ABSTRACT BOOK

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Content

21 May 2025

Receiver Autonomous Integrity Monitoring and GNSS Meta Signals

Conference Room A, May 21, 2025, 2:30 PM - 3:50 PM

Advanced RAIM Safety development for Rail, Maritime and UAVs Sectors

Buendia F[1], Labrador E[2], Clopot R[3], del Toro J[2], Fidalgo J[2], Dominguez E[2], Sanz C[2], Moreno G[2], Mistrapau F[3], Cezón A[2], Snijders M[4], Engwerda H[4], Casals J[4], Damy S[5], Sgammini M[5], Boyero J[6]
[1]Gmv, [2]Gmv, [3]GMV-RO, [4]NLR, [5]EC, [6]EC

Biography:
Mr. Fulgencio Buendia has a MSc In Physics and a MSc in Electronic Engineering from the Universidad of Valladolid. He joined Dimetronic Signals in 2000, working in high integrity Safety Critical systems for the Railway field. In 2005 he join GMV Aerospace & Defence, as Project Manager for Real Time developments in the scope of the Eurofighter project. During more than 10 years he has been working as Safety Manager in different GMV sectors as Defense, Aviation, Intelligent Transport systems and Automotive projects.

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) is an enhancement of RAIM, designed to leverage the advantages of dual-frequency, multi-constellation GNSS. Initially developed for the aviation industry, ARAIM is now being considered for broader applications. This paper focuses on the Safety processes, supporting the ARAIM Evolution Architecture, Algorithm, and local error modeling, enabling the use in three specific sectors: rail, maritime, and Unmanned Aerial Vehicles (UAV)s.
The paper presents a Safety Methodology and proposes an ARAIM Threat Model, subsequently tailored to sector-specific local error models. The proposed high-level ARAIM Evolutions Architecture focusses on:

- Rail: Integration of Space Based Augmentation System (SBAS) with ARAIM and IMU/odometer hybridization.
- Maritime: An ARAIM solution utilizing multiple antenna processing in combination with SBAS.
- UAVs: A hybrid ARAIM and Preside Point Positioning (PPP) solution, enhanced by IMU integration.

A Safety Methodology is presented, along with an ARAIM Threat Model tailored to sector-specific local error models. The Safety process encompasses the Failure Modes Effect Analysis (FMEA) and Hazard Analysis of the ARAIM application in the different fields, and finally the elaboration of different Fault Tree Analysis (FTA)s to provide confidence in the architecture, algorithm and monitors suggested by the Safety process.

Through the synergy of design and safety engineering efforts, the project characterized the local effect models for multipath and Non-Line-Of-Sight (NLOS) errors, using data gathered from real-world GNSS experiments and the updated ARAIM Threat Model. The paper discusses future work aimed at validating the proof-of-concept for these ARAIM enhancements across the three sectors.

The safety development provides preliminary evidence of the feasibility of meeting Integrity requirements when applying the proposed Safety requirements for ARAIM beyond aviation.

This work is conducted as part of the Horizon Europe project ARAIMFUSE (Advanced RAIM for Rail, Maritime, and UAS), led by GMV and funded by the EC.

ARAIM Protection Level Calculation Method Based on Bayesian Optimization

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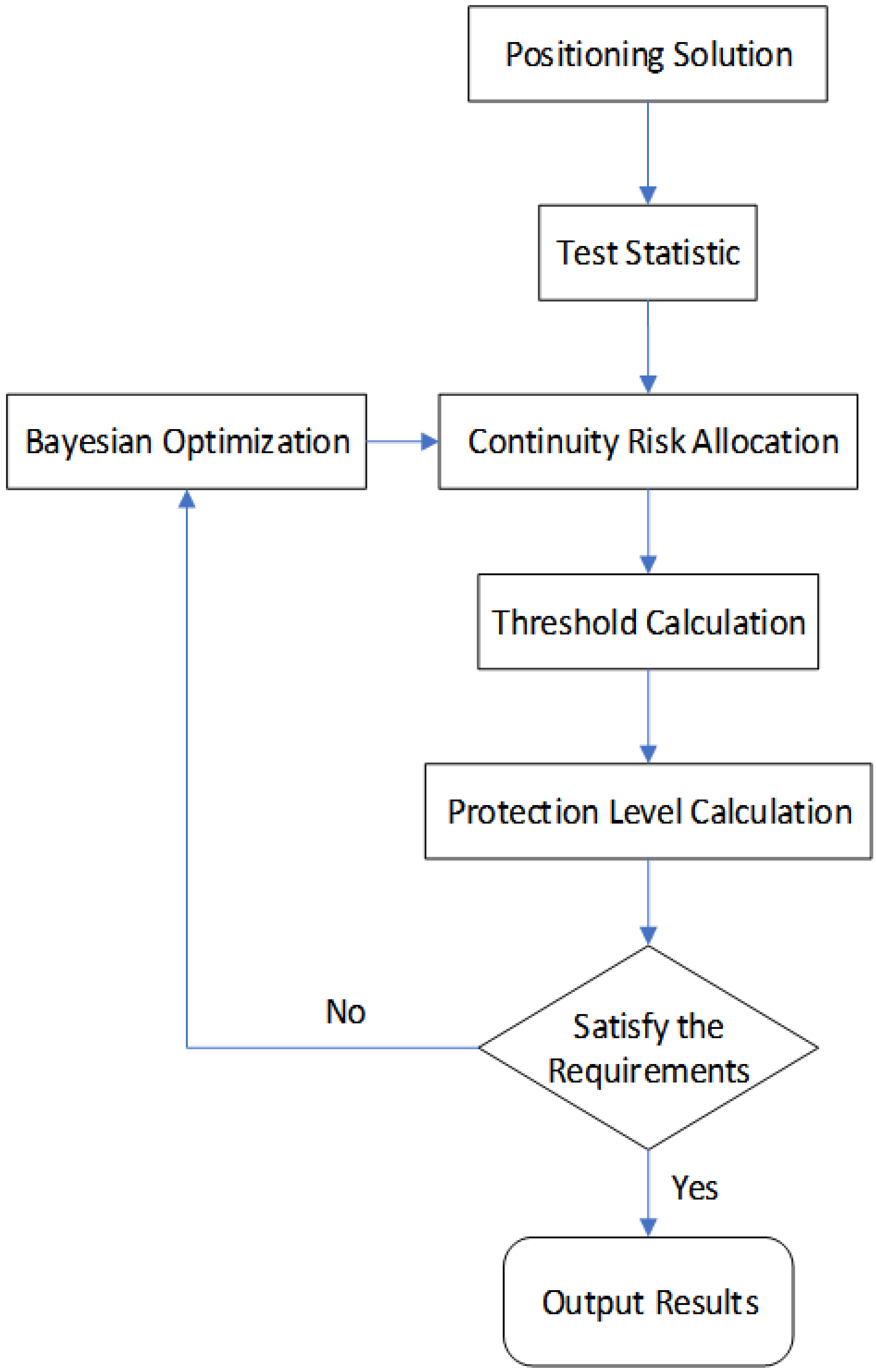
[1]Beijing Institute Of Technology, [2]Beihang University, [3]National Key Laboratory of Science and Technology on Space-Born Intelligent Information Processing

Biography:
Liu Sitong, a graduate student at the School of Astronautics, Beijing Institute of Technology. Main research direction is satellite fault detection methods. The topic of introduction is "ARAIM Protection Level Calculation Method Based on Bayesian Optimization."

Integrity monitoring systems are intended to assess the reliability of the information provided by the navigation systems. Advanced Receiver Autonomous Integrity Monitoring (ARAIM) is a primary method for integrity monitoring of multiple satellite failures. The allocation of continuity risk is associated with the threshold of fault detection. High fault detection thresholds may increase the probability of hazardous misleading information, leading to a high integrity risk. However, existing ARAIM integrity monitoring methods often adopt an equal allocation of continuity risks, which leads to redundancy in the allocation of false alarm probabilities. This problem results in a conservative estimation of integrity, thereby reducing the availability of the method. This paper proposes an ARAIM optimization method based on Bayesian Optimization. In this method, the minimum protection level is taken as the objective function of the Bayesian Optimization. The continuity risks allocated to different fault modes are used as parameters to be optimized in the Bayesian Optimization. These parameters are normalized to connect with the continuity risk allocation. Constructing the surrogate model based on a Gaussian process and appropriately selecting the acquisition function can help optimize the allocation of continuity risks. Optimized continuity risk allocation improves the selection of fault detection thresholds for test statistics to achieve the optimal protection level. This method is implemented and validated, and the results are compared with those of traditional methods. The results indicate that the continuity risk allocation strategy based on the Bayesian Optimization algorithm optimizes the protection level and improves the global availability of ARAIM.


Positioning Solution
Test Statistic
Bayesian Optimization
Continuity Risk Allocation
Threshold Calculation
Protection Level Calculation
No
Satisfy the Requirements
Yes
Output Results

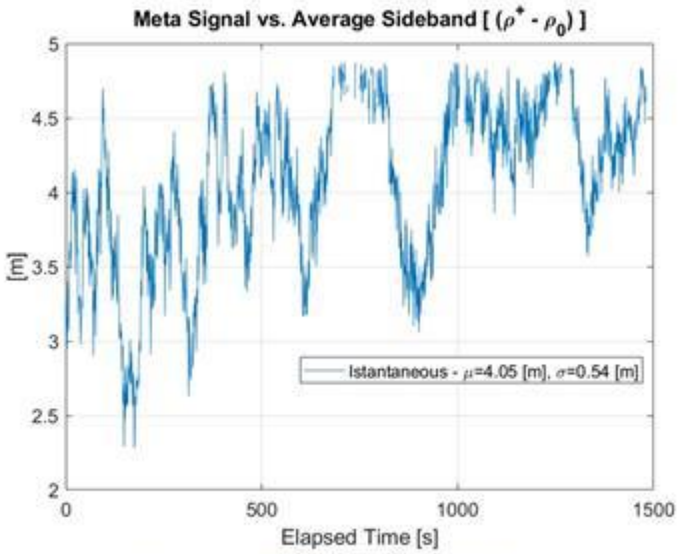
The Synthetic GNSS Meta-signal Approach at a New Extent: The Dynamic Challenge, Proposals, and Results

Di Grazia D[1], Pisoni F[2], Crasta S[1], Ardiero S[1], Gogliettino G[1], Renna M[1]
[1]STMicroelectronics, [2]STMicroelectronics

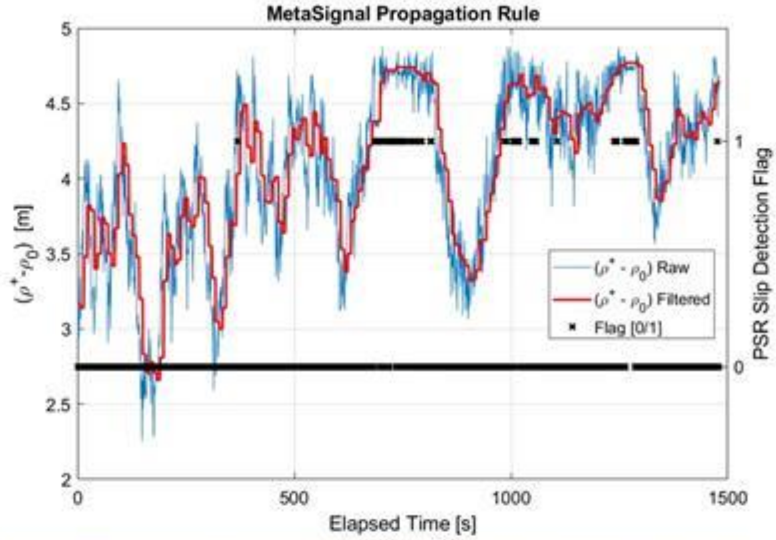
Biography:
Domenico Di Grazia is a GNSS System Architecture and Software R&D Principal Engineer at STMicroelectronics and a Senior Member of the ST Technical Staff. He has over 15 years of experience in the telecom and semiconductor industries. He holds a Ph.D. in Information and Communication Technology and Engineering (2024) from the University of Naples 'Parthenope', specializing in GNSS Receivers Modernization. He also holds an MSc degree in Telecommunications Engineering from the University of Naples Federico II (2001), Naples, Italy.
He is the (co)author of more than twenty technical publications, including international conferences and journals, and holds over ten granted patents.

The Synthetic Meta-signal reconstruction approach enables the generation of wideband Global Navigation Satellite System (GNSS) measurements from side-band observations and is of paramount interest for high-accuracy code solutions in modern receivers because the wide Gabor bandwidth of the resulting signals does not require any hardware redesign. In the Synthetic generation framework, wideband high-accuracy Pseudorange (PSR) measurements are delivered by combining side-band code measurements smoothed using the side-band wide-lane linear Carrier Phase (CP) combination. The Meta-Signal Carrier Phase, which averages the side-band CPs, is further resolved for half-cycle ambiguity using a Half-Cycle Ambiguity Resolution (HCAR) detector based on the Hatch-Melbourne-Wübbena (HMW) combination of side-band observations. This approach has already proven effective in static conditions, and its embedded implementation has been proposed for automotive receivers. This article explores more the challenge of Synthetic Meta-Signal usability in dynamic conditions. In such environments, the carrier phase observable from sidebands can become unavailable due to cycle slips and loss of lock caused by multipath and other impairments. This can severely degrade the availability of Meta-Signals in critical cases, limiting the method's usability to quasi-static conditions. The article introduces a novel technique to produce high-accuracy PSRs when CP is lost, and in principle synthetic measurement formation cannot be executed. The method exploits the statistical nature of the predicted contribution from the difference between the latest available high-accuracy PSRs and the low-accuracy sideband-information average from previous epochs. This allows continued generation of usable high-accuracy PSRs in urban canyons and under short obscurations, tackling the synthetic generation in dynamic conditions. The proposal has been validated by several tests, executed on next-generation STMicroelectronics Teseo platform. Results demonstrate that using synthetic meta-signal observables improves the positioning performance of dual-frequency (L1-L5) receivers and leads to the conclusion that wherever Meta-Signal wideband measurements are adopted, the attainable overall accuracy is significantly enhanced.

Synthetic Meta Signal Availability degradation in dynamic condition because of CP loss.
Green color on the tracked points indicates that Metasignal availability matches the L1 signal one,
Orange and red the progressive degradation when passing under obscurations.

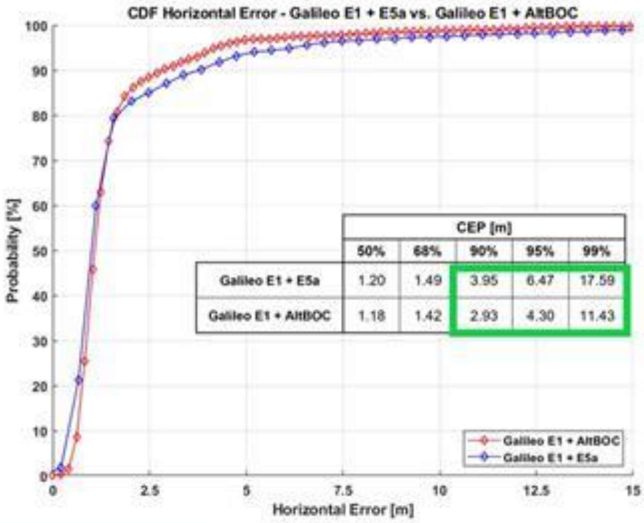


Difference between High accuracy PSR and Low-quality Sideband average for a Galileo E5 satellites in a dynamic test. The quantity represents the best leveling contribute to the formation of the high-accuracy PSR when only code-based quantities are available.



Meta Signal Dynamic propagation rule. Difference between High and Low accuracy Meta-Signal, both raw and filtered version, is reported on the left. The usage of the predicted difference is signaled by a flag (namely PSR Slip) as reported on the right

Test Drive Path and Setup. Both Teseo Next Generation and an Applanix Positioning tool used for reference recording



Performance Result from Dynamic Test.
Galileo Case, E1-E5a vs E1-AltBoc [Synthetic with The PSR Recovery method applied when Carrier Phase is not available]

Synthetic Measurements of Triple-Component GNSS Meta-Signals

Borio D[1], Susi M[2], Wężka K[3]
[1]European Commission, Joint Research Centre, [2]Topcon Positioning Systems Inc., [3]Warsaw University of Technology

Biography:
Daniele Borio received the M.S. degree in Communications Engineering from Politecnico di Torino, Italy, the M.S. degree in Electronics Engineering from ENSERG/INPG de Grenoble, France, in 2004, and the doctoral degree in electrical engineering from Politecnico di Torino in April 2008. From January 2008 to September 2010 he was a senior research associate in the PLAN group of the University of Calgary, Canada. In October 2010, he joined the European Commission Joint Research Centre (JRC). He is a scientific technical officer in the JRC "Food Security" unit where he supports the European Common Agricultural Policy (CAP) through the European satellite programs, Galileo and Copernicus.

The accuracy of Global Navigation Satellite System (GNSS) pseudoranges is bounded by the Cramer-Rao Lower Bound (CRLB), which involves the Gabor bandwidth of the corresponding received signal. A large Gabor bandwidth promotes measurement accuracy. This result and the fact that modulations with energy concentrated far from the zero frequency have larger Gabor bandwidths motivate research on GNSS meta-signals, which are obtained by jointly processing components from different frequencies. When two side-band components are considered, the resulting meta-signal has characteristics close to that of a pure carrier and measurement ambiguities can arise. This fact is not accounted for by the CRLB and signal energy in between side-band components can alleviate the ambiguity problem. Thus, meta-signals with three components can lead to more reliable measurements than the corresponding dual-frequency signal with a large spectral gap. While a signal processing framework for effectively tracking triple-component meta-signals has been recently proposed, the measurement evaluation from the observations of its individual components is still an open problem. This is the focus of the paper, which provides a synthetic measurement generation framework for triple-component GNSS meta-signals. The whole meta-signal is at first decomposed as two dual-component meta-signals with the central component used as pivot. Measurements on the dual-component meta-signals are computed using the synthetic approach based on the Hatch-Melbourne-Wübbena (HMW) combinations. Triple-component pseudoranges are then obtained as the narrow lane combination of the pseudoranges from the dual-component meta-signals. Theoretical results have been experimentally analysed using measurements from two Septentrio PolaRx5S multi-frequency, multi-constellation receivers set up in a zero-baseline configuration. The Galileo E5a, E5b and E6 case has been specifically considered. Ambiguity resolution on the dual-component meta-signals has been improved using satellite bias corrections and by implementing a receiver bias estimation approach. Results in the measurement and position domains show the effectiveness of the proposed framework.

