Höstevent med Radionavigeringsnämnden
"Robust navigation i maritim miljö"
Stockholm, Sweden, 8th October 2026



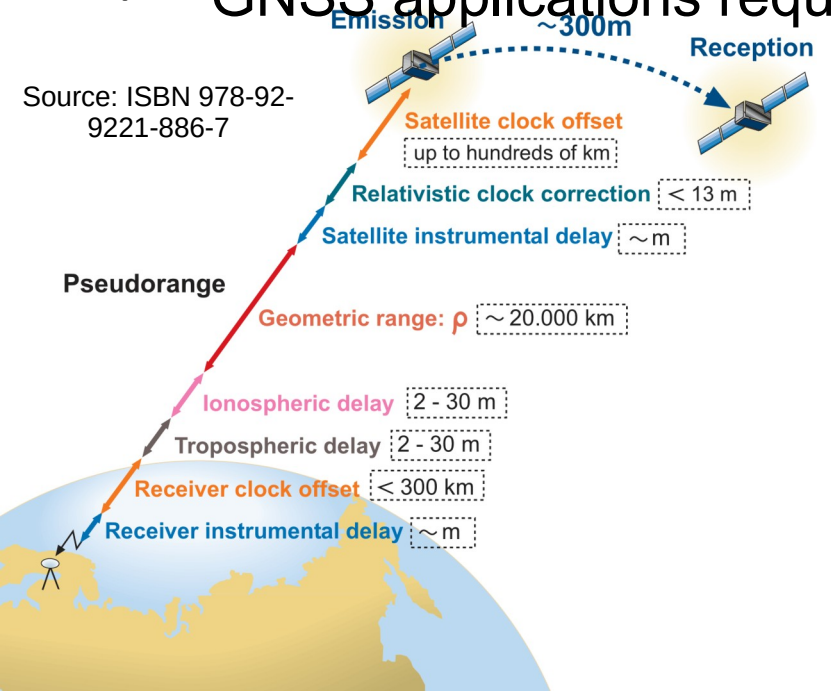
An application-aligned GNSS interference detection and spatial uncertainty estimation based on voluntary network of Android smartphone observations

Renato FILJAR[1,2]
[1]Faculty of Engineering, University of Rijeka, Rijeka, Croatia
[2]Laboratory for PNT & Spatial Intelligence, Zagreb University of Applied Sciences, Krapina, Croatia

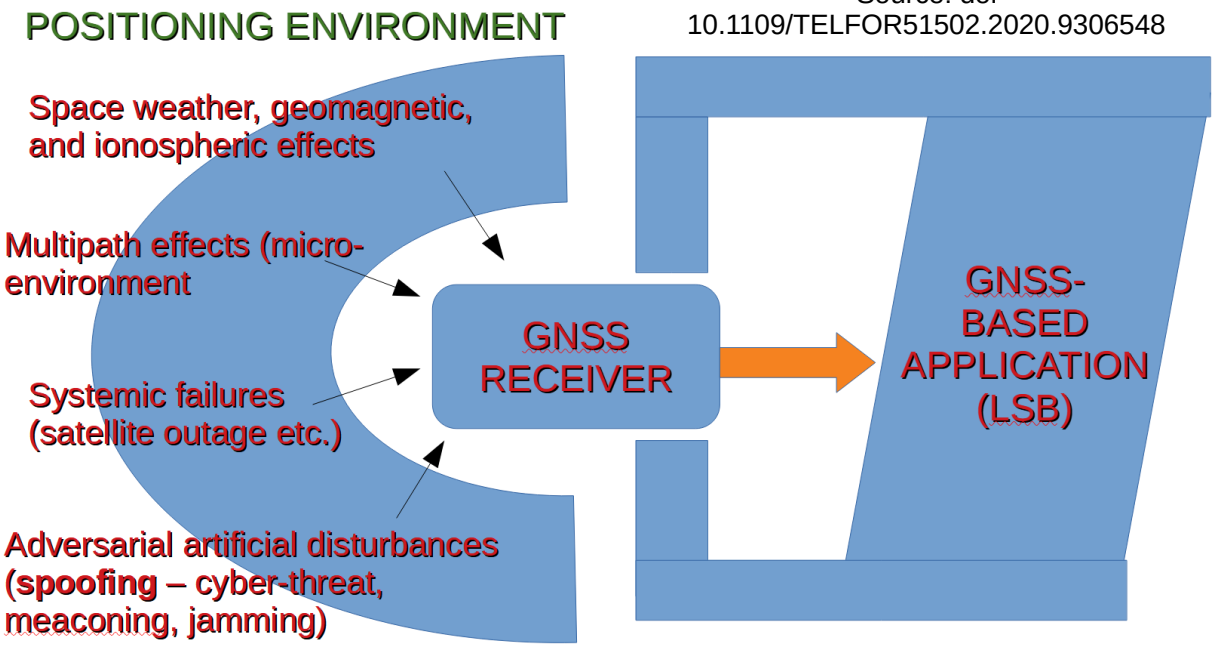
Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- Resilient GNSS development, a requirement
- Exposure to systematic, natural, and artificial interferences originated in the positioning environment
- Position estimation process associated with a black-box GNSS receiver
- GNSS operators required to guarantee PNT QoS, in the uncontrollable positioning environment
- GNSS applications require their PNT QoS needs are met



Source: ISBN 978-92-9221-886-7



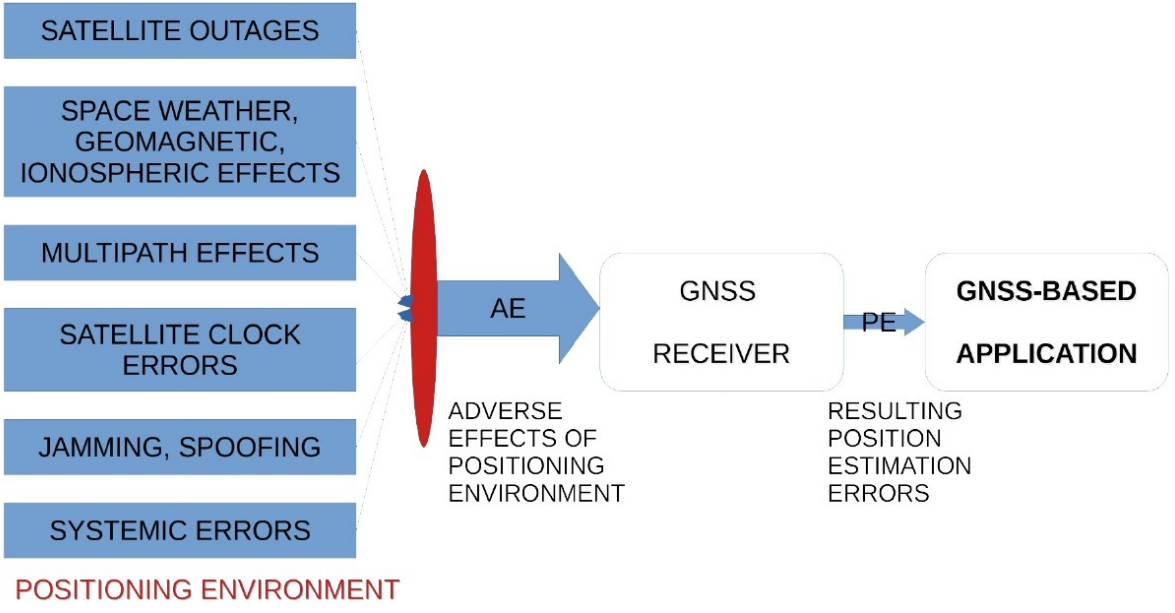
Source: doi 10.1109/TELFOR51502.2020.9306548

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- Resilient GNSS development, a requirement
- GNSS PNT degrading effects from the positioning environment
- PNT process contained in a black-box GNSS receiver
- GNSS PNT QoS guarantees required by application developers, operators and users, in the uncontrollable positioning environment
- GNSS PNT QoS and GNSS apps QoS requirements not aligned

Source: Filjar, R. (2022). Long Beach, CA. doi: https://doi.org/10.33012/2022.18247



Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- Resilient GNSS development, a requirement
- Spoofing (FAA, 2026, https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/afx/afs/afs400/afs410/GNSS/GPS_GNSS_Interference_Resource_Guide.pdf)
- Emissions of GNSS-like signals that may be acquired and tracked in combination with or instead of the intended signals by civil receivers.
- The onset of spoofing effects can be instantaneous or delayed, and effects can persist after the spoofing has ended.
- Spoofing can result in false and potentially confusing, or hazardously misleading, position, navigation, and/or date/time information in addition to loss of GNSS use.

