On the 30th anniversary of EuroCOW: where does sensor fusion go?

European Calibration and Orientation Workshop (EuroCOW) 2025

I.Colomina

history & prehistory of the EuroCOWs

dedicated to workshop organisers...

Popular wisdom saying in Spanish-speaking countries.

"Hay tres cosas que cada persona debería hacer durante su vida:

1. plantar un árbol,

2. tener un hijo y

3. escribir un libro."

Tres Héroes, José Martí (1853-1895)

"There are three things every person should do during their life::

1. plant a tree,

2. have a child, and

3. write a book."

dedicated to workshop organisers...

"There are four things every person should do during their life::

1. plant a tree,

2. have a child,

3. write a book, and

4. organise a conference."

everything started there and then...

– ISPRS 1992-1996 Commission III "Theory and Algorithms" (H. Ebner)

– ISPRS Working Group 3.1 "Integrated Sensor Orientation" (I.Colomina, J. Lucas)

– Workshop

- Barcelona 1995-09-04/08
- "Integrated Sensor Orientation: Theory, Algorithms, and Systems"
- 95 participants, 14 countries, 4 continents
- Co-organised by FIG, IAG, ISPRS, IUSM
  always wanted to avoid making it too-photogrammetric...


INSTITUT CARTOGRÀFIC DE CATALUNYA

the context in 1995

- 1992-1996 ISPRS WG III.2
  "Geometric-Radiometric Models & Object Reconstruction" (K. Torlegard, W.Förtsner)
- 1995 mobile mapping concept just matured
  [1st] Mobile Mapping Symposium (Center for Mapping, OSU, Columbus, OH, USA)

- Amazon and eBay launched
- Windows 95 launched
- Just GPS (with SA) and GLONASS (SA disabled in 2000-05-01)
- PPP not yet invented (1997)
- John Deere's real-time PPP (StarFire) not yet deployed (1999)
- David Lowe's SIFT not yet invented (1999)
- SLAM was already established in the robotics community

The EuroCOW series

- 1995 Barcelona 1995-09-04/08 ISPRS WG 3.1
- 1999 Barcelona 1999-11-25/26 ISPRS WG 3.1
  "Direct vs. indirect methods for sensor orientation"
- 2003 Castelldefels 2003-09-22/23 ISPRS WG 1.5
  "Theory, Technology & Realities Of Inertial/GPS/Sensor Orientation"
- 2006 Castelldefels 2006-01-25/27 together with EuroSDR
- 2008 Castelldefels 2008-01-30/02-01
- 2010 Castelldefels 2010-02-10/12
- 2012 Castelldefels 2012-02-08/10
- 2014 Castelldefels 2014-02-12/14
- 2016 Lausanne 2016-02-10/12
- 2019 Entschede 2019-06-13/14
- 2025 Warsaw 2025-06-16/18 WG 1.6 (K. Bakula, G.Zhang, H. Meißner)

The EuroCOW series

the essential truth is that everything started

when someone decided to put a GPS receiver on a photogrammetric aircraft.

30 years evolution

everything started there and then...

– 1990s
  - laser scanning (1991)
  - Internet boom

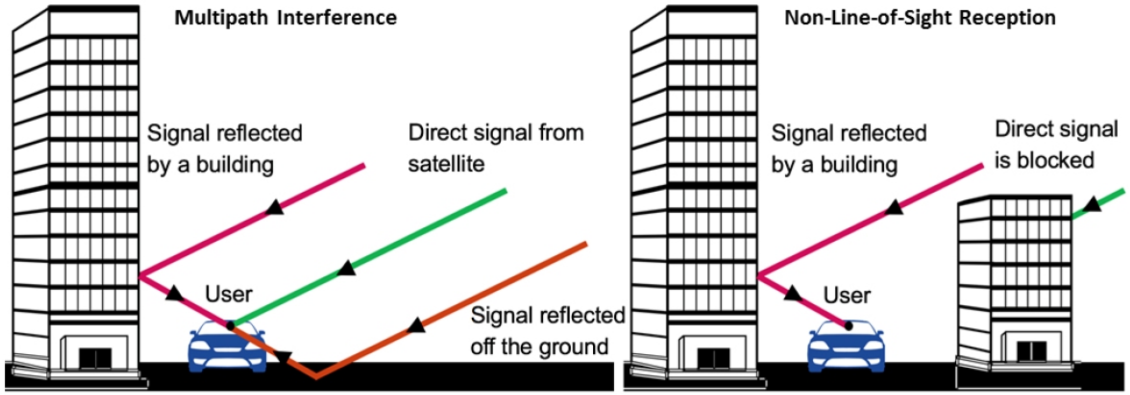
– 2000s
  - drones
  - GIS software emergence
  - connectivity and mobile revolution: smartphones
  - consumer technology for professional applications
  - Galileo and BDS

