

HOP-5G: Hybrid Overlay Positioning with 5G and GNSS (NAVISP-EL1-050)

Final Presentation (FP)

DEFENCE AND SPACE

HOP-5G consortium

7 October 2026

© Copyright Airbus (2026)
The copyright in this document is vested in Airbus.
This document may only be reproduced in whole or in part, or stored in a retrieval system, or transmitted in any form, or by any means electronic, mechanical, photocopying or otherwise, either with the prior permission of Airbus or in accordance with the terms of ESA Contract No. 4000134155/21/NL/PS.

AIRBUS

Agenda

- Features and demonstrations
- Real-time 5G processing
- Offline 5G processing
- GNSS and synchronization modules
- Hybrid positioning engine
- Performance benchmarking
- Conclusions and recommendations



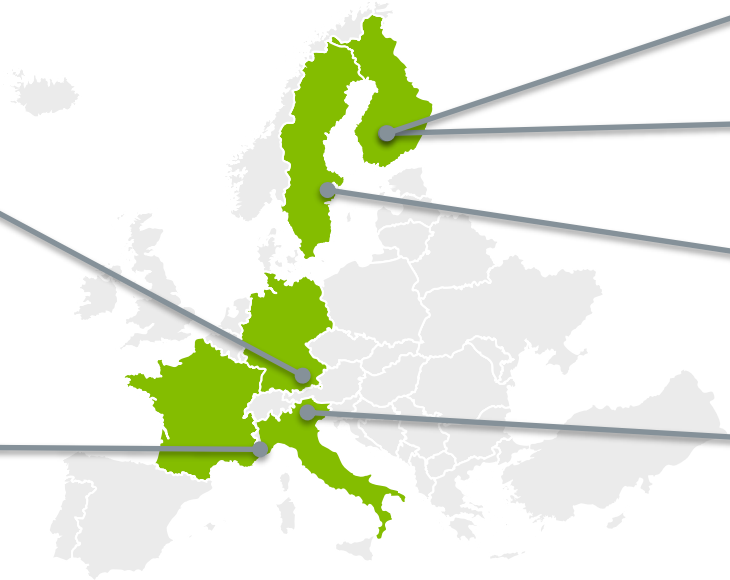
© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

HOP-5G Consortium

HOP-5G

AIRBUS

Testbed architect, integration and demo



Tampere University

Offline 5G processing

exafore

Hybrid positioning engine

ERICSSON

Performance benchmarking

EURECOM
Sophia Antipolis

Real-time 5G with OAI

Qascom
Trust is Nice, Control is Better.

GNSS and sync. modules

© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)



Features & demos

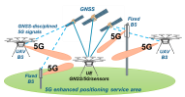
© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

AIRBUS

Evolution of HOP-5G Proof-of-Concept

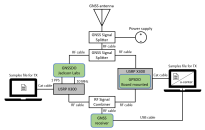
2021
NAVITEC

HOP-5G technology definition



2022
ION

5G FR1 network design and lab characterization



2023
EUC ION

World's first aerial 5G positioning network



New feature
Release of OAI PRS L1

2024
EUC ION

Real-time 5G FR2 open-source AoA demo



2025
NAVITEC

Real-time flying 5G FR2 demo



2026

Real-time 5G permanent node in unlicensed band



timeline

HOP-5G

- ✓ 5G PRS FR1 ToA
- ✓ 5G PRS FR2 AoA
- ✓ Real-time 80MHz
- ✓ Flying 5G network

FR: Frequency Range
FR1: <6GHz
FR2: >24GHz
PRS: Positioning Reference Signal

© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)
AIRBUS

Pioneering Multi-Layer 5G PNT Demonstrator

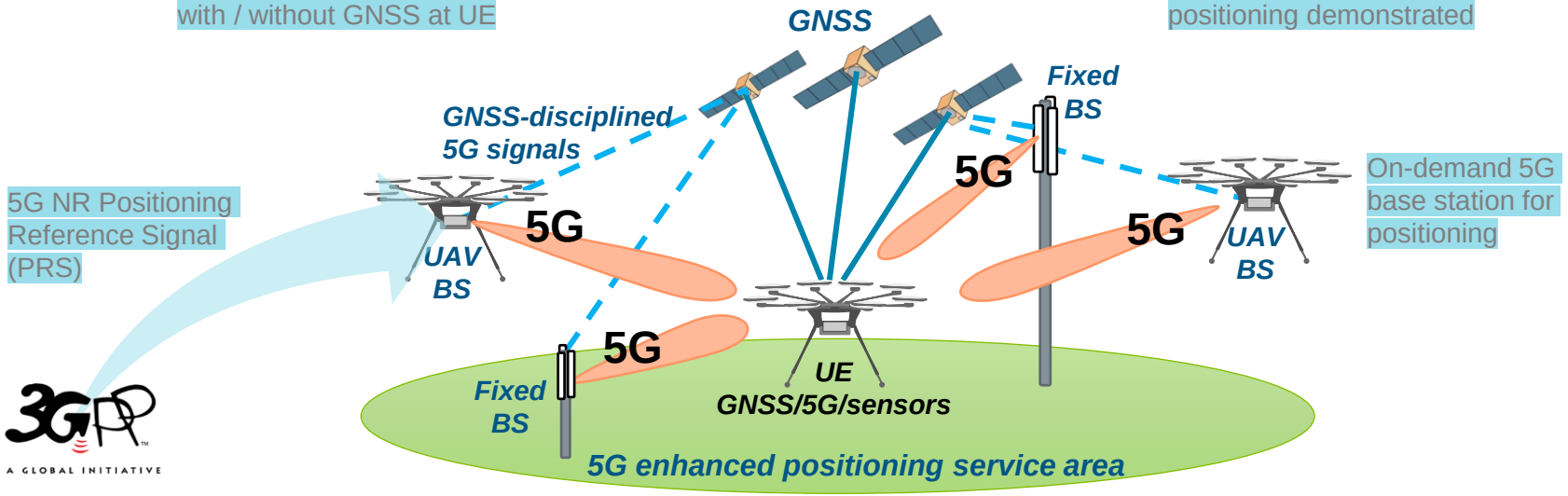
World's first airborne 5G network dedicated for positioning

HOP-5G

Hybrid Overlay Positioning with 5G and GNSS (HOP-5G) testbed

FR1 and FR2 5G PNT with / without GNSS at UE

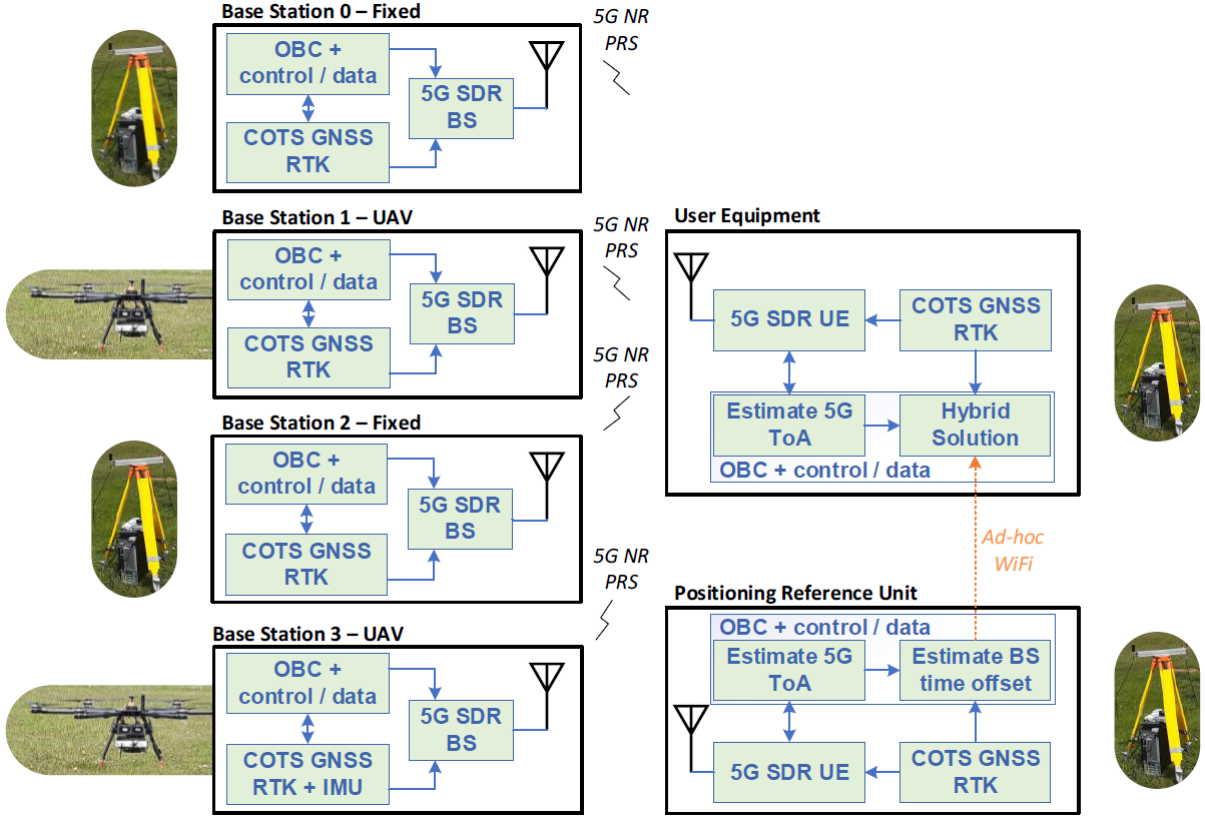
Sub-meter real-time 5G positioning demonstrated