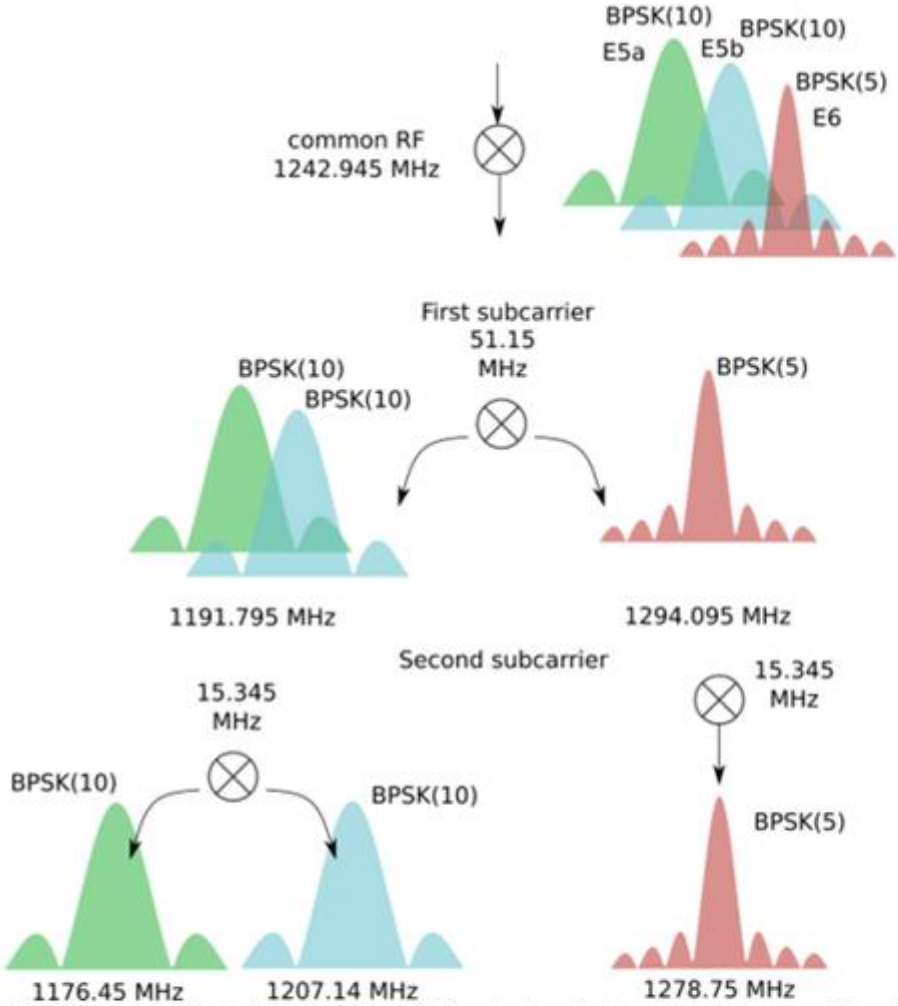


Figure 1. Construction of a triple-component GNSS meta-signal using two subcarriers. The subcarrier components are directly related to the wide- and extra-wide-lane combinations obtained using the E5a, E5b and E6 signals. In analogy with the dual-component case, they are at the basis for the synthetic generation of triple-component meta-signal measurements.

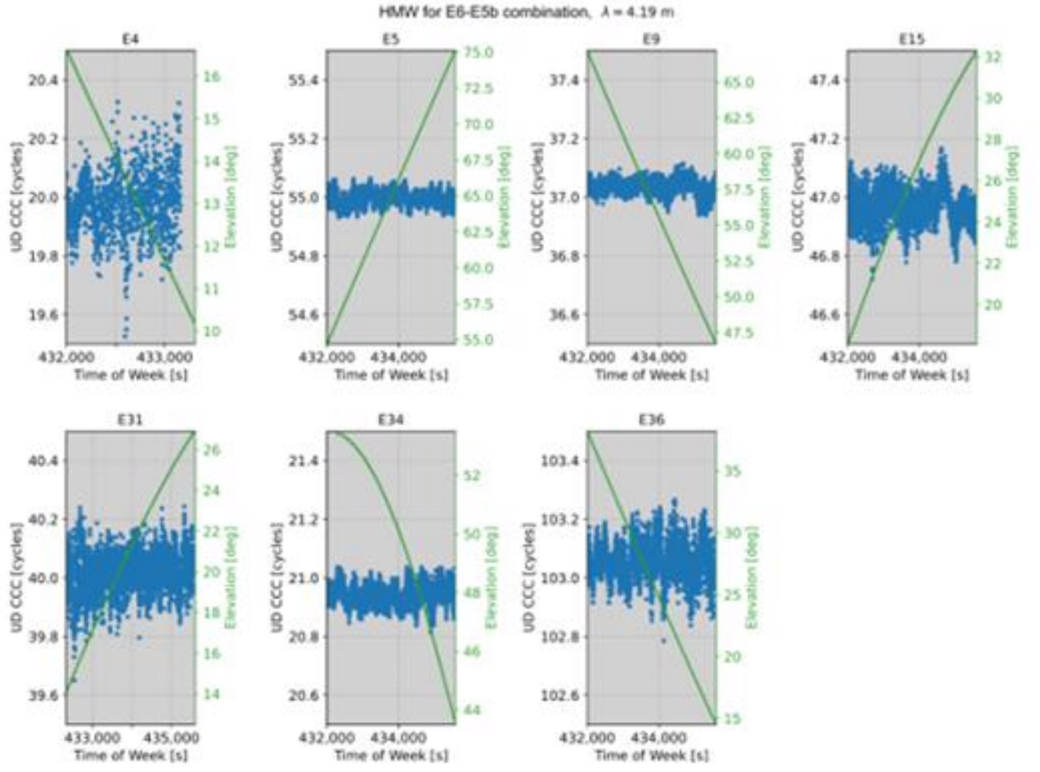


Figure 2. HMW combinations (in cycles) obtained using the Galileo E6 and E5b measurements. After subtracting the satellite and receiver biases, the HMW combinations align closely to an integer value and wide-lane integer ambiguities can be reliably solved.

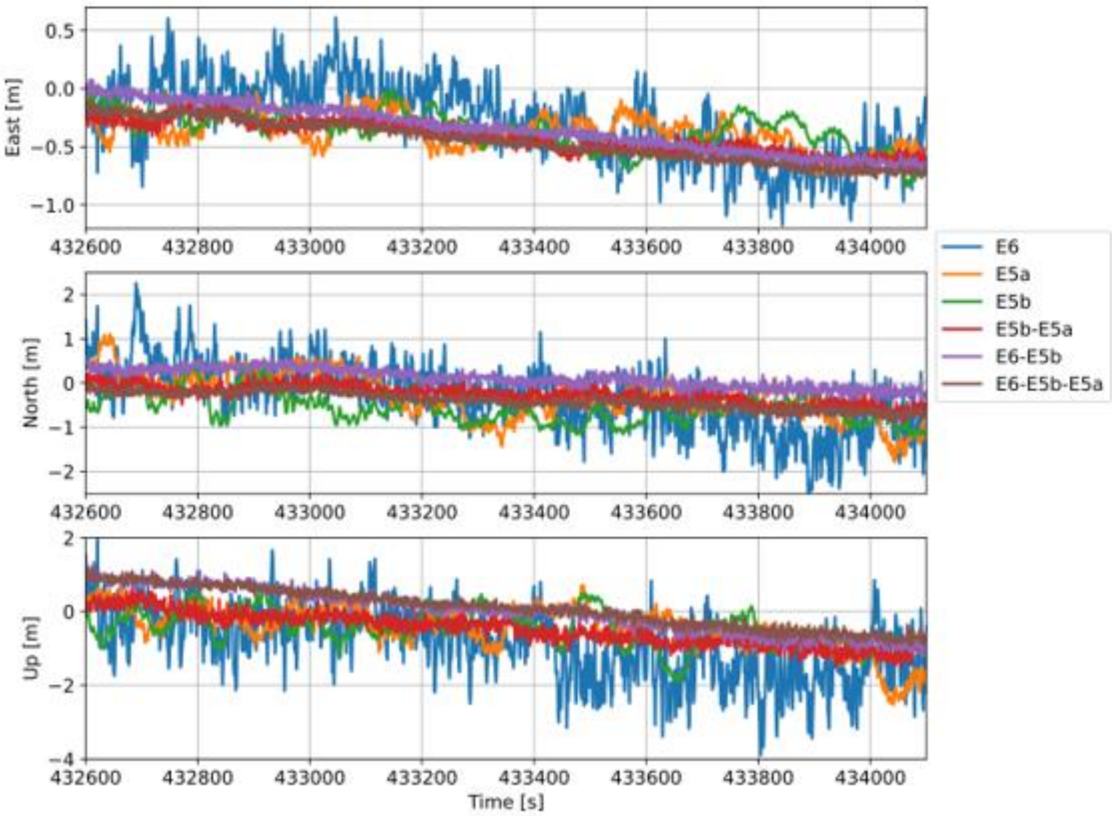


Figure 3. Comparison between different SPP solutions obtained considering original measurements and dual- triple-component synthetic observations. The noisiest solution is the one obtained using E6 pseudoranges. The solution quality improves as more components are combined.

GNSS Jamming and Spoofing Detection

Conference Room B, May 21, 2025, 2:30 PM - 3:50 PM

Jammertest: An open GNSS interference test arena to accelerate the development of resilient GNSS applications

Levin T[2], Schjetne C[2], Hauglin H[1], Rødningen T[1], Rødningsby A[3], Solend T[3], Gerrard N[6], Svartveit K[5], Solberg A[4]

[1]Justervesenet - Norwegian Metrology Service, [2]Norwegian Public Roads Administration, [3]Norwegian Defence Research Establishment, [4]Norwegian Mapping Authority, [5]Norwegian Space Agency, [6]Norwegian Communications Authority

Biography:

Tomas Levin is Senior Principal Engineer in the technology division of the Norwegian Public Roads Administration. He holds a PhD in Transport Engineering from NTNU (Trondheim, Norway). He is currently heading activities to get the public road sector ready for automated intelligent transport systems and to get automated transportation technology ready for public roads. A significant initiative is establishing Jammertest - the world's largest open arena for testing and improving the resilience of GNSS-based applications against jamming and spoofing.

Jammertest, held annually at Andøya, Norway, is the world's largest open global navigation satellite system (GNSS) resilience test. This unique event provides a real-world testing environment for participants to evaluate their positioning, navigation, and timing (PNT) systems against various hostile jamming and spoofing attacks. The location, far north of the Arctic Circle, offers minimal societal impact and optimal conditions for high-power radio frequency (RF) signal transmission. With open sea to the west and the island’s mountains in the east, RF signals are blocked from interfering with more populated areas and air traffic, making room for much higher RF transmission power than is possible in other areas of the world.

Organised by a coalition of Norwegian public organisations, including the Norwegian Public Roads Administration, Norwegian Communications Authority, Norwegian Defence Research Establishment, Norwegian Metrology Service, Norwegian Space Agency, and Norwegian Mapping Authority, Jammertest fosters cross-sectoral cooperation and innovation. The event lasts for five days, with tests ranging from simple jamming attacks to advanced timing attacks, with a focus on learning and improvement.

The participants are from industry, research institutions and government organisations and engage in over two hundred tests that are hand-picked from the comprehensive and up-to-date test catalogue. The arrangers encourage participants to share results and experiences to promote a culture of continuous improvement in GNSS resilience. Emphasis is put on collaboration, inclusion, and respect to ensure a productive and enjoyable experience for arrangers and attendees alike.

The significance of Jammertest lies in Andøya’s unique environment and the event’s ability to adapt the test campaigns to evolving threats and geopolitical landscapes. The diverse mix of participants and the combined experience and knowledge of the people and equipment make unparalleled impacts on the GNSS community.

A Novel Method for the Detection and Classification of GNSS Anomaly Incidents

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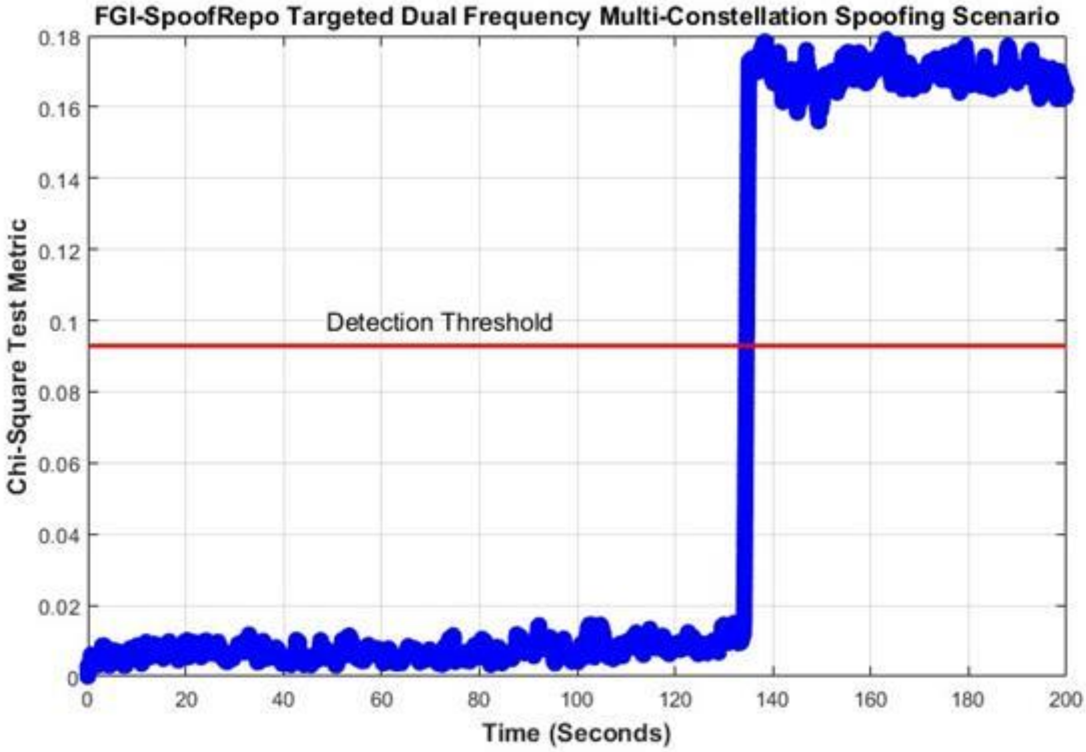
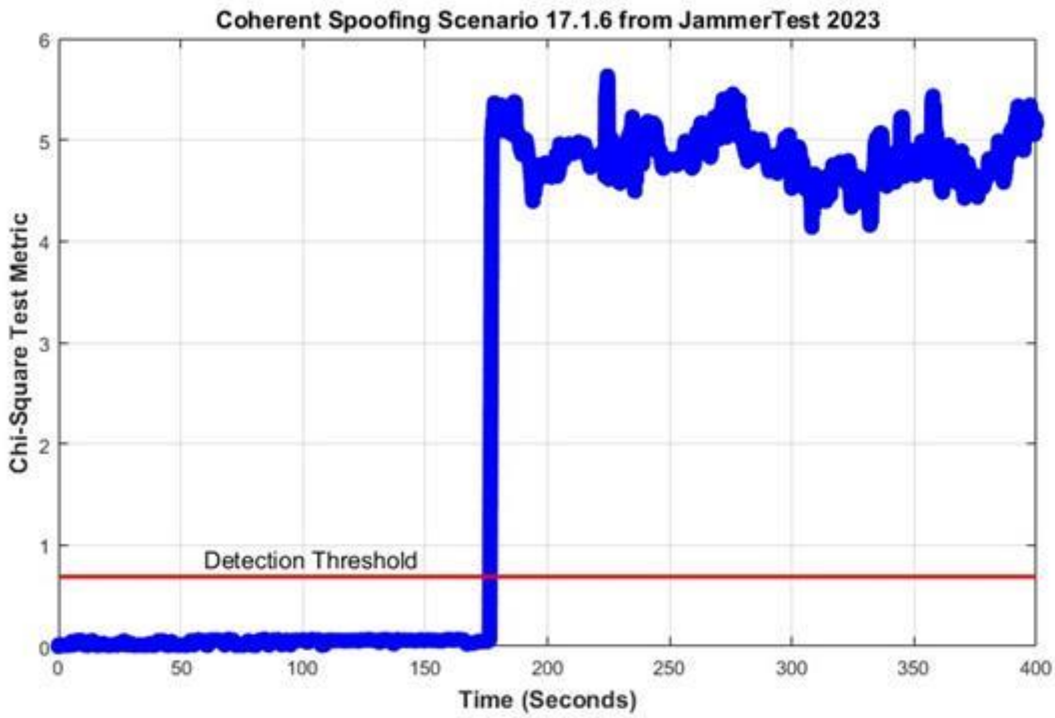
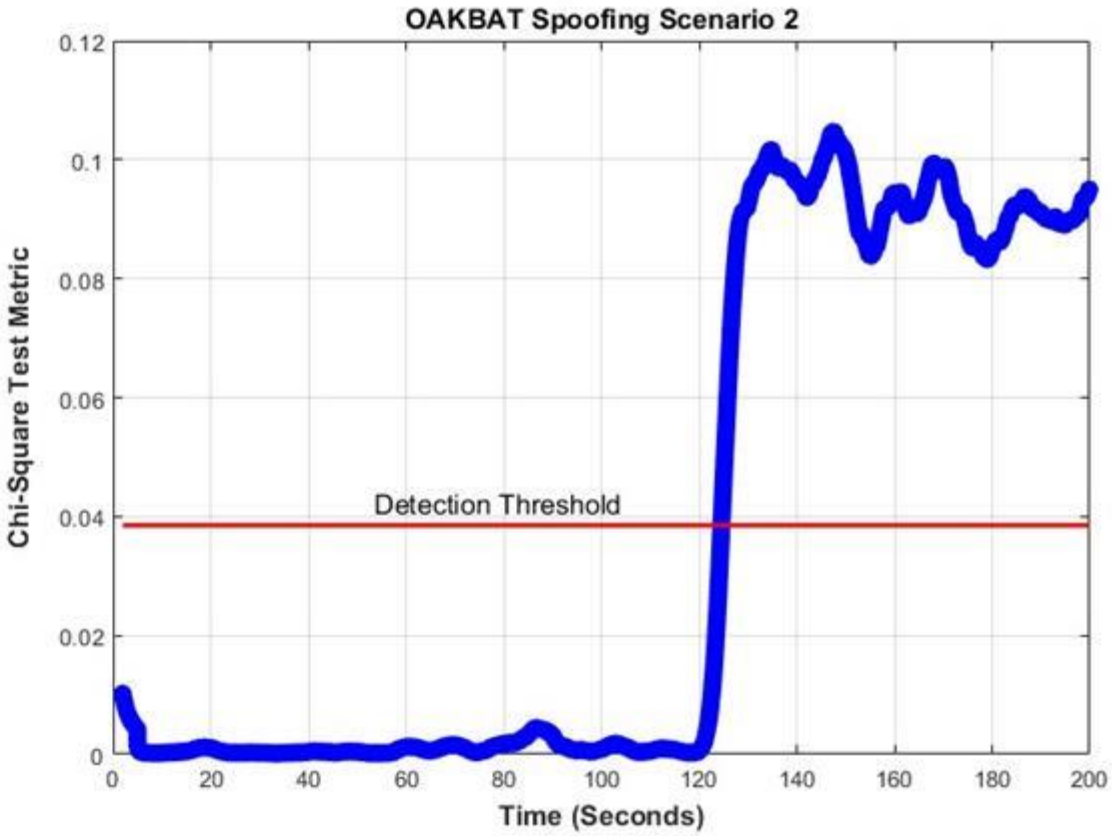
[1]Finnish Geospatial Research Institute

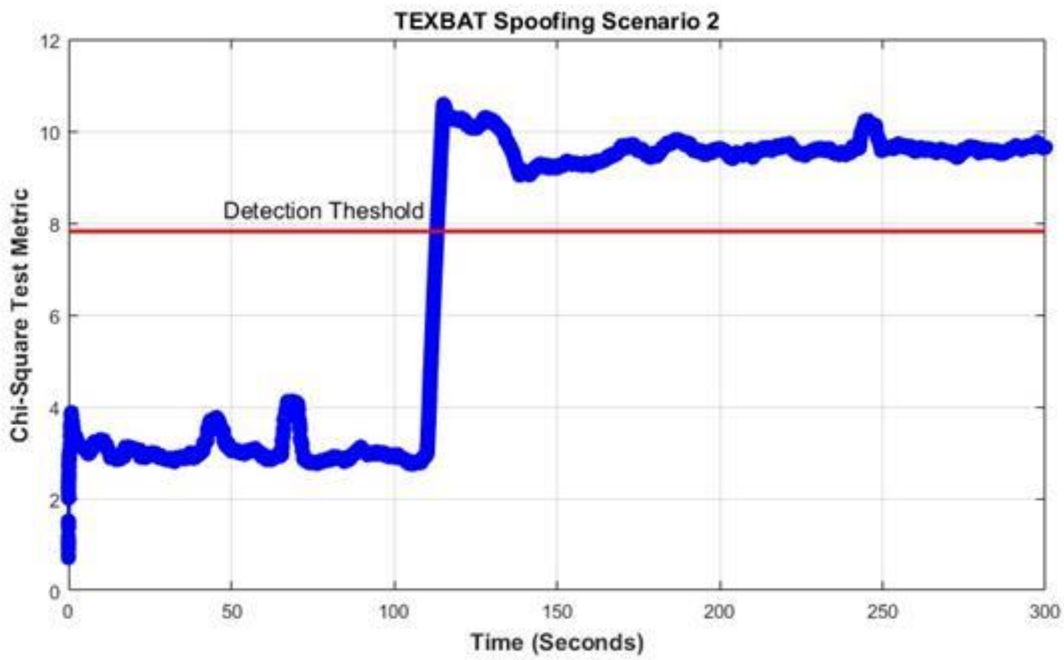
Biography:
M. Zahidul H. Bhuiyan is a Research Professor at the Department of Navigation and Positioning in Finnish Geospatial Research Institute. He is also acting as an Adjunct Professor in Tampere University. He also serves as a Group Leader for 'Resilient Position, Navigation and Timing' group. His main research interests include multi-GNSS receiver development, PNT robustness and resilience, seamless positioning, LEO-PNT user receiver development, etc. He has been also working as a Technical Expert for the European Commission in Horizon Europe project reviewing, monitoring and proposal evaluation. He also actively takes part in various GNSS related international workgroups.