– 2010s
  - AI & machine learning
  - autonomous vehicles

– 2020s
  - boom of AI & machine learning

on today & tomorrow

potential and limits of satellite radionavigation
occlusions, multipath & NLOS reflexions



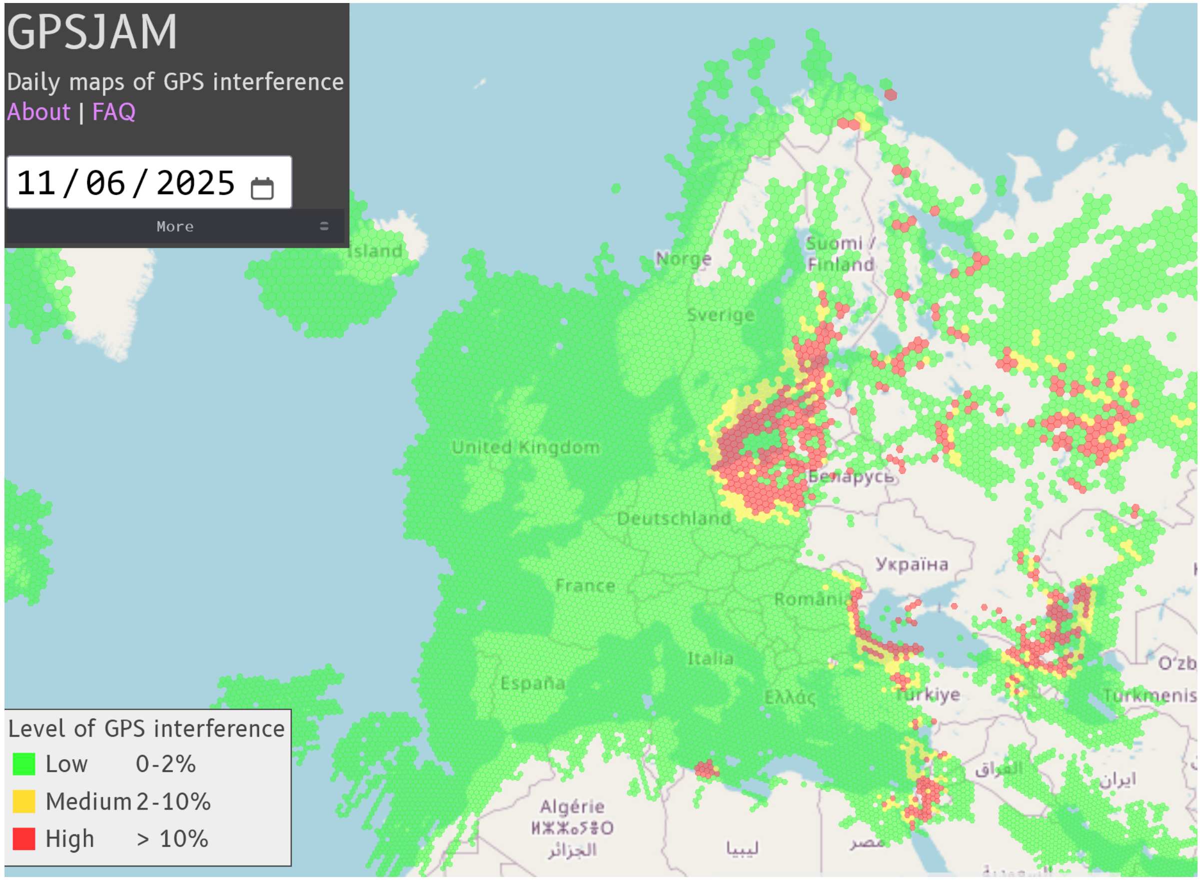
© McGraw et al.