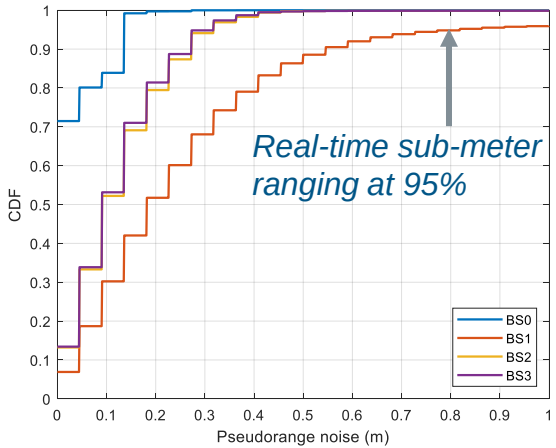
© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

AIRBUS

HOP-5G FR1: Dedicated Flying 5G Network for User Positioning



5G pseudorange noise at UE

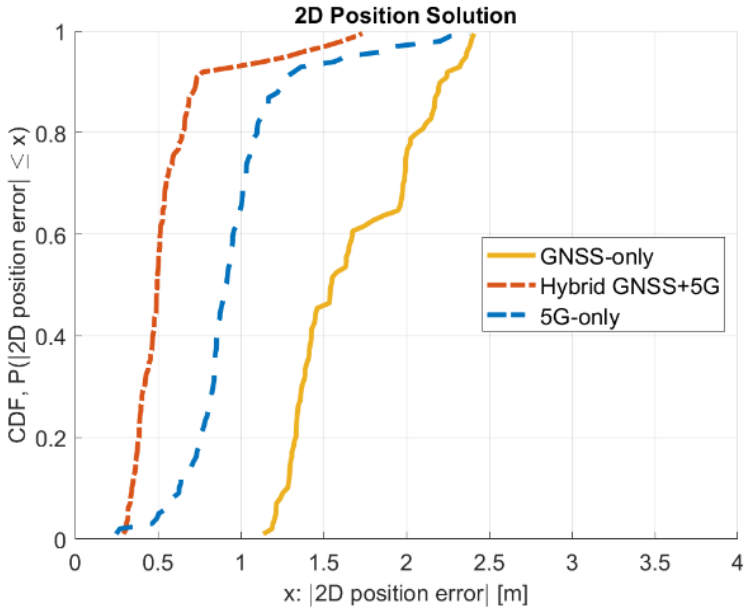


J.A. del Peral-Rosado et al, "First field trial results of hybrid positioning with dedicated 5G terrestrial and UAV-based non-terrestrial networks," in Proc. ION GNSS+ 2023.

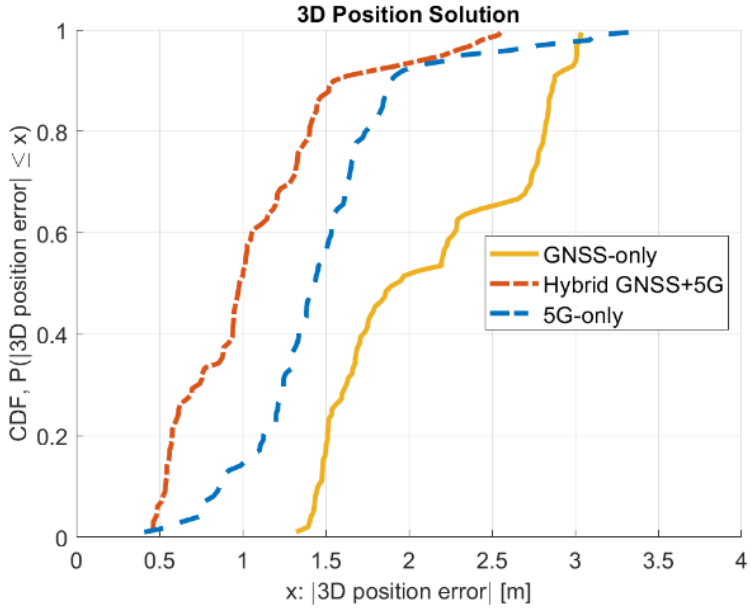
© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

HOP-5G FR1 Field Results: Hybrid GNSS and 5G Positioning Performance

► 2D sub-meter positioning above 90% with hybrid solution



► 3D positioning error below 1.4m at 80% with hybrid solution

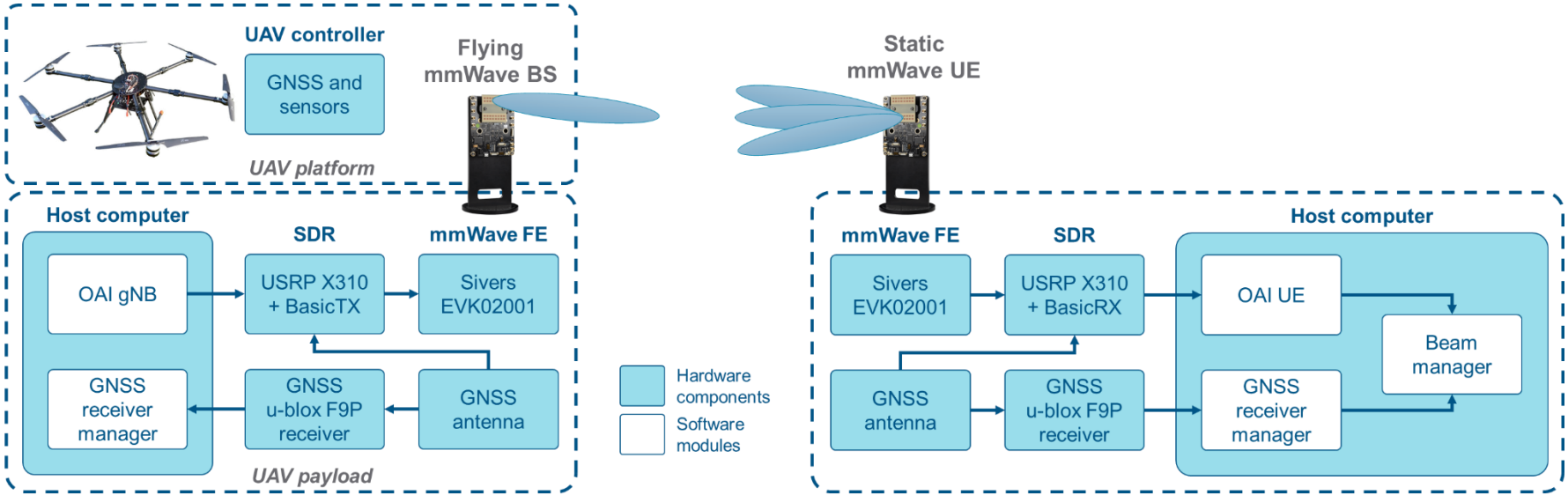


J.A. del Peral-Rosado et al, "Sub-Meter Hybrid Positioning with Flying 5G Networks and Synchronization Corrections," in Proc. ION GNSS+ 2024.

 © Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

AIRBUS

HOP-5G FR2: mmWave Positioning Testbed



J.A. del Peral-Rosado et al, "Initial Experimentation of a Real-Time 5G mmWave Downlink Positioning Testbed," in Proc. ENC, 2024.