Recent increase in radio frequency interferences on Global Navigation Satellite Systems (GNSS) frequency bands have raised the need for successful detection, localization, classification, and mitigation of such unwanted interferences on those protected bands. Due to relatively low signal power at the time of reception at the user receiver antenna and the openly accessible signal structure, the GNSS signals are inherently vulnerable to intentional interference (i.e., jamming or spoofing). In this work, we propose a novel GNSS interference detection technique that applies a Chi-Square test [1] on the raw digitized Intermediate Frequency (IF) samples to detect the presence of any unauthorized signal on the GNSS frequency bands. The proposed technique measures the deviation of bin distribution of the digitized samples with respect to the expected bin distribution of the digitized samples in a nominal scenario. GNSS signal at the receiver antenna is typically well below the noise floor. Thus any unwanted received power on the GNSS frequency bands starts to saturate automatic gain control leading to impact the nominal bin distribution of digitized samples. The proposed technique has been tested rigorously with various publicly available GNSS data sources from TEXBAT [2], OAKBAT [7], FGI-SpoofRepo [3], a real-world jamming test campaign from JammerTest 2023 [4], and an EU-funded research project named AIRING (Aviation Resilience to GNSS frequency jamming and cyber threats) [5]. An open-source software-defined receiver named FGI-GSRx [6] has been used to develop, test and analyze the performance of the proposed technique in various nominal and GNSS interference scenarios. Some preliminary results are presented in Figures 1 to 4. The proposed Chi-Square based technique can successfully detect GNSS anomaly incidents in all the presented scenarios. The authors are currently working to classify the anomaly incidents into two broad groups: i) Jamming incident, and ii) Spoofing incident.


FGI-SpoofRepo Targeted Dual Frequency Multi-Constellation Spoofing Scenario
Chi-Square Test Metric
Time (Seconds)
Detection Threshold
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0
20
40
60
80
100
120
140
160
180
200


Coherent Spoofing Scenario 17.1.6 from JammerTest 2023
Chi-Square Test Metric
Time (Seconds)
Detection Threshold
0
1
2
3
4
5
6
0
50
100
150
200
250
300
350
400


OAKBAT Spoofing Scenario 2
Chi-Square Test Metric
Time (Seconds)
Detection Threshold
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
120
140
160
180
200


TEXBAT Spoofing Scenario 2
Chi-Square Test Metric
Time (Seconds)
Detection Theshold
12
10
8
6
4
2
0
0
50
100
150
200
250
300

New approach for Jamming and Spoofing detection mechanisms for High Accuracy solutions

Crespo M[1], Chamorro A[1], Azanza M[1], Benedetti E[2], Gonzalez Sainz A[1]
[1]GMV, [2]GMV NSL

Biography:
María Crespo Estrada holds a double MSc in Aerospace Engineering by the Technical University of Madrid and Computational Software and Techniques in Engineering by Cranfield University. She has worked as an Advanced Engineer for five years in GMV in the field of GNSS high accuracy positioning with a high focus in GNSS Integrity. She is currently leading the development and integration GMV GSharp Safe and Accurate Positioning Engine in Autonomous Driving Application for automotive customers.

GNSS high accuracy solutions are increasingly vulnerable to jamming and spoofing attacks, posing significant challenges to their reliability, security, and accuracy. In the past years, GNSS communities have witnessed an increase in the frequency and sophistication of these attacks, driven, among other factors, by the widespread availability of low-cost, off-the-shelf equipment capable of denying or even totally mislead GNSS based positioning systems.

On one hand, jamming attacks aim at inhibiting signal reception by introducing high-power noise or interference, leading to degraded performance or complete failure in determining position. Jamming detection mechanisms need to be traced to GNSS receiver mitigation measures at signal processing level, to analyze the radio frequency (RF) environment or receiver behavior. Signal-to-noise ratio (SNR) monitoring, power spectrum analysis, and signal power monitoring are commonly used to detect anomalies in signal characteristics. Jamming is often indicated with the presence of a combination of one or more dedicated indicators, opening a space to characterize different levels of jamming attack allowing to optimize a response at user level.

On the other hand, detecting spoofing attacks requires different advanced techniques to identify anomalies in satellite signals, receiver behavior, or consistency of computed position data. Indicators regarding internal consistency checks, as well as unexpected evolutions of GNSS signals typically are suspicious behaviors to be analyzed as possible attacks. Additionally, ensuring trust in the received navigation information by including cryptographic authentication mechanisms is key to quickly detect some kinds of spoofing.

This paper presents the latest enhancements on Jamming and Spoofing detection and mitigation mechanisms for GMV GSharp high accuracy and safe positioning solution. New logic allows to distinguish between different levels of attack and adapt the reactions to reduce as much as possible the impact the final user. Additionally, test results obtained from real GNSS attacks datasets will be shown.

Enhanced GNSS Threat Detection: On-Edge Statistical Approach with Crowdsourced Measurements and Fuzzy Logic Decision-Making

Matera E[1], Lagrange O[1], Olivier M[1]
[1]Thales Services Numeriques

Biography:
Eustachio Roberto Matera received a Ph.D. in GNSS signal processing from the French Civil Aviation University (ENAC) in Toulouse, France, in 2021. He has been significantly involved in the integrity performance analysis for the EGNOS program for several years. His research interests encompass signal processing for positioning in challenging environments, multipath mitigation and constructive use for cognitive navigation, and PNT resilience against intentional and unintentional threats. Eustachio currently leads navigation research and development activities at Thales "Services Numeriques."

Global Navigation Satellite System (GNSS) technology's widespread adoption has exposed its vulnerability to jamming and spoofing threats, compromising the reliability and accuracy of critical applications.
Nowadays, several research focus on machine learning and network-centralized detection approaches, requiring extensive data training, struggling with adaptability to unexpected events, and limited responsiveness to counteract potential threats.
To address these limitations, this work presents an on-edge threats detector, based on a statistical approach, leveraging crowdsourced measurements belonging to the same GNSS receiver, and offering enhanced adaptability to unforeseen scenarios through a fuzzy logic decision-making approach.
The methodology integrates various GNSS raw measurements acquired from the same receiver to estimate anomaly event indicators. Each of them is associated with a probability curve, providing a measure of the likelihood of the anomaly event.
The compilation of anomaly event indicators comprises a versatile array of elements, ranging from those primarily oriented towards direct attacks on receivers, (i.e., receiver position variation, receiver clock bias variation) to indicators focused on direct attacks aiming to manipulate satellite navigation parameters (i.e., variation of ephemeris parameters and satellite clock bias).
The foremost feature is the integration of a crowdsourcing-based indicator employing the Carrier-to-Noise-density ratio (C/N0) metric. This is crucial as C/N0 values for various satellites exhibit similar variations when a jammer or spoofer targets the receiver under observation.
The second key feature is the employment of fuzzy logic for event detection based on the integration of the compilation of interference event indicators, overcoming limitations of traditional decision threshold methods by enabling more nuanced decision-making. This approach allows for a more flexible and robust detection system.
Experimental analyses are promising, demonstrating a detection accuracy exceeding 98%, with false positive rates below 1% and high responsiveness, even within the constraints of a limited dataset.

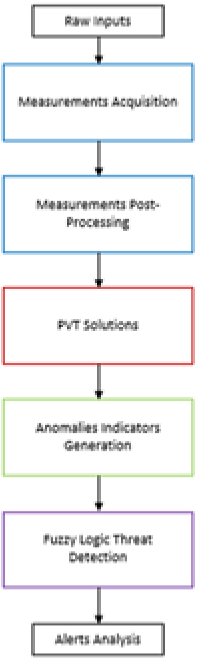


Figure 1 – Overview Scheme of the proposed GNSS Threat Detection Methodology

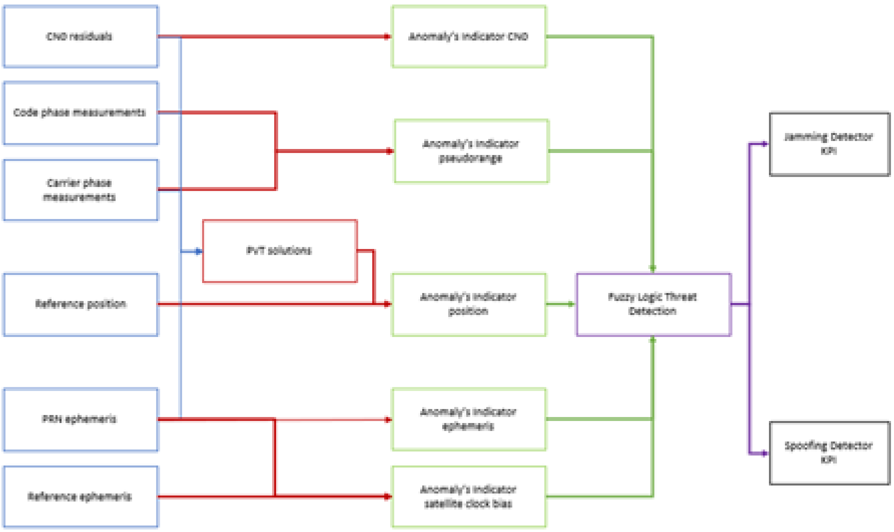


Figure 2 – Details of Anomalies Indicators Generation module

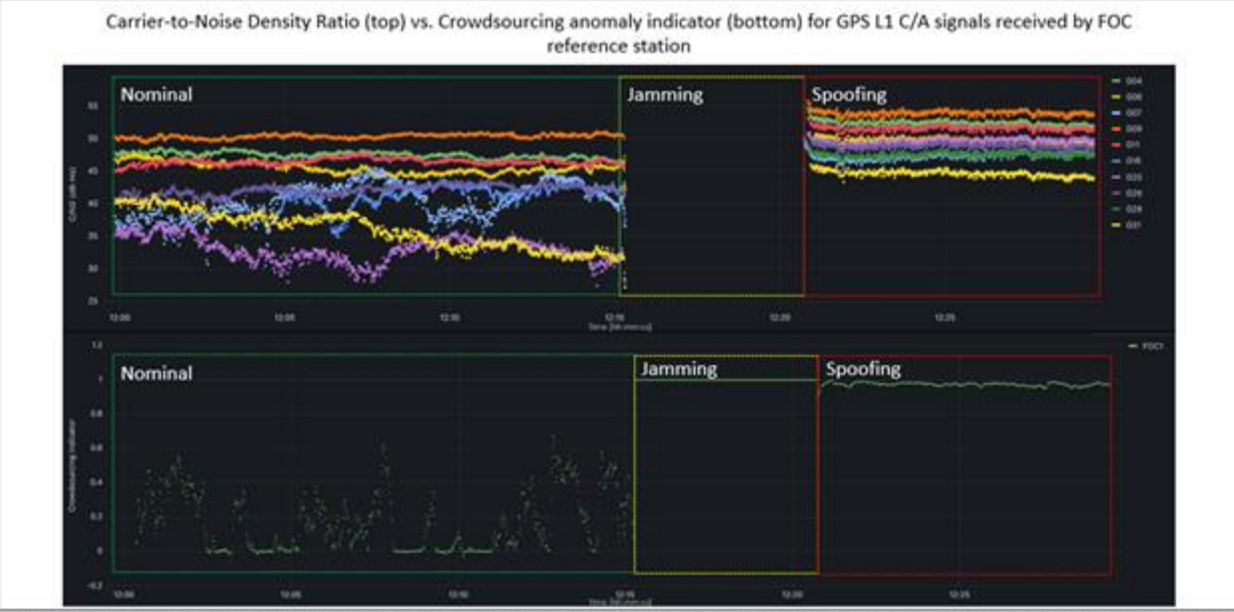


Figure 3 – Analysis of CN0 measurements and the corresponding crowdsourcing anomaly indicator based on the analysis of CN0 measurements. The figures are divided in three different sections defined by the presence of three different boxes (green, yellow, red). These sections correspond to nominal case without interferences (green), strong jamming attack (yellow) followed by a spoofing attack (red)

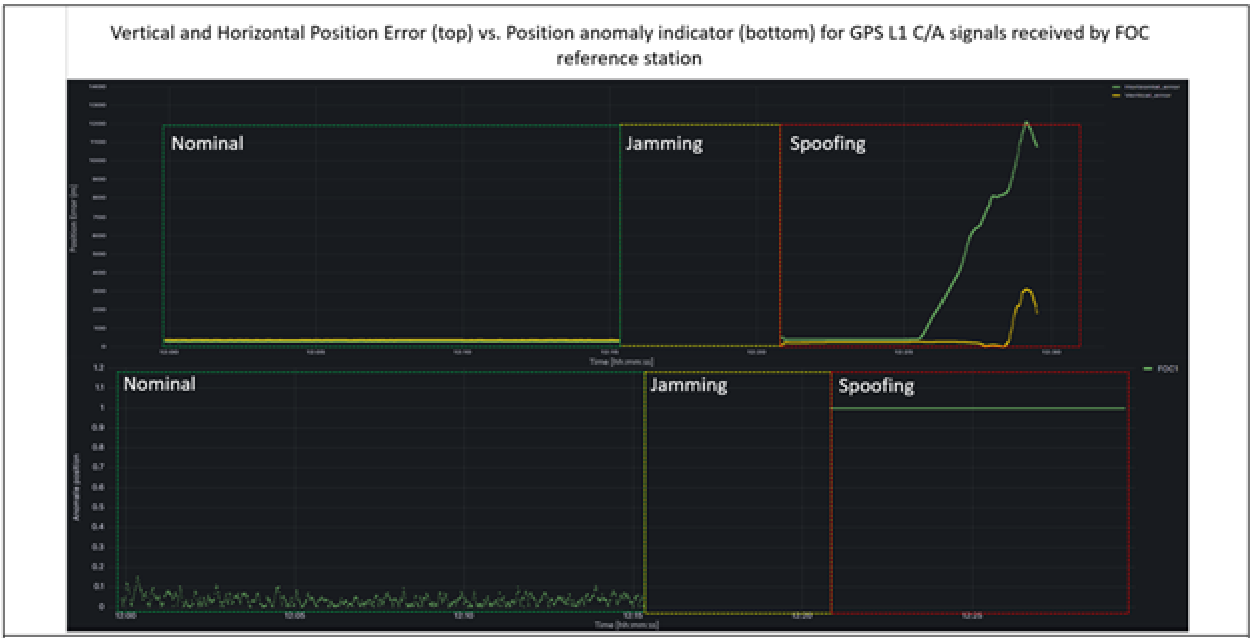


Figure 3 – Analysis of Vertical and Horizontal Position Errors and the corresponding position anomaly indicator based on the analysis of position errors. The figures are divided in three different sections defined by the presence of three different boxes (green, yellow, red). These sections correspond to nominal case without interferences (green), strong jamming attack (yellow) followed by a spoofing attack (red)

Code-phase measurements coherence anomaly indicator (top) vs. Fuzzy Logic Jamming and Spoofing detectors (bottom) for GPS L1 C/A signals received by FOC reference station

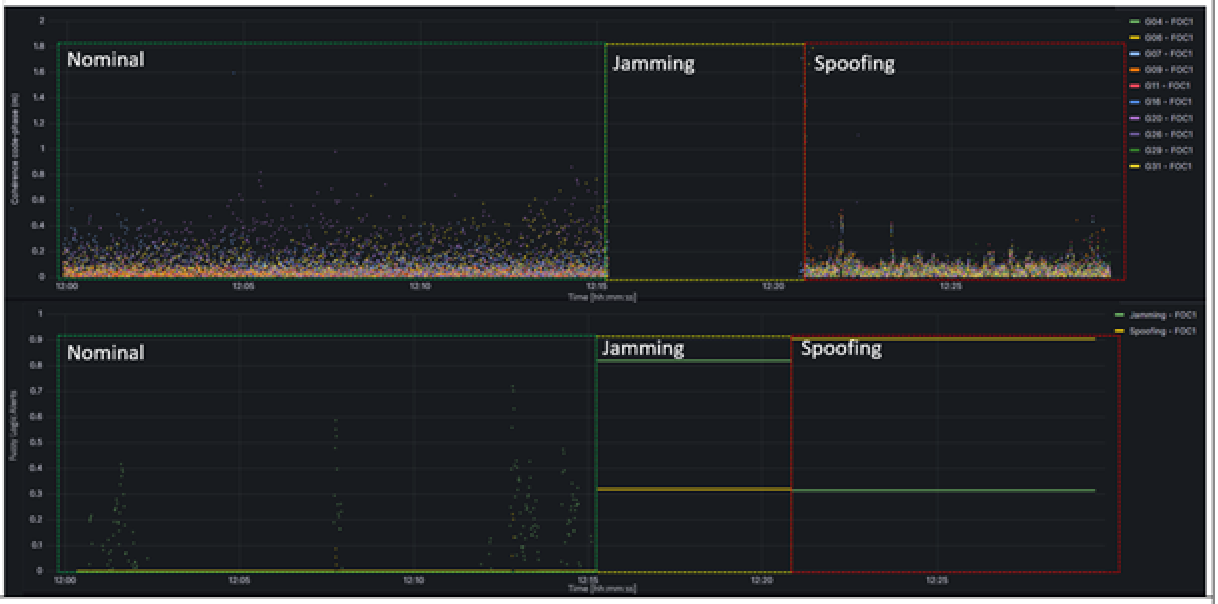


Figure 4 – Analysis of code-phase coherent anomaly variation and the Fuzzy Logic Output Alerts (Aggregation of all Anomaly Event Indicators), notably Jamming and Spoofing Alerts. The figures are divided in three different sections defined by the presence of three different boxes (green, yellow, red). These sections correspond to nominal case without interferences (green), strong jamming attack (yellow) followed by a spoofing attack (red)

Absolute Position Fixing Using live-streamed Radar data in ASTERIX format

Hargreaves C[1]
[1]GRAD

Biography:
Chris Hargreaves is an R&D Engineer working for GRAD: the Research & Development Directorate for the General Lighthouse Authorities of the UK&Ireland. His work has mainly focused on developing resilient position-fixing systems for ships, able to accurately position a vessel in the absence of GNSS. He worked for many years on the UK's eLoran programme, but has recently concentrated more on integrity systems, and position-fixing using existing ship sensors such as Radar. He holds an MSC Degree in Navigation Technology from Nottingham University and an MSci degree in Mathematics and Physics from Durham University.

The GLA have, for some time now, highlighted the extent to which a lot of the World's industry is dependent upon GNSS as a single point of failure. GNSS signals are comparatively weak, able to be easily swamped by jamming or interference, and both civilian and military GNSS spoofing capability is a rapidly growing threat.

A system has been developed that streams live data from a ship's Radar in Asterix (All-purpose STructured EUROCNTORL Radar Information eXchange) format. The machine learns the radar background and builds a map of conspicuous radar targets, this map is referenced to a Latitude / Longitude datum when GNSS is available.

Should GNSS be lost or degraded for any reason, live radar data can be correlated against the map, and the position of the vessel derived. This system operates without user input, and can provide a resilient position solution even in GNSS denied environments.

This report presents early results obtained from an installation of this technology onboard a GLA vessel and describes our intended development of the system. This technology is intended to be openly available such that it could be incorporated into any existing radar system, for the benefit and safety of all mariners.