- GNSS signals can be blocked and reflected by nearby objects: non-line-of-sight reflection (NLOS-R).
- They can also be reflected by the ground and by water: multipath interference (MP-I).
- MP-I & NLOS-R are the dominant source GNSS positioning errors in dense urban environments.
- In the GNSS community it is commonplace to classify NLOS-R as "multipath." But...

$$\text{NLOS-R} \neq \text{MP-I (reflective and diffractive)}$$

potential and limits of satellite radionavigation
jamming & spoofing attacks

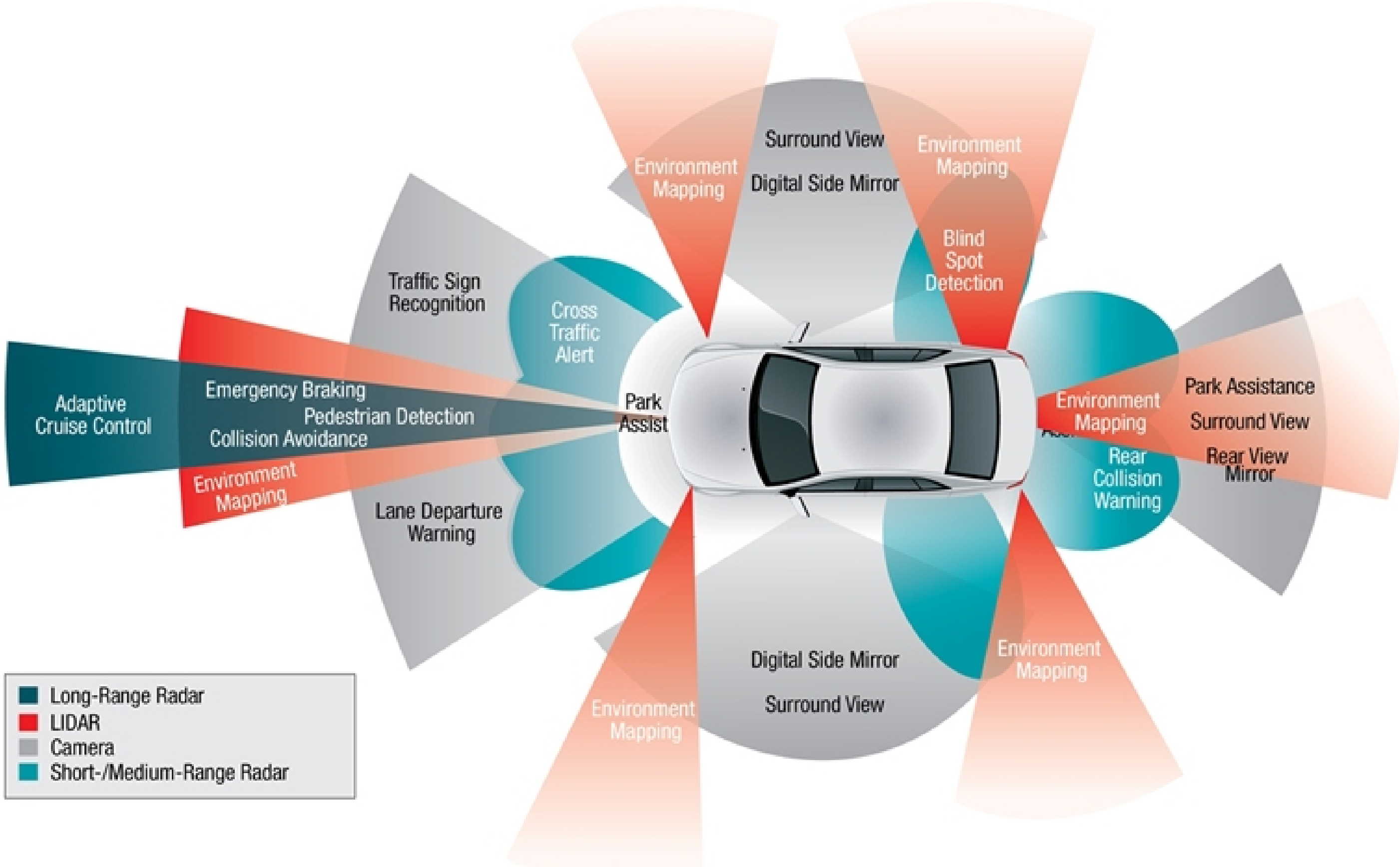
– 900 flights a day on average are now encountering GNSS Spoofing (ObsGroup)