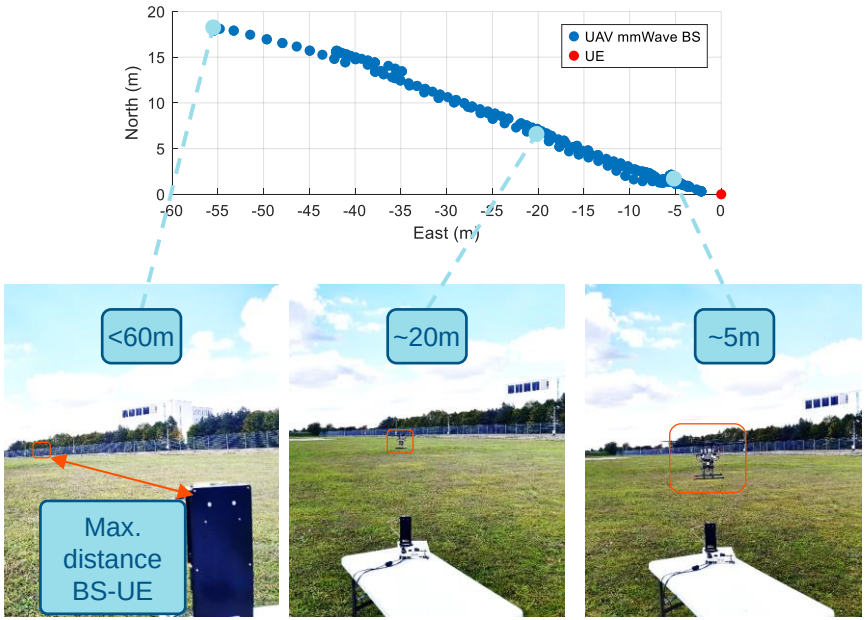
J.A. del Peral-Rosado, E. Ince, P. Nolle, I. Lapin, "Beam Characterization of a Flying 5G mmWave Base Station via Field Measurements," in Proc. NAVITEC, 2026.

 © Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

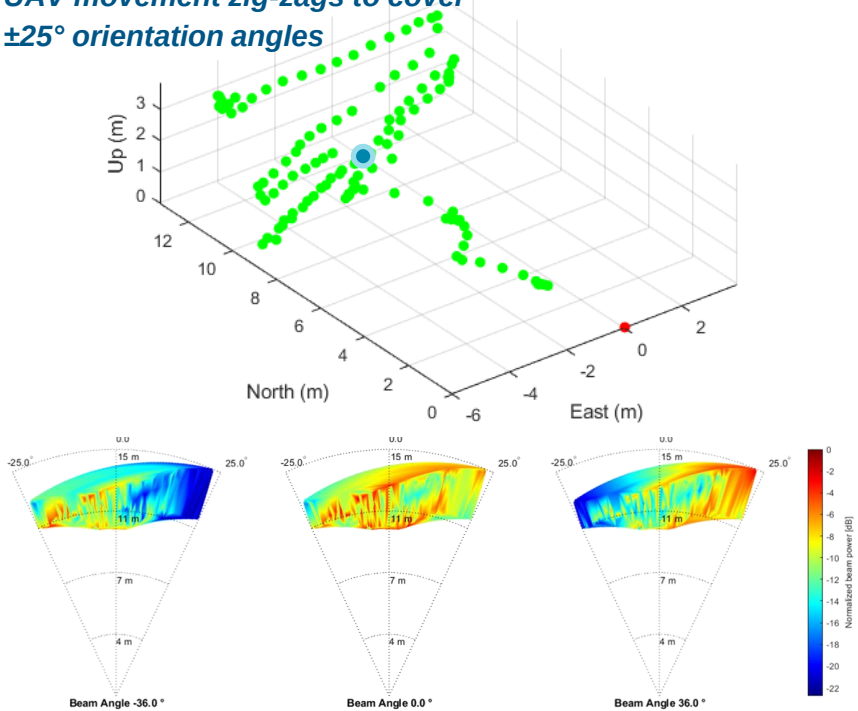
AIRBUS

HOP-5G FR2 Field Results: Flying mmWave Experimentation

Linear UAV trajectory over three consecutive tests



UAV movement zig-zags to cover ±25° orientation angles



J.A. del Peral-Rosado, E. Ince, P. Nolle, I. Lapin, "Beam Characterization of a Flying 5G mmWave Base Station via Field Measurements," in Proc. NAVITEC, 2026.

 © Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

AIRBUS

HOP-5G ESTEC Demonstration

Flying 5G base station for positioning in unlicensed ISM band





© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

HOP-5G ESTEC Demonstration

Extended coverage to around 100 m



HOP-5G BS with amplification chain

Movable user equipment





© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

AIRBUS

Real-time 5G with OAI



© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

AIRBUS

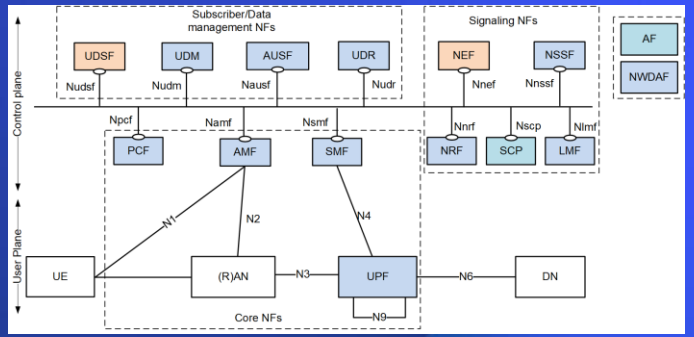
What is OpenAirInterface?

Duranta
LFNETWORKING

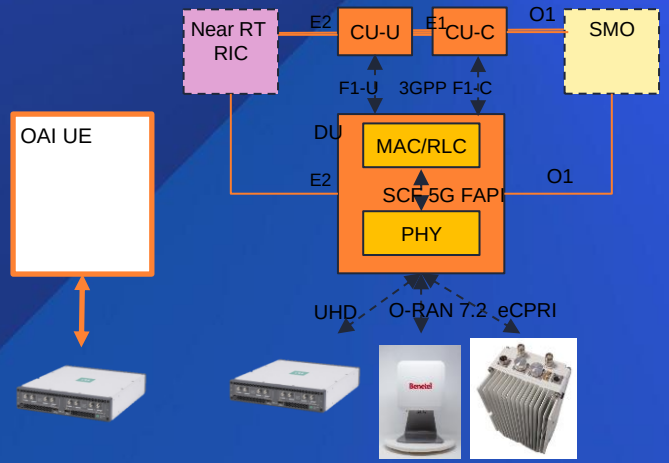
OPEN AIR INTERFACE

- End-to-end 3GPP and O-RAN-compliant 4G/5G RAN, UE, and Core Network software
  - Running on commodity x86/ARM hardware or cloud infrastructures (with hardware acceleration)
  - Interfacing with SDR or commercial radios
- Created by **EURECOM** - managed by the **OpenAirInterface Software Alliance (OSA)** – hosted by **Linux Foundation Networking (LFN) Duranta** project
- Uses 3GPP friendly **Collaborative Standards Software License v1.0** (Previously know as OAI public license)
- Community driven development
- Supported by key industrial players

Core Network



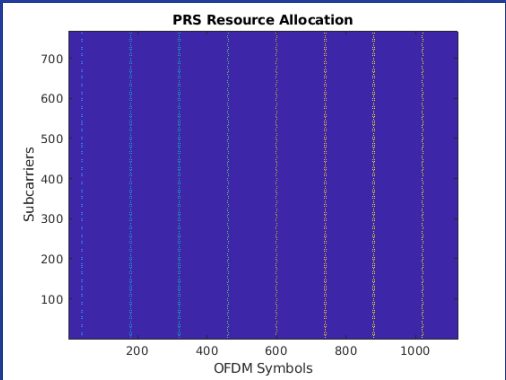
Radio Access Network



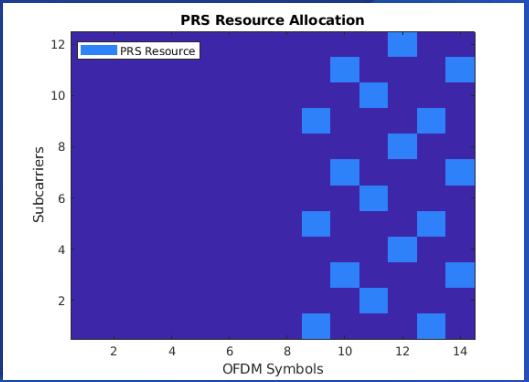
© Copyright EURECOM (2026)