Enhancing maritime navigation: a novel approach to validate GNSS solutions with a single R-Mode station

Rizzi F[1], Grundhöfer L[1], Gewies S[1], Hehenkamp N[1]
[1]DLR - German Aerospace Center

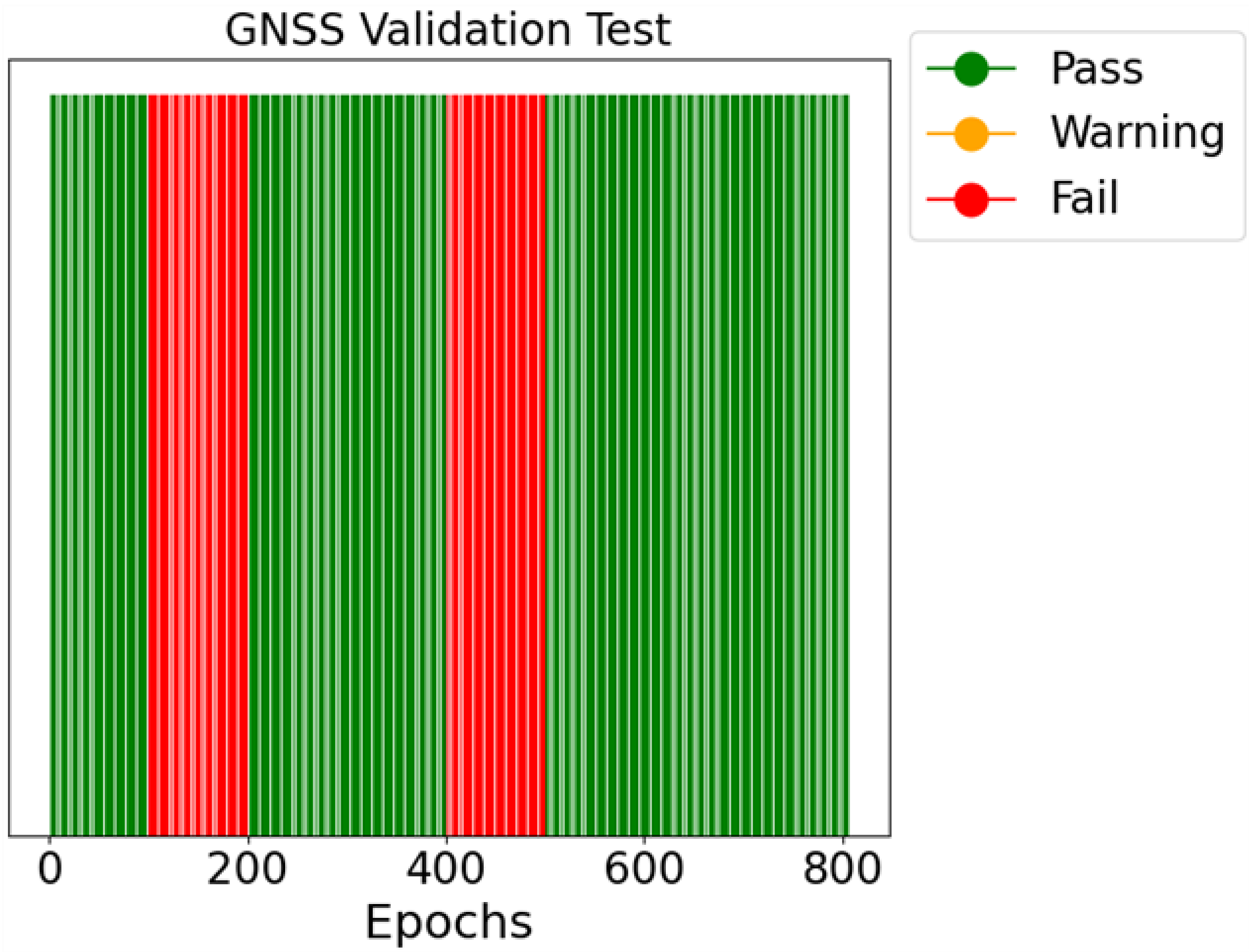
Biography:
He received a Bachelor Degree in Aerospace Engineering and a Master in Communication and Computer Network Engineering (CCNE) from Politecnico di Torino, respectively in 2016 and 2020. He joined the DLR Institute of Communications and Navigation in 2020 where he currently works in the Multi-sensors Group of the Nautical System Department. His research focuses on signal processing and positioning algorithms for Medium Frequency R-Mode. He also works on sensor fusion for PNT systems, PNT integrity concepts and radio threats resiliency.

The reliance on Global Navigation Satellite Systems (GNSS) for modern vessel navigation poses a critical single point of failure. GNSS is vulnerable to jamming, spoofing, and other threats that can increase the risk of accidents. In response, alternative sources of navigational information are being sought.

Among the alternatives, R-Mode offers a promising solution by leveraging terrestrial infrastructure to provide PNT data independently of GNSS. Its coverage is limited to specific service areas and a minimum of three stations in view is needed to obtain a position and timing information. While a single R-Mode station in view cannot provide independent positioning information, the received data can still be used to validate GNSS positioning solutions. This concept is particularly valuable during periods of GNSS outages or spoofing attacks.

In this study, we introduce a novel approach to validate GNSS positions using R-Mode ranging information and detect potential threats. By combining the expected GNSS and R-Mode ranging accuracy with the geometrical relationship existing between the GNSS position estimate and the known R-Mode transmitter location, our technique provides a method for detecting spoofing events.

Our method was tested with real measurements in post-processing, where simulated GNSS spoofing events were introduced to mimic real-world scenarios. During these events, the GNSS positioning solution deviated by approximately 100 meters. Our technique successfully detected the spoofing instances and raised warnings, demonstrating its effectiveness in mitigating GNSS-based navigation threats. This is fundamental to enhance the reliability and resilience of modern vessel navigation equipment ensuring safety at sea.


GNSS Validation Test
Pass
Warning
Fail
0
200
400
600
800
Epochs

VDES R-Mode Advanced User Technologies for Alternative PNT (VAUTAP) final Developments

Bransby M[1], Whitworth T[1], Peltola P[1], Mercy L[1], Bjørnevik A[2], Alagha N[3]
[1]Telespazio UK, [2]Kongsberg Discovery, [3]European Space Agency, ESTEC

Biography:
Martin Bransby is the Head of Navigation at Telespazio UK. He is accountable for delivering Telespazio's research, innovation and product development programme in resilient PNT, focusing on a multi-layered, multi-systems approach to PNT provision, whilst setting and delivering the company's PNT strategy and direction. Telespazio UK's navigation strategy is currently focused on maritime user terminals and services, timing, autonomy, and Moon exploration and space logistics. Martin is a Chartered Engineer, Fellow, Trustee and Council member of the Royal Institute of Navigation, and an Associate Fellow of the Nautical Institute. Martin is also the Chair of the UKSpace PNT Committee.

GNSS have become the primary Navigation Aid at sea. Yet, all GNSS are vulnerable to natural interference, deliberate and accidental jamming, and spoofing. Degraded GNSS produce hazardously misleading information without an alarm being raised by the vessels' systems. Notwithstanding these vulnerabilities, GNSS have poorer coverage at higher latitudes: a weakness when vessels wish to operate in regions such as along the Northern Sea Route.
PNT accuracy, integrity, continuity, and availability have become increasingly critical and so these vulnerabilities pose problems.
A System-of-Systems approach to the provision of PNT for maritime and other critical infrastructure is preferable to provide resiliency. National Governments and other bodies recognise this System-of-Systems approach and are now looking to implement various systems.
One such system is the Very High Frequency Data Exchange System (VDES). VDES is a chiefly, terrestrial based maritime radio communication system being developed internationally. The maritime community has investigated the potential use of these VDES communication signals for positioning—a concept commonly referred to as "ranging-mode," or R-Mode.
VDES R-Mode is still at a low TRL and much of the standardisation required for System-of-Systems components are not in place, giving developers the opportunity to develop better waveforms and techniques to provide truly resilient-PNT.
VAUTAP has investigated, consolidated, and developed new algorithms, waveforms, software, and hardware, to evolve VDES R-Mode closer to an operational and viable component of a resilient-PNT System-of-Systems. Some of these activities are:

- In-field capture and positioning demonstration.
- Design of new signals, taking advantage of OQPSK modulation.
- Meta-signal design, taking advantage of the lower and upper VDES bands.
- Differential Positioning, providing user corrections.
- Multi-Epoch Doppler Positioning simulations for LEO satellites.

This paper provides an update on the activities undertaken so far and will look to provide conclusions of all technical developments and aspects post the testing campaign.

INSTINCT - A flow-based open-source PNT toolkit for integrated navigation concepts and training

Topp T[1], Maier M[1], Hobiger T[1]
[1]Institute of Navigation / University of Stuttgart

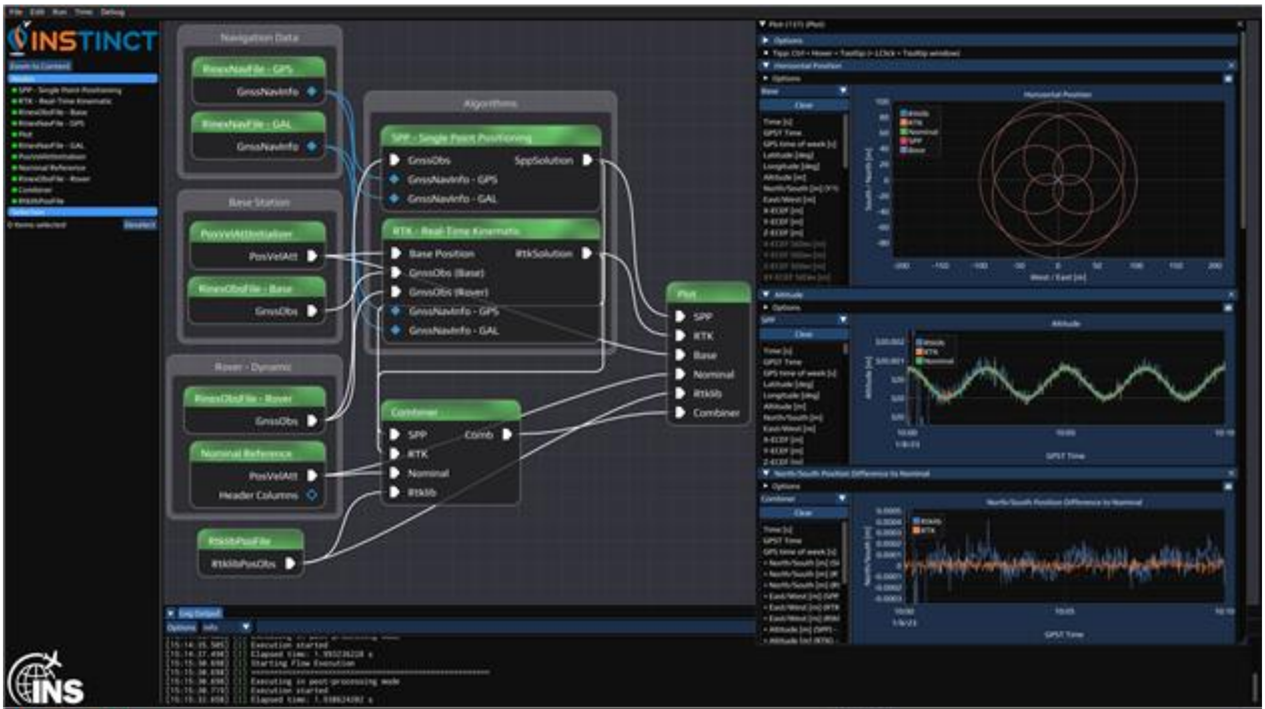
Biography:
Thomas Topp is a research associate and PhD candidate at the Institute of Navigation of the University of Stuttgart, Germany. In the course of his work he created the software framework INSTINCT and is its current lead developer. His field of expertise covers satellite navigation (RTK), inertial navigation, sensor fusion, factor graph optimization and C++ programming. He is an active member of the open-source community on GitHub. He will present the software INSTINCT and how it can be utilized for RTK-GNSS/INS sensor-fusion.

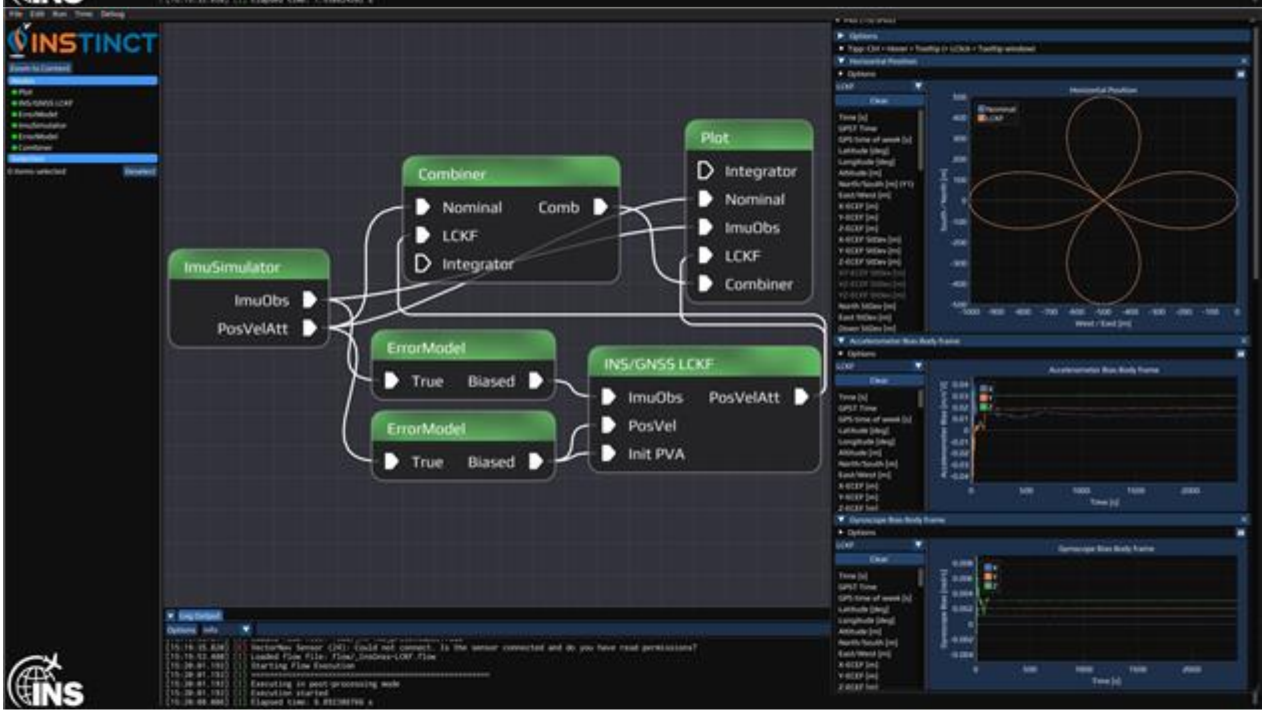
Designing navigation software can be a very time-consuming task. Novice navigation engineers often have to start implementing everything anew and even professionals spend a lot of time adapting algorithms from other projects. This prolongs development cycles and shortens the time available for actual research. Furthermore, when projects shall be realized on test platforms, algorithms often need to be executed on low-cost hardware, like a Raspberry Pi, which can be challenging as the processing capabilities are limited.

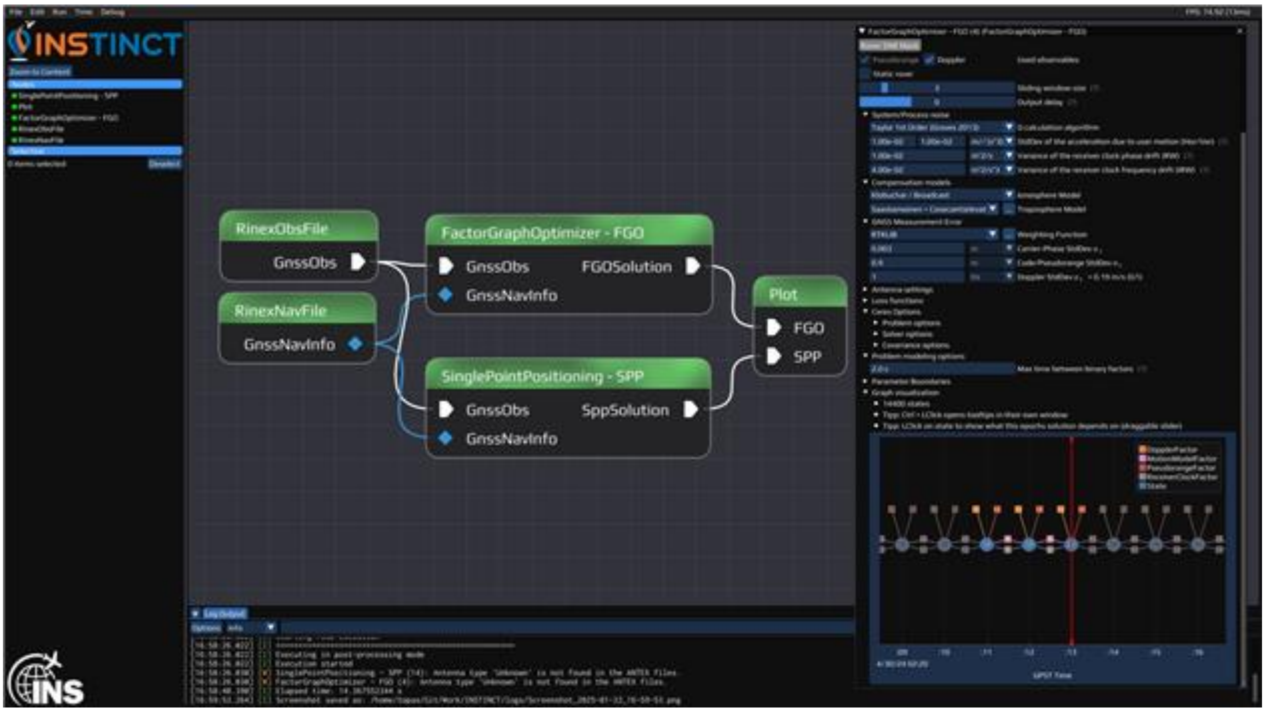
To solve these problems, the position, navigation and timing software framework INSTINCT (INS Toolkit for Integrated Navigation Concepts and Training) was developed. It is based on the flow-based programming paradigm, which abstracts functionality, like reading a file or preprocessing data, into separate modules, so-called nodes, to make the implementation more self-contained and reusable. Data flows between nodes over links and triggers the calculation of algorithms, which enables parallelization of tasks and improves the performance on multi-core processor systems. In order to create links and configure algorithm parameters, INSTINCT provides an intuitive graphical user interface (see figure 1).

Besides the implementation of various file formats (e.g. RINEX, UBX) and sensor protocols from different manufacturers, algorithms like multi-constellation/multi-frequency Real-Time Kinematic (RTK), INS/GNSS data fusion and a Factor Graph Optimization based positioning algorithm are available (see figure 2&3), providing a stable foundation for research or navigation product development. To share this software and enable potential collaboration, INSTINCT is released under an open-source license (https://github.com/UniStuttgart-INS/INSTINCT).

The presentation will cover the basic principles of flow-based programming and illustrate its advantages over existing solutions. It will showcase different use cases of INSTINCT like processing of real-time data from sensors, IMU simulation and RTK processing. Results will be compared to other state of the art software. Moreover, we are going to offer live demonstrations during the poster session attendance time slots.