potential and limits of satellite radionavigation

the inconvenient truth of autonomous navigation

– autonomous vehicles (AVs) make a rather limited use of GNSS



– what for GNSS is a nightmare [for the time being], for SLAM is perfect

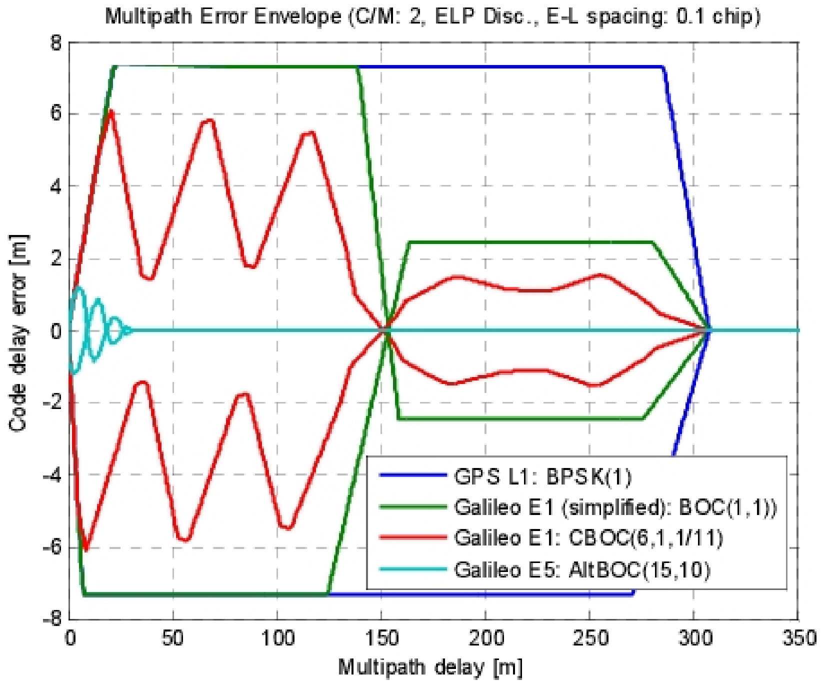
potential and limits of satellite radionavigation

incremental improvement of GNSS

– more satellites (new constellations)

- Galileo (27 operational satellites)
- BDS ($\approx$ 45, GEO, IGSO & MEO)

– better signals, e.g. E5 AltBOC



potential and limits of satellite radionavigation

incremental improvement of GNSS

– new and better services

- High-Accuracy Service (HAS) on top of the Open Service (OS) for GPS and Galileo
  - $\sigma_H \approx 10cm$, $\sigma_h \approx 20cm$
  - orbit and clock corrections, satellite ranging biases (SL1)
  - regional atmospheric corrections (SL2)

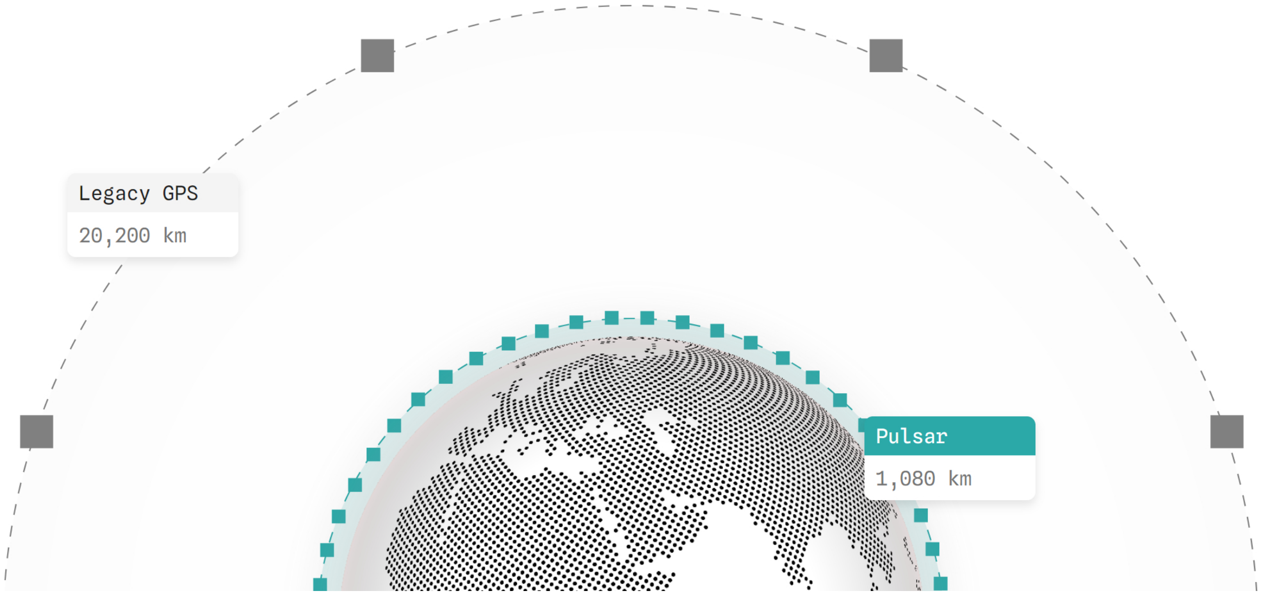
potential and limits of satellite radionavigation