Positioning Reference Signal (PRS) Implementation

- PRS Transmission (gNB) and Reception (UE)
- Supports Flexible PRS configuration
- Supports both FR1 and FR2
- Integrated in OpenAirInterface using test MAC scheduler (phy_test)
- Program to transmit pre-recorded waveform
- Simulation with rfsim



PRS over radio frame



PRS over slot

© Copyright EURECOM (2026)

PRS validation

Frequency range 1

GNSS





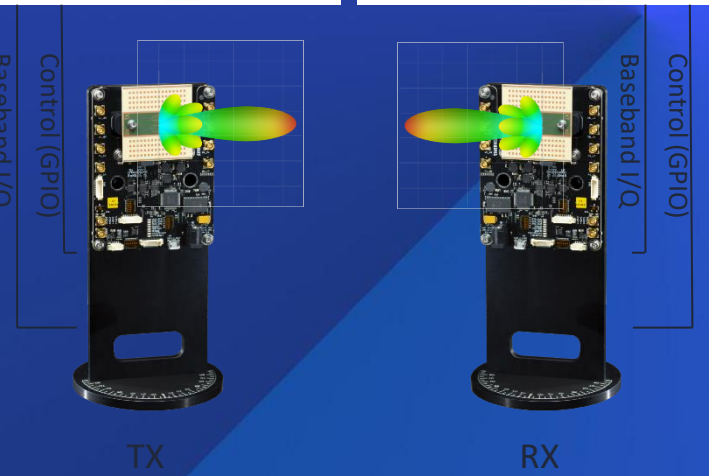


R&S Spectrum Analyzer validating PRS and multi gNB synchronization

Frequency range 2







Sivers EVK02001

© Copyright EURECOM (2026)



Offline 5G

© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

AIRBUS

© Copyright TUNI Luottamuksellinen (3Y), 2026

Tampere University

Frequency Range 1 (FR1) Angle-Of-Arrival (AOA)

- All tests concerning AOA estimation at FR1 were performed using USRP N310 as the receiver
  - Transmitted signals followed standardized 5G NR waveforms
  - Considering line-of-sight (LoS) conditions in all measurements
  - Due to very limited maturity of research and earlier work related to the desired USRP-based AOA estimation at FR1, the testing procedures involved various problem solving and error management tasks

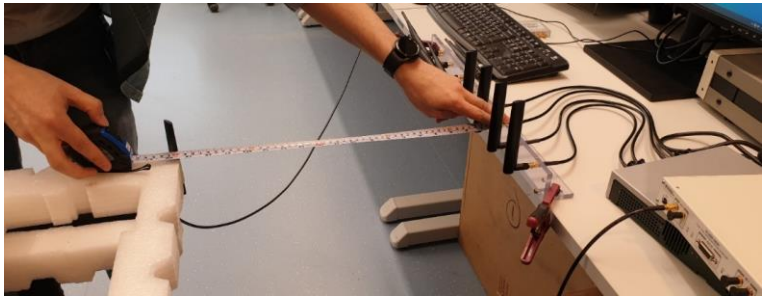


Illustration of the FR1 test setup for multi-channel measurements. A single transmitter dipole antenna (Linx) is connected to the signal generator, and the receiver antenna array with four Linx dipoles is mounted on the table, while connected to the USRP N310 via SMA cables.

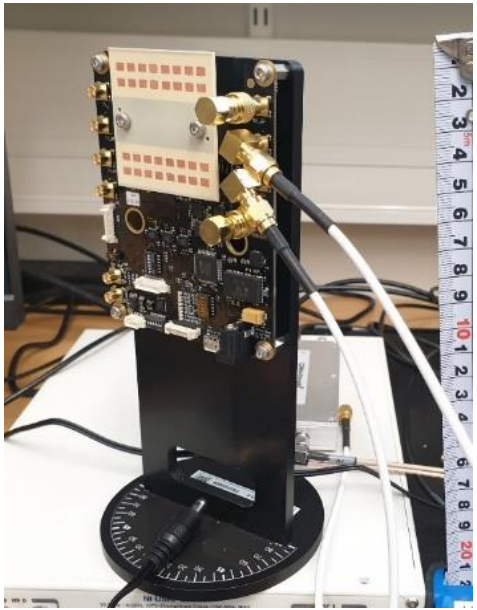
- One of the most severe encountered issues was related to synchronization of USRP N310
  - Such synchronization was attempted by using an external LO without proper functional success due to various hardware and software issues
  - Unsynchronous operation is introduced after the execution of the run command → has to be calibrated at every run
- The utilization of the FR1 COTS equipment for AoA estimation was identified as immature technology, requiring a lot of further development for desired utilization
  - If the issues with phase synchronization between different antenna ports can be solved, there is potential for utilization of the equipment in AoA-based positioning

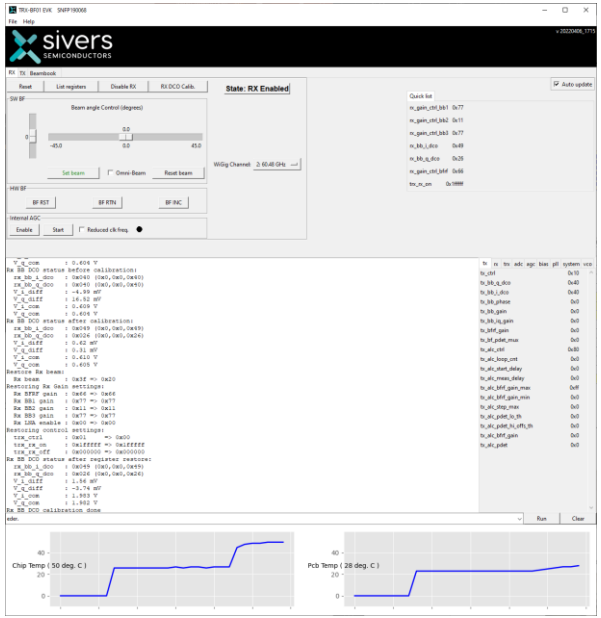
© Copyright TUNI Luottamuksellinen (3Y), 2026

Tampere University

Frequency Range 2 (FR2) COTS equipment

- The FR2 mmWave equipment (both TX and RX) is based on the use of EVK02001 antenna arrays from Sivers
- During initial end-to-end testing, certain recommendations were made concerning, e.g., the use of DC-blocks and gain settings
- It was observed that when using the internal clock of Sivers EVK02001 for frequency reference, a significant CFO occurred with up to +/-1.6 MHz offset
  - This should be compensated in post-processing unless using external clock synchronization

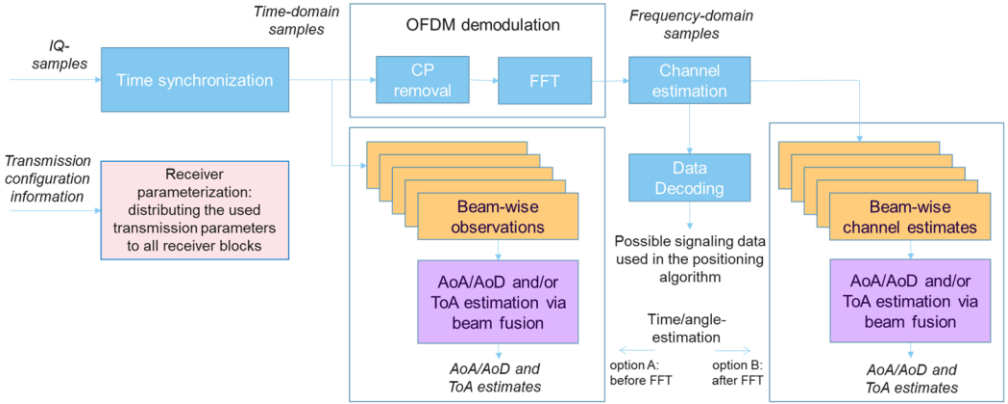




© Copyright TUNI Luottamuksellinen (3Y), 2026

FR2 AOA algorithm and the offline receiver

- The developed FR2 AoA estimation is based on processing of beam-power measurements
  - The mmWave receiver front end performs a beam sweeping procedure with pre-selected beam directions
- The proposed AoA estimation algorithm is built upon a polynomial fitting of the beam power profile using the weighted least squares (WLS) method
  - Results in relatively robust and reliable AOA estimation
- The AoA estimate is conditioned ensuring that the parabola is not inverted or degenerate
  - This type of issues can be encountered, e.g., in case the power measurements suffer from errors due to very low SNR or interference

