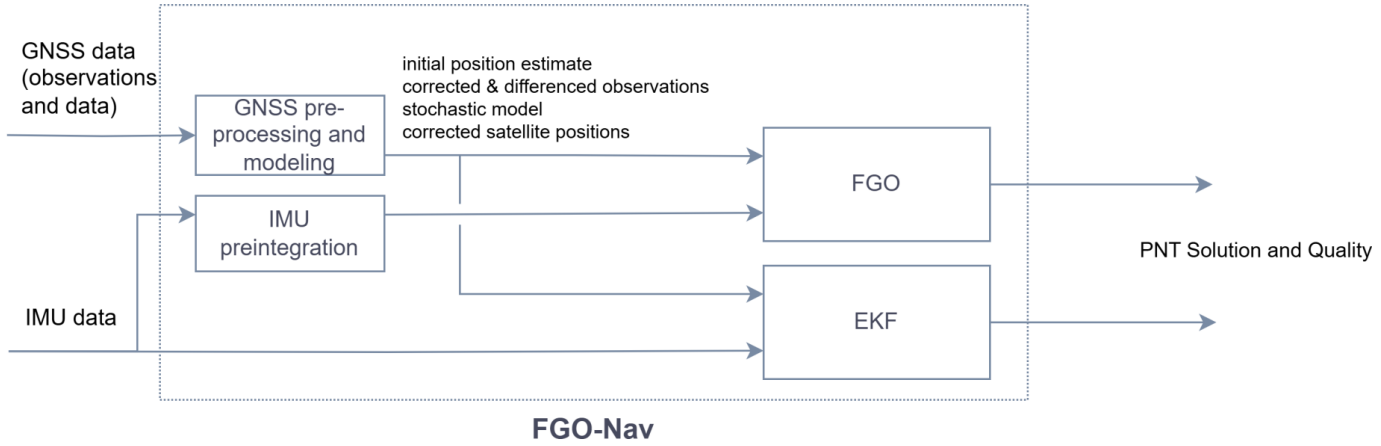



**Figure 6: System design | Estimators.** The FGO-based smoothing and EKF-like filtering estimator are embedded in parallel in the FaGO system.

# EVALUATION APPROACH

## PNT MODE SPECIFIC

| Setting | SPP1F | SPP2F | PPP1F | PPP2F | RTK |
|---|---|---|---|---|---|
| **Signals** | E1,<br>L1 C/A | E1, E5b,<br>L1 C/A, L2C | E1,<br>L1 C/A | E1, E5b,<br>L1 C/A, L2C | E1, E5b,<br>L1 C/A, L2C |
| **Observables** | pseudorange,<br>Doppler | pseudorange,<br>Doppler | pseudorange,<br>carrier phase,<br>Doppler | pseudorange,<br>carrier phase,<br>Doppler | pseudorange (DD),<br>carrier phase (DD),<br>Doppler (SD) |
| **Orbit** | broadcast | broadcast | broadcast +<br>Galileo HAS | broadcast +<br>Galileo HAS | broadcast |
| **Sat. clock & code bias** | broadcast | broadcast | broadcast +<br>Galileo HAS | broadcast +<br>Galileo HAS | eliminated by DD |
| **Rec. clock** | estimated | estimated | estimated | estimated | eliminated by DD |
| **Ionospheric delays** | corrected | estimated | corrected | estimated | eliminated by DD |
| **Tropospheric delays** | corrected | corrected | corrected | corrected | eliminated by DD |
| **Ambiguities** | n/a | n/a | PER_EPOCH,<br>no IAR | PER_TRACK,<br>no IAR | PER_TRACK,<br>IAR by PAR |

**Table 3: PNT mode specific processing settings.**

**Remarks:**

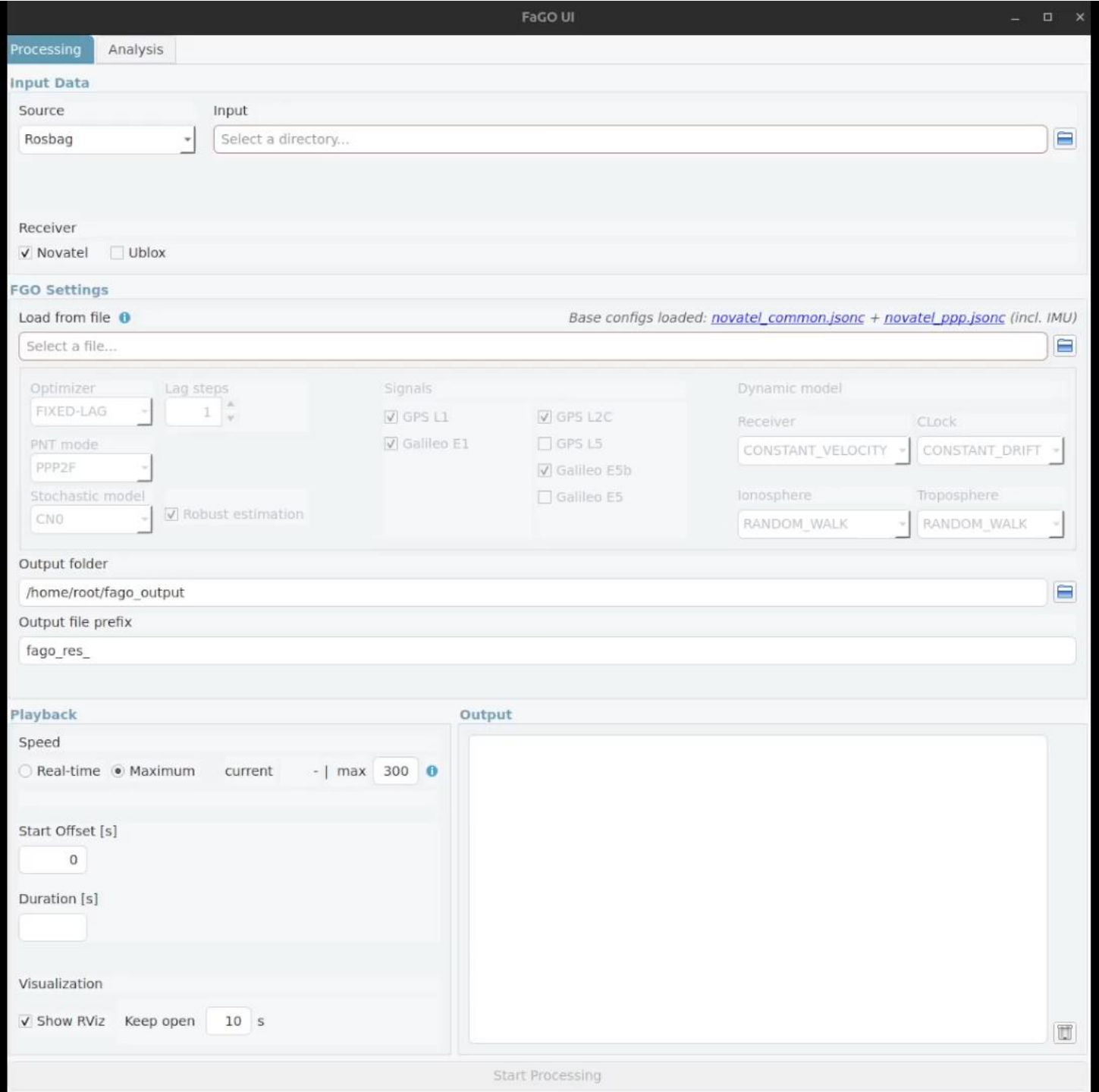
- **Signal availability:**
  FT-16–FT-18: different NovAtel signal combination (L1 C/A, L5, E1 and E5 AltBOC).

  FT-07–FT-09: only 1F data
- **Carrier-phase ambiguities:**
  PPP1F estimates ambiguities per epoch without integer ambiguity resolution.
  PPP2F estimates them per track without integer ambiguity resolution.
  RTK uses per-track ambiguities with partial ambiguity resolution (PAR).