INSTINCT
Navigation Data
RinexNavFile - GPS
GnssNavInfo
RinexNavFile - GAL
GnssNavInfo
Algorithms
SPP - Single Point Positioning
GnssObs
SppSolution
GnssNavInfo - GPS
GnssNavInfo - GAL
Base Station
PosVelAttInitializer
PosVelAtt
RinexObsFile - Base
GnssObs
RTK - Real-Time Kinematic
Base Position
RtkSolution
GnssObs (Base)
GnssObs (Rover)
GnssNavInfo - GPS
GnssNavInfo - GAL
Rover - Dynamic
RinexObsFile - Rover
GnssObs
Nominal Reference
PosVelAtt
Header Columns
Combiner
SPP
Comb
RTK
Nominal
Rtklib
RtklibPosFile
RtklibPosObs
Plot
SPP
RTK
Base
Nominal
Rtklib
Combiner
Horizontal Position
Altitude
North/South Position Difference to Nominal
GPST Time
INS

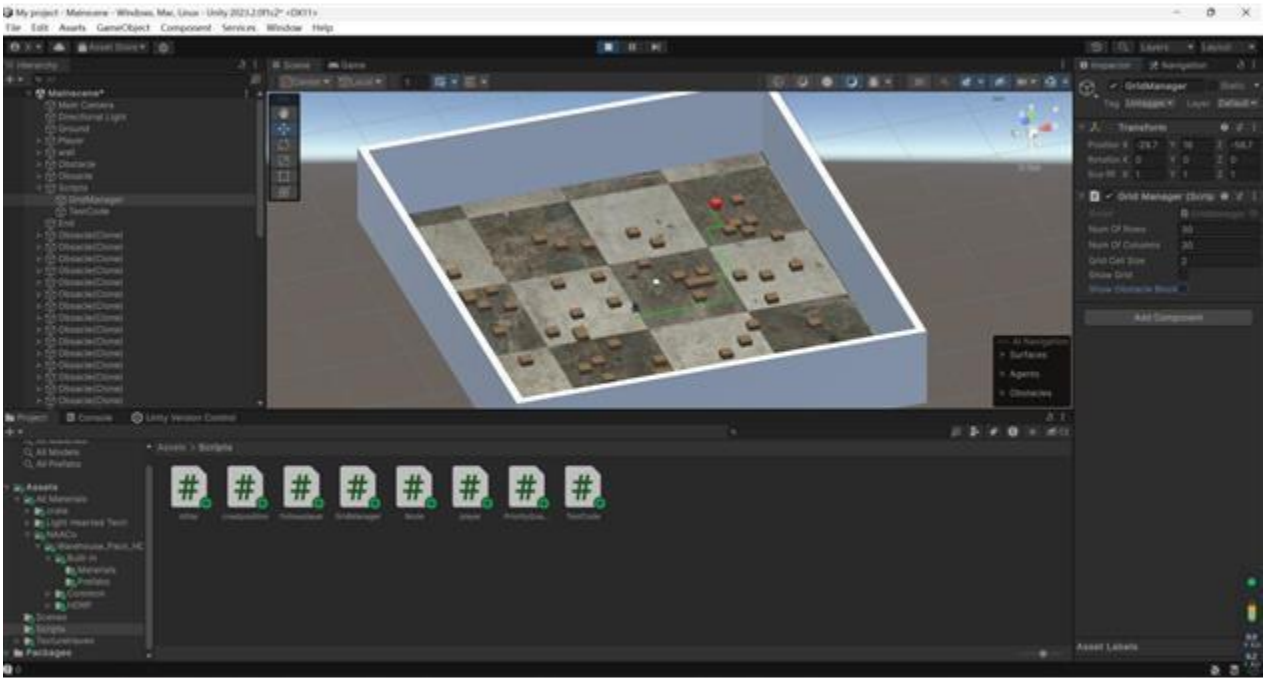

INSTINCT
Combiner
Nominal
Comb
LCKF
Integrator
Plot
Integrator
Nominal
ImuObs
LCKF
Combiner
ImuSimulator
ImuObs
PosVelAtt
ErrorModel
True
Biased
ErrorModel
True
Biased
INS/GNSS LCKF
ImuObs
PosVelAtt
PosVel
Init PVA
Horizontal Position
Accelerometer Bias Body Frame
Gyroscope Bias Body Frame
INS

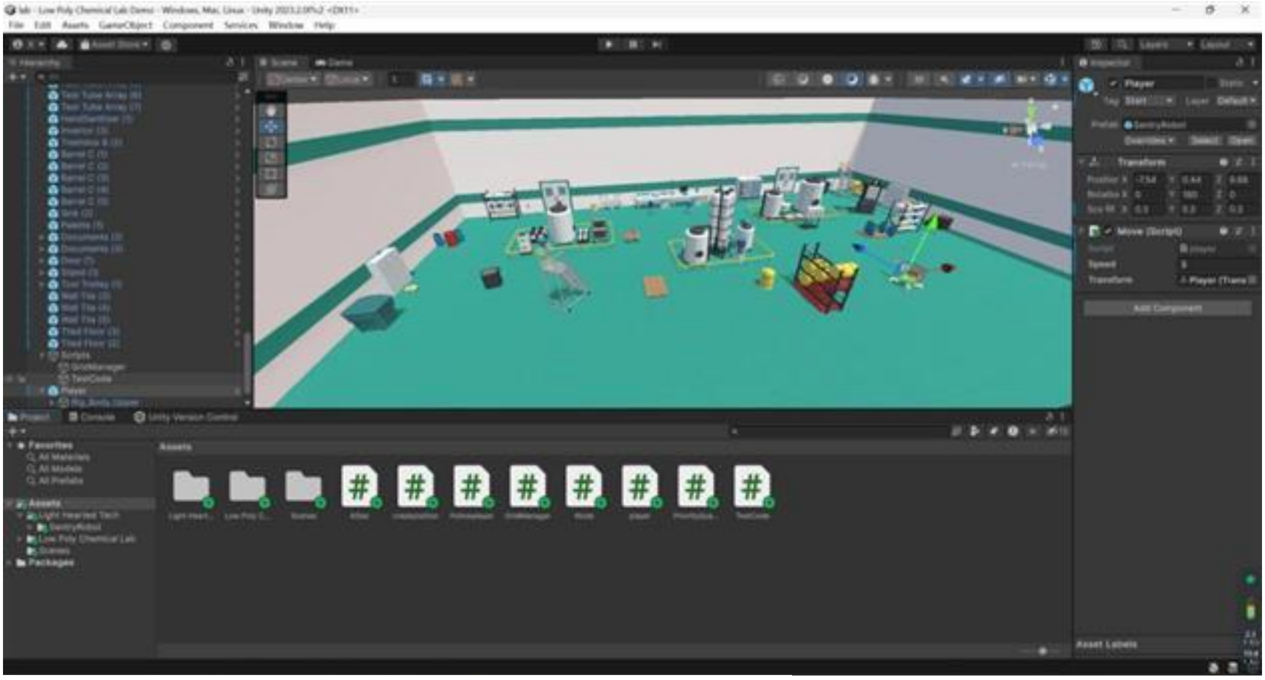

INSTINCT
RinexObsFile
GnssObs
RinexNavFile
GnssNavInfo
FactorGraphOptimizer - FGO
GnssObs
FGOSolution
GnssNavInfo
SinglePointPositioning - SPP
GnssObs
SppSolution
GnssNavInfo
Plot
FGO
SPP
INS

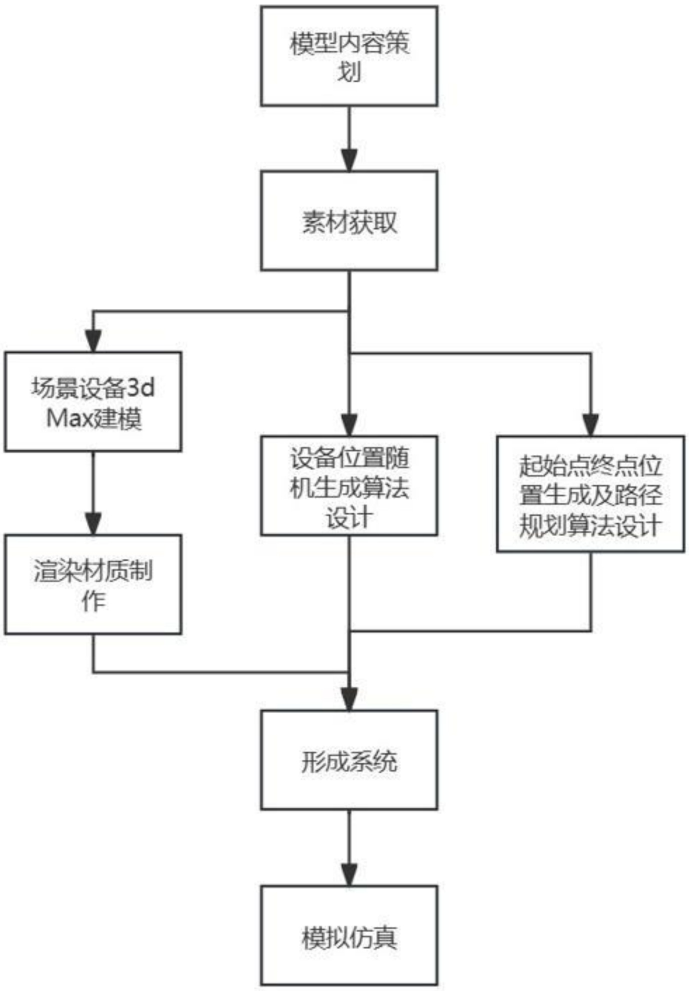
Optimization of path planning for contraband reconnaissance in random environments based on digital twin

Zheng D[1,6], Wang Y[2], Li Z[3,4,6], Xiao M[2], Liang X[5,7], Zhang X[8], Qiu R[9], Yan S[10]
[1]State Key Laboratory of Environment Characteristics and Effects for Near-Space, Beijing Institute of Technology, Beijing 100081, China , [2]School of Information and Electronics, Beijing Institute of Technology, [3]National Key Laboratory of Science and Technology on Space-Born Intelligent Information Processing, Beijing 100081, China , [4]Yangtze Delta Region Academy of Beijing Institute of Technology (Jiaxing), Jiaxing 314019, China , [5]Beijing Institute of Technology (Zhuhai), Zhuhai 519088, China , [6]Advanced Research Institute of Multidisciplinary Science, Beijing Institute of Technology, Beijing 100081, China, [7]School of Aerospace, Beijing Institute of Technology, [8]International Cooperation Department, Science and Technology Research Center of China Customs, [9]Standards Center of the First Research Institute of the Ministry of Public Security, [10]Criminal Science and Technology Institute,Shandong Public Security Department

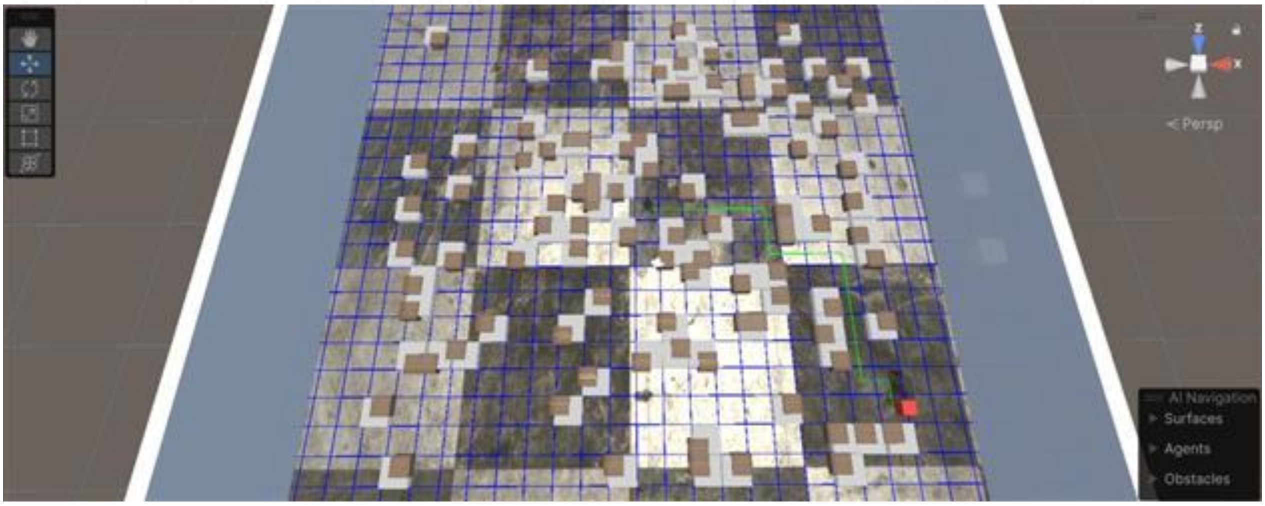
The detection of contraband in complex scenarios such as customs cargo yards and criminal investigation identification is critically important, as it is closely related to national security, social stability, and the safety of people's lives and property. The utilization of unmanned systems for non-contact detection of contraband has emerged as a prominent research frontier and a cutting-edge focus area. In reconnaissance missions involving unmanned systems for contraband detection, the optimization of shortest path planning is a pivotal factor for enhancing task efficiency and success rates. This paper proposes a novel path planning method based on a 3D Digital Twin and Reinforcement Learning DQN algorithm (3D-DQN), designed for random operational scenarios to achieve optimal reconnaissance path planning. By utilizing 3D Digital Twin technology, reconnaissance scenarios with randomly distributed obstacles and targets are simulated, enabling precise multi-functional scenario modeling. A comparative performance analysis of the Reinforcement Learning DQN algorithm and the A* automatic routing algorithm in random scenarios demonstrates that the 3D-DQN method offers better environmental adaptability. It exhibits higher efficiency and accuracy in various randomly generated scenarios, enabling the rapid identification of the shortest path and enhancing the reliability of task completion. This approach provides a new method for shortest path planning in non-contact reconnaissance missions using unmanned systems.






模型内容策划
素材获取
场景设备3d Max建模
设备位置随机生成算法设计
起始点终点位置生成及路径规划算法设计
渲染材质制作
形成系统
模拟仿真

比较维度	3D-DQN算法	A*算法
核心思想	基于强化学习，通过智能体在环境中的探索与学习动态生成最优路径	基于启发式搜索，在网格或图结构中找到从起点到终点的最短路径
输入环境	高维连续环境（3D空间）	离散化网格或图结构环境
学习能力	具有学习能力，可适应动态变化的环境	无学习能力，每次重新规划路径
路径规划过程	通过奖励函数指导，逐步优化路径选择	通过启发式函数计算估值，扩展最优节点
适用场景	动态环境、复杂3D空间、需自适应的任务（如机器人、无人机路径规划）	静态环境、2D或简单图结构的路径规划（如迷宫求解、网络路由）
计算复杂度	高，尤其在大规模环境中，训练时间较长	较低，但在复杂环境中可能因扩展节点过多而增加计算成本
优点	动态学习能力强，可处理高维复杂场景	精确、高效，适用于小规模问题
缺点	训练成本高，难以保证全局最优解	缺乏动态适应性，环境变化需重新运行算法
扩展性	可扩展到多智能体系统和更复杂的强化学习模型	受限于启发式函数的设计和计算能力



Temporal-Correlated Deep-Learning based GNSS signal classification in the built environment: a comparative experiment

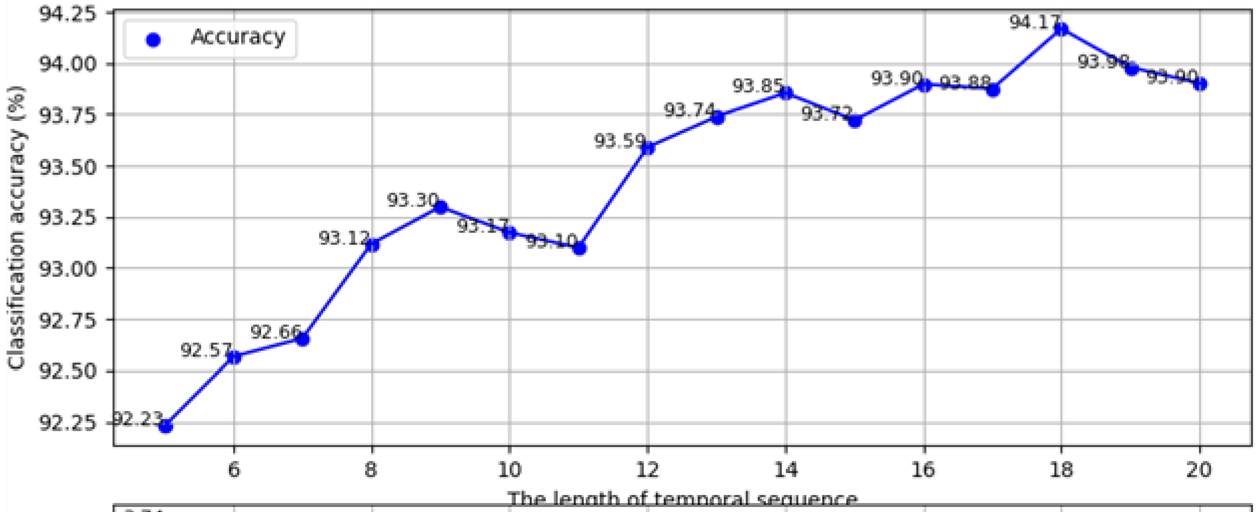
Li L[1], Ochieng W[1]
[1]Imperial college london

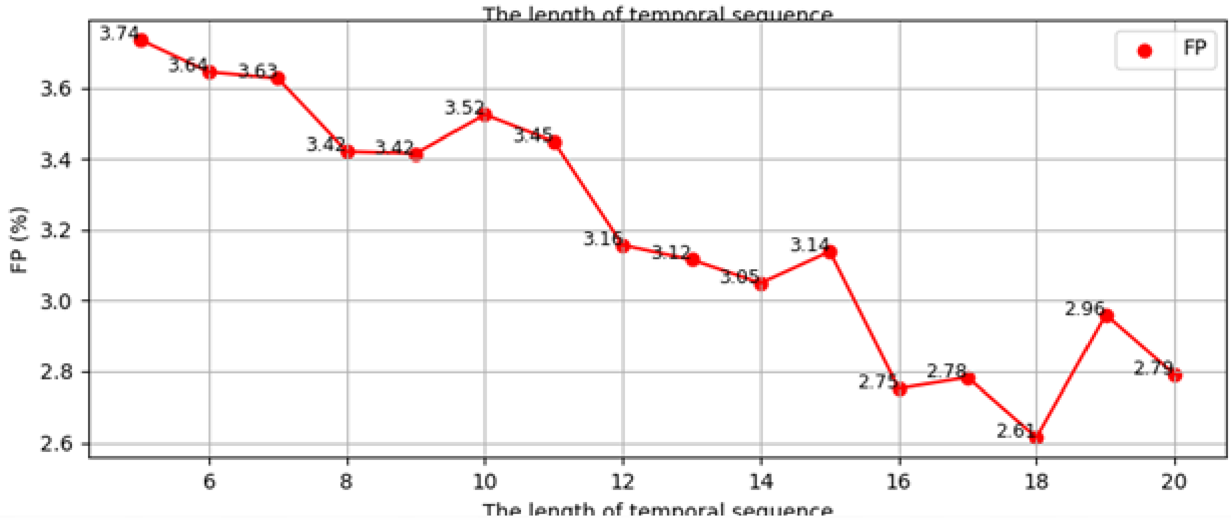
Biography:
Dr Lintong Li
Post Graduate in Centre for Transport Engineering and Modelling, Civil and Environmental Engineering Department, Imperial College London
A researcher on spatiotemporal correlated deep learning models, GNSS signal classification, positioning accuracy and integrity monitoring

Accurate Line-of-Sight (LOS) and None-Line-of-Sight (NLOS) signal classification is essential for Global Navigation Satellite System (GNSS) services and applications, especially in the built environment with frequent signal obstruction and multipath interference. Existing classification methods often rely on binary classification approaches, leading to insufficient remaining signals for positioning, satellite geometry degradation, and reduced positioning performance. To address these challenges, this study explores an advanced GNSS signal classification framework that incorporates temporal correlated deep learning models to enhance classification accuracy.