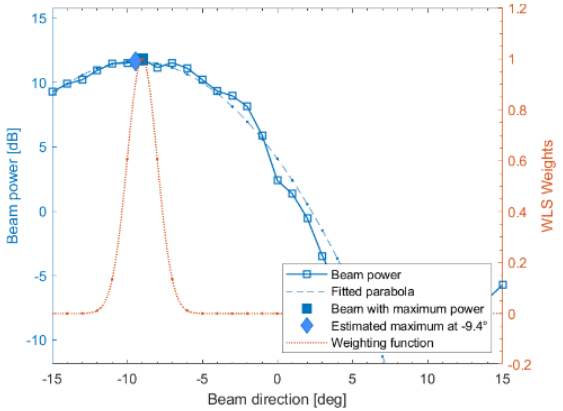


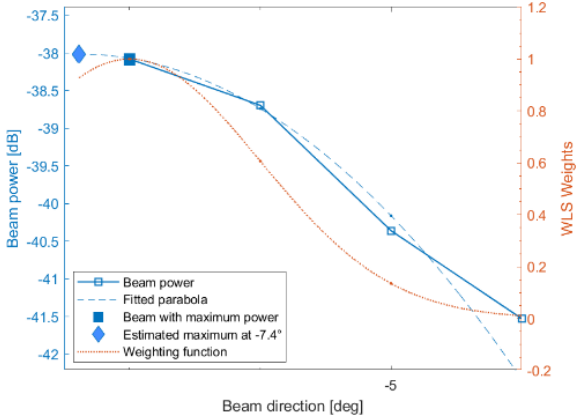
© Copyright TUNI Luottamuksellinen (3Y), 2026

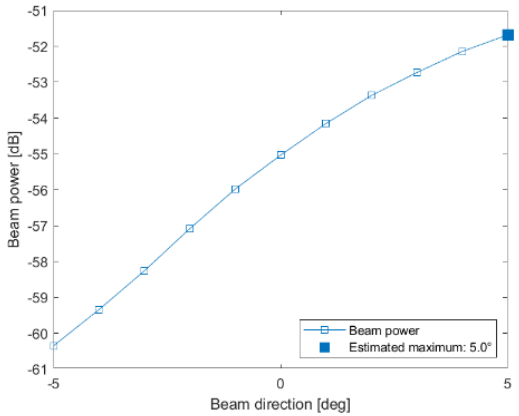
Tampere University

Example AOA estimation results and related beam patterns

- Example of FR2 AoA estimation results using the beam sweeping algorithm with the proposed parabola fitting algorithm
- Three types of the example outputs are demonstrated below:
  - Left figure – defined power maximum, successful fit, interpolation between beams allows estimating the angle
  - Middle figure – maximum at boundary, successful fit, extrapolation beyond beams allows estimating the angle
  - Right figure – maximum at boundary, unsuccessful fit, a beam with maximum power can serve as the angle estimate









GNSS & sync

© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

AIRBUS

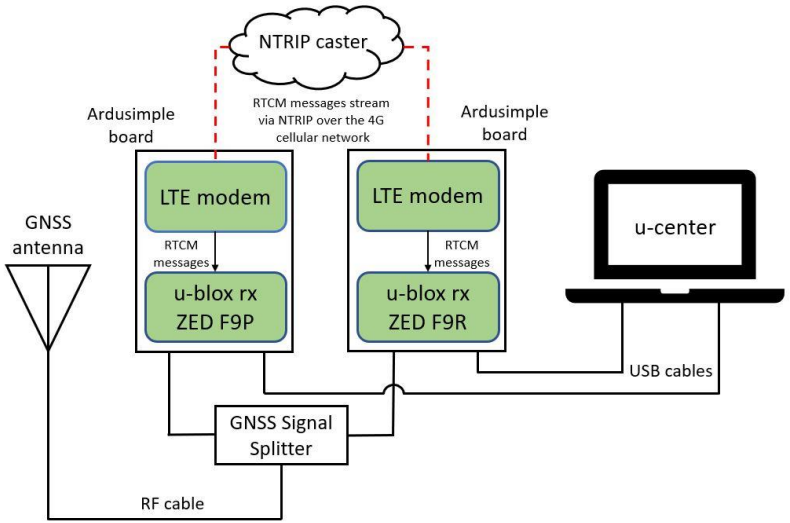
Implementation of different SW modules

- PRCM: module for inter-unit messaging, each unit sends to/receives data from other units
  - Receive data receive from other physical units to the network of SW module in the local unit
  - Send data generated by a given SW module in the local unit to other physical units of the testbed
- GRM: GNSS receiver manager, module interfacing with GNSS COTS rx
  - Connect and configure the COTS u-blox rx
  - Retrieve GNSS data and share with other SW module
- ADM: module to receive aiding data and to generate navigation RINEX in real-time (only in the GSE)
  - Exploiting a u-blox service to perform “warm start”, it download the GNSS eph and clock data
  - Generate NAV RINEX and share with other units
- BSTOE: module in charge of estimating clock corrections of the base stations (only in the UE)
  - Receive BSs position and ToA measurements
  - Compute via KF clock bias and drift for each pair of BSs and share with other units

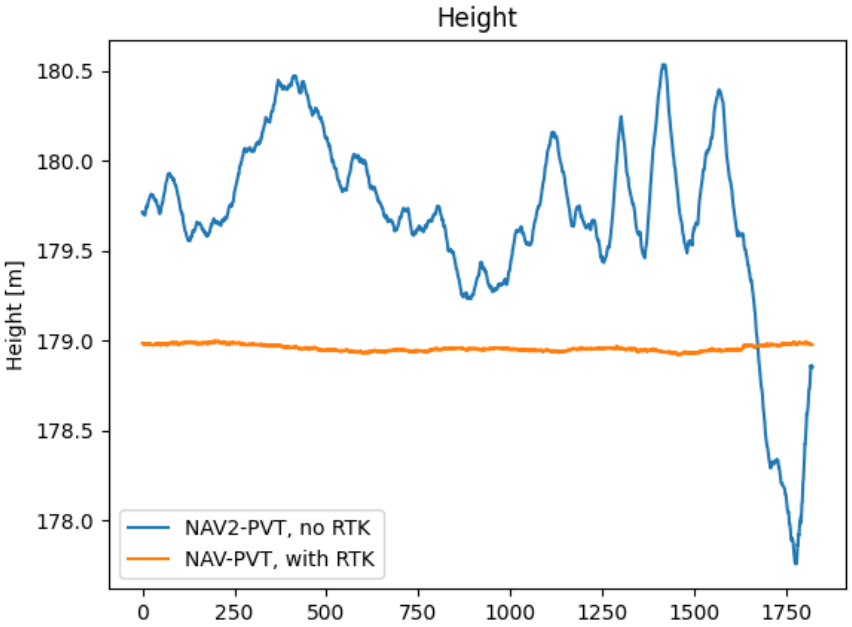
© Copyright QASCOM (2026)

RTK performances assessment

- Achieving RTK corrections with the selected COTS
- Assessment of PVT enchantment when using RTK correction w.r.t. PVT solution with GNSS stand alone



Test setup

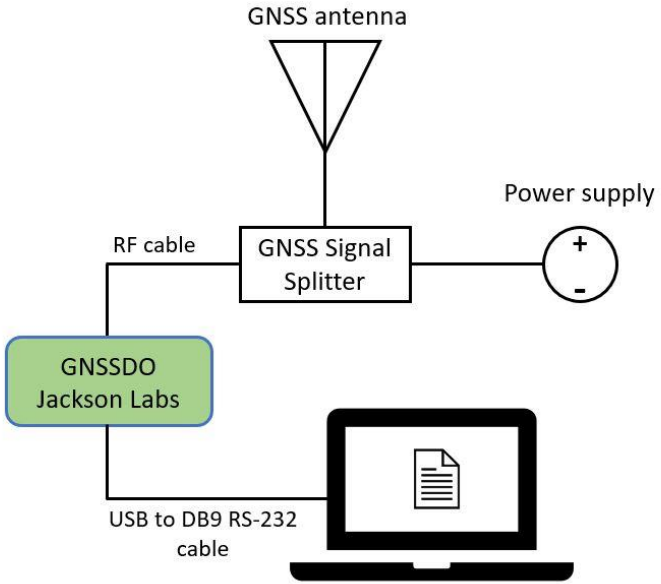


PVT with RTK vs GNSS only

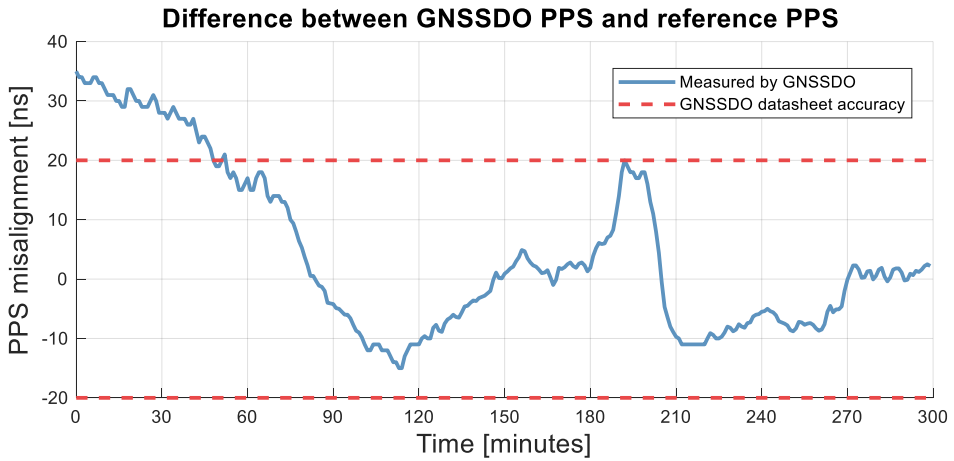
© Copyright QASCOM (2026)