# GRAPHICAL USER INTERFACE

## POST-PROCESSING UI

**Video demonstration**


FaGO UI
Processing
Analysis
Input Data
Source
Rosbag
Input
Select a directory...
Receiver
Novatel
Ublox
FGO Settings
Load from file
Base configs loaded: novatel_common.jsonc + novatel_ppp.jsonc (incl. IMU)
Select a file...
Optimizer
FIXED-LAG
Lag steps
1
PNT mode
PPP2F
Stochastic model
CN0
Robust estimation
Signals
GPS L1
GPS L2C
Galileo E1
GPS L5
Galileo E5b
Galileo E5
Dynamic model
Receiver
CONSTANT_VELOCITY
CLock
CONSTANT_DRIFT
Ionosphere
RANDOM_WALK
Troposphere
RANDOM_WALK
Output folder
/home/root/fago_output
Output file prefix
fago_res_
Playback
Speed
Real-time
Maximum
current
- | max
300
Start Offset [s]
0
Duration [s]
Visualization
Show RViz
Keep open
10
s
Output
Start Processing

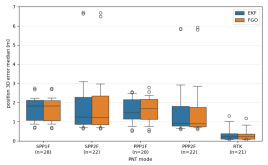
# 4

# PERFORMANCE ANALYSIS



# EVALUATION METHODOLOGY

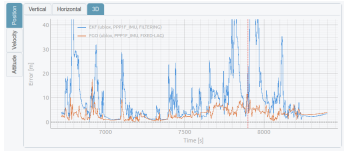
## PERFORMANCE ANALYSIS



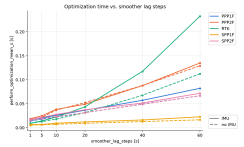
**1. Run-level positioning performance analysis.** The distributions of 3D position errors were evaluated across all processing runs: P50 (typical positioning performance), P95 and P99 (robustness against larger errors).

$$\Delta_i = FGO_i - EKF_i$$

**2. Matched FGO-EKF comparisons.** The 3D position errors (P50, P95, P99) for runs using identical field-test data and processing configurations were compared. Paired FGO—EKF differences were evaluated to identify systematic tendencies across receivers, PNT modes and operating conditions.



**3. Detailed field-test analysis.** Selected runs were examined in greater detail using 3D, horizontal and vertical position errors, including P50, P95, P99 and RMS. Error CDFs, time series and trajectories were used to investigate differences not captured by summary metrics.



**4. Computational performance.** Processing and optimization times were evaluated for different FGO smoother lag lengths. The corresponding positioning accuracy was also assessed to investigate the trade-off between computational cost and estimation performance.



**5. Open dataset evaluation.** FGO and EKF were additionally evaluated using publicly available GNSS datasets to assess their relative positioning performance beyond the project-specific field tests.

# POSITIONING PERFORMANCE

OVERALL ASSESSMENT: **P50**

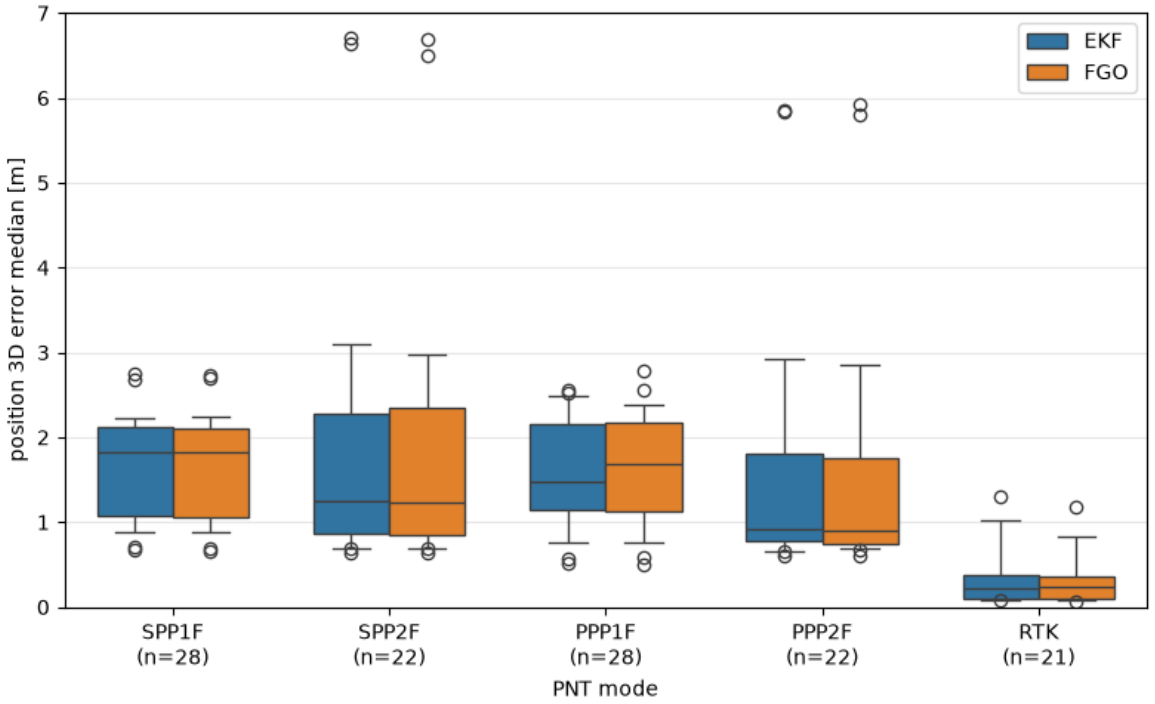



**Figure 7: NovAtel | P50.** Distribution across PNT modes for EKF and FGO.

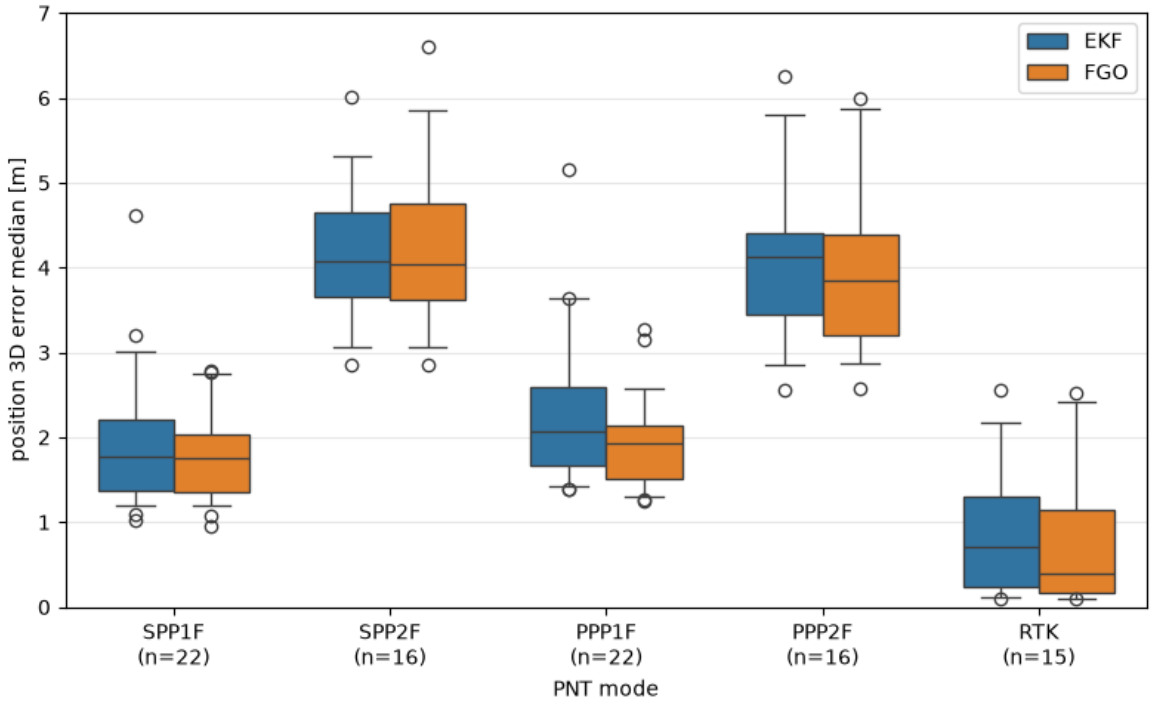



**Figure 8: u-blox | P50.** Distribution across PNT modes for EKF and FGO.

- **Comparable performance:** FGO and EKF show broadly comparable P50 positioning performance across all configurations, particularly for the NovAtel receiver.
- **u-blox:** FGO tends to achieve slightly lower median errors, although differences vary between PNT modes.