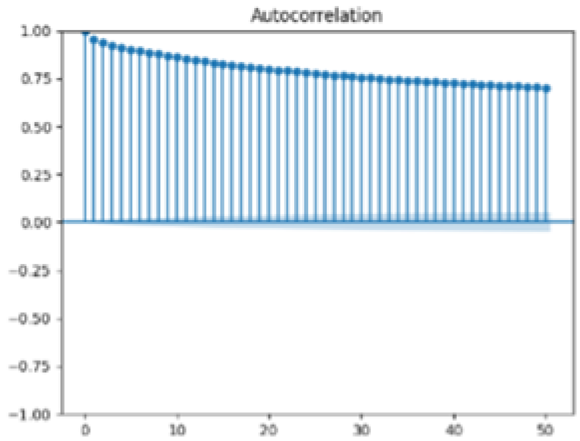
A comprehensive Quality Indicator (QI) analysis was conducted to identify the most relevant features for signal classification. Key QIs, including Carrier-to-Noise Ratio, elevation angle, code measurement's standard deviation, and azimuth angle difference, were selected for machine learning models based on their high feature importance. While point-wise models such as Random Forest (RF) performed well, achieving 93.07% accuracy with a 2.81% False Positive (FP) rate, they failed to capture temporal correlations within signal characteristics. To address this, deep learning models such as Long Short-Term Memory (LSTM), Gated Recurrent Unit (GRU), CNN-LSTM, and Bidirectional LSTM (Bi-LSTM) were implemented to leverage temporally correlated signal features.

Experimental results demonstrated that the Bi-LSTM model, with a sequence length of 18, 4 hidden layers, and 64 hidden units, achieved the best performance, with 94.17% accuracy and a 2.61% FP rate, outperforming traditional models. This improvement in classification accuracy and FP reduction enables more effective NLOS impact mitigation, ensuring that high-quality NLOS signals are retained when necessary, thus enhancing positioning accuracy and integrity. The findings highlight the potential of temporal-correlated deep learning models in improving GNSS signal classification for mission-critical applications.

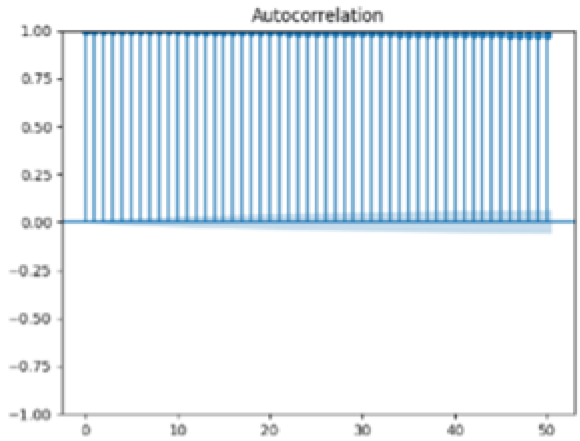




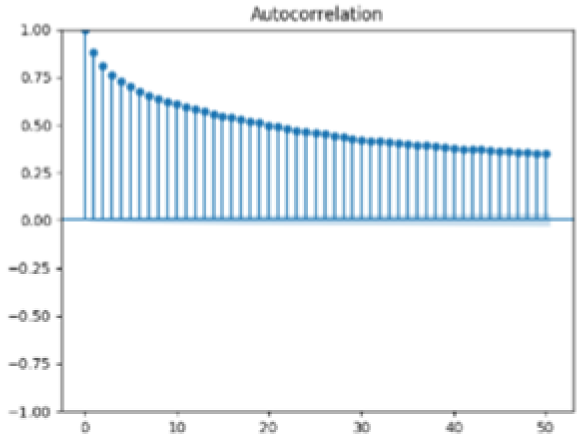
Layers/Size	LSTM Accuracy (%) / FP (%)	GRU Accuracy (%) / FP (%)	CNN-LSTM Accuracy (%) / FP (%)	Bi-LSTM Accuracy (%) / FP (%)
1/16	85.10 / 8.13	84.15 / 8.40	84.37 / 8.42	84.36 / 8.51
2/16	86.13 / 7.43	85.70 / 7.97	84.74 / 8.39	86.97 / 7.48
3/16	87.05 / 7.43	86.21 / 7.93	85.08 / 7.73	87.58 / 7.01
4/16	87.71 / 7.08	87.10 / 7.53	84.43 / 7.56	88.77 / 6.54
1/32	86.51 / 7.66	85.84 / 8.01	85.12 / 8.23	86.41 / 7.85
2/32	88.95 / 6.47	87.53 / 7.36	86.28 / 7.98	89.76 / 5.58
3/32	90.47 / 5.52	89.48 / 6.07	86.48 / 7.51	91.06 / 4.94
4/32	91.05 / 5.06	90.48 / 5.54	86.23 / 7.94	92.02 / 4.18
1/64	88.97 / 6.24	88.19 / 7.15	85.55 / 8.38	89.21 / 6.08
2/64	92.55 / 3.87	91.33 / 4.88	87.67 / 6.94	92.76 / 3.79
3/64	92.94 / 3.31	92.81 / 3.61	87.71 / 7.22	93.16 / 3.46
4/64	92.60 / 3.81	93.00 / 3.50	90.16 / 6.10	93.17 / 3.52



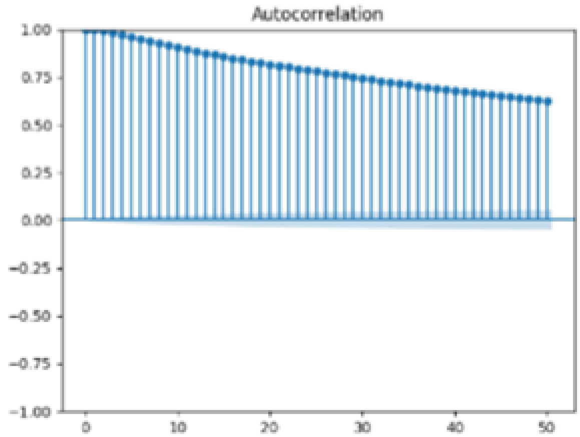
(a) C/N_0



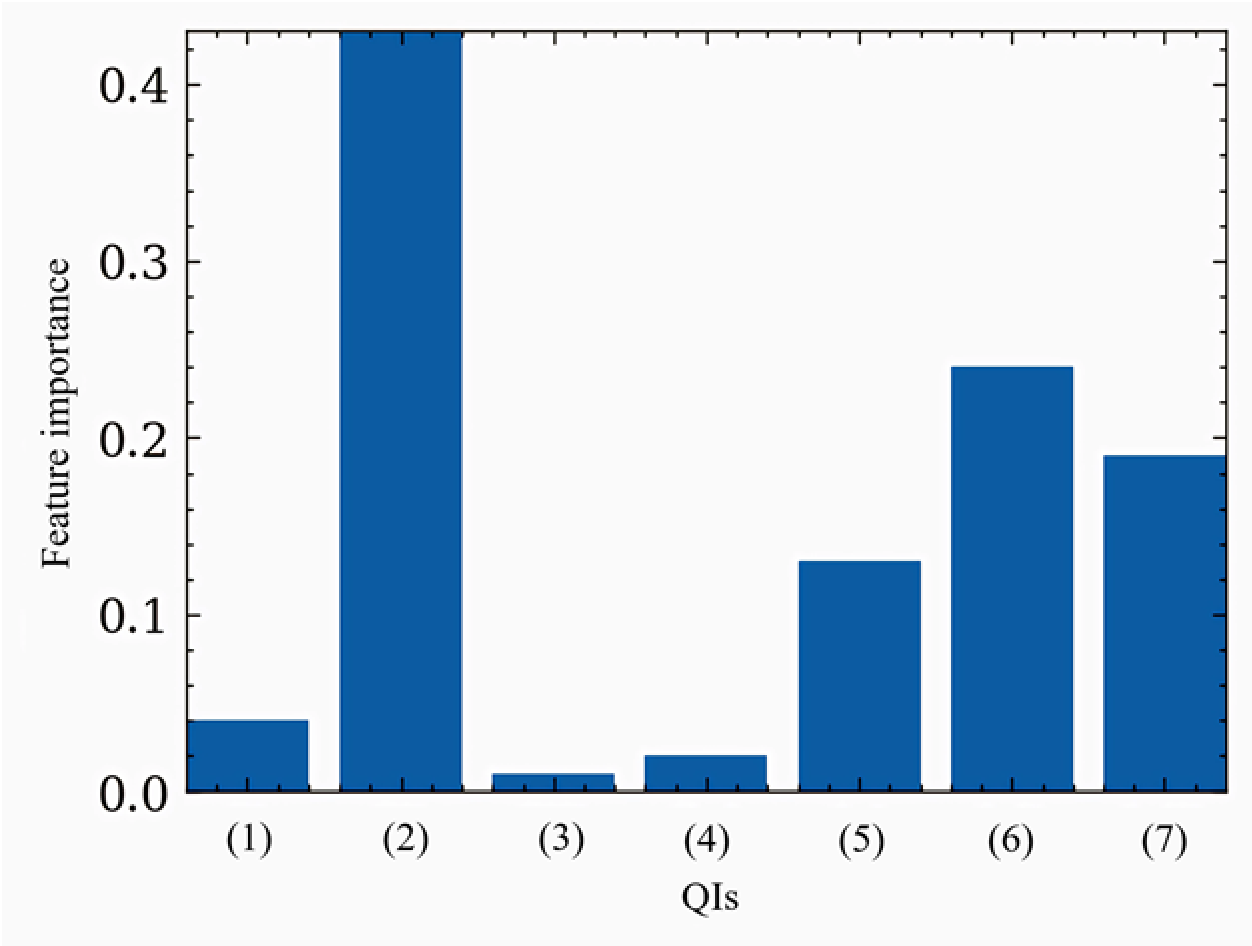
(b) Elevation angle



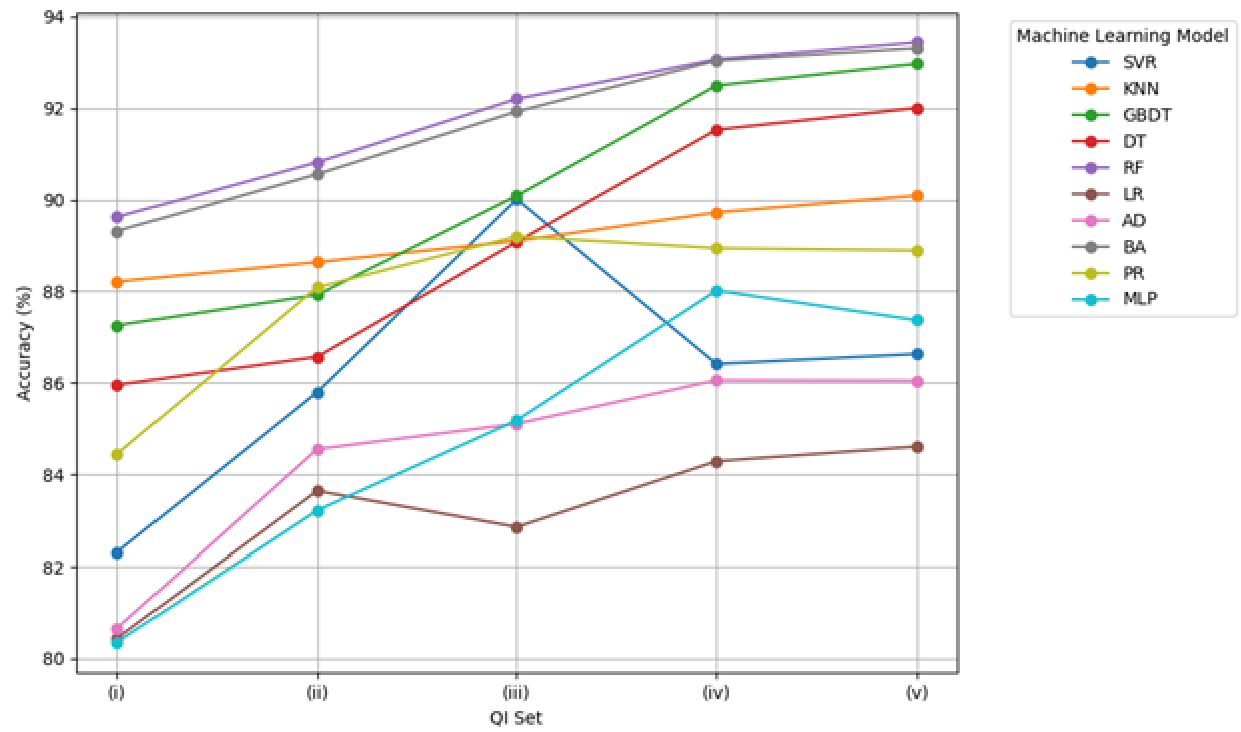
(c) Code measurement's STDEV



(d) Difference in azimuth



Feature importance
0.4
0.3
0.2
0.1
0.0
(1)
(2)
(3)
(4)
(5)
(6)
(7)
QIs



Accuracy (%)
94
92
90
88
86
84
82
80
(i)
(ii)
(iii)
(iv)
(v)
QI Set
Machine Learning Model
SVR
KNN
GBDT
DT
RF
LR
AD
BA
PR
MLP

Impact of station coordinates and troposphere delay modeling on multi-GNSS time transfer results

Mikoś M[1], Sośnica K[1], Kazmierski K[1]
[1]Wrocław University of Environmental and Life Sciences, Institute of Geodesy and Geoinformatics, Grunwaldzka 53, 50-375 Wrocław, Poland

Biography:
Marcin Mikoś received his Master of Engineering in Geodesy and Cartography from the Wroclaw University of Environmental and Life Sciences in 2022 and is currently a Ph.D. student. His main task includes multi-GNSS positioning with clock modeling.

In Multi-GNSS Precise Point Positioning (PPP), the receiver clock parameter (Clc), station height component (Up), and Zenith Tropospheric Delay (ZTD) are correlated. However, some of these parameters are treated as known values to minimize correlations and improve convergence time. In PPP, the receiver clock parameter is estimated at each measurement epoch together with the coordinates and potentially ZTD. However, coordinates can be taken from daily solutions, whereas ZTD can be taken from an external model and fixed. This study evaluates different PPP strategies for IGS stations equipped with hydrogen masers, testing two ZTD models and various approaches to estimating or fixing the Up component and ZTD. Results show that the most accurate solutions either estimate all three parameters (Clc, Up, and ZTD) or derive station coordinates from the last epoch of a daily PPP solution. Fixing tropospheric parameters to GMF or VMF3 models results in a worse performance compared to estimating corrections for wet delay. The best strategy for stability and time transfer involves estimating Up, Clc, and ZTD using VMF3, updated every 6 hours. These findings underscore the importance of flexible parameter estimation in PPP, demonstrating that simultaneously estimating the Clc, Up, and ZTD parameters leads to the most robust and stable solutions despite correlations between these parameters.

Enhanced eLoran data channel demodulation using deep learning

Nezafati M[1], Lotfalizadeh M[1]
[1]Ipm

Biography:

Mr. Nezafati is educated from Khajeh Nasir University of Technology and has worked on signal processing for more than 10 years. His main interest subjects are decoding and demodulation, link adaptation, error correction codes, 5G standard and navigation.

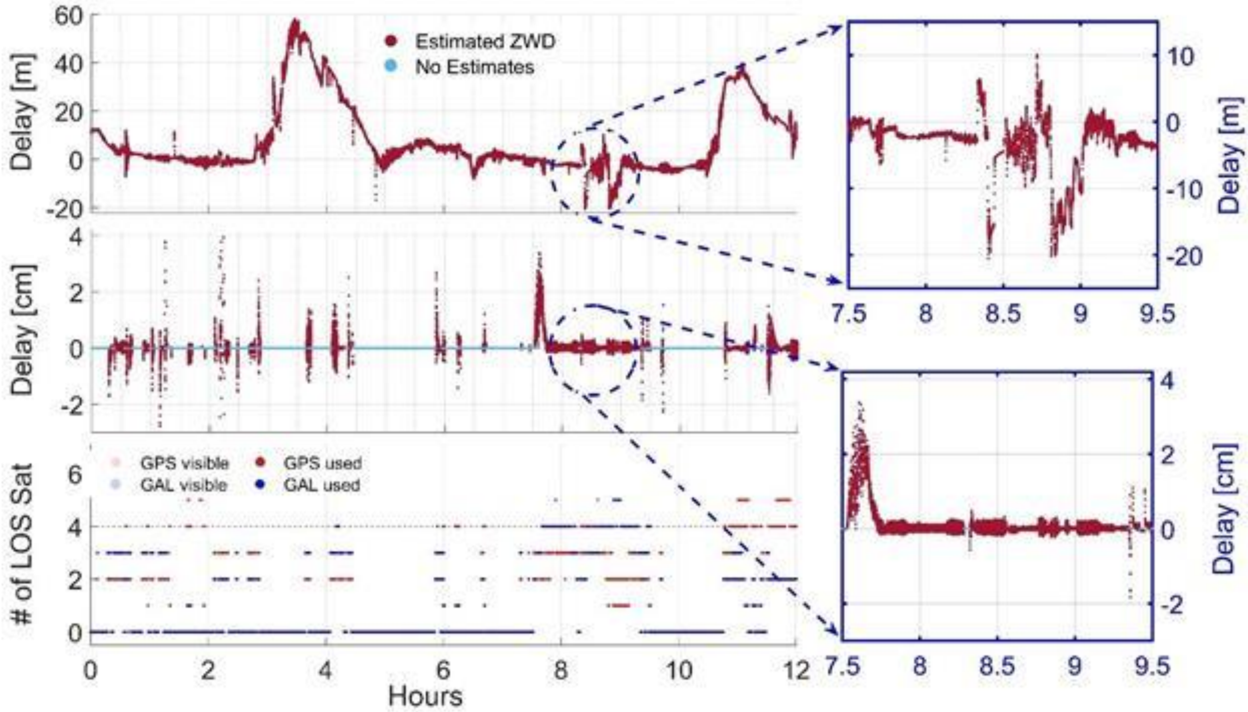
Low bit error rate (BER) demodulation of eLoran navigation systems' data channel, is vital for message time transmission in this system. In this paper we proposes a novel demodulation algorithm using a deep learning calcification algorithm for pulse position modulation (PPM) of eLoran signals. We will consider 9'th pulse data channel standard and time message transmission through noisy and CWI channels. After review of classical existing demodulation method based on envelope phase detection and recent neural networks used in for data channel demodulation of Eurofix standard, a new low complexity and more BER efficient demodulation algorithm is proposed for 9'th pulse PPM demodulation. Subsequently, through comprehensive simulation, the algorithm parameters are optimized, and the comparison of different demodulation methods is carried out in noisy environments. This algorithm fully meets the high-precision message transmission requirements of the 9'th pulse eLoran navigation and timing system.

Ray-Tracing for Precise GNSS Troposphere Estimation in Urban Environments

Mehdi S[1], Rohm W[1]
[1]Wrocław University of Environmental and Life Sciences

Biography:
Saqib Mehdi, a PhD candidate at Wroclaw University of Environmental and Life Sciences in Poland, specializes in GNSS-based troposphere sensing and urban ray-tracing techniques. His research focuses on advancing tropospheric delay estimation in urban environments. Today, he will present his work on Optimized Urban Areas for GNSS Troposphere Estimation Using Ray-Tracing Techniques.

This study integrates urban ray-tracing techniques with GNSS observations to enhance tropospheric sensing in urban environments, focusing on Zenith Wet Delay (ZWD) estimation. Using detailed 3D building models, GNSS signals are classified into Line of Sight (LOS), reflected, and diffracted paths. Tram stops with optimal sky view factors (SVF) and maximum LOS visibility are identified as ideal locations for accurate ZWD estimation. To assess the influence of urban obstructions, software-simulated RINEX datasets incorporating only multipath effects are analyzed. The findings show that ray-tracing effectively filters multipath-contaminated signals, significantly improving the accuracy of GNSS-based ZWD estimates. Additionally, spatial-temporal LOS maps are demonstrated to identify optimal areas for ZWD estimation.



Flight Test & Simulation Performance Assessment of a Novel Alt-PNT Absolute Position Estimation System

Furse G[1], Sequeira C[1], Rider C[1], Palmer-Jorge D[1], Sanby B[1]
[1]Flare Bright Ltd

Biography:
Gabriel joined Flare Bright after graduating with a First Class degree in Mathematics from Durham University. As part of the Flare Bright team, he has helped develop pioneering UAS technology, with a particular focus on novel alternative PNT capabilities. Now, as a Senior Software Engineer, he combines his technical expertise in complex mathematical algorithms with core software engineering capabilities to deliver breakthrough Flare Bright R&D.