GNSSDO PPS synchronization

- Characterization of GNSS disciplined oscillators: time shift between reference source and PPS output
- GNSSDO by Jackson Labs



Test setup

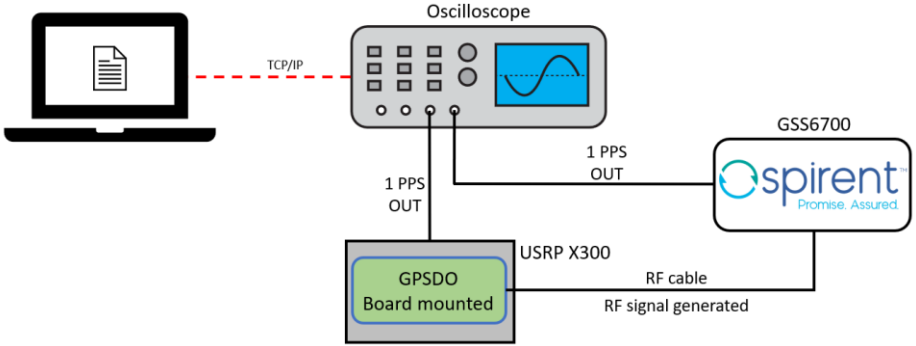


Results (after 16h)

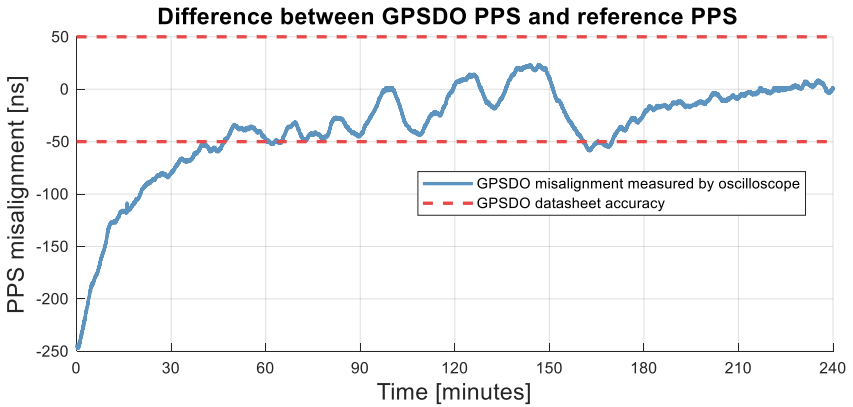
© Copyright QASCOM (2026)

GPSDO PPS synchronization

- GPSDO by Ettus Research



Test setup

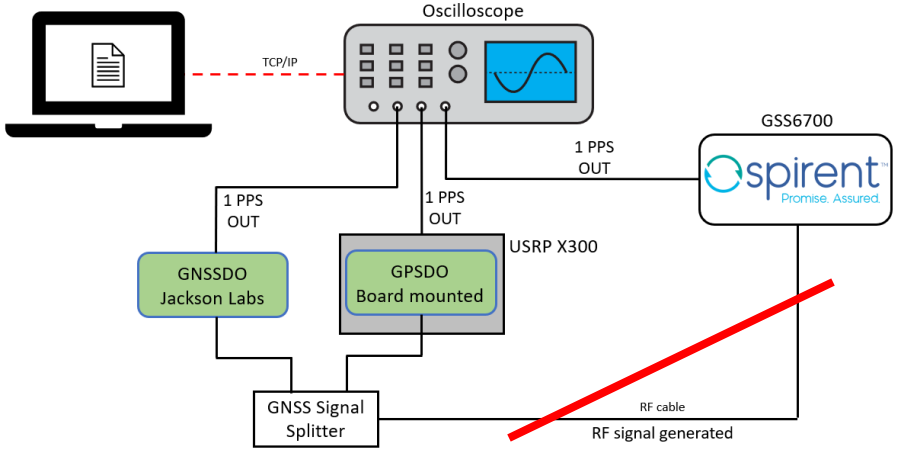


Results (after 5 min)

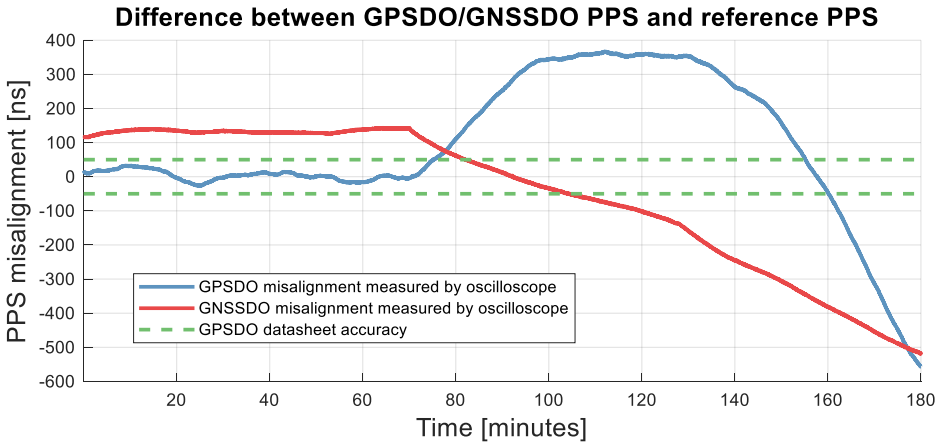
© Copyright QASCOM (2026)

GPSDO PPS synchronization – holdover

- Characterization of the GNSSDO/GPSDO synch when GNSS signal is not fed anymore
- GNSSDO started in cold start (data recorded after 5 minutes)
- Misalignment smaller than microseconds over minutes