new GNSS concepts

– LEO-based GNSS as a complement to [MEO-based] GNSS: LEOPNT

– PNT-dedicated LEO constellations (LEO.PNT)

- private, e.g. PULSAR (Xona Space Systems)
  L-band, S-band, C-band
  planned: 250-300 satellites, 500 kE/satellite, 5-year lifespan



- public, e.g. ESA initiative (2 × 78.4 ME)
  L-band, S-band, C-band

potential and limits of inertial navigation

essential limitations of technology

as we know

- sensing errors that translate into drift

even perfect inertial sensors do not translate into perfect navigation

- sensor installation errors
- initial position, velocity and attitude errors
- gravity model errors
- vertical channel (height) instability

potential and limits of inertial navigation

progress in low- and high-end inertial sensing

batch production of E-level IMUs

– low-end tactical-grade IMUs

quantum inertial sensing

– cold-atom atomic interferometry [6, 7]
– thermal-atom interferometry [1]
– NV centers
– miniaturisation of quantum angular rate sensors [2]

– almost no turn-on biases (TOBs), very low in-run bias stability (IRBS) 0.001 deg/h
– angular random walk (ARW) 0.0008 deg/$\sqrt{\text{h}}$
– limited bandwidth → hybridisation with conventional IMUs

potential and limits of inertial navigation

TIMU

future time and inertial measurement unit (TIMU)

- chip-scale atomic clock (CSAC)
- IMU

all what we need is to calibrate them from time to time

accurate, assured & affordable (A^3) PNT

the Holy Grail of PNT

the obvious requirement

- accurate (depends on application)
- assured (available at any time)
- affordable

originally developed for aviation, it begins to matter in other applications

- urban air mobility (taxi drones, drone delivery)
- autonomous vehicles
- any robotic application critically dependent on navigation

accurate, assured & affordable (A^3) PNT
the Holy Grail of PNT

the not so obvious requirements

– accurate (depends on application)... with some probability over time periods
– assured (available at any time)... with some probability over time periods
– affordable

originally developed for aviation, it begins to matter in other applications

– urban air mobility (taxi drones, drone delivery)
– autonomous vehicles
– any robotic application critically dependent on navigation

A^3 PNT example: RNP for CAT I

CAT I: operation of precision instrument approach and landing

operation	**accuracy** e-n	d	**integrity** IR	HAL	VAL	TTA	**continuity risk**	**availability**
units	m	m	-	m	m	s	-	-
CAT 1	16	≈ 5	2×10^{-7}	40	≈ 15	6	$\approx 5 \times 10^{-7}/15$ s	≈ 0.9999

e-n: east-north. d: down.

References for required navigation performance (RNP) specifications: [3], [4], [5]