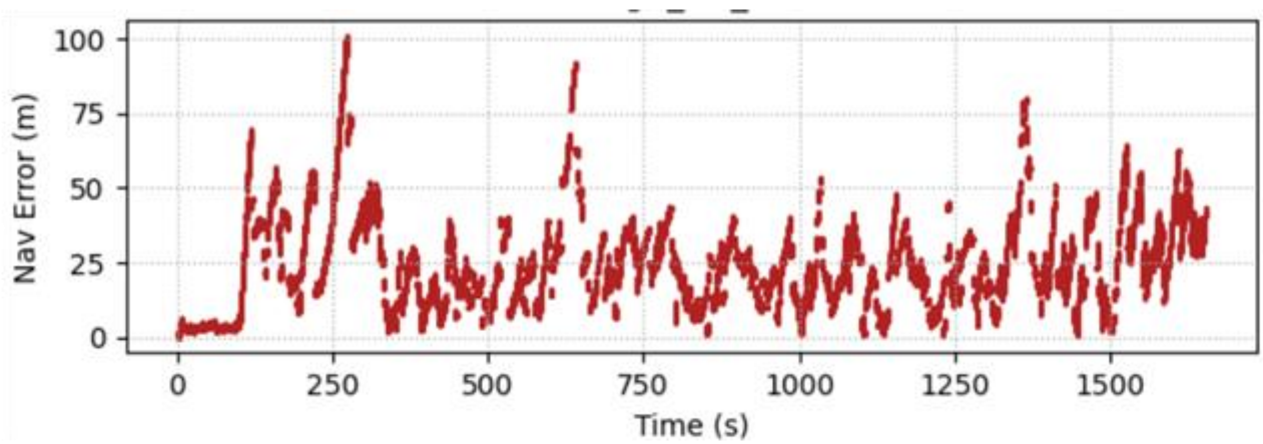
Flare Bright has developed a novel, Machine Learning optimised, absolute positioning system that enables the safe, continuous, use of Uncrewed Aerial Systems (UAS) in GNSS denied environments over extended periods of time.

Relying on low cost, low weight and widely available sensors, ordinarily already deployed on many commercially available UAS, Flare Bright's software based solution can give highly accurate position data when GNSS fails without the use of compute processor intensive vision systems. Importantly, this new capability also complements traditional Inertial Navigation Systems (INS), or enhanced INS systems such as Flare Bright's software enhanced GNSS-free capability presented at ENC2023/2024, by correcting for 'position estimation drift'. Consequently, Flare Bright's new technique adds redundancy to flight safety critical systems and can also provide an alternative, complementary, source of truth to existing UAS navigation systems.

Flare Bright has flight tested a proof of concept of this absolute position estimation system using a 2m wingspan fixed wing UAS, with the software deployed real-time on a Raspberry Pi 3b. In this paper, results from these flight tests will demonstrate how Flare Bright's novel technique produces an average position estimation error of ~35m (Figure 1) in a representative operational environment.

The flight data will be analysed in conjunction with simulation data to provide a critical review of the constraints and potential capability achievable with this novel technique, demonstrating the significant scope for further optimisation of the system. The results shown will enable an assessment to be made about how the system performance may be scaled, for example for faster drones or across different operating scenarios.

Overall, the results will demonstrate a credible route towards a practical, operational, capability within the emerging UAS sector and the potential value of using mass-market sensors with software enhancements within the wider aviation sector where safety is paramount.



Nav Error (m)
100
75
50
25
0
0
250
500
750
1000
1250
1500
Time (s)

Factor Graph Based Precise Point Positioning (PPP) Framework

Uyanik H[1], Belles A[1], Medina D[1]
[1]DLR - German Aerospace Center

Biography:
Hakan Uyanik is a Research and Development Engineer at German Aerospace Center - DLR since 2024. His main area of research focuses on multi-sensor fusion, specifically on tightly coupled integration systems utilizing factor graph optimization for GNSS, IMU, and Doppler Velocity Log data. He is exploring the performance of PPP-INS navigation using factor graph optimization for enhanced precision and availability in multi-sensor systems.

This work presents a utilization of the factor graph optimization approach on Precise Point Positioning (PPP) navigation. While PPP solutions already achieves high precision (~ 20 cm), their performance can degrade under multiple simultaneous faults or sensor degradation. Here, we focus on enhancing overall precision and availability by leveraging a resilient factor graph formulation, integrating SSRZ/HAS corrections, and possibly combining data from multiple sensors.

Our approach systematically compares three methods for state estimation: (A) recursive filtering, (B) smoothing, and (C) batch least squares. These methods differ primarily in how past and current information are incorporated to estimate the integer and real-valued parameters critical to PPP. By applying these estimation strategies within a simple, controlled simulation, we highlight their relative strengths and weaknesses in terms of accuracy, computational load, and robustness to sensor or measurement faults.

In this study, we evaluate an extensive performance evaluation via Monte Carlo simulation. The metrics considered include positioning performance, solution availability and integrity.

We further discuss the implications of these findings for a broader inertial stack, as part of an ongoing effort to develop resilient navigation solutions for autonomous vessel systems. Preliminary conclusions suggest that hybrid solutions—where real-time filtering is complemented by periodic smoothing or batch processing—may offer the most advantageous balance of robustness and availability.

This work represents the initial results from factor graph optimization on PPP systems, with plans to validate the proposed methods using real-world datasets in a subsequent journal publication. By unifying PPP estimation within a factor graph, we aim to advance fault-tolerant precision and availability in next-generation navigation systems.

Satellite navigation in navigation safety-critical decision-making.

Lahtinen J[1], Helenius W[1], Kajander H[1]
[1]Satakunta University of Applied Sciences

Biography:
Janne Lahtinen a doctoral candidate in Aalto University, Department of Mechanical Engineering where he researches safety of remote pilotage in intelligent fairway. He has graduated from Satakunta University of Applied Sciences as a Master of Maritime of Management and a Master Mariner. After graduation he gathered extensive experience from dynamically positioned offshore construction vessels where he was responsible for computerized propulsion systems in deep water subsea construction operations. As a Nautical institute accredited senior dynamic positioning instructor Janne runs a dynamic positioning training center in Satakunta University of Applied Sciences, where he works as a senior lecturer of maritime studies.

GPS disturbance in shipping can result in significant navigational challenges, leading to various impacts on operations, such as potential delays, increased operational costs, and heightened safety risks for crews and vessels. Understanding these disturbances and their implications is crucial for enhancing maritime safety and efficiency. Common causes of GPS disturbances in shipping include atmospheric effects such as ionospheric and tropospheric delays, satellite signal obstructions due to terrain or buildings, satellite malfunctions or failures, and intentional interference like jamming. These factors can lead to inaccuracies in positioning, affecting navigation and safety. GPS signals are vulnerable to various cyber threats, including spoofing, jamming, and signal interference. Spoofing involves sending counterfeit GPS signals to mislead receivers, while jamming disrupts the legitimate signals. Ensuring the integrity and security of GPS systems is crucial for applications like navigation, timing, and critical infrastructure. Advanced encryption and authentication methods can help safeguarding of GPS signal security. These vulnerabilities can have serious implications for navigation systems and critical infrastructure. Enhancing GPS security requires a combination of advanced technologies and policies aimed at improving signal integrity and authentication processes. This paper introduces a behavioural approach to enhancing cyber security in commercial shipping through European collaboration in CyberSEA project. The topic will also be addressed from the perspective of the development of a digital tool in the framework of the EU co-funded Sustainable Flow project.

Investigations of Anomalies in Ship Movement During a Voyage

Wielgosz M[1], Pietrzykowski Z[1], Uriasz J[1], Góra P[1]
[1]Maritime University of Szczecin

Biography:
Dr. Miroslaw Wielgosz, Master Mariner.
Current employment: Maritime University of Szczecin, Poland.
Main area of activity: safety of navigation, MASS, maritime search and rescue
Topic to present: Selection of suspicious ships and their activities for further investigation based on AIS data.

Investigations of Anomalies in Ship Movement During a Voyage

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Abstract
Growing attention is being devoted to the analysis of vessel movement processes concerning ship, cargo, and environmental safety. In addition to identifying navigational incidents, including 'near-miss' situations, anomalies in vessel behavior are also of significant importance. These anomalies in ship movement include sudden speed reductions, deviations from designated routes, AIS transponder deactivations, and more. They may arise from a range of factors, including unlawful activities, intentional damage to underwater energy and communication infrastructure, environmental pollution, and other non-compliant actions. To facilitate the preselection of vessels for further investigation, criteria and methods for identifying anomalies were proposed. An analysis of AIS (Automatic Identification System) records was conducted, focusing on the trajectory data of selected vessels transiting between the North Sea and the Baltic Sea. A case study was conducted on selected ship voyages using the proposed evaluation criteria.
Keywords: ship voyage, movement anomaly, AIS data, investigation

Smartphone-Based Indoor Cooperative Positioning Solution For BIM

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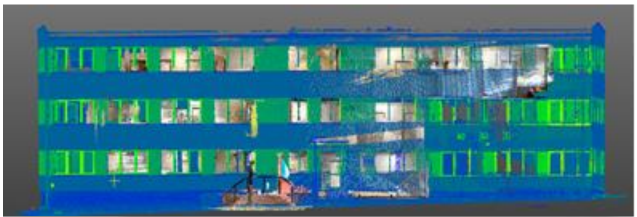
[1]TU Wien, [2]University of Warmia and Mazury

Biography:
Jelena Gabela is a Project Assistant at the Department of Geodesy and Geoinformation at TU Wien, Vienna, Austria. She received her PhD at the University of Melbourne, Australia in 2021. Her main research and teaching interests are multi-sensor and cooperative positioning in GNSS challenged and denied environments, estimation theory and positioning quality, and position integrity monitoring.

The goal of this case study is to develop a multi-sensor and cooperative positioning solution, based on dual-frequency Wi-Fi (Wireless Fidelity), IMU (Inertial Measurement Unit) Ultra-Wide Band (UWB) sensors available on smartphones as a future signal of opportunity, for supporting BIM (Building Information Model). We propose the development of BIM with an additional layer, i.e., seamless indoor navigation. This approach will allow for full information not only about the object but also about its interior and obtaining information for designers, especially when there are building projects for old, historical buildings. In addition, the LiDAR sensor which now can also be found in smartphones will be applied.
The proposed method aims to enhance real-time positioning accuracy and improve indoor navigation efficiency. The results show that integrating BIM with smartphone-based LiDAR navigation can provide precise indoor localization, offering potential applications in smart buildings, emergency response, and assistive navigation.
Figure 1 shows the resulting integrated point cloud for the chosen building in this study obtained using point cloud processing and Figure 2 the created BIM in Blender. For the navigation, the BIM serves as map base and augmentation.



An Approach to the Development of a Privacy Preserving PNT Processing Techniques Concept Demonstrator

Sararu A[1], Mistrapau F[1], Olteanu V[1], Rahimian S[2], Hurtado Ramirez D[3], Perea Fernandez I[2], Mosiezny J[2], Tejedor Munoz M[2]
[1]GMV RO, [2]GMV DE, [3]GMV ES

Biography:
Andra Mihaela Săraru is a GNSS Software Engineer with experience in software development, data analysis, and PNT technologies. She joined GMV in 2023 and is currently working for the Consultancy and Advanced Navigation Solutions Division in GMV Romania. She is actively involved in ESA projects, with a key role in the VALLE demonstrator, focusing on privacy-preserving PNT processing.
Prior to joining GMV, she spent over five years at Trimble in Germany, leading quality assurance initiatives for GNSS applications in automotive and smart agriculture.

The current paper presents the development of a concept demonstrator including innovative privacy preserving Positioning Navigation and Timing (PNT) concepts that explore the possibilities and capabilities of the Privacy Enhancing Technologies (PET).
The work presented in this paper has been performed in the VALLE Project, part of the ESA NAVISP Element 1 programme.
VALLE analysed a set of techniques that guarantee data privacy via different mechanisms, most of them based in cryptography, but also via statistical methods or hardware solutions such as differential privacy and trusted execution environments, respectively.
Different data sharing scenarios or use cases have been assessed, showing the main conclusion: there is no single PET that solves all privacy issues or covers all possible use cases. Privacy does not come for free, and it is critical to consider the trade-off between privacy, complexity, and performance in the design phases of any application targeting privacy, especially when it comes to PNT.
The use of PET is not yet widespread in PNT applications due to the levels of accuracy or real-time requirements imposed, with Location Based Services (LBS) being the ones that most frequently introduce PET in PNT data processing.
The demonstrator uses advanced techniques, such as Anonymization, Homomorphic Encryption (HE) or Secure Multi Party Computation (SMPC) to enhance data security and privacy.
The paper will show the analysis of PNT use cases and privacy enhancing techniques performed in the scope of VALLE leading to the design and implementation of a flexible concept demonstrator focused on different types of PNT data and corresponding PET targeting to enable private cloud computation in several domains where PNT plays major roles. The conclusions of the performance analysis will complement the paper thus providing an overview on the feasibility of the proposed privacy preserving PNT processing concepts.

Lunar Reference Frames for the Moonlight – the ESA PNT System

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[1]Wroclaw University Of Environmental And Life Sciences, Institute of Geodesy and Geoinformatics, [2]Geoazur, Observatoire de la Cˆote d'Azur, [3]IMCCE, Observatoire de Paris

Biography:
Krzysztof Sośnica graduated from the University of Bern, Switzerland, in 2014, obtaining a Ph.D. degree in Physics. He is now a full professor of satellite geodesy. His activities include precise orbit determination of GNSS and geodetic satellites, reference frame realizations, Earth's gravity field recovery, and the enhancement of the consistency between GNSS and SLR solutions.

All lunar exploitation programs require high-accuracy reference frames and time systems. This contribution describes the proposal of the lunar reference frames for the positioning, navigation, and timing system that is currently prepared by ESA in the framework of the Moonlight program. Two reference systems typically define the lunar body-fixed coordinate system: the Mean Earth Axis (ME) and the principal axis (PA) reference system. The ME system is used because of historical reasons and it is commonly adopted for data distribution proposes of lunar surface or topography and archiving maps. The PA corresponds to the orientation characterized by the diagonal tensor of inertia for the Moon. The PA system is typically recommended for practical applications in positioning, navigation, and communication. Three static Euler angles are employed for the transformation between these two reference systems and depend on a lunar ephemeris. We discuss the transformation between the barycentric celestial reference system (BCRS) and the lunocentric celestial reference system (LCRS), and further to the lunar body-fixed PA and ME systems. This contribution deliberates on the precision of the realization of the lunar reference frames using the lunar laser ranging (LLR) observations to existing laser retroreflectors, as well as the errors in the scale, translation, and rotation parameters because of using inconsistent selenoid gravity field models. We will also address the potential improvement of the lunar reference frames by installing new retroreflectors, such as NASA NGLR-1 (Next Generation Lunar Retroreflector) recently accepted by the International Laser Ranging Service (ILRS) for tracking, as well as the active multi-technique reference station realized in the framework of future ESA project NOVAMOON.

Interference cancellation algorithm for LEO-PNT with LoRaWAN

Sánchez-Costa Y[1], Egea-Roca D[1], López-Salcedo J[1], Seco-Granados G[1]
[1]Ieec-uab

Biography:
Daniel Egea Roca received the PhD in Electrical Engineering in 2017 from Universitat Autònoma de Barcelona (UAB). Currently, he is a post-doctoral researcher at the SPCOMNAV group at UAB, hired by the Institute of Space Studies of Catalonia (IEEC). His research interests lie in the field of statistical signal processing applied to GNSS, and signal design and processing for LEO-PNT. The topic to be presented deals with the proposal of a novel interference cancellation technique useful for LEO-PNT with LoRaWAN. The technique will cancel the interference of colliding LoRaWAN packets, thus allowing the separation of LoRaWAN packets from different satellites.

The Internet of Things (IoT) has transformed various aspects of life, driven by advancements in low-power wide-area networks (LPWAN) like LoRaWAN; and global navigation satellite systems (GNSSs). While LoRaWAN enables long-distance connectivity with low power consumption, its coverage is limited by terrestrial infrastructure. GNSS, though essential for positioning, navigation and timing (PNT), can be power-intensive and vulnerable in harsh environments. Leveraging low-Earth orbit (LEO) satellite constellations can enhance IoT interconnectivity, and alternative signal designs for LEO-based PNT may simplify GNSS receivers and improve performance in harsh conditions.

New signal designs for LEO-PNT using chirp spread spectrum (CSS) indicates an important complexity reduction compared to existing GNSS signals [1]. While LoRaWAN's physical layer employs CSS modulation, these optimized designs cannot be adapted to LoRaWAN. Other studies considered LoRaWAN in terrestrial positioning systems based on round-trip time (RTT) measurements [2], which are unsuitable for satellite applications. Recently, the potential for transmitting LoRaWAN from LEO for communication has been explored [3], but it has not yet been applied to LEO-PNT. This paper explores for the first time LEO-PNT solutions with LoRaWAN.

To effectively use LoRaWAN for LEO-PNT, addressing potential collisions from its time division multiple access (ALOHA) is crucial. While various interference cancellation algorithms exist [4], they do not apply to the LoRaWAN preamble, which is essential for extracting PNT measurements like time-delay and Doppler. This work contributes in two ways: (i) we propose a simple interference cancellation technique utilizing the intersection of 8 chirp signals in the LoRaWAN preamble (see Figure 1), and (ii) we detail signal detection, measurement estimation, and satellite identification for LEO-PNT with LoRaWAN. Additionally, numerical results from simulations and real signal captures using Arduino will be presented to support our findings.

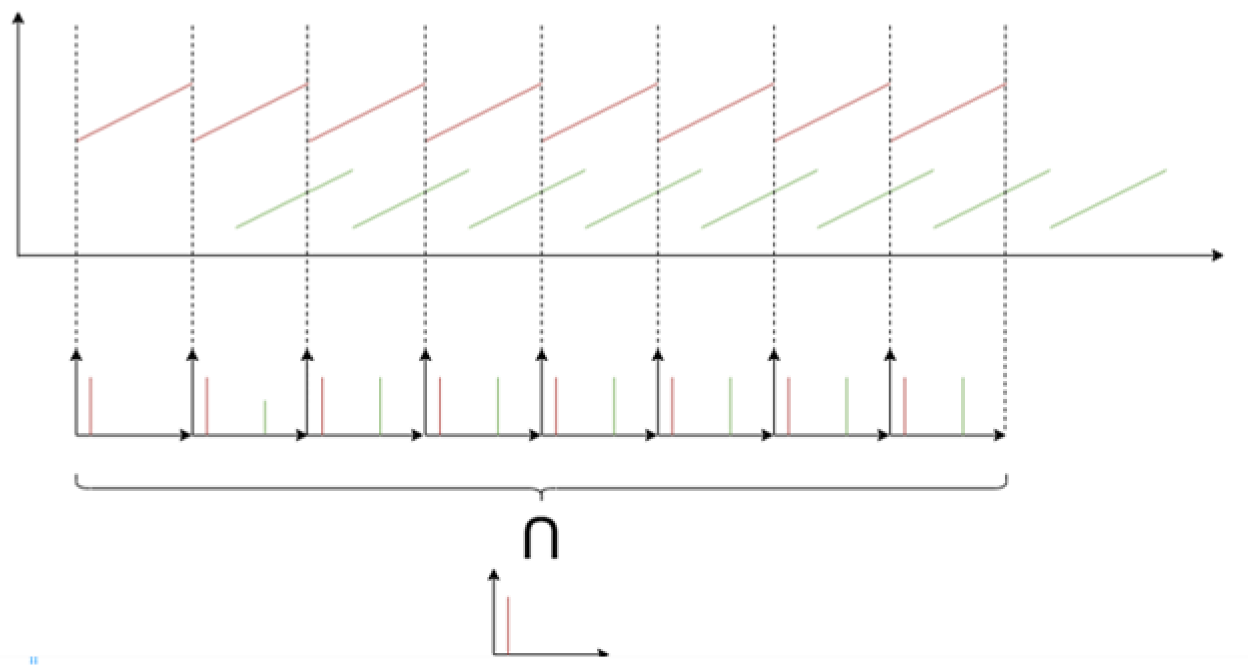

Figure 2 (References)

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Analysis of Radio Signals of the RSDN-20 System Recorded Using Antennas with a Magnetic Component

Jaskólski K[1], Felski A[1]
[1]Polish Naval Academy

Biography:
D.Sc. Krzysztof Jaskólski
Assistant professor, Polish Naval Academy, Faculty of Navigation,
Navigational instruments, radio-navigational systems, digital signal processing, digital signal filtering.
The issue of interference with the useful signal of global positioning systems
Detection of signals from the Russian long-range system ALPHA - codename: RSDN-20
The use of antennas with a magnetic component for detecting signals from the ALPHA system
The problem of positioning system redundancy in the presence of interference in the band of global radio navigation systems

The aim of this presentation is to outline the current state of knowledge regarding the operation of global radionavigation systems and long-range systems.
The authors will address the present situation related to the phenomenon of deliberate interference with positioning systems and the issue of spoofing useful signals from the GPS NAVSTAR global positioning system. Referring to the currently operating long-range systems in Russia, the authors will explain the general principles of the Russian hyperbolic system ALPHA.
Moreover, they will present time-domain waveforms of radio signals against the background of noise, as well as the amplitude spectrum of the signal using the Fast Fourier Transform (FFT) algorithm in the frequency band from 10 kHz to 20 kHz. They will also present spectrograms of time-domain waveforms against noise in the same frequency band.
Additionally, the authors will perform a cepstral analysis of the signals, emphasizing the periodicity of the harmonic components of the ALPHA system's radio signals. They will also demonstrate time delays in the received signals using the mathematical apparatus of cross-correlation.
Finally, the authors will suggest directions for future research in the detection and digital signal processing of radionavigation systems.