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

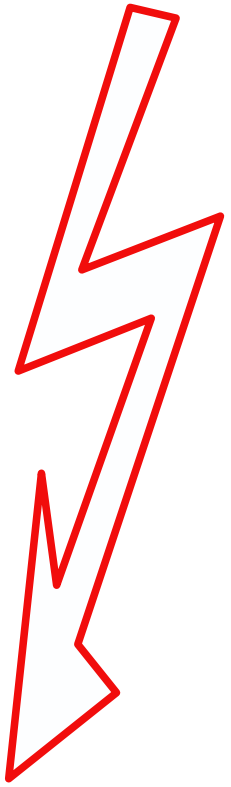
An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- Resilient GNSS development, a requirement
- A continuous gap between GNSS operators' specifications (ideal conditions, from users' perspective) and PNT requirements of GNSS applications (real conditions, and scenarios of utilisation)

GNSS PNT specifications:

- accuracy
-availability
- integrity
- continuity

(without consideration of utilisation scenarios)



GNSS applications requirements:

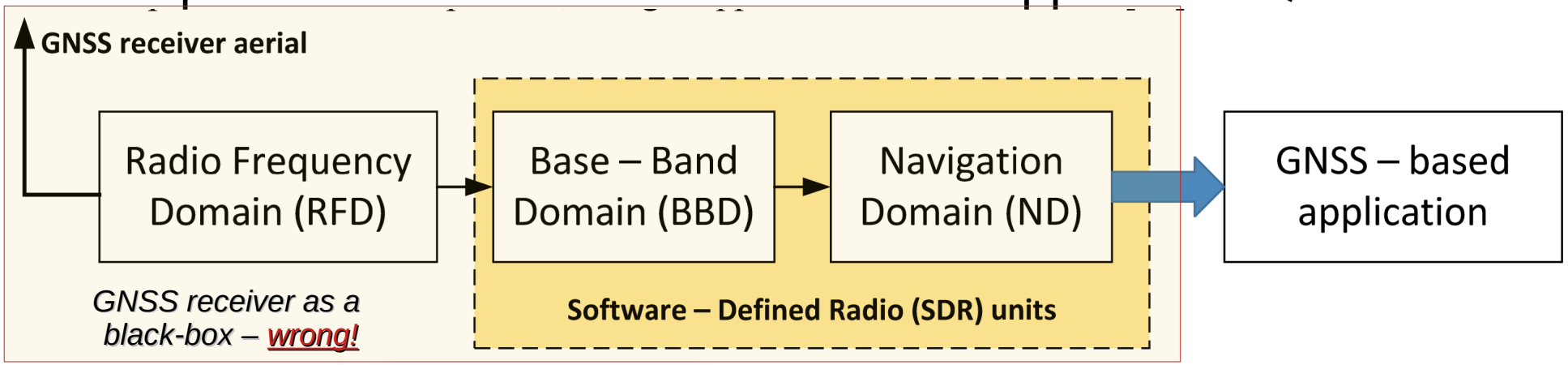
- accuracy
-availability
- integrity
- continuity

(in particular environment and its conditions)

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- State-of-the-art - GPS/GNSS PNT process
- **Unnecessary equivalence between a GPS/GNSS receiver and a GPS/GNSS PNT algorithm** as a considerable obstacle in transparent definition of the GPS/GNSS application QoS



Source: Filić & Filjar, doi: https://doi.org/10.33012/2018.16016, Filić & Filjar, doi: 10.23919/MIPRO.2018.8400087

GPS/GNSS receiver

GNSS RECEIVER

Through a dedicated API: position, velocity, time, positioning error

GNSS application defined by its needs for GNSS PNT QoS

Source: Filić & Filjar. (2018). ISBN 978-613-9-90118-0

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- State-of-the-art - GPS/GNSS PNT process: Mathematical foundations of GPS/GNSS PNT
- GPS/GNSS PNT algorithm as a solution of the optimisation problem

$$d_1=\sqrt{(x-x_{s1})^2+(y-y_{s1})^2+(z-z_{s1})^2}+c\cdot d_T$$
$$d_2=\sqrt{(x-x_{s2})^2+(y-y_{s2})^2+(z-z_{s2})^2}+c\cdot d_T$$
$$d_3=\sqrt{(x-x_{s3})^2+(y-y_{s3})^2+(z-z_{s3})^2}+c\cdot d_T$$
$$d_4=\sqrt{(x-x_{s4})^2+(y-y_{s4})^2+(z-z_{s4})^2}+c\cdot d_T$$

$$\hat{\boldsymbol{x}}=\arg\min_{\boldsymbol{x}} \boldsymbol{p}(\boldsymbol{x})^T \boldsymbol{\Sigma}^{-1} \boldsymbol{p}(\boldsymbol{x})$$

$$\boldsymbol{\Sigma} \stackrel{\text{def}}{=} cov(\boldsymbol{v})$$

Source: Filić, Grubišić & Filjar, https://www.pfri.uniri.hr/web/hr/dokumenti/zbornici-gnss/2018-GNSS-11.pdf

$$\boldsymbol{\rho}:=(d_1,d_2,d_3,d_4)^T \quad \boldsymbol{v}:=(v_1,v_2,v_3,v_4)^T$$

$$\boldsymbol{x}:=(x,y,z,d_T)^T$$

$$\boldsymbol{x}_{1:3}:=\boldsymbol{x}[1:3]$$

$$\boldsymbol{s}_i:=(x_i,y_i,z_i)^T$$

$$\boldsymbol{h}(\boldsymbol{x}):=\begin{bmatrix}[\![(\boldsymbol{s}_1-\boldsymbol{x}_{1:3}+x_4\cdot c)]\!]\\ [\![(\boldsymbol{s}_2-\boldsymbol{x}_{1:3}+x_4\cdot c)]\!]\\ [\![(\boldsymbol{s}_3-\boldsymbol{x}_{1:3}+x_4\cdot c)]\!]\\ [\![(\boldsymbol{s}_4-\boldsymbol{x}_{1:3}+x_4\cdot c)]\!]\end{bmatrix}$$

Conclusion: Mitigation of the GNSS positioning environment effects may be embedded within the GNSS position estimation algorithm, should the statistical properties of the effects are known or identified.

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

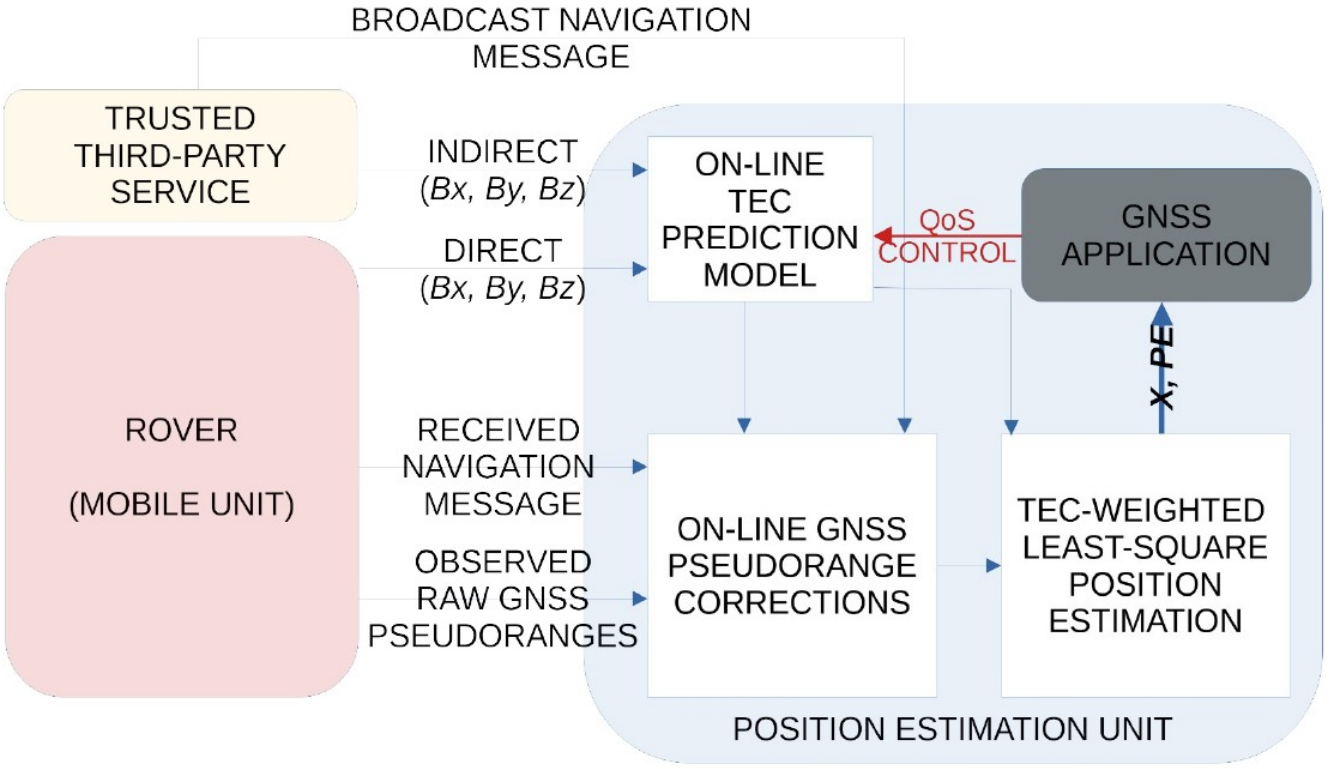
- Ambient-Aware Application-Aligned $(AA)^2$ PNT is a solution for GNSS resilience

- (AA)2 PNT → Active role of a rover in observing the immediate positioning environment

- (AA)2 PNT → Active role of a GNSS application in configuration of the GNSS PNT algorithm

- A concept of Positioning-as-a-Service developed by R Filjar

Source: Filjar, R. (2022). Long Beach, CA. doi: https://doi.org/10.33012/2022.18247



Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

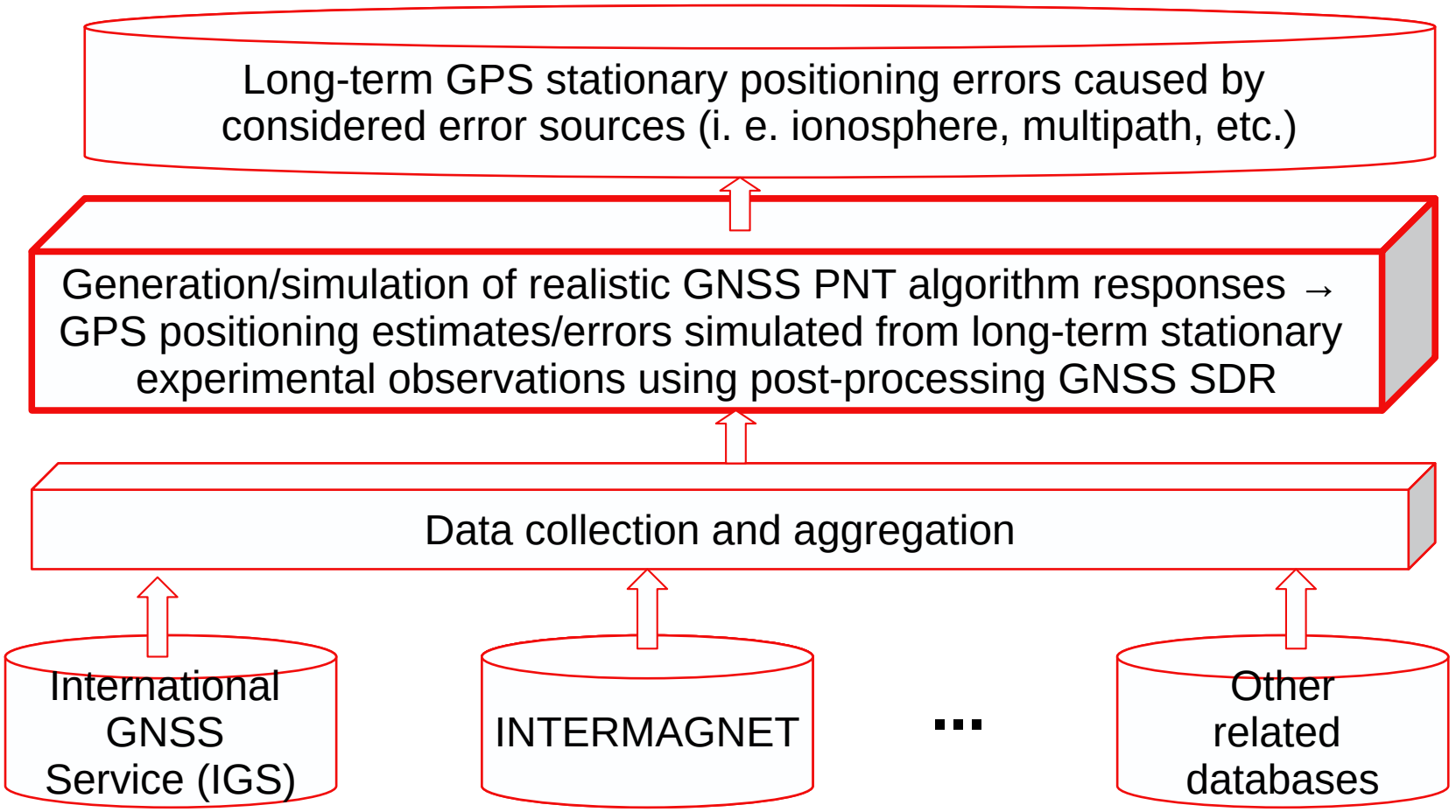
An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- Ambient-Aware Application-Aligned $(AA)^2$ PNT is a solution for GNSS resilience
- Probability of Occurrence (PO) to support application alignment in (AA)2 PNT
- Probability of Occurrence → a novel model and an estimator of risk of GNSS PNT performance not meeting the GNSS application requirements
- PO emerges as a knowledge based on experience → *database(s) of experimental observations*
- PO model developed for:
  - Particular PNT environmental conditions
  - Specific scenario(s) of GNSS utilisation

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

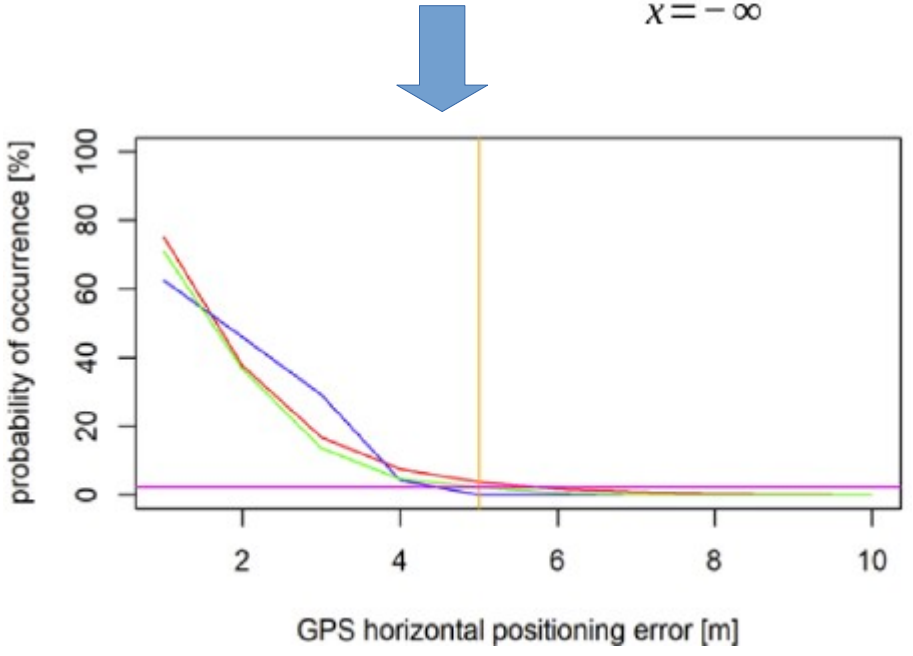
- $(AA)^2$ PNT Probability of Occurrence (PO)
- *Case study*: PO considering GPS ionospheric effects
- Development methodology



An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- $(AA)^2$ PNT Probability of Occurrence (PO)
- *Case study*: PO considering GPS ionospheric effects
- *Fisherian statistics* applied on a long-term GPS positioning error observations in a targeted environment and scenario of utilisation

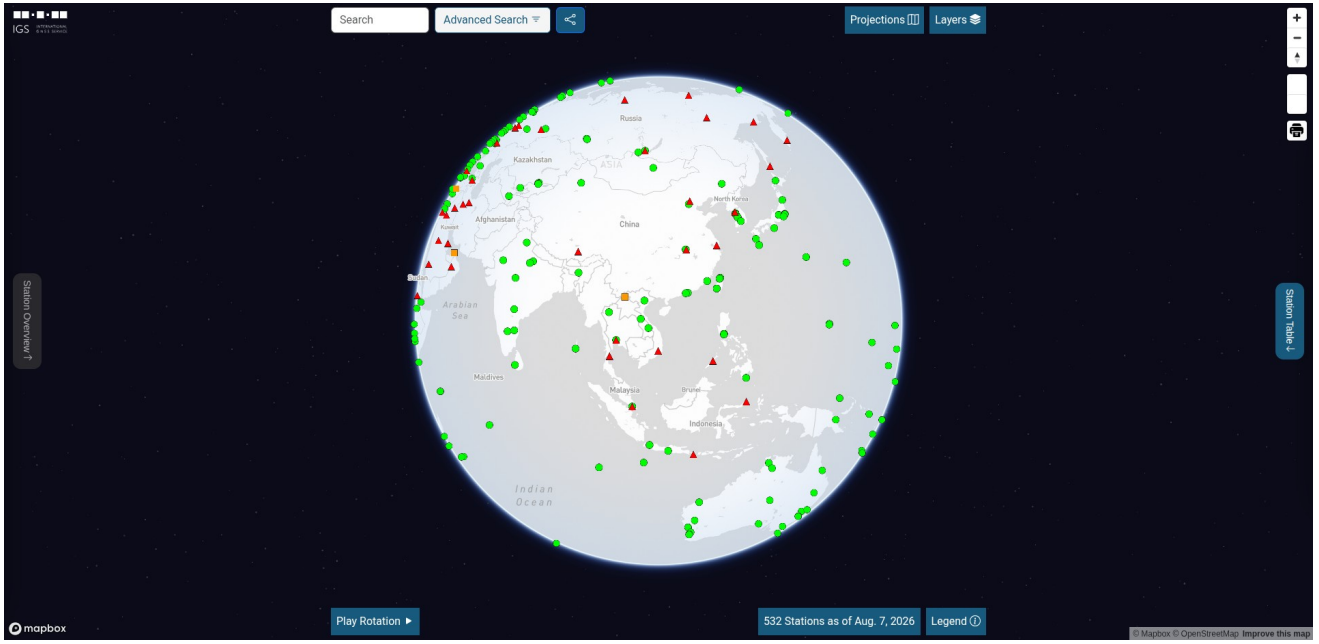
$$PoO = \bar{F}_X(x) = P(X > x) = 1 - \int_{x=-\infty}^{x=X} f_X(x)\,dx$$



Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- $(AA)^2$ PNT Probability of Occurrence (PO)
- *Case study*: PO considering GPS ionospheric effects
- Material: annual IGS observations of GPS pseudoranges, requirements for GPS positioning accuracy of particular GPS/GNSS applications



Source: https://network.igs.org/



Source: https://www.euspa.europa.eu/publications-multimedia/publications/user-needs-and-requirements

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- (AA)^2 PNT Probability of Occurrence (PO)
- Probability of Occurrence (PO) in practice