# POSITIONING PERFORMANCE

OVERALL ASSESSMENT: **P99**

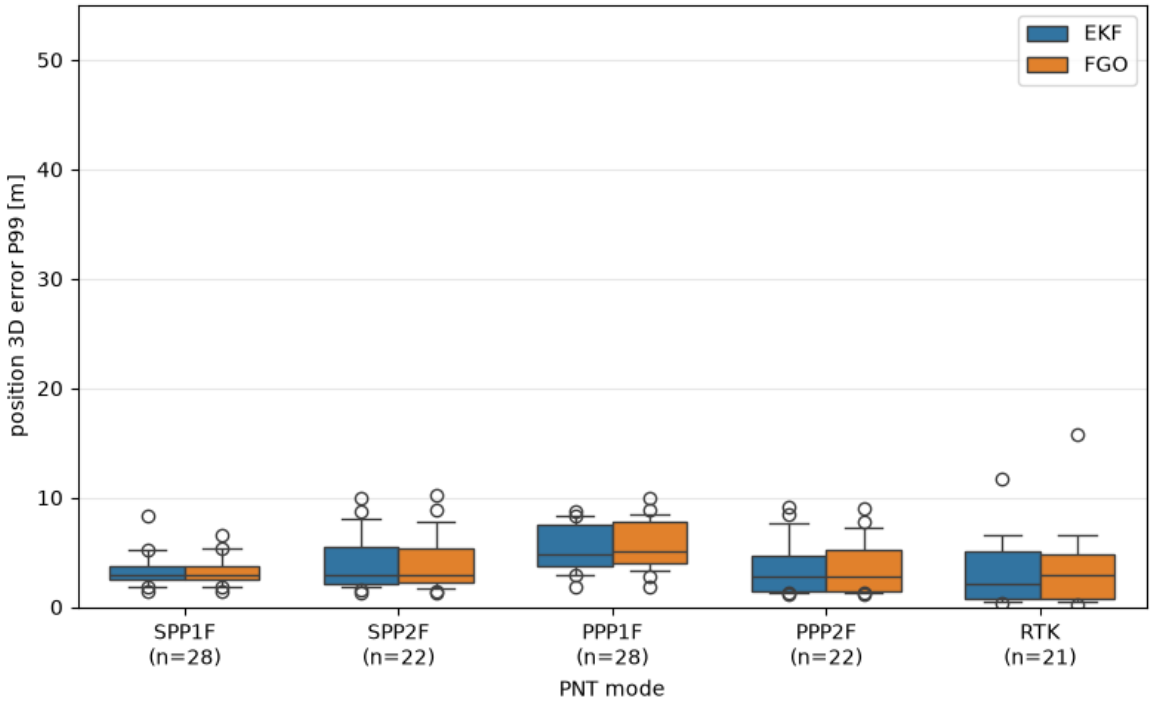



**Figure 9: NovAtel | P99.** Distribution across PNT modes for EKF and FGO.

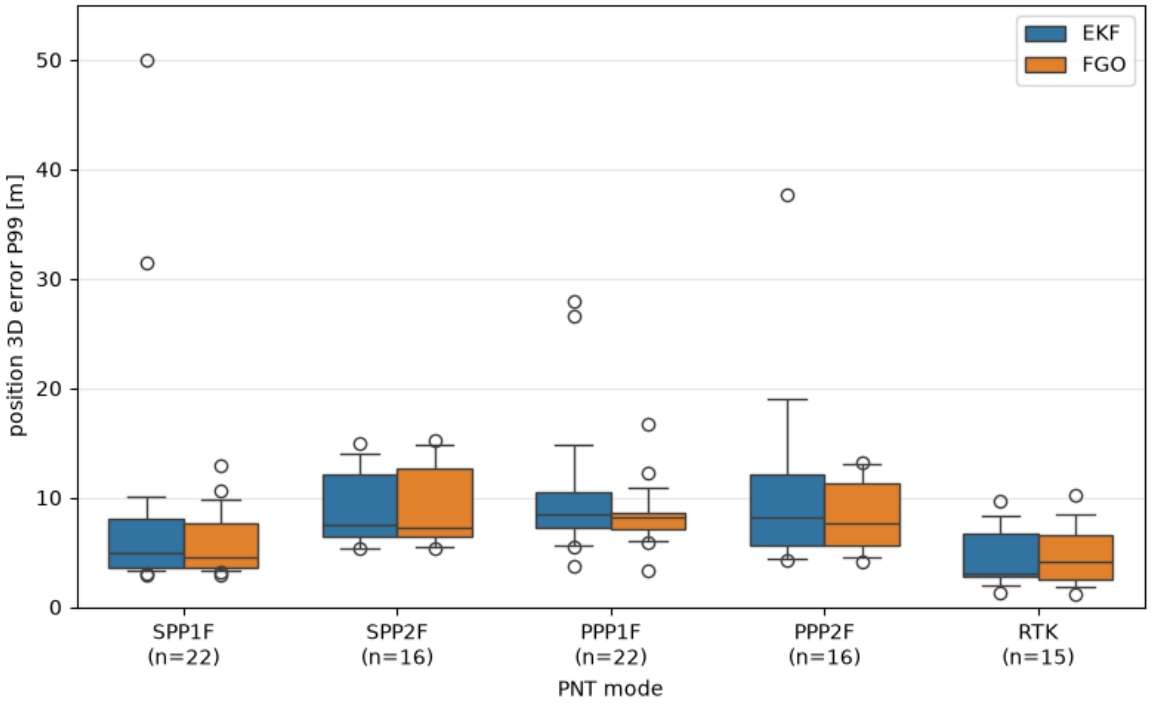



**Figure 10: u-blox | P99.** Distribution across PNT modes for EKF and FGO.

- **NovAtel:** FGO and EKF show broadly comparable P99 positioning errors across the evaluated PNT modes.
- **u-blox:** FGO shows a tendency towards lower P99 errors, particularly for SPP1F and PPP configurations.
- **Large-error behaviour:** FGO can reduce large positioning errors in certain configurations, but improvements are not systematic.

# POSITIONING PERFORMANCE

## FGO VS. EKF: **MATCHED COMPARISONS**

| Receiver | PNT mode | $n$ | $\Delta_{P50}\ (m)$ | $\Delta_{P95}\ (m)$ | $\Delta_{P99}\ (m)$ |
|---|---|---|---|---|---|
| **NovAtel** | **All** | **121** | **−0.005** | **−0.004** | **−0.020** |
| | SPP1F | 28 | −0.001 | −0.002 | −0.011 |
| | SPP2F | 22 | −0.008 | −0.002 | −0.075 |
| | PPP1F | 28 | +0.010 | +0.253 | +0.262 |
| | PPP2F | 22 | −0.022 | −0.033 | −0.063 |
| | RTK | 21 | −0.003 | −0.018 | +0.008 |
| **u-blox** | **All** | **91** | **−0.028** | **−0.041** | **−0.208** |
| | SPP1F | 22 | −0.020 | −0.094 | −0.249 |
| | SPP2F | 16 | +0.053 | +0.190 | −0.036 |
| | PPP1F | 22 | −0.155 | −0.244 | −0.261 |
| | PPP2F | 16 | +0.018 | +0.054 | −0.461 |
| | RTK | 15 | −0.094 | −0.005 | +0.066 |

**Table 4: Matched comparisons by PNT mode.** Values represent the median of matched FGO-EKF differences.

$$\Delta_i = FGO_i - EKF_i$$

- **NovAtel:** Median FGO–EKF differences are very small across all three percentiles (≤ 0.02 m in the aggregate), indicating broadly equivalent performance.
- **u-blox:** The aggregate differences favour FGO, with the largest improvement at P99 (−0.208 m), compared with −0.028 m at P50.
- **PNT-mode dependence:** The direction and magnitude of the differences vary between configurations, FGO does not consistently outperform EKF in every mode.