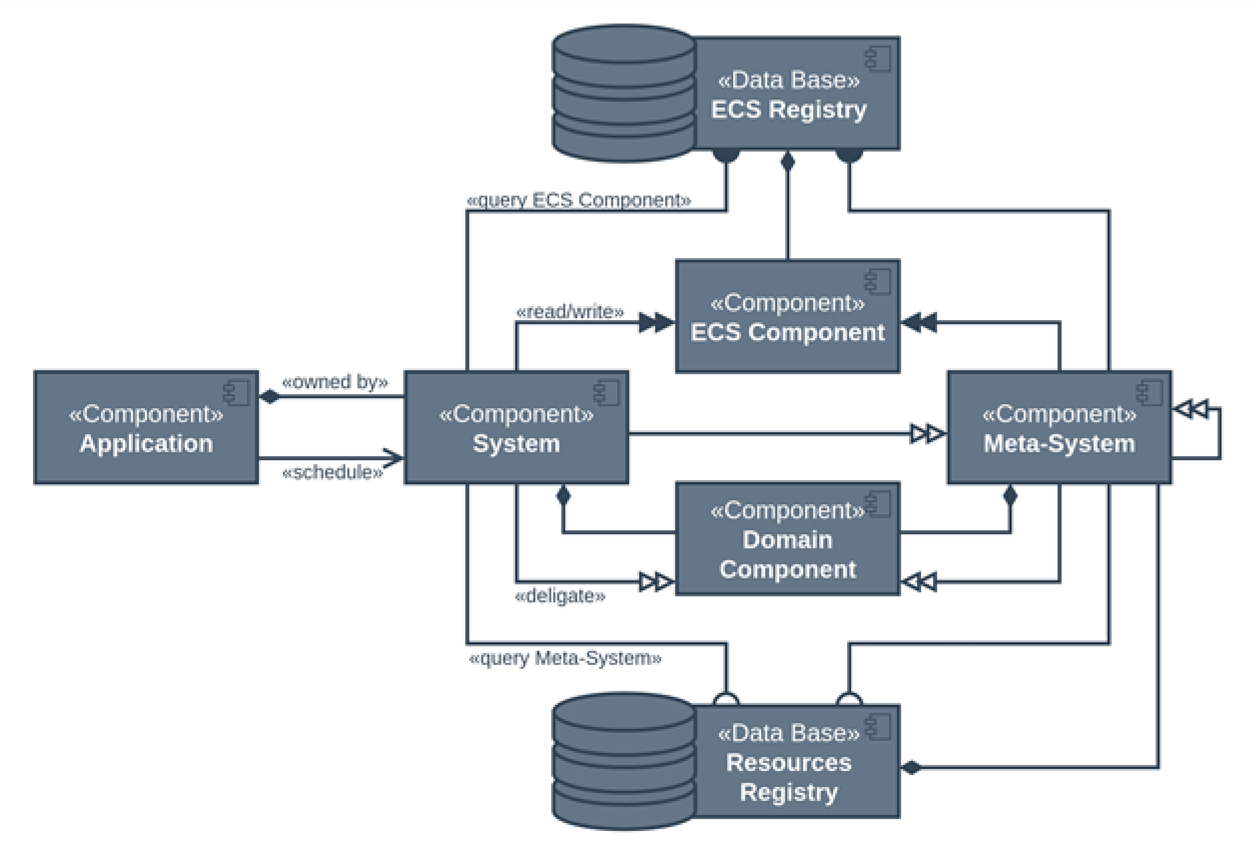
Precise orbit determination of constellations and VLEO satellites with PODCAST 2.0

Stucke M[1,2], Krückel R[1], Ghribi A[1,2], Hobiger T[1]
[1]Institute of Navigation, University of Stuttgart, [2]Airbus Defence and Space GmbH

Biography:
Roman Krückel graduated with a degree in Aerospace Engineering in May 2024. He is currently a Research Associate and PhD candidate at the Institute of Navigation, University of Stuttgart, Germany. His research focuses on Precise Orbit Determination (POD) of satellites in Very Low Earth Orbit (VLEO), as part of the Collaborative Research Centre "Advancing Technologies of Very Low Altitude Satellites (ATLAS)".

Precise Orbit Determination (POD) and Precise Baseline Determination (PBD) are crucial for the operation of modern and future space missions. An orbital solution which combines POD and PBD is beneficial for cooperative Low Earth Orbit (LEO) satellite swarms. Furthermore, the increased use of Very Low Earth Orbit (VLEO) comes with the need to better model non-gravitational forces and consider errors that follow non-Gaussian distributions. Therefore, a flexible framework to design, test and assess different orbit estimation approaches is needed. Moreover, fast and sub-cm accurate POD solvers need to be developed to meet the requirements for near-future missions including VLEO missions and satellite constellations. Up to our knowledge, such flexible and powerful POD software packages do not exist, yet.

Thus, equipped with the knowledge gained in developing our in-house POD estimator PODCAST [Gutsche et al. 2022], we have completely re-designed the software under the name PODCAST 2.0 by making use of professional data-oriented software architectural patterns and implementing a flexible estimation framework. Building on existing modules we created a new architectural design, gearing up for constellation POD and VLEO missions. The realization as an Entity Component System (ECS), allows for flexible system design and fast computation due to a data-oriented architecture. All modifications are based on the proven capabilities of PODCAST including the existing high-fidelity modeling of satellite dynamics and the state-of-the-art GNSS observation processing. Additionally, the estimation components were overhauled to enable for easy switching between different estimators. The new implementation allows for flexible use of multiple observation combinations in a stochastically consistent way, while allowing the users to choose between different Bayesian estimators. Moreover, new high-fidelity non-gravitational force models are currently being implemented. This will allow users to estimate atmospheric density as well as gravity field coefficients with unprecedented accuracy.


«Data Base»
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«query ECS Component»
«Component»
ECS Component
«read/write»
«Component»
Application
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System
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Meta-System
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Domain
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«deligate»
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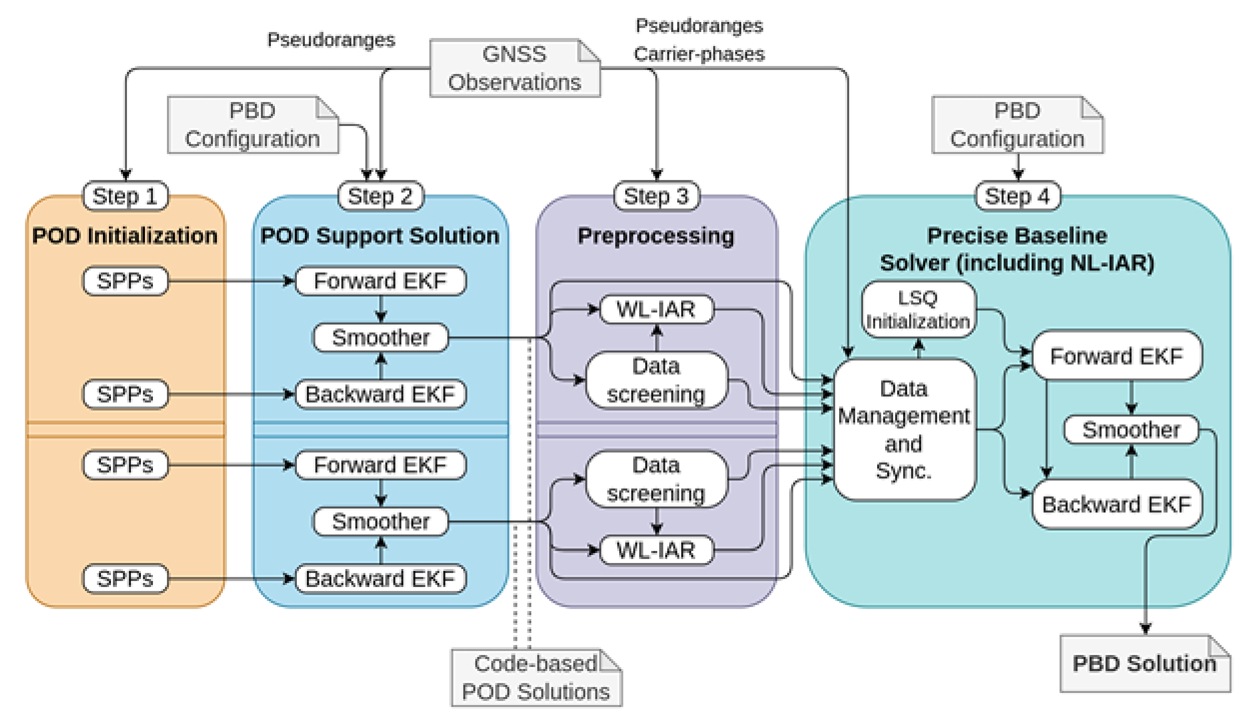
Resources
Registry


Pseudoranges
GNSS
Observations
Pseudoranges
Carrier-phases
PBD
Configuration
PBD
Configuration
Step 1
POD Initialization
Step 2
POD Support Solution
Step 3
Preprocessing
Step 4
Precise Baseline
Solver (including NL-IAR)
SPPs
SPPs
SPPs
SPPs
Forward EKF
Smoother
Backward EKF
Forward EKF
Smoother
Backward EKF
WL-IAR
Data
screening
Data
screening
WL-IAR
LSQ
Initialization
Data
Management
and
Sync.
Forward EKF
Smoother
Backward EKF
Code-based
POD Solutions
PBD Solution

Development of ML-based navigation capabilities for rendezvous and proximity operations in space

Lauer L[1], Zurad M[1], Regad D[1], Lebègue S[1]
[1]Lmo Sàrl

Biography:
Luc Lauer graduated in aerospace engineering from the University of Stuttgart. Since June 2024, he has been working as a GNC engineer for LMO Sàrl, mainly focusing on the development of simulations and navigation filters for rendezvous and proximity operations.

Providing in-orbit services in geostationary orbit (GEO) requires precise knowledge of a client's state, especially during rendezvous and proximity operations (RPO). This is particularly challenging when approaching a non-communicating client, where onboard estimation of the relative pose is essential for the servicer. To address this, LMO is developing a machine learning (ML)-based, image-driven RPO sensor designed to enhance autonomous navigation capabilities in space.
This work presents an overview of the system, focusing on key algorithms and challenges in developing an ML-based navigation sensor. A critical aspect is ensuring reliable measurement acquisition, which requires identifying an appropriate sensor model and selecting a robust navigation filter. The advantages and limitations of mission-specific filtering approaches versus more generalized architectures that handle complex scenarios are examined. The discussion includes methods to improve measurement accuracy and system robustness.
Our sensor leverages a hybrid neural network architecture to regress the six degrees of freedom (6DOF) pose of a known object. The model is trained in a supervised manner using synthetic data, and the quality of this training data is crucial for ensuring reliable operation in space. The discussion includes a method to generate synthetic data for training and acquiring real world lab data to characterize and validate performance in a representative environment.
Finally, the remaining challenges for deploying a commercial navigation unit for RPO are outlined. Overcoming these obstacles is crucial to enabling safe, precise, and autonomous in-orbit servicing missions, ultimately advancing sustainability of space activities.

Leveraging Vibration Effects on Clock Performance for GNSS Receiver Fingerprinting in Dynamic Environments

Lin Q[1], Schön S[1]
[1]Institut Für Erdmessung, Hannover University

Biography:
Ms. Qianwen Lin, is a PhD student at the Institut für Erdmessung (IfE), Leibniz University Hannover. Currently, she is involved in the 'FIRST' project, funded by the German Federal Ministry for Economic Affairs and Climate Action. Her research focuses on GNSS receiver fingerprinting and integrity monitoring for timing applications, using miniature atomic clock technology. Today, she will discuss how vibrations in dynamic environments affect clock performance and explore their role in advancing GNSS receiver fingerprinting.

Global Navigation Satellite Systems (GNSS) are vulnerable to spoofing attacks, where unauthentic signals can be generated by a simple simulator to mislead especially a commercial GNSS receiver. A promising solution is fingerprinting GNSS receivers based on clock-related metrics like Allan Variance (AVAR) and Time Interval Error (TIE). Our prior work has demonstrated that Chip-Scale Atomic Clocks (CSAC), known for their superior stability and accuracy compared to the internal receiver clock, enable effective receiver identification in static environments by extracting key features from clock metrics.

In dynamic environments, however, additional factors complicate the results, with vibration being a significant influence, e.g. when GNSS receivers are used in vehicles running on (uneven) ground or in flight. Vibration can degrade AVAR by modulating the output frequency of oscillators and introduces phase jitters contributing to measurement errors in the Phase Lock Loop (PLL) tracking loop. Despite these findings, the specific relationship between vibrations and receiver clock errors in dynamic settings remains underexplored.

This study investigates the impact of vibration on clock performance, aiming to mitigate or correct these effects to improve the possibility of receiver fingerprinting in dynamic environments. The novelty of this research lies in exploring the relationship between 3D acceleration time series, Doppler observation noise and estimated clock drifts. Building on findings from previous research, we hypothesize that vibration-induced distortions can be compensated for to regenerate AVAR values that more closely resemble nominal performance observed in static conditions.

Furthermore, this work lays the foundation for future experiments in automotive environments, where vibration profiles may differ, introducing new challenges and opportunities for improving clock-based fingerprinting techniques. Ultimately, the goal is to enhance GNSS receiver resilience in dynamic environments, offering a robust solution for secure and accurate Position, Velocity and Timing (PVT) information in real-world applications.

Pseudo-Random Sequence Generator Using Cascade Chaotic Maps for DSSS and GNSS

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[1]Yonsei University, [2]LIG Nex1

Biography:

Hyojeong Choi received the BS degree in Communication and Information Engineering and the MSEE degree in Electrical Engineering both from Yonsei University in 2018 and 2021, respectively. She is currently a graduate student working toward for PhD under the supervision of Prof. Hong-Yeop Song in Yonsei University, Seoul, South Korea. The area of research interest includes coding theory, PN sequences, related discrete mathematics and their applications to digital communication systems.

Direct Sequence Spread Spectrum (DSSS) is widely employed in satellite navigation systems such as the Global Navigation Satellite System (GNSS) [1]. DSSS systems use pseudo-random noise (PN) sequences to spread signals over a wide frequency band, enabling high reliability even under low-power conditions. However, traditional PN codes exhibit fixed periods, which limit their flexibility and security. For example, GPS, the first commercialized system, has experienced numerous cases of signal spoofing and jamming.

Chaos systems, known for their nonlinearity and extreme sensitivity to initial conditions, can generate sequences with high complexity and unpredictability. These characteristics make chaos systems a promising alternative to address the limitations of conventional PN codes [2].

This presentation introduces the cascade chaotic system (CCS) [3] and analyzes the complexity and correlation properties of chaotic binary sequences generated by CCS. The experimental results, as summarized in Tables I and II, demonstrate that the generated binary sequences exhibit excellent correlation properties, higher complexity compared to m-sequences, and high randomness. Furthermore, the system can produce a diverse set of random binary sequences by varying the control parameters, making it highly suitable for DSSS applications. The analysis compares these sequences with traditional PN codes, such as m-sequences, to evaluate the potential of CCS for DSSS systems.

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TABLE I: Correlation properties for binary chaotic sequences and m-sequence

<table>
<tr><th rowspan="3">Classification</th><th colspan="4">Length: 10000
Initial value: 0.4001 – 0.4100</th><th colspan="4">Length: 100000
Initial value: 0.4001 – 0.4100</th></tr>
<tr><th colspan="2">Normalized Auto-correlation</th><th colspan="2">Normalized Cross-correlation</th><th colspan="2">Normalized Auto-correlation</th><th colspan="2">Normalized Cross-correlation</th></tr>
<tr><th>Average (sidelobe)</th><th>Average (sidelobe max)</th><th>Average</th><th>Max Average</th><th>Average (sidelobe)</th><th>Average (sidelobe max)</th><th>Average</th><th>Max Average</th></tr>
<tr><td>Double-Logistic</td><td rowspan="6">≈ 0.008
≈ -21dB</td><td rowspan="6">≈ 0.04
≈ -14dB</td><td rowspan="6">≈ 0.008
≈ -21dB</td><td rowspan="6">≈ 0.04
≈ -14dB</td><td rowspan="6">≈ 0.002
≈ -27dB</td><td rowspan="6">≈ 0.01
≈ -20dB</td><td rowspan="6">≈ 0.002
≈ -27dB</td><td rowspan="6">≈ 0.01
≈ -20dB</td></tr>
<tr><td>Triple-Logistic</td></tr>
<tr><td>Double-Chebyshev</td></tr>
<tr><td>Triple-Chebyshev</td></tr>
<tr><td>Logisitc-Sine</td></tr>
<tr><td>Logisitc-Sine-Logisitc</td></tr>
<tr><td>m-sequence</td><td>≈ 0.006
≈ -22dB</td><td>≈ 0.02
≈ -16dB</td><td>–</td><td>–</td><td>≈ 0.001
≈ -28dB</td><td>≈ 0.007
≈ -21dB</td><td>–</td><td>–</td></tr>
</table>

TABLE II: NIST Test Results for Various Cascade Chaotic Maps

Classification	Frequency	Run	Rank	FFT	Universal	Serial	Linear Complexity
Double-Logistic	P	P	P	P	P	P	P
Triple-Logistic	P	P	P	P	P	P	P
Double-Chebyshev	P	P	P	P	P	P	P
Triple-Chebyshev	P	P	P	P	P	P	P
Logistic-Sine	P	P	P	P	P	P	P
Logistic-Sine-Logistic	P	P	P	P	P	P	P
m-sequence	P	P	F	F	F	F	F

Analysis of Interleaving and FEC for Improving Galileo Signal Reliability in Urban Environments

Kim G[1], Choi H[1], Chae S[1], Song H[1], Shin J[2], Ahn J[2], Ahn J[3]
[1]Yonsei University, [2]Chungnam National University, [3]Korea Aerospace Research Institute

Biography:
Gangsan received his BS degree in Electronic Engineering from Yonsei University in 2016 and his PhD degree in 2025 under the supervision of Prof. Hong-Yeop Song at Yonsei University, Seoul, South Korea. He is currently a post-doctoral researcher in the same department. In 2022, he served as an AI Science and Technology Soldier at Republic of Korea Army Training and Doctrine Command, where he focused on quantum devices and quantum information theory. His area of research interest includes coding theory, PN sequences, related discrete mathematics and their applications to digital communication systems.