Source:https://www.euspa.europa.eu/sites/default/files/report_on_maritime_user_needs_and_requirements.pdf

Table 88: Port authorities' interest in int

Application	Horizontal accuracy in A 22/Res.915
Navigation in ports	1 metre
Tugs and pushers operations	1 metre
General port approaches	10 metres
Aids to navigation management	1 metre

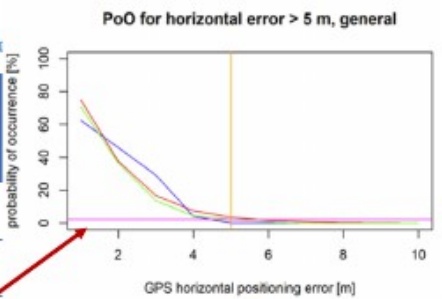
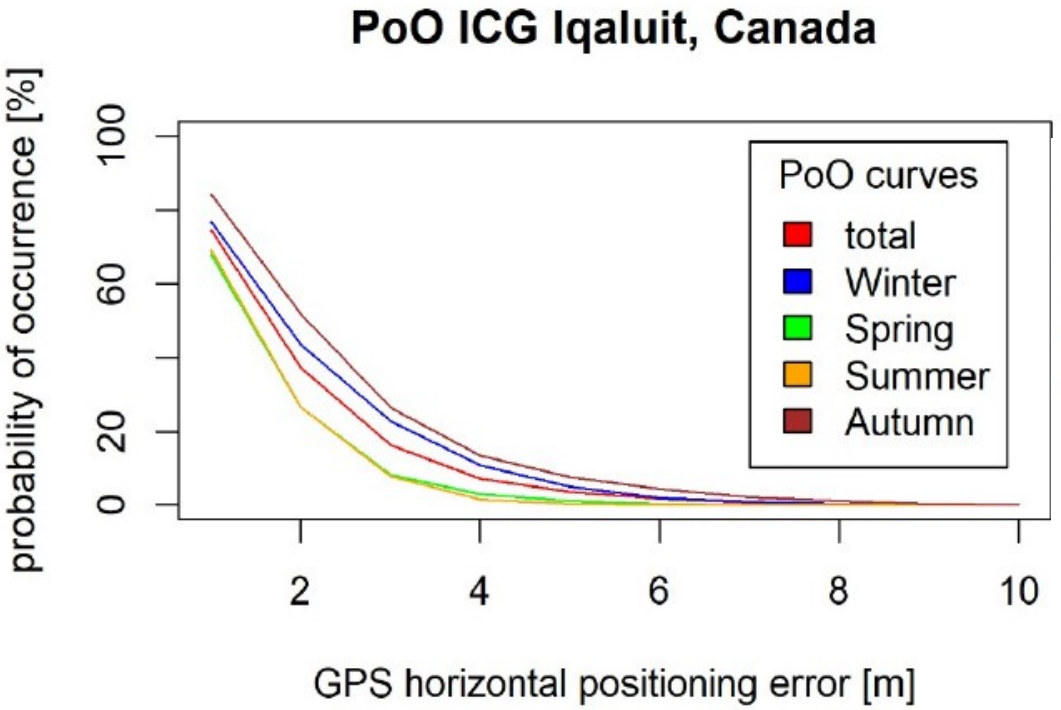


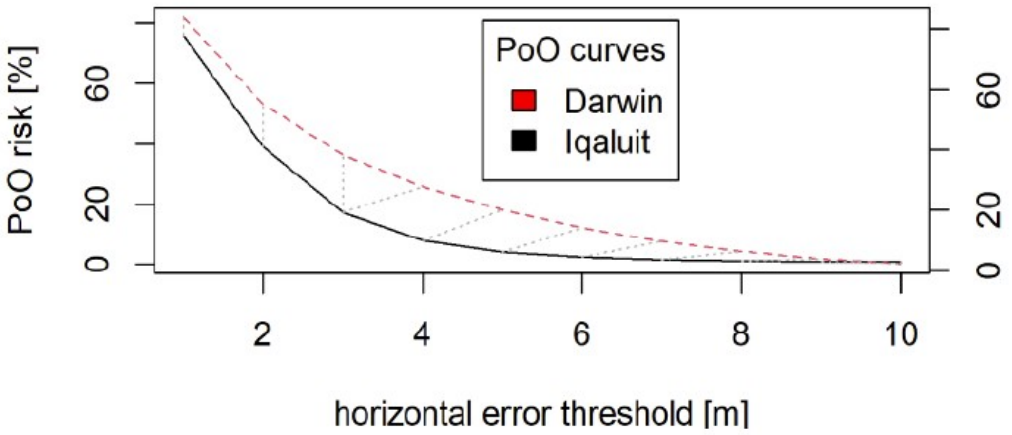
Table 90: e-GNSS performance requirements for autonomous vessels according to survey results.

Performance parameter	Oceanic deep-sea navigation	Coastal navigation
Horizontal accuracy 95%	<15m	<5m
Continuity (over 15 minutes)	$1{\cdot}1x10^{-5}$	$1{\cdot}1x10^{-6}$
AL	<28m	<12,5m
TTA	<8s	<6s
Integrity risk	$1{\cdot}1x10^{-6}$	1·1x10-7
Availability	99.8%	99.8%

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- $(AA)^2$ PNT Probability of Occurrence (PO)
- PO is space-time agnostic, as confirmed with a set of statistical tests → the same curve, independent of either latitude or time





Source: Alvir, M et al. (2025). Rio de Janeiro, Brazil. doi: 10.23919/FUSION65864.2025.11124048

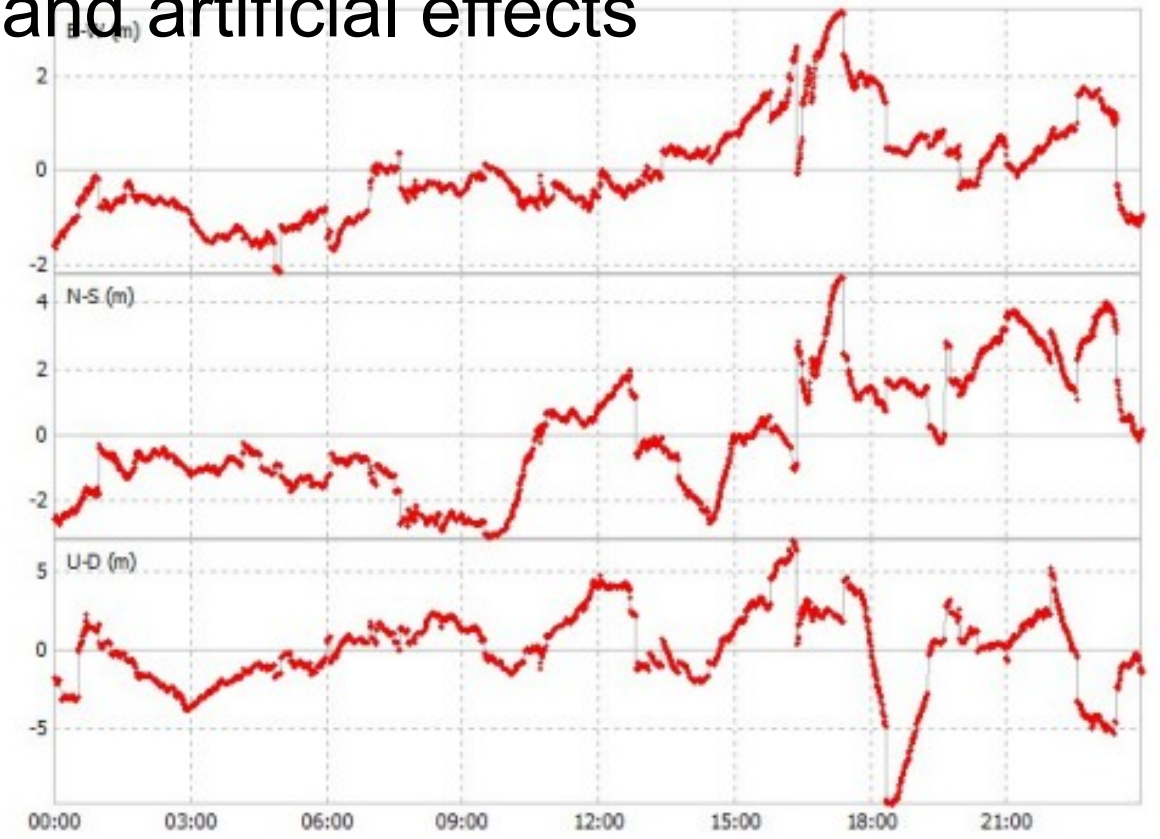
Source: Sikirica, N et al. (2025). Gdynia, Poland. doi:10.12716/1001.19.01.11

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- Importance of GNSS performance monitoring in real application environments
- GNSS performance monitoring to advise applications on adversarial natural and artificial effects