# POSITIONING PERFORMANCE

## FGO VS. EKF: **MATCHED COMPARISONS**

| Receiver | Condition | $n$ | $\Delta_{P50}\ (m)$ | $\Delta_{P95}\ (m)$ | $\Delta_{P99}\ (m)$ |
|---|---|---|---|---|---|
| **NovAtel** | without IMU | 74 | −0.002 | −0.002 | +0.007 |
| | with IMU | 47 | −0.019 | −0.004 | −0.050 |
| | deep urban | 35 | −0.003 | +0.017 | −0.133 |
| | suburban | 43 | −0.007 | −0.013 | −0.034 |
| | light urban | 43 | −0.002 | −0.004 | +0.006 |
| **u-blox** | without IMU | 59 | −0.014 | +0.002 | −0.068 |
| | **with IMU** | **32** | **−0.098** | **−0.140** | **−1.498** |
| | deep urban | 25 | −0.094 | +0.012 | −0.336 |
| | suburban | 33 | −0.012 | −0.053 | −0.597 |
| | light urban | 33 | −0.017 | −0.054 | −0.145 |

**Table 5: Matched comparisons by processing configuration.** Values represent the median of matched FGO-EKF differences.

$$\Delta_i = FGO_i - EKF_i$$

- **NovAtel:** FGO and EKF remain broadly comparable across all processing conditions, with only small median differences.
- **IMU integration:** For u-blox, the matched comparisons with IMU show a stronger advantage for FGO, particularly at P99 (−1.498 m), compared with −0.068 m without IMU.
- **Environment:** For u-blox, median P99 differences favour FGO in all three environments, although the magnitude varies (−0.145 m to −0.597 m).

# POSITIONING PERFORMANCE

## DETAILED DEEP URBAN EXAMPLE: **NOVATEL PPP1F WITH IMU**

| Estimator | Vertical Position Error (m) | | | | Horizontal Position Error (m) | | | | 3D Position Error (m) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P50 | P95 | P99 | RMS | P50 | P95 | P99 | RMS | P50 | P95 | P99 | RMS |
| **EKF** | -0.806 | 5.785 | 8.686 | 2.385 | 0.931 | 2.885 | 4.949 | 1.376 | 1.521 | 5.934 | 8.812 | 2.754 |
| **FGO** | **-0.756** | 6.025 | **8.208** | 2.406 | **0.893** | **2.766** | **4.889** | **1.342** | 1.561 | 6.207 | **8.370** | 2.756 |

**Table 6: NovAtel | PPP1F with IMU | Position errors per estimator.** Shaded cells indicate better FGO performance.

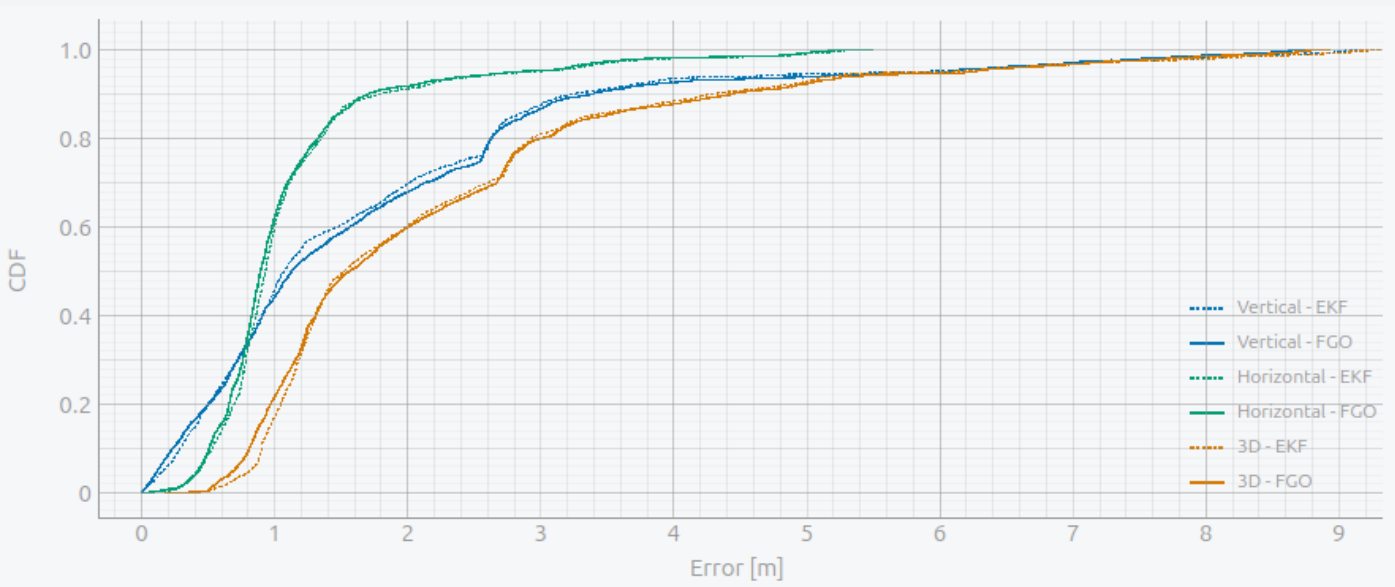



**Figure 11: NovAtel | PPP1F with IMU | Position error CDFs.** Solid lines for FGO, dotted lines for EKF.

- **Overall performance:** FGO and EKF achieve broadly comparable positioning accuracy.
- **Horizontal positioning:** FGO provides slightly lower errors across all reported metrics, with reductions of 4% at P50, 4% at P95, 1% at P99 and 2% in RMS.
- **Vertical and 3D positioning:** Results are mixed. FGO slightly reduces P99 errors, but does not consistently improve the median, P95 or RMS.

# POSITIONING PERFORMANCE

## DETAILED DEEP URBAN EXAMPLE: **U-BLOX PPP1F WITH IMU**

| Estimator | Vertical Position Error (m) | | | | Horizontal Position Error (m) | | | | 3D Position Error (m) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P50 | P95 | P99 | RMS | P50 | P95 | P99 | RMS | P50 | P95 | P99 | RMS |
| **EKF** | 1.558 | 9.055 | 14.755 | 5.545 | 1.838 | 11.056 | 31.211 | 7.161 | 3.644 | 14.891 | 37.916 | 9.057 |
| **FGO** | 1.737 | **7.951** | **11.589** | **3.714** | **1.581** | **4.956** | **7.334** | **2.833** | **3.270** | **8.416** | **13.326** | **4.671** |

**Table 7: u-blox | PPP1F with IMU | Position errors per estimator.** Shaded cells indicate better FGO performance.

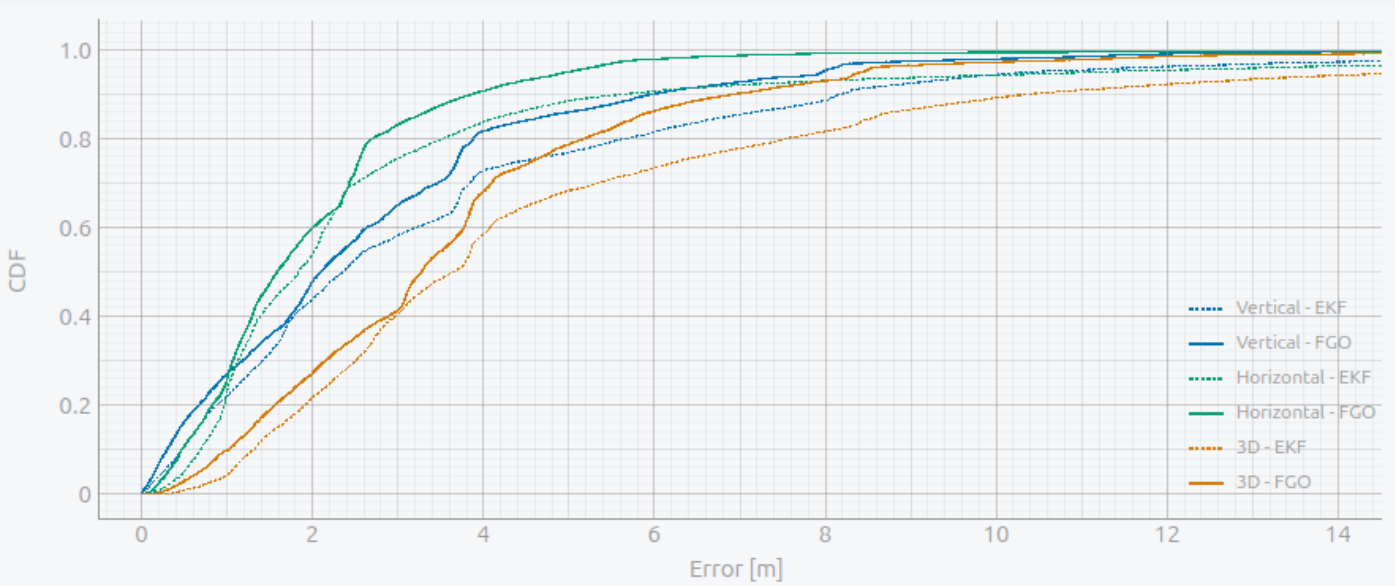



**Figure 12: u-blox | PPP1F with IMU | Position error CDFs.** Solid lines for FGO, dotted lines for EKF.

- **3D positioning:** FGO reduces positioning errors by 10% at P50, 43% at P95, 65% at P99 and 48% in RMS compared with EKF.
- **Horizontal positioning:** Particularly pronounced improvements, with 14% lower P50, 55% lower P95, 77% lower P99 and 60% lower RMS errors.
- **Vertical positioning:** FGO reduces P95 by 12%, P99 by 21% and RMS by 33%, while P50 is slightly higher (+11%).