Test setup

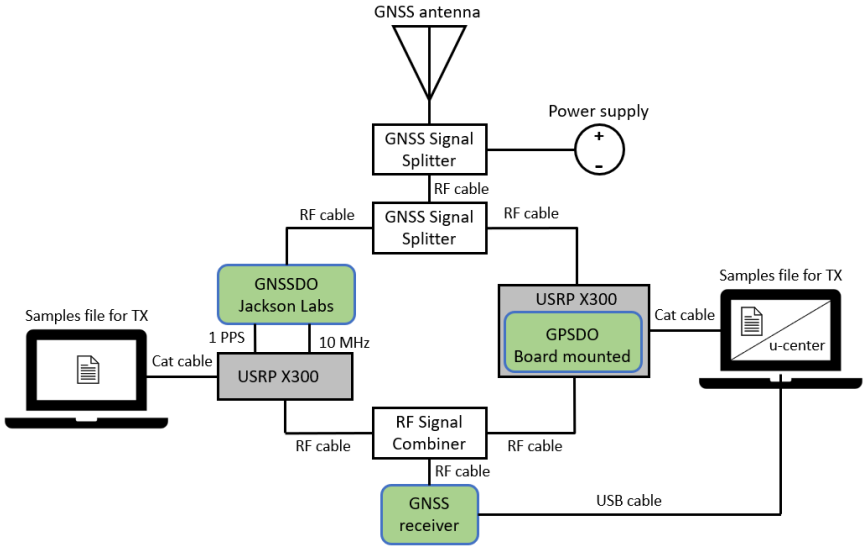


Results

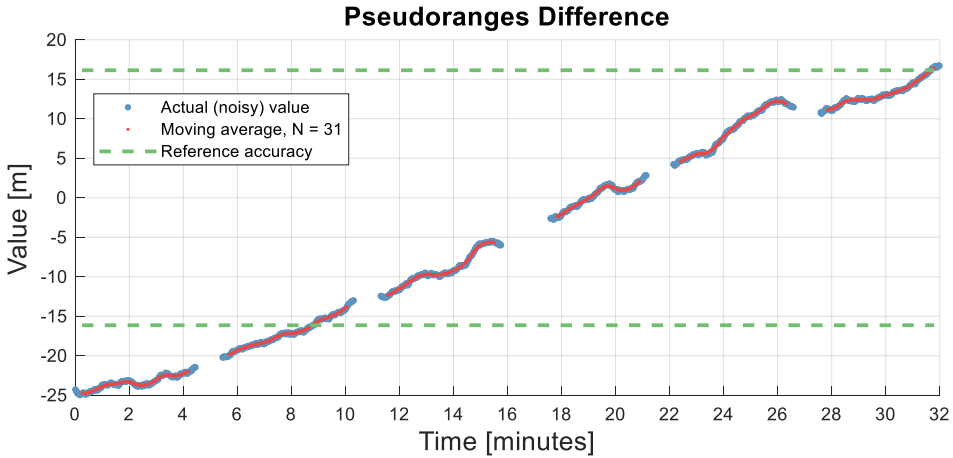
© Copyright QASCOM (2026)

USRP transmission synchronization

- Use of GNSSDO/GPSDO output PPS as trigger for USRP transmission



Test setup

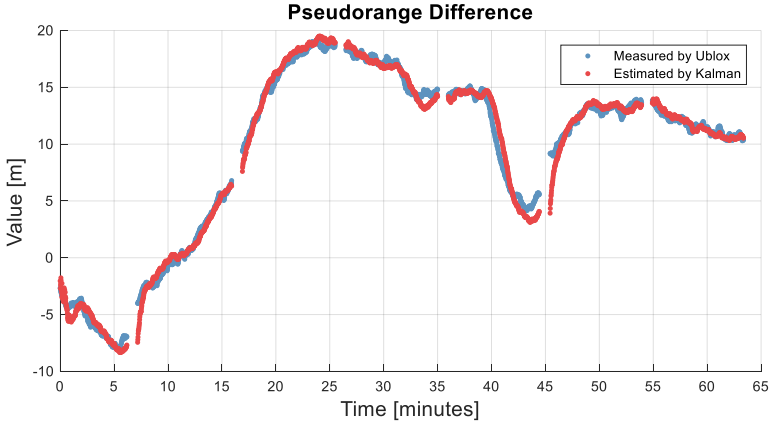


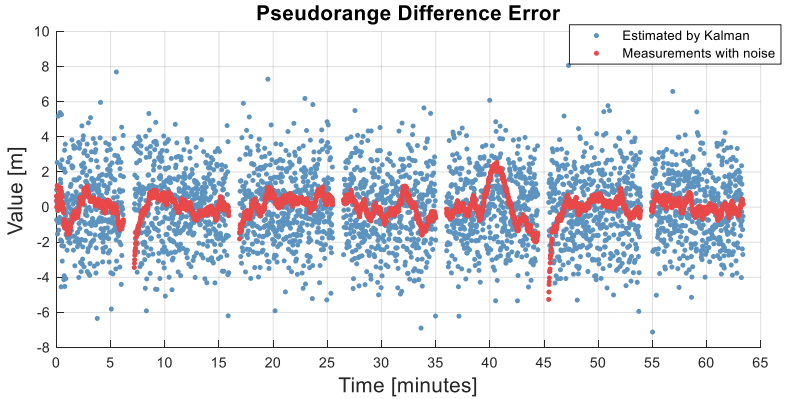
Results

© Copyright QASCOM (2026)

Base Station Time Offset Estimation

- Results of the USRP transmission synchronization tests (previous slide) are saved
- Measurements provided by the GNSS rx are considered the ground truth
- Noise is added to the measurements
- BSTOE (Matlab implementation) is used to estimate the pseudorange difference
  - Kalman filter parametrization obtained via post-processing of 5G ToA measurements collected during preliminary testing activities





© Copyright QASCOM (2026)

Hybrid positioning



© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

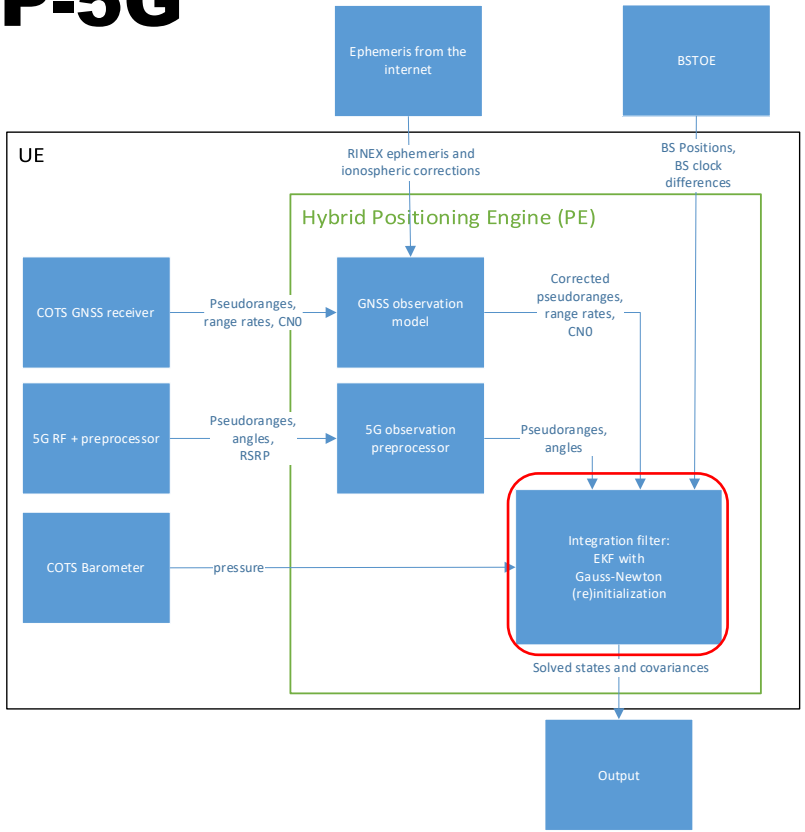
AIRBUS

Hybrid positioning in HOP-5G

Design goals of the integration filter:

- Flexible state parametrization
- Flexible measurement types and modelling
- Keep the signal modelling aspects separate from the integration filter

Implementation:
- real-time Python implementation
- interfaces with MQTT
- playback capability from recorded message logs
- playback capability through a MQTT broker



exafore © Copyright (2026)

State parametrisation

State name	Dimension	Units	Description
position	3	m	UE position in ECEF coordinates (mandatory)
velocity	3	m/s	UE velocity in ECEF coordinates
reference pressure	1	kPa	reference pressure at sea level
UE GNSS clock bias	nSig	m	the range equivalent of UE GNSS clock bias for each enabled GNSS signal
UE GNSS clock drift	1	m/s	the range rate equivalent of UE GNSS clock drift
BS clock biases	nBS	m	the range equivalents of the clock biases of the nBS=4 base stations in the system against the UE 5G clock
BS clock drifts	nBS	m/s	the range rate equivalents of the clock drifts of the nBS=4 base stations in the system against the UE 5G clock

Only the 3D position is mandatory state component, others can be enabled/disabled in configuration. State dimension is thus between 3 and 20.

exafore © Copyright (2026)

Measurement types

Measurement name	Dimension	Units	Description
5G TOA	1	m	range between UE and base station, biased with UE and BS clock biases
GNSS pseudorange	1	m	range between UE and satellite, biased with UE and satellite clock biases
GNSS deltarange	1	m/s	range rate between UE and satellite, biased with UE and satellite clock drifts
barometer	1	kPa	barometer pressure reading
BS clock diff	1	m	difference between the clock biases of two BSs

Measurement types and GNSS signals can be enabled/disabled in configuration.

exafore © Copyright (2026)

Algorithms

Preprocessing:

- Buffer measurements and trigger solution at requested intervals
- Down-sample raw 5G TOA measurements to 1Hz, take robust mean
- Measurement selection (based on health, elevation, CN0/RSSI, and age)

Initial state and reinitialization when solution is lost:

- **Weighted Least Squares** (Gauss-Newton) with down-weighting of excessive residuals

Continuous solution:

- **Extended Kalman Filter** with innovation exclusion/down-weighting

Output:

- Solution state, uncertainty estimates, measurement diagnostics and labels

exafore © Copyright (2026)



Benchmark

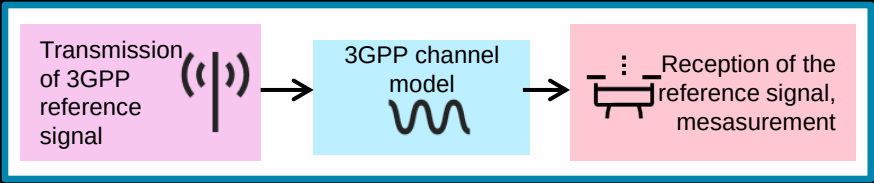
© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

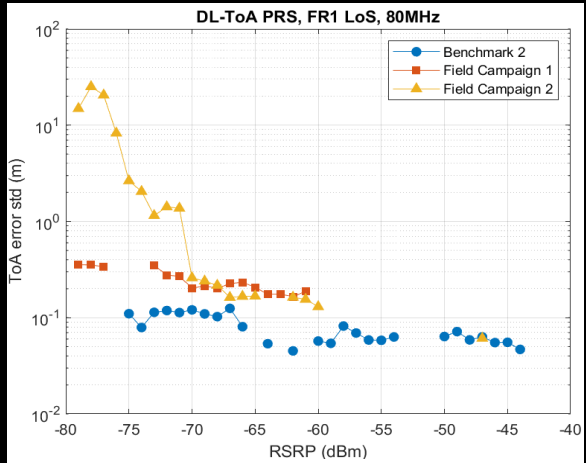
AIRBUS

Link level simulations and benchmarking, 5G

- Simulations using the 3GPP Urban Micro channel model, compared with measurements from the testbed w.r.t:
  - ToA estimation error
  - RSRP
  - SINR
- Parameters:
  - Distance between BS and UE: 10 m to 4 km.
  - Carrier frequency,
  - Reference signal bandwidth and
  - Line-of-sight / non-line-of-sight conditions

→ The simulation benchmark validates the field campaign results in terms of ranging and signal level performance, and thus confirming the achievable sub-meter ranging accuracy.





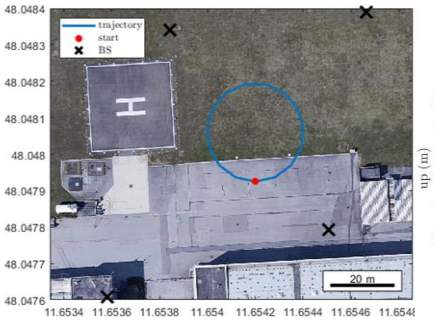
* The divergence on the standard deviation between Field Campaign 1 and Field Campaign 2 below -70dBm of RSRP is expected to be due to the outliers resulting from the BS flying dynamics in Field Campaign 2.

© Copyright Ericsson (2026)

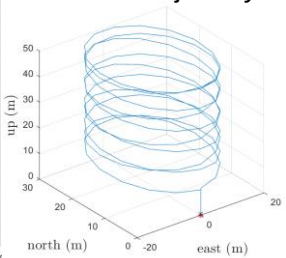
System level simulations, 5G

Deployment

- Tracking scenario with a UAV at the site of the testbed
- 3D map of the site with BS positions and UAV trajectory to determine relative positions and LoS/NLoS conditions,
- Tracking EKF



UAV trajectory



Observations

- Link budget assessment
  - Relatively short distances – Tx power not a bottleneck in LOS conditions. 10 dBm is sufficient
- Horizontal and vertical positioning performance
  - Horizontal accuracy in general good with TDOA/Multi-RTT
  - Vertical accuracy – There need to be spatial diversity in the vertical dimension among the BSs to reach good accuracy
- LoS vs. NLoS
  - Horizontal accuracy in LoS: a few decimeter, NLOS – tens of meters
- Synchronization errors between UE and NW
  - Synchronization errors between base-stations has a large impact on the positioning performance

© Copyright Ericsson (2026)

System level simulations, Hybrid GNSS and 5G

Simulations with nominal resp. degraded conditions:

5G: Nominal: 0 ns sync error, 80 MHz BW, 23 dBm Tx power

Degraded: 20 ns sync error, 40 MHz BW, 0 dBm Tx power

GNSS: Nominal: Open sky scenario

Degraded: 60 deg. elevation mask for reduced satellite visibility

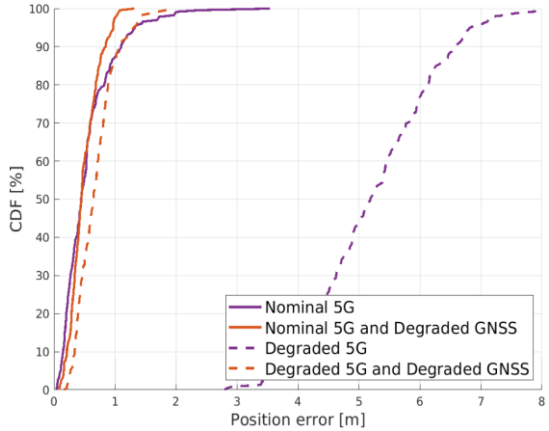
GNSS based on GPS + Galileo

Scenarios:

1) Nominal 5G
2) Nominal GNSS + Nominal 5G
3) Degraded 5G
4) Degraded GNSS + Degraded 5G

Observations

- Nominal 5G performs well, even without GNSS
- Degraded 5G: Large improvements from fusion with GNSS (~6m error → <1m error)
- Even degraded GNSS improves the results



© Copyright Ericsson (2026)



Conclusion

© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

AIRBUS

HOP-5G Achievements

World's first flying 5G network for positioning
(in July 2023)

Real-time 5G operations from radio to positioning

Real-time precise reference system and network corrections

Licensed / unlicensed frequency range 1 (FR1)
< 6GHz

Licensed frequency range 2 (FR2)
> 24GHz

Multiple bandwidth operations
(up to 80MHz)

Extensive laboratory and field testing
+10 field campaigns

Sub-meter positioning in static and dynamic network/user conditions

Numerous publications
8 conference papers
1 best presentation award

© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

HOP-5G Publications

1. J. A. del Peral-Rosado et al., "**Design Considerations of Dedicated and Aerial 5G Networks for Enhanced Positioning Services**," in *Proc. NAVITEC* 2022.
2. J. A. del Peral-Rosado et al., "**Proof-of-Concept of Dedicated Aerial 5G and GNSS Testbed for Enhanced Hybrid Positioning**," in *Proc. ION GNSS+ 2022*.
3. F. Rothmaier and J. A. del Peral-Rosado, "**A Parametric Study on Autonomous Integrity Monitoring using non-GNSS Signals**," in *Proc. IEEE/ION PLANS* 2023.
4. J.A. del Peral-Rosado et al, "**Preliminary Field Results of a Dedicated 5G Positioning Network for Enhanced Hybrid Positioning**," in *Proc. ENC 2023*.
5. J.A. del Peral-Rosado et al, "**First field trial results of hybrid positioning with dedicated 5G terrestrial and UAV-based non-terrestrial networks**," in *Proc. ION GNSS+ 2023*, **Best Presentation Award**.
6. J.A. del Peral-Rosado et al, "**Initial Experimentation of a Real-Time 5G mmWave Downlink Positioning Testbed**," in *Proc. ENC 2024*.
7. J.A. del Peral-Rosado et al, "**Sub-Meter Hybrid Positioning with Flying 5G Networks and Synchronization Corrections**," in *Proc. ION GNSS+ 2024*.
8. J. A. del Peral-Rosado, E. Ince, P. Nolle, I. Lapin, "**Beam Characterization of a Flying 5G mmWave Base Station via Field Measurements**", in *Proc. NAVITEC*, May 2026.

© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)

Conclusions and Recommendations

- ✓ Pioneering flying 5G testbed demonstrates sub-meter positioning
- ✓ Real-time operations proven with experimental platforms:
  - *Downlink 5G positioning reference signal (PRS)*
  - *Licensed/unlicensed FR1 and licensed FR2 bands*
  - *Ranging measurements with wide bandwidth (80 MHz)*
  - *Angle measurements with FR2 analogue beamformer*
  - *Network synchronization corrections*
  - *Stand-alone 5G and hybrid GNSS+5G positioning*
- ➲ Deployment evolution towards COTS radio units
- ➲ Integration with 3GPP positioning protocols

HOP-5G



© Copyright Airbus (2026) / HOP-5G (NAVISP-EL1-050) Final Presentation (FP)