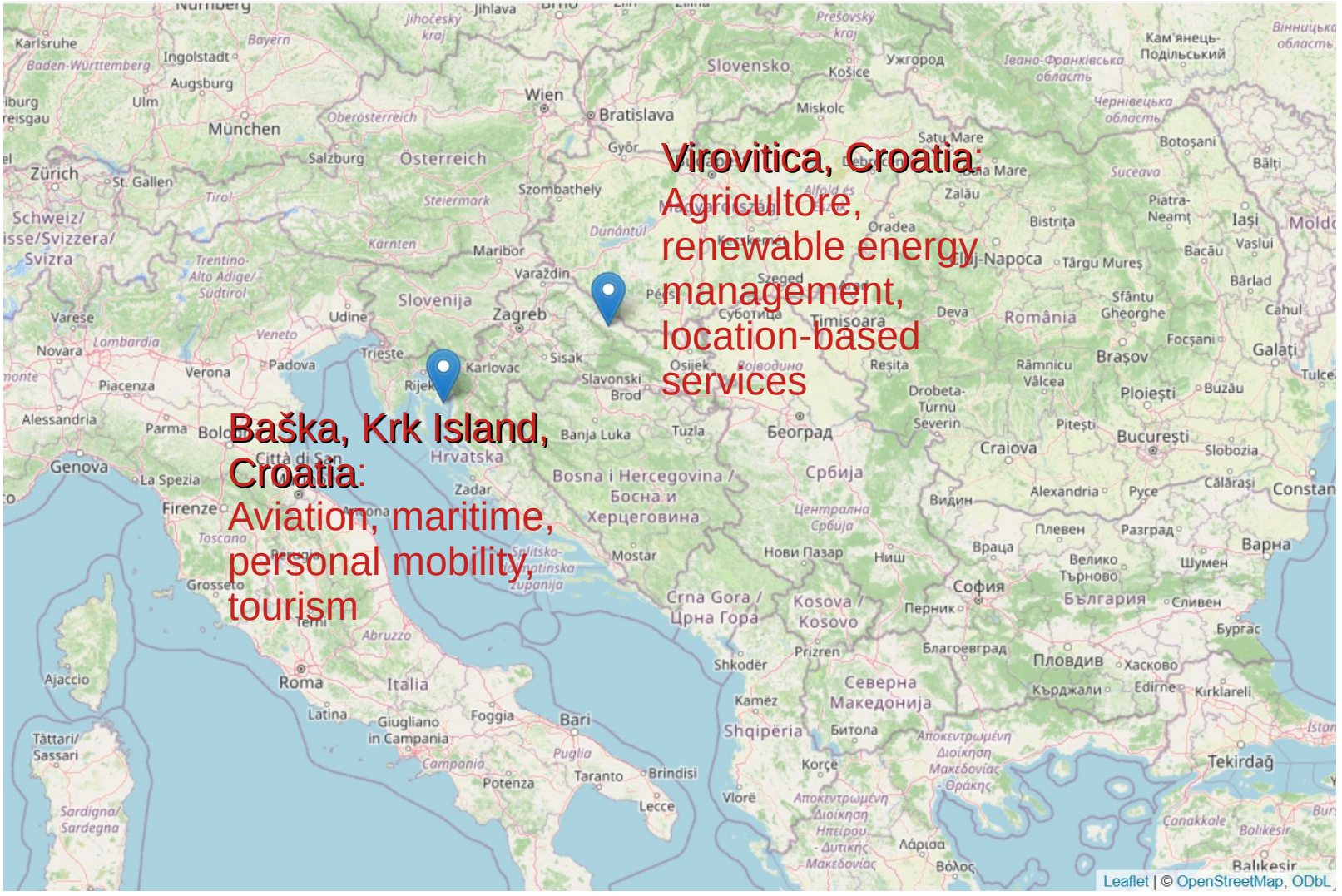


Source: (Filić, Filjar, Routsalainen, 2016), doi: 10.12716/1001.10.03.03

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

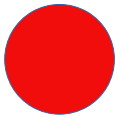
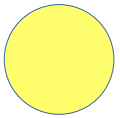
- Systematic GNSS performance monitoring in real application environments – a pilot in Croatia



Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- Importance of GNSS performance monitoring in real application environments – benefits for GNSS-based applications (systems & services) developers, operators, and end-users
- GNSS application QoS assurance

Actual Her = 2 m Day: DDMMYY Time: HHMMSS.SS	Geotechnical analysis for mining companies Hor < (1 – 5) m	Soil condition monitoring2 Hor < 1 m	ADS-B ATSA Surface traffic Awareness3 Hor<30 m
RED – a significant PNT degra-dation			
ORANGE – a moderate PNT degra-dation			
YELLOW – a modest PNT degra-dation			
GREEN - All clear			

Sources:

1 https://www.gsc-europa.eu/sites/default/files/sites/all/files/report_on_energy_and_raw_materials_user_needs_and_requirements.pdf

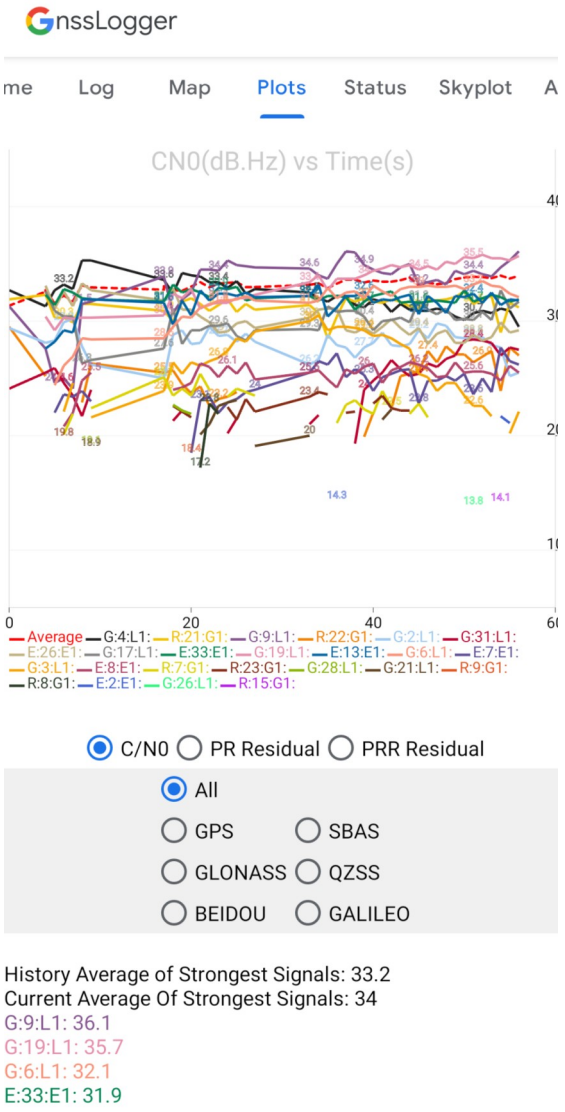
2 https://www.gsc-europa.eu/sites/default/files/sites/all/files/Report%20on%20Agriculture%20and%20Forestry%20User%20Needs%20and%20Requirements.pdf

3 https://www.gsc-europa.eu/sites/default/files/sites/all/files/report_on_aviation_and_drones_user_needs_and_requirements.pdf

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- GNSS performance monitoring in real application environments
- Raw GNSS pseudorange observations taken with a stationary commercial-grade multi-GNSS single-frequency GNSS receiver in an Android smartphone
- GNSSLogger app for Android