# POSITIONING PERFORMANCE

## DETAILED DEEP URBAN EXAMPLE: **BOTH RECEIVERS PPP1F WITH IMU**




**Figure 13: u-blox PPP1F with IMU | trajectory.** FGO is orange, EKF is blue, reference trajectory is green.




**Figure 14: u-blox PPP1F with IMU | environment.**

**Environment:** Graz “deep-urban” = narrow streets with four/five-storey buildings on both sides

# POSITIONING PERFORMANCE

## DETAILED DEEP URBAN EXAMPLE: **BOTH RECEIVERS PPP1F WITH IMU**

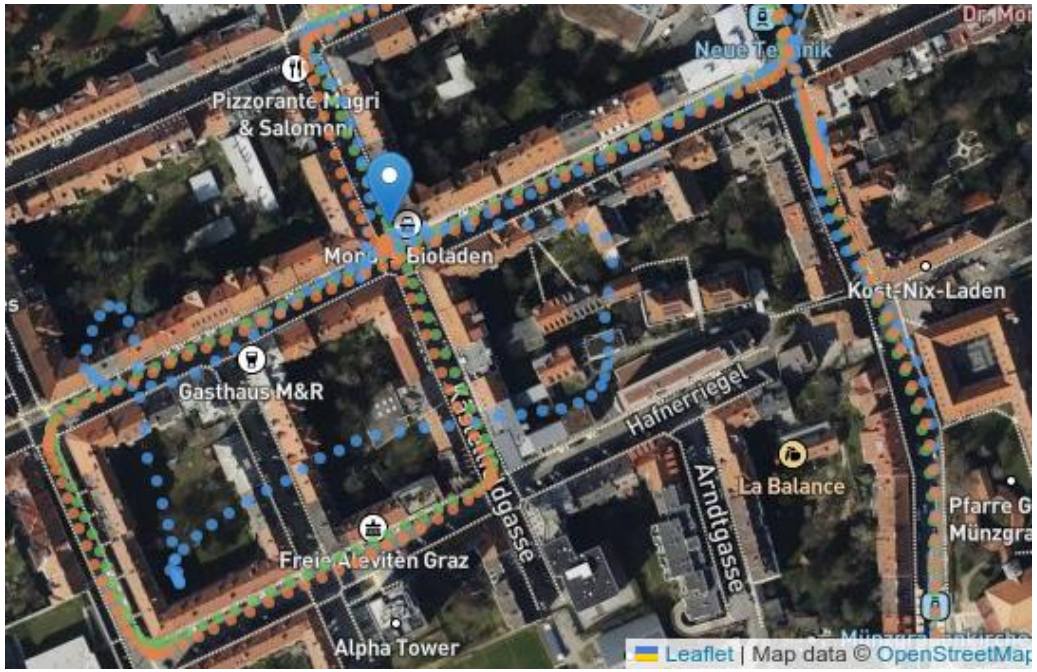



**Figure 15: u-blox PPP1F with IMU | trajectory.** FGO is orange, EKF is blue, reference trajectory is green.

- **u-blox:** FGO substantially reduces the magnitude and frequency of large positioning-error peaks compared with EKF
- **NovAtel:** FGO and EKF exhibit very similar error profiles throughout the trajectory
- **Based on this example, it seems that the benefit of FGO is most pronounced for the lower-cost receiver in deep urban environments.**




**Figure 16: PPP1F with IMU | 3D position error time series.** FGO is orange, EKF is blue. *Top:* u-blox. *Bottom:* NovAtel.

# COMPUTATIONAL PERFORMANCE

## LAG LENGTH VS. PROCESSING TIME

- Estimator: **FGO fixed-lag smoothing**
- Lag lengths: **[1 (= filtering), 5, 10, 20, 40, 60]**
- We analyzed the mean of the **total observation callback time** and the mean of the **optimization time** as a function of lag length.

- The optimization time makes up most of the total observation callback.
- **Lag-length dependence:** As expected, the optimization time increases with the smoothing window size.
- **PNT-mode/configuration dependence:** RTK shows the highest optimization times and strongest increase with lag length, SPP1F remains computationally least demanding; including IMU measurements generally increases the optimization time.
- **Real-time performance** was always achieved.