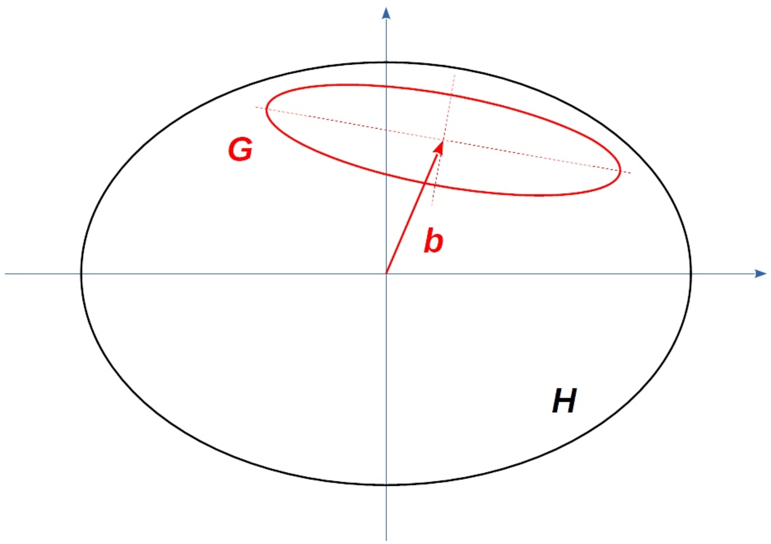
$\mathbf{A}^3$ PNT example: RNP for CAT I
assumptions

- signal-in-space arrives "well" (no multipath, no NLOS reflexions)
  "well" means $p_s = 10^{-5}$ error probability
  $p_{emd} = p_s \times p_{md}$
- GNSS receiver works (based on long MTBF)
- IMU works (based on long MTBF)

A^3 PNT example: RNP for a multi-sensor-based AV

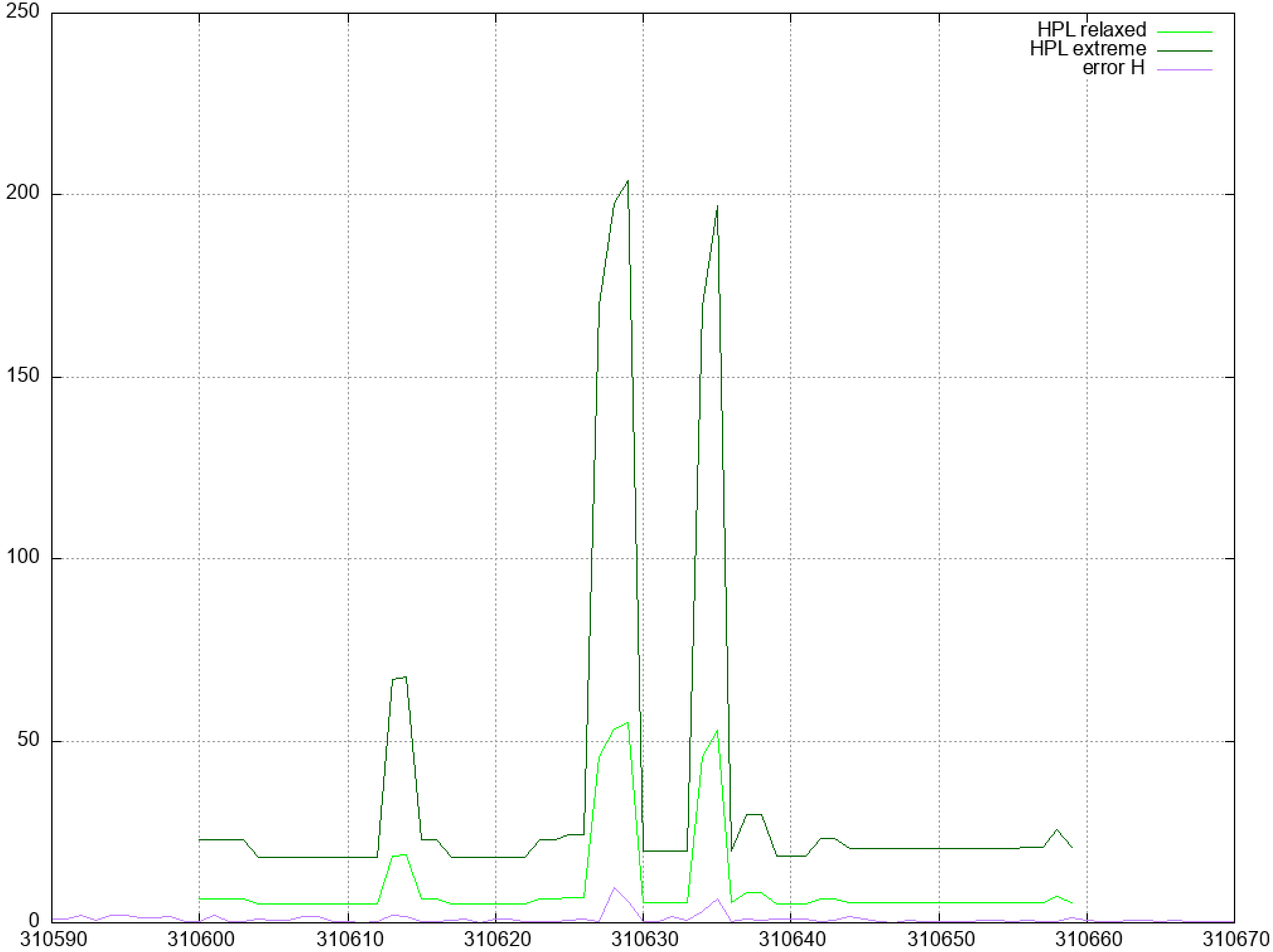
assumptions?