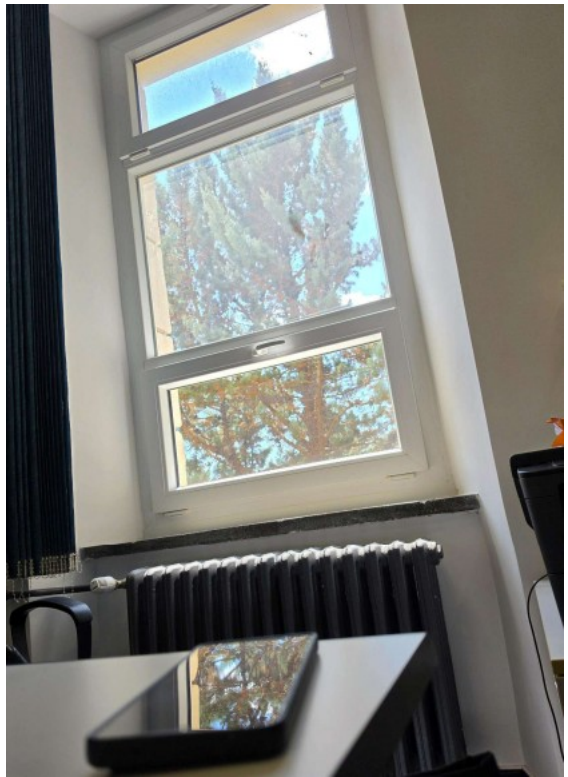


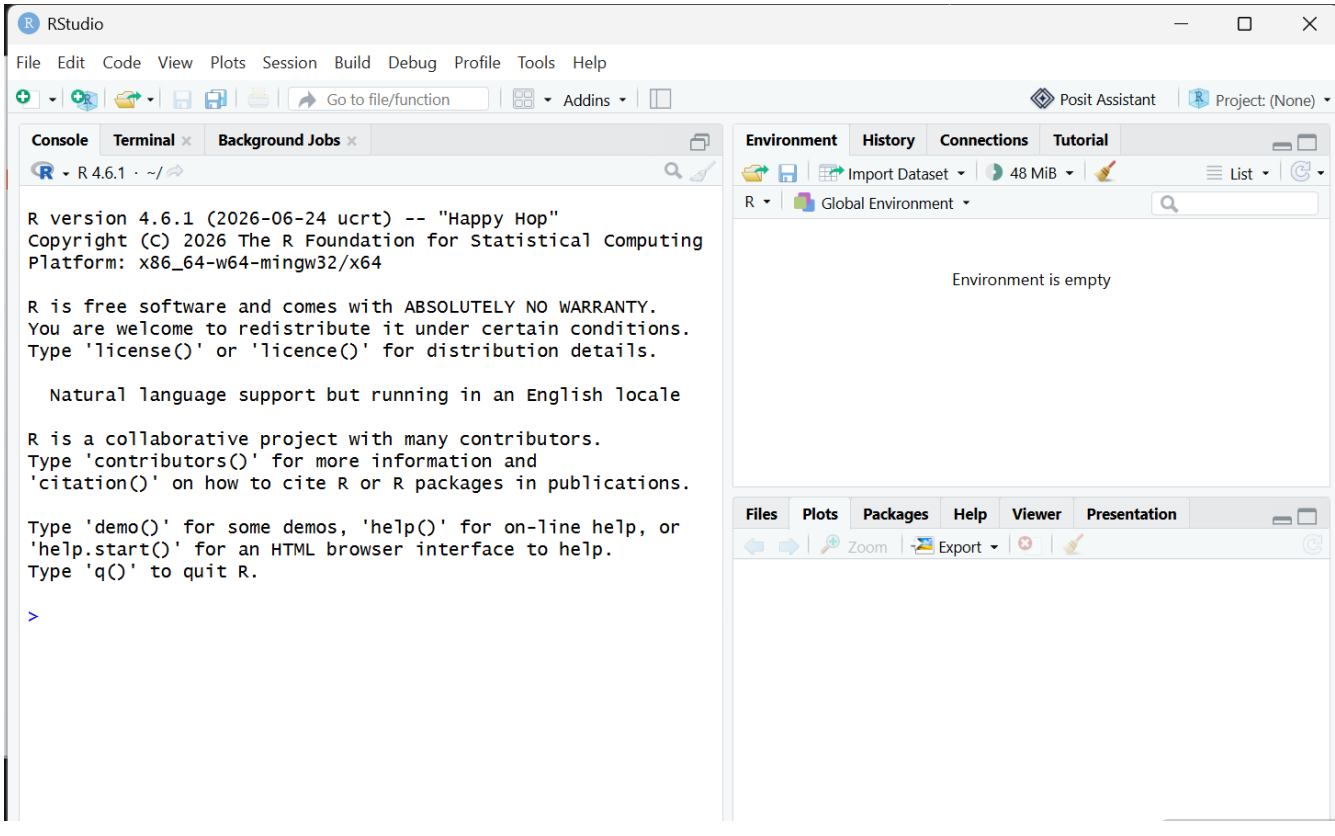
ID	GNSS	Freq	C/N0	Used	Azim	Elev
2		L1	24.7	Y	157	14
3		L1	21.6	Y	78	61
4		L1	30.0	Y	214	83
6		L1	31.2	Y	313	30
9		L1	35.6	Y	234	46
17		L1	31.9	Y	245	23
19		L1	34.7	Y	270	28
21		L1	22.3	Y	154	7
26		L1	13.8		86	1
28		L1	16.5	Y	38	14
31		L1	28.9	Y	57	30
22		G1	27.4	Y	212	54
9		G1	16.0		113	14
15		G1	14.1		9	6
23		G1	22.9	Y	312	46
21		G1	31.3	Y	178	13
7		G1	19.9	Y	352	68
8		G1	20.6	Y	267	38
6		G1			55	28
16		G1			58	22
24		G1			339	1
2		E1	16.5		62	2
7		E1	21.6	Y	62	82

Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- GNSS performance monitoring in real application environments
- Statistical analysis of positioning error estimation time series
- R enviroment for statistical computing (https://www.r-project.org/)

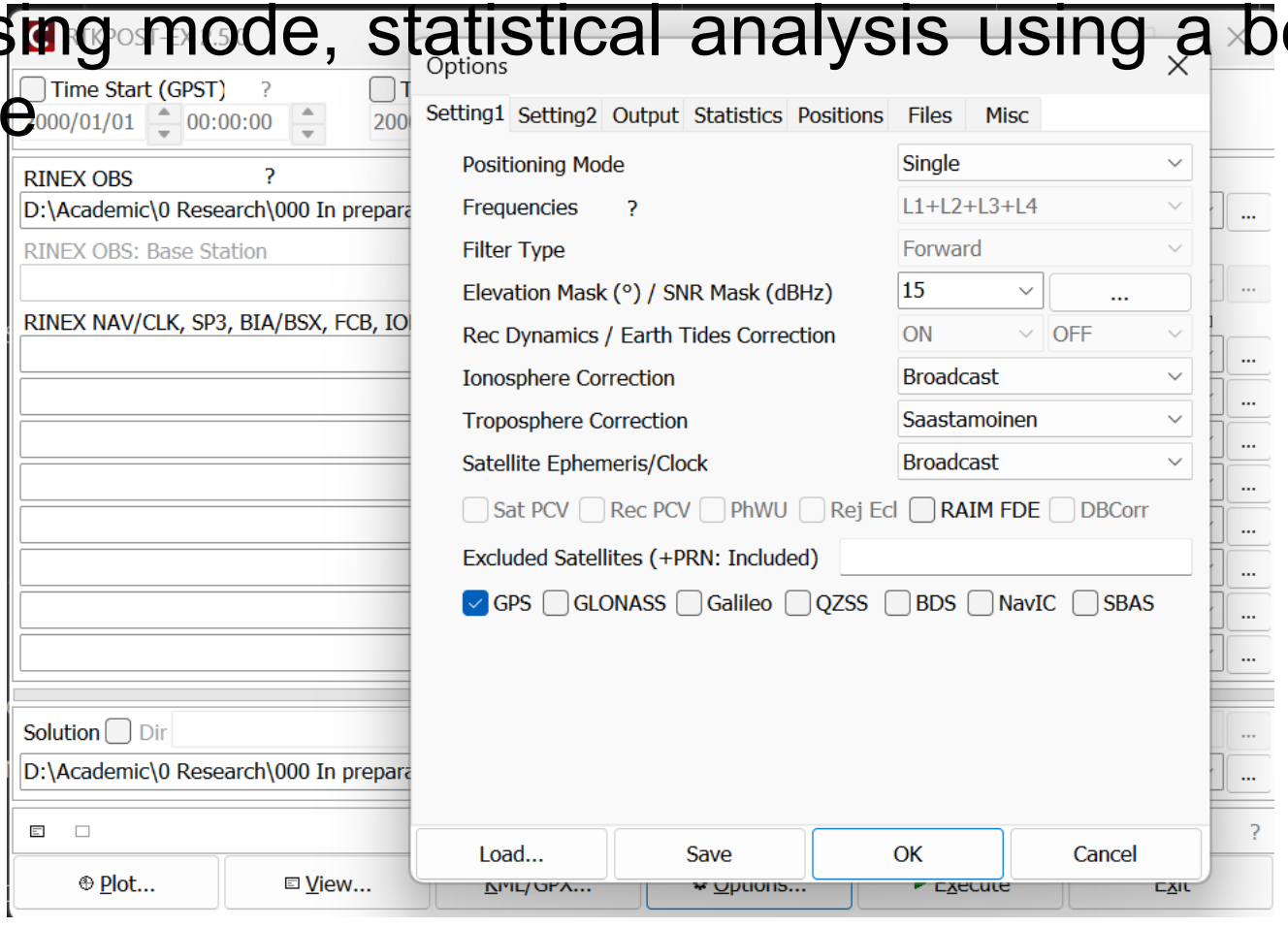




Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- GNSS performance monitoring in real application environments
- GNSS position estimates → RTKLIB/RTKPOS in post-processing mode, statistical analysis using a bespoke R software



Radionavigeringsnämnden, "Robust navigation i maritim miljö"
Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

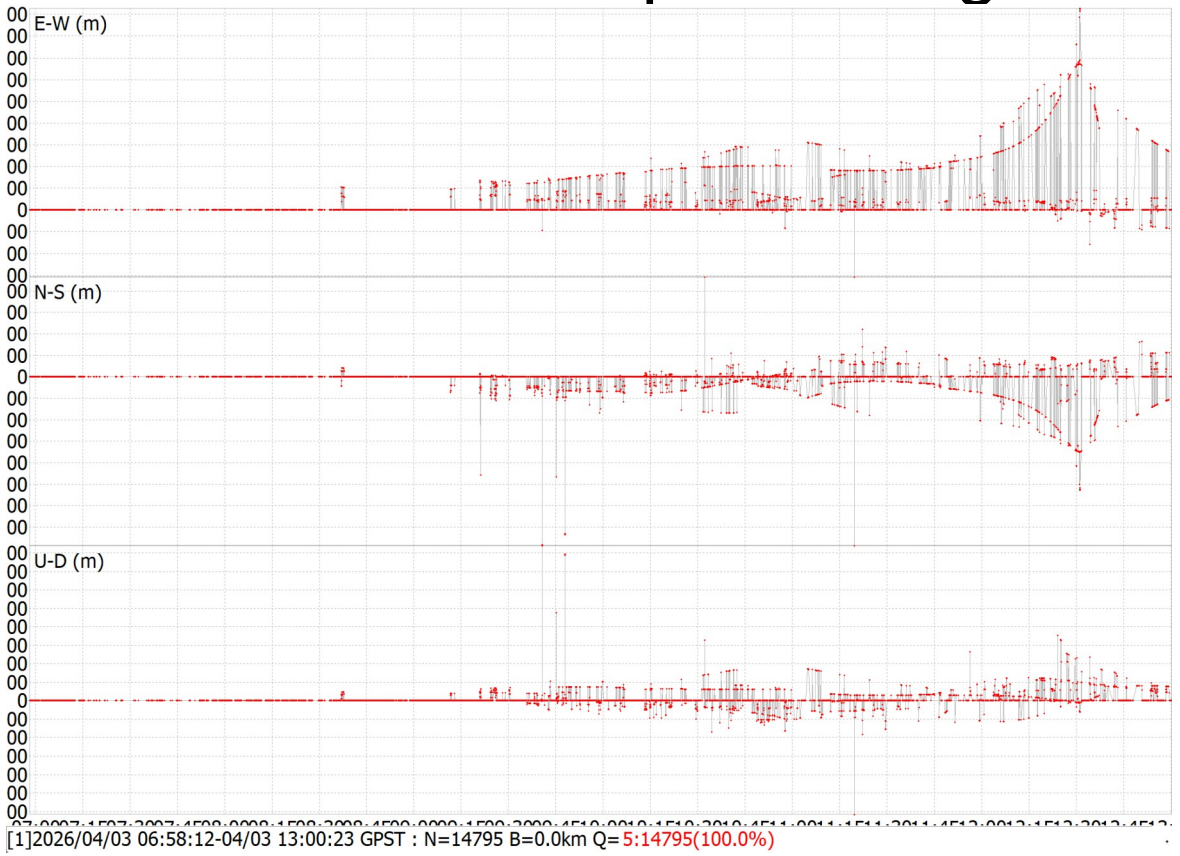
- GNSS performance monitoring in real application environments
- Case study: Virovitica, Croatia, on 3rd April, 2026
- GPS – ground track



Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

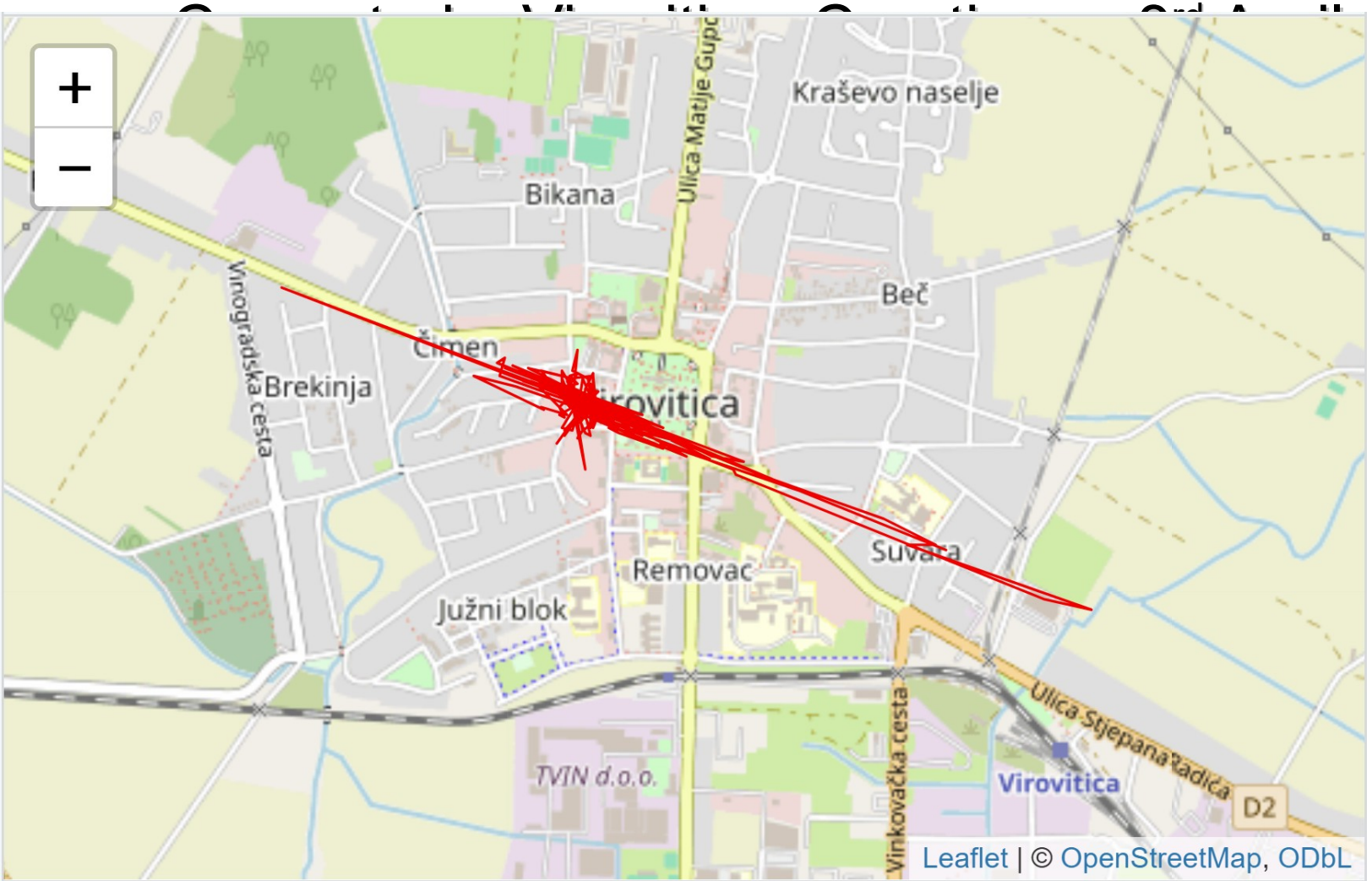
- GNSS performance monitoring in real application environments
- Case study: Virovitica, Croatia, on 3rd April, 2026
- GPS – time series of positioning errors



Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

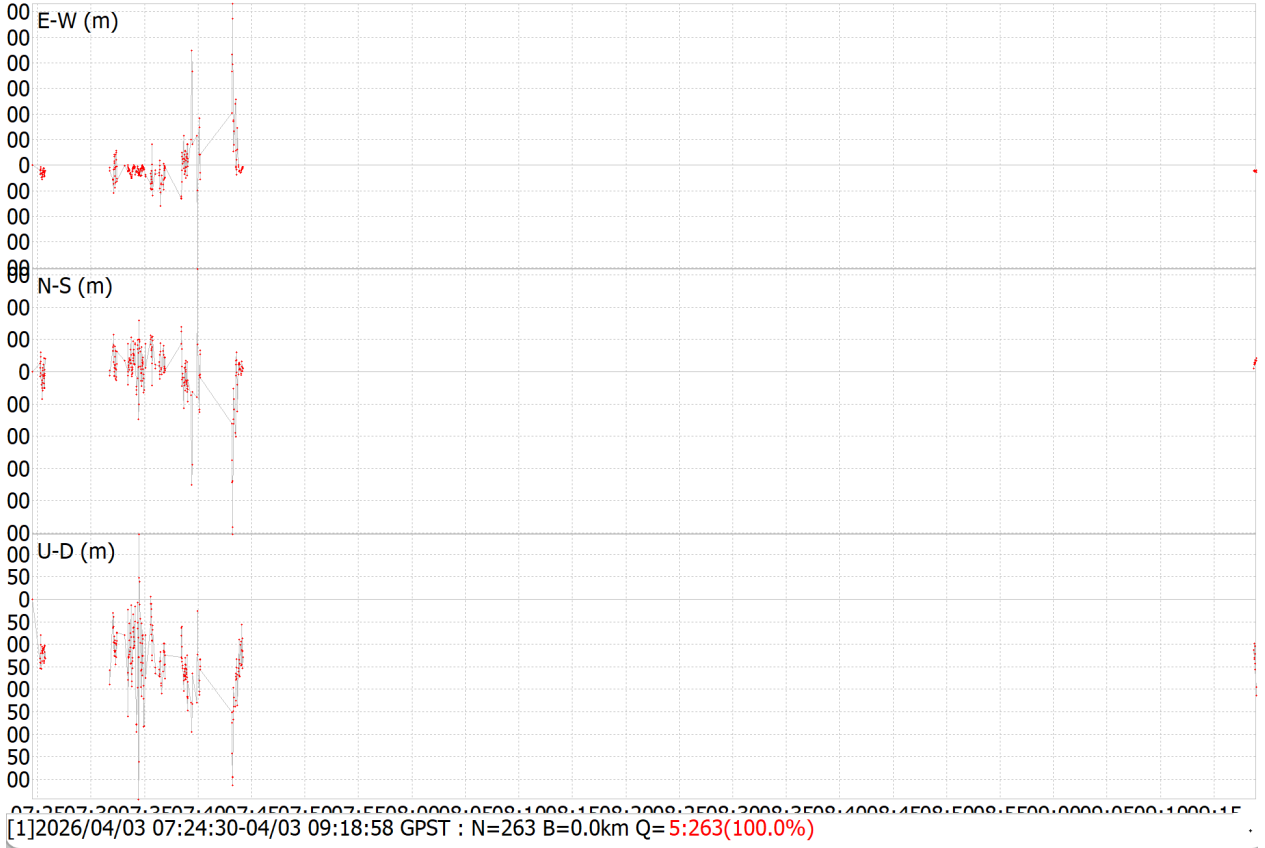
- GNSS performance monitoring in real application environments



Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

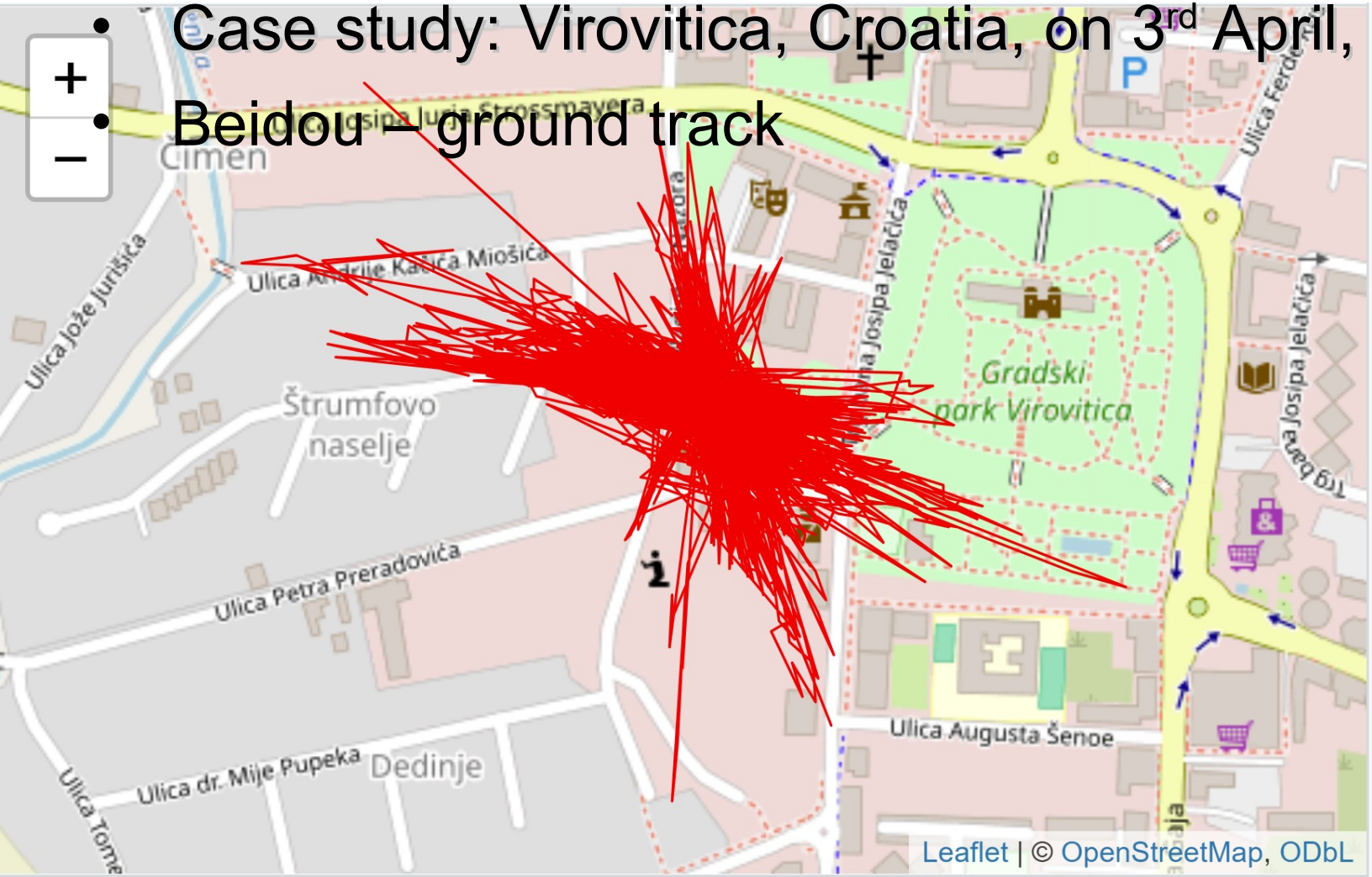
- GNSS performance monitoring in real application environments
- Case study: Virovitica, Croatia, on 3rd April, 2026
- GLONASS – time series of positioning errors



Radionavigeringsnämnden, "Robust navigation i maritim miljö"
Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

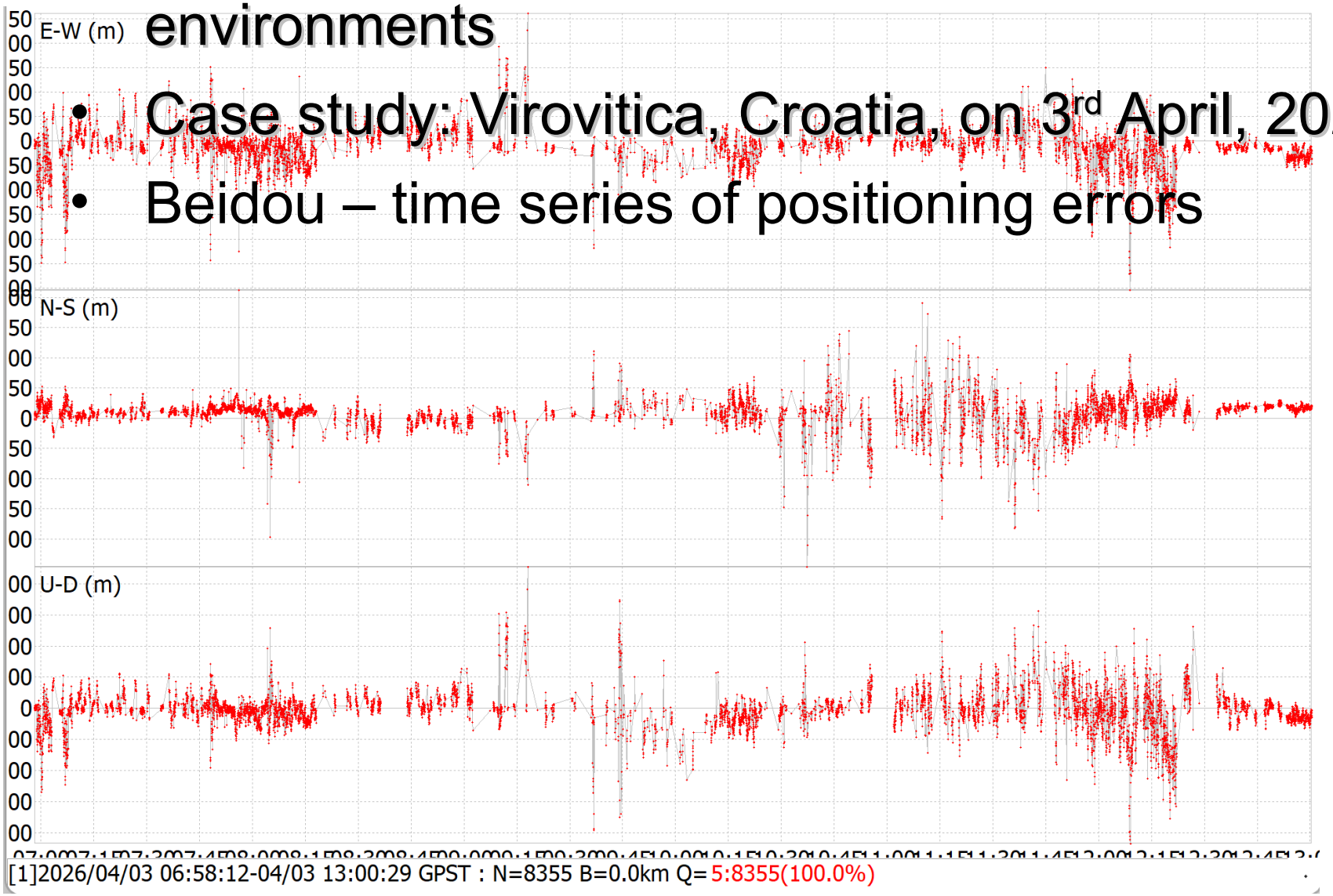
- GNSS performance monitoring in real application environments
- Case study: Virovitica, Croatia, on 3rd April, 2026
- Beidou – ground track



Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- GNSS performance monitoring in real application environments
- Case study: Virovitica, Croatia, on 3rd April, 2026
- Beidou – time series of positioning errors



Radionavigeringsnämnden, "Robust navigation i maritim miljö" Stockholm, 27th - 30th September, 2026

An application-aligned GNSS interference detection and spatial uncertainty estimation using voluntary Android smartphone observations (Renato Filjar, Croatia)

- GNSS performance monitoring in real application environments
- Case study: Virovitica, Croatia, on 3rd April, 2026
- Galileo – ground track and time series of positioning errors

- Discussion
- Anomalous GPS ground track raised attention during a routine GNSS performance evaluation
- Considerably degraded GPS PNT performance found → spoofing
- Partial (GLONASS) or complete (Galileo) absence of PNT signals → jamming
- Moderately degraded Beidou PNT performance
- Evidence of degradation of velocity estimation using GPS and Beidou

- Conclusion

- Exploratory statistical analysis may point to identification of natural causes of the GNSS PNT performance degradation or a sophisticated spoofing & jamming attack
- No effort made to identify either the perpetrator or the victim/target
- Importance of continuous monitoring of GNSS performance
- Need for monitoring and alert system associated with targeted GNSS applications to allow for sustained QoS


Höstevent med Radionavigeringsnämnden
"Robust navigation i maritim miljö"
Stockholm, 27th - 30th September, 2026
An analysis of a suspected GNSS spoofing event in Virovitica, Croatia, on 3rd April, 2026 (Renato Filjar)
APPRECIATE YOUR ATTENTION!
With an invitation to
Baška SIF (Spatial Information Forum) Meeting 2027
to be held in Baška, Krk Island, Croatia
20th - 23rd June, 2027
Prof Dr Renato Filjar, FRIN
Faculty of Engneering, University of Rijeka, Croatia, and
Laboratory for PNT & Spatial Intelligence,
Zagreb University of Applied Sciences, Croatia
E-mail: renato.filjar@gmail.com