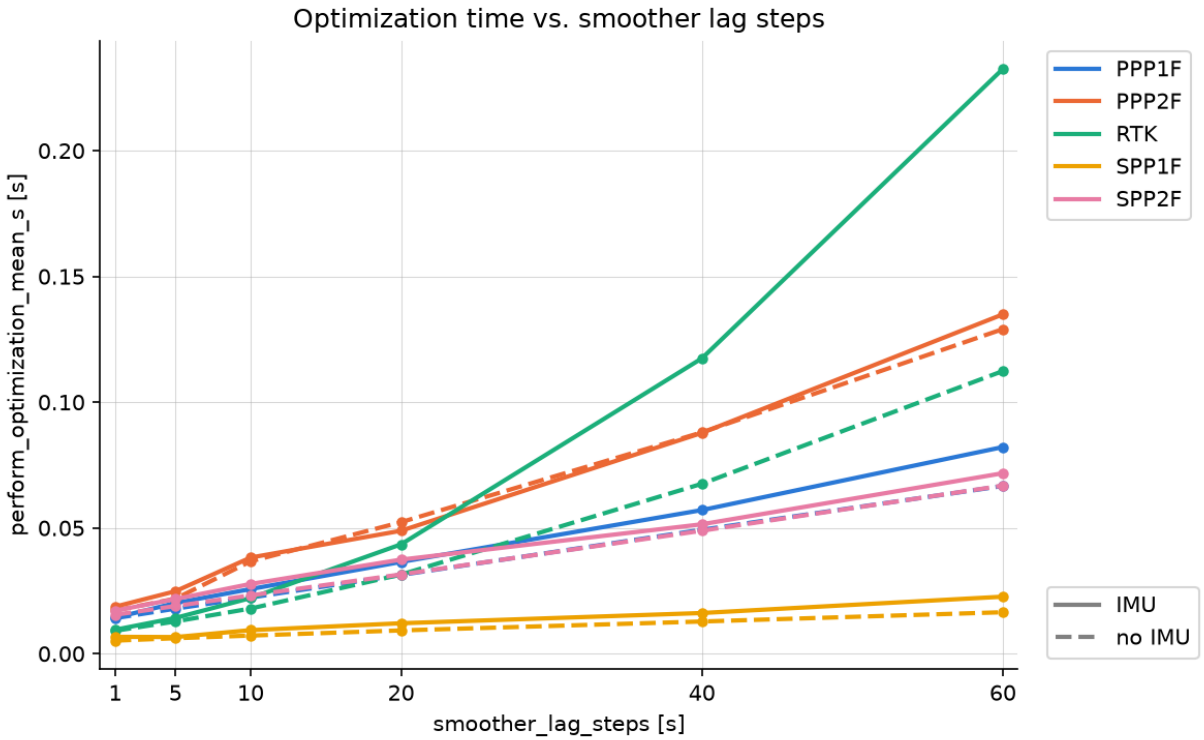



**Figure 17: Both receivers | Optimization time as a function of lag length.**

# COMPUTATIONAL PERFORMANCE

## LAG LENGTH VS. POSITION ACCURACY

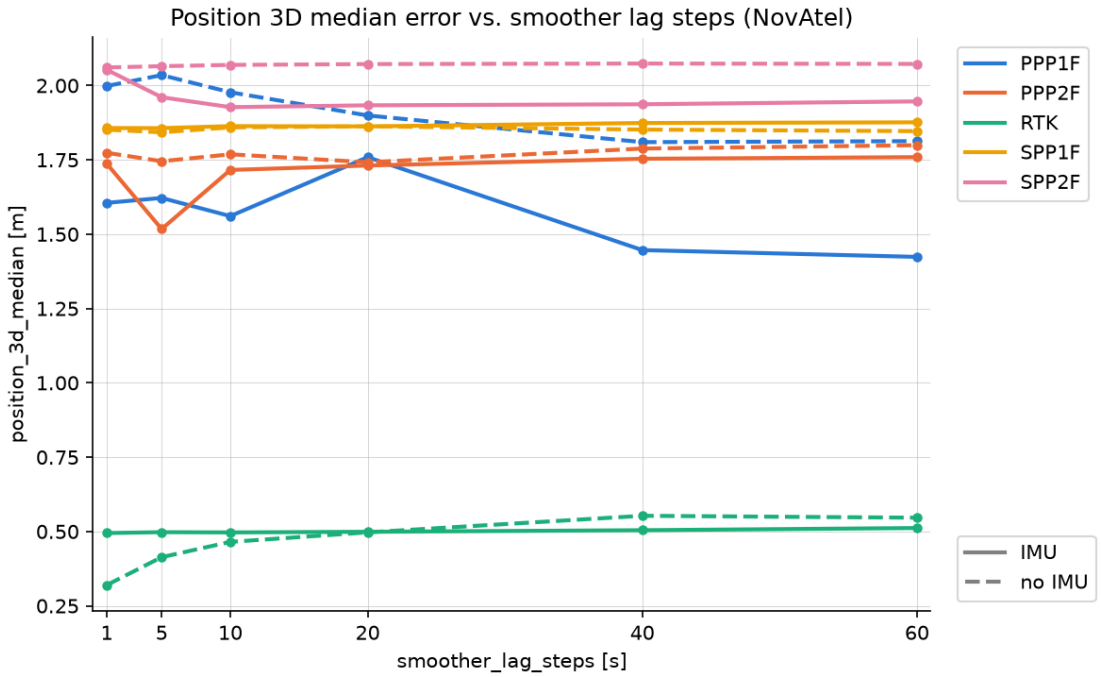



Figure 18: NovAtel | 3D position error P50 as a function of lag length.

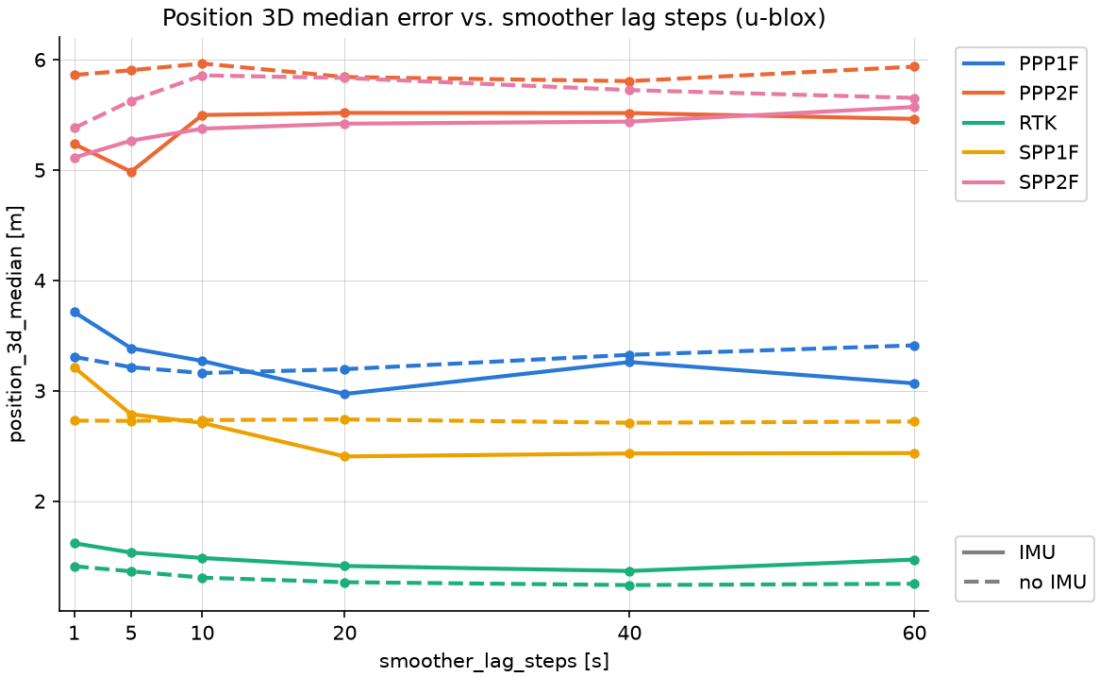



Figure 19: u-blox | 3D position error P50 as a function of lag length.

- **Limited accuracy benefit:** Increasing lag length does not lead to a systematic reduction in 3D positioning error (P50) across PNT modes / receivers.
- **Benefit for low-cost data processing:** We see improvements in 3 out of 5 positioning modes when processing u-blox data

# COMPUTATIONAL PERFORMANCE

## LAG LENGTH VS. POSITION ACCURACY

- **Horizontal pos. errors:**
  without IMU: improvements with increasing leg length (except Novatel-RTK)
  with IMU: the curves stay flat.
- **Vertical pos. errors:** flat/slightly increasing error curves

**Position accuracy-computational time trade-off:**
A 10 s lag provides a practical compromise for the evaluated configurations, longer lags generally increase computational cost without consistent accuracy gains.

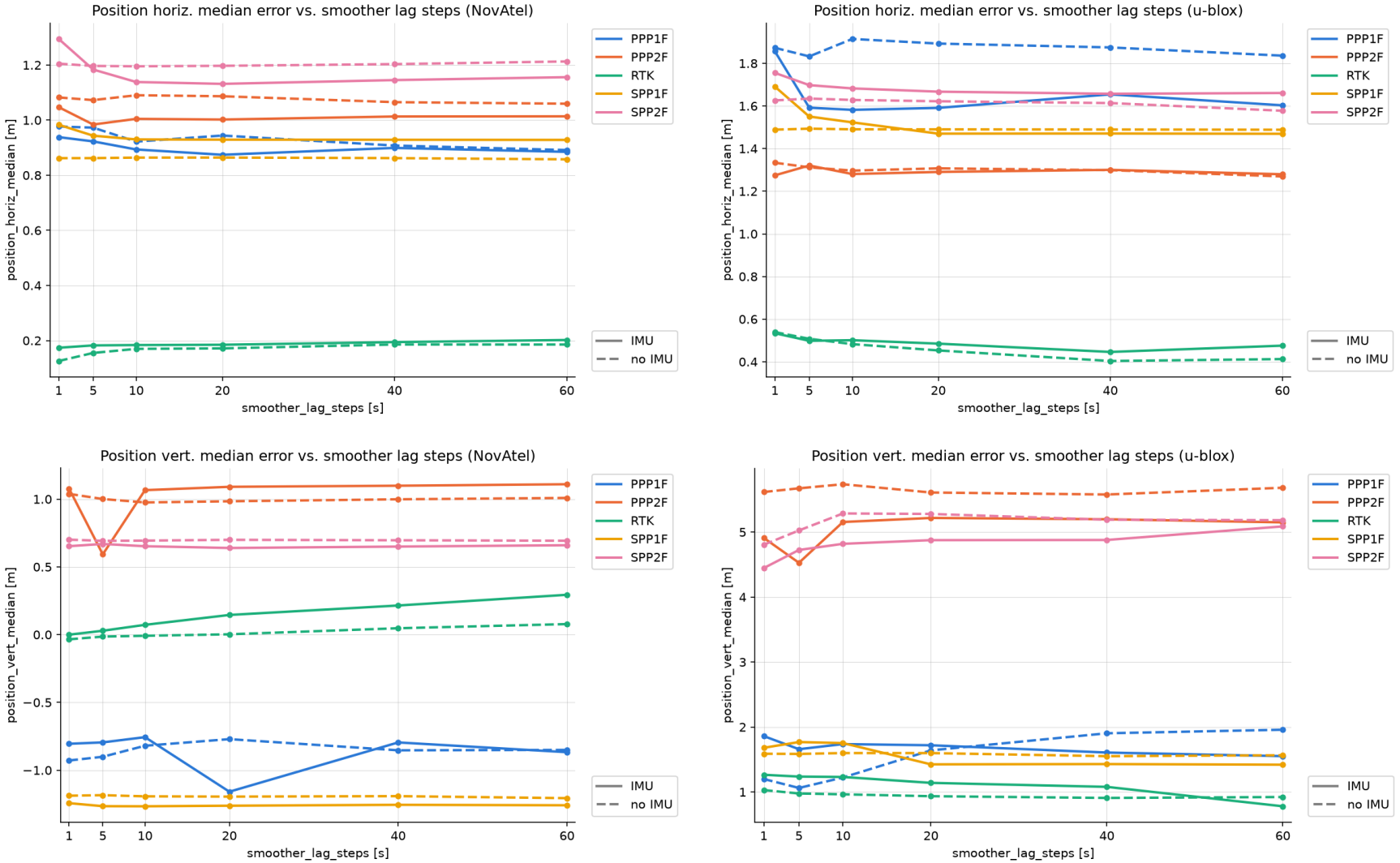



**Figure 20: Horizontal (top) and vertical (bottom) position error P50 as a function of lag length.** *Left:* NovAtel. *Right:* u-blox.

# EVALUATION USING OPEN DATASETS

## GOOGLE SMARTPHONE DECIMETER CHALLENGE 2023-2024

**Run**: 2023-05-26-18-51-us-ca-sjc-ge2 (San Jose, California)

### Google Pixel 5: RTK with IMU

| Estimator | Horizontal Position Error (m) | | 3D Position Error (m) | | SDC Score |
|---|---|---|---|---|---|
| | P50 | P95 | P50 | P95 | |
| **EKF** | 1.58 | 3.10 | 2.57 | 5.67 | 2.34 |
| **FGO** | 1.67 | 3.21 | 2.58 | 5.95 | 2.44 |

**Table 8: Pixel 5 | RTK with IMU | Position errors per estimator.**
Shaded cells indicate better FGO performance.

### Google Pixel 7 Pro: RTK with IMU

| Estimator | Horizontal Position Error (m) | | 3D Position Error (m) | | SDC Score |
|---|---|---|---|---|---|
| | P50 | P95 | P50 | P95 | |
| **EKF** | 1.60 | 3.01 | 2.52 | 5.74 | 2.30 |
| **FGO** | **1.49** | **2.95** | **2.45** | 5.79 | **2.22** |

**Table 9: Pixel 7 Pro | RTK with IMU | Position errors per estimator.**
Shaded cells indicate better FGO performance.




**Figure 21: Pixel 7 Pro RTK with IMU| trajectory.** FGO is orange, EKF is blue, reference trajectory is green.

- **Similar results** between EKF and FGO
- **SDC Score** is derived from Horizontal P50 and P95 performance
- **Online Leaderboard**:
  Rank 1: 0.88
  Rank 3: 1.34
  Rank 10: 1.83
- **Caveats**: Algorithm not optimized for phone data; real-time performance instead of post-processing

# EVALUATION USING OPEN DATASETS

## URBANNAV DATASET

**Run**: Medium Urban 1

| | Mode | Horizontal Position Error (m) | | | GNSS Epochs processed in % |
|---|---|---|---|---|---|
| | | P50 | P95 | RMSE | |
| **EKF** | SPP2F | 7.59 | 24.72 | 16.70 | 94.0 |
| | SPP2F + IMU | 5.94 | 16.81 | 14.13 | |
| | RTK | 4.40 | 50.43 | 20.91 | 54.4 |
| | RTK + IMU | 3.89 | 12.81 | 6.63 | |
| **FGO** | SPP2F | **6.95** | **23.73** | **16.47** | 94.0 |
| | SPP2F + IMU | 6.03 | 17.96 | 14.48 | |
| | RTK | 4.88 | **48.25** | 21.40 | 54.4 |
| | RTK + IMU | 4.01 | 16.88 | 9.78 | |

**Table 10: UrbanNav position errors per estimator for SPP2F and RTK with and without IMU.** Shaded cells indicate better FGO performance.

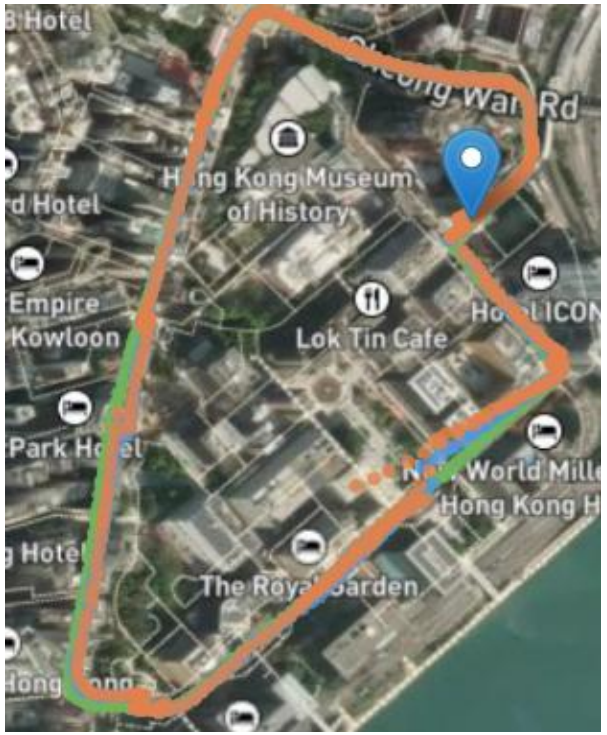



**Figure 22: Pixel 7 Pro RTK with IMU| trajectory.** FGO is orange, EKF is blue, reference trajectory is green.

- **EKF vs FGO** again perform similarly
- **IMU helps** especially in the tails (P95)
- **Solution availability** drops for RTK
- **Height Errors are large:** deep-urban multipath; vertical component dominates in 3D error
- **SPP benchmark: RMSE 16.67 m**; results are similar
- **FGO benchmark: RMSE 8.00 m**; RTK without IMU has high P95; worse than the benchmark; IMU improves results

# 5

# CONCLUSIONS AND OUTLOOK



# PERFORMANCE ASSESSMENT

## CONCLUSIONS

**1. Overall positioning performance.** FGO achieved positioning accuracy comparable to EKF-like filtering across receivers, PNT modes and operating environments, demonstrating its viability as an alternative navigation estimator. No consistent positioning-performance advantage of FGO was established.

**2. Receiver-dependent differences.** FGO-EKF differences were generally small for the high-end NovAtel receiver. For the mass-market u-blox receiver, FGO showed a tendency towards lower positioning errors, particularly at higher percentiles and in configurations with IMU integration.

**3. Performance under challenging conditions.** Selected deep urban scenarios demonstrated substantial reductions in large positioning errors with FGO. However, these improvements were scenario-dependent and cannot be generalized to all challenging GNSS conditions.

**4. Computational performance.** Real-time processing was achieved in the evaluated implementation. Computational effort increased with smoother lag length, while the corresponding accuracy improvements were generally limited and configuration-dependent. A lag of 10 s was selected as a practical compromise.

**5. Assessment limitations & Outlook.** As an initial proof-of-concept assessment, the evaluation prioritized broad coverage over configuration-specific optimization and controlled testing. Observed performance trends therefore remain indicative and require further investigation to establish their statistical significance and general applicability.

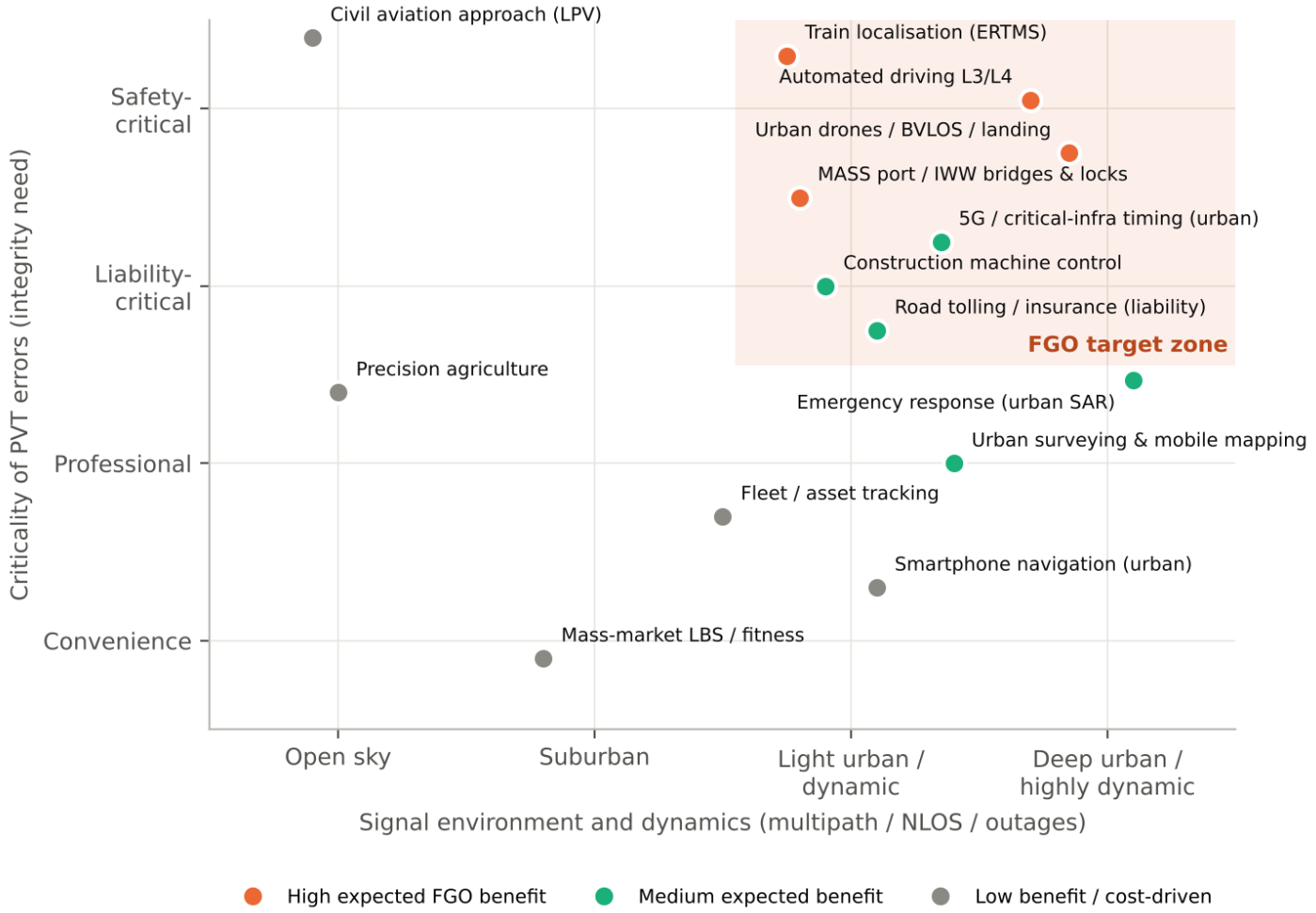
**Overall conclusion: FGO-Nav demonstrated its feasibility as an alternative to EKF-like filtering for GNSS/IMU navigation. While no general positioning accuracy advantage was established, the results identified configurations and challenging scenarios in which FGO may offer benefits, providing a basis for more targeted investigations.**

# EXPECTED BENEFIT

## LITERATURE EXPECTATIONS AND SUITABLE USE CASES

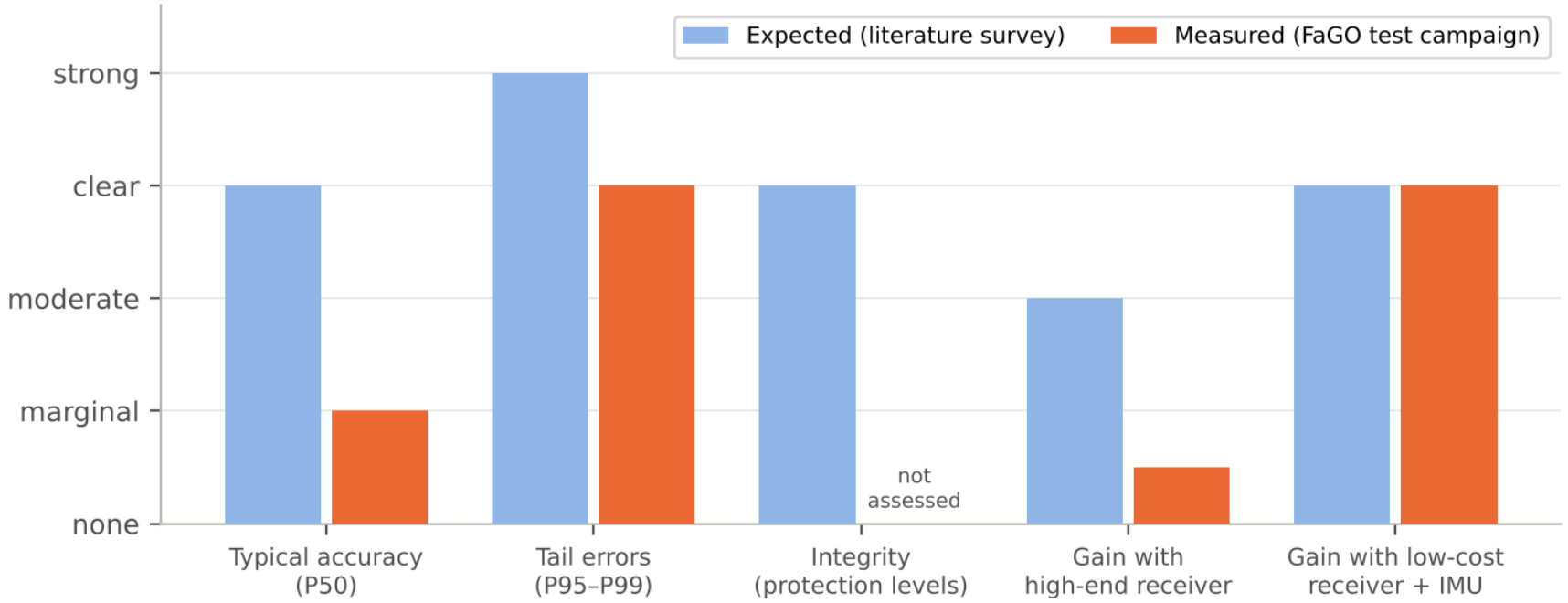
### LITERATURE EXPECTATIONS

- **Accuracy in urban/dynamic scenarios:** 30–70 % lower mean error than EKF in urban canyons, especially with tight coupling and long windows.
- **Reliability/outlier robustness:** the largest relative gains are in the maximum and tail errors.
- **Integrity:** first FGO-based fault detection and protection-level concepts exist but are not mature or certified.
- **Multi-sensor extensibility and smoothing:** better covariance consistency, faster attitude convergence and plug-in integration of new sensors.
- **Drawbacks:** computational load up to 50–400× EKF.



# MEASURED BENEFIT

## COMPARISON WITH EXPECTATION




- **Typical accuracy:** significant benefit only for low-cost receiver
- **Reliability:** larger gain in tail of error distributions → suitable for future integrity applications
- **Environment:** no consistent benefit for a specific environment

Contrary to other publications, FaGO chose **identical preprocessing and weighting** for both estimators ⟶ this isolates the pure estimator effect decoupled from other processing steps for a fair comparison. Therefore, the **performance benefit is smaller** and more distinct to certain cases.

# BUSINESS MODEL CANVAS (EXCERPT)

FGO-BASED ROBUST POSITIONING ENGINE (SOFTWARE LIBRARY)

## COSTS / NEXT STEPS

- Software engineering, algorithm tuning
- Validation
- Certification / Qualification
- Support

## REVENUES

- Per-unit software license
- Engineering services
- Support & update fees

## VALUE PROPOSITION

- Fewer large position errors (P99) in urban & dynamic conditions
- Better performance from lower-cost GNSS + IMU hardware
- Modular multi-sensor fusion (add sensors as factors)

## CUSTOMER SEGMENTS

- Automated driving / ADAS (primary)
- Urban drones
- Rail localisation
- Autonomous vessels / Inland Waterways

# THANK YOU!

**The FaGO project team**

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# 6

# QUESTIONS?