- p_s? depends on the environment
- what about the other a priori p_s
- what about p_s of visual and lidar sensors?
- what about outlier detection for the complex multi-sensor system?
- what about outlier detection of dynamic measurements? e.g., DMI, VO, IMU,...
- what about the impact of non-detected outliers in accuracy estimates?



realistic integrity

HPL against actual errors



A^3 PNT example: the EGENIOUSS project

EGNSS-based Visual Localisation to enable AAA-PNT in small devices & applications

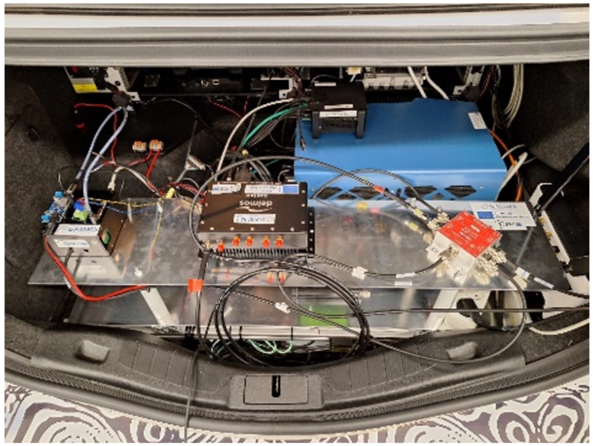
The goal of EGENIOUSS is to provide **affordable, accurate and assured positioning**, navigation and timing (AAA-PNT) for any modern computing **GNSS**-compatible device with a **camera** by a novel base technology: a hybrid EGNSS-based **Visual Localisation (VL) cloud-based service** for accurate (< 10 cm RMS) and reliable (99.9 % availability) absolute positioning with the aim for global scalability and high application-oriented transferability.

egeniouss
the better where

A^3 PNT example: GAMMS "robots mapping for robots"

Galileo/GNSS-based Autonomous Mobile Mapping System

GAMMS



HD maps market

2020	1400 M€
2028	15000 M€

final words

references

[1] C.L. Garrido Alzar. "Atom interferometers warm up". In: *Physics* 10 (2017), p. 2. DOI: `10.1103/Physics.10.41`.

[2] C.L. Garrido Alzar. "Compact chip-scale guided cold atom gyrometers for inertial navigation: enabling technologies and design study". In: *AVS Quantum Science* 1.1 (2019), pp. 014702–1–014702–18. DOI: `10.1116/1.5120348`.

[3] GEAS Panel. *GNSS evolutionary architecture study, phase II report*. Tech. rep. FAA, Feb. 2010, p. 121.

[4] ICAO. *Aeronautical Telecommunications. Annex 10 to the Convention on International Civil Aviation. Volume I Radio Navigation Aids*. International Standards and Recommended Practices. 6th edition. Montréal, Quebec, Canada: International Civil Aviation Authority, July 2006, p. 574.

[5] ICAO. *Performance-based Navigation (PBN) Manual*. International standard 9613. Montréal, Quebec, Canada: International Civil Aviation Authority, 2008, p. 294.

[6] M. Travagnin. *Cold atom interferometry for inertial navigation sensors. Technology assessment: space and defence applications*. Tech. rep. EUR 30492 EN / JRC122785. Luxembourg: Publications Office of the European Union, Dec. 2020. DOI: `10.2760/237221`.

[7] M. Travagnin. *Cold atom interferometry sensors: physics and technologies. A scientific background for EU policymaking*. Tech. rep. EUR 30289 EN / JRC121223. Luxembourg: Publications Office of the European Union, July 2020. DOI: `10.2760/315209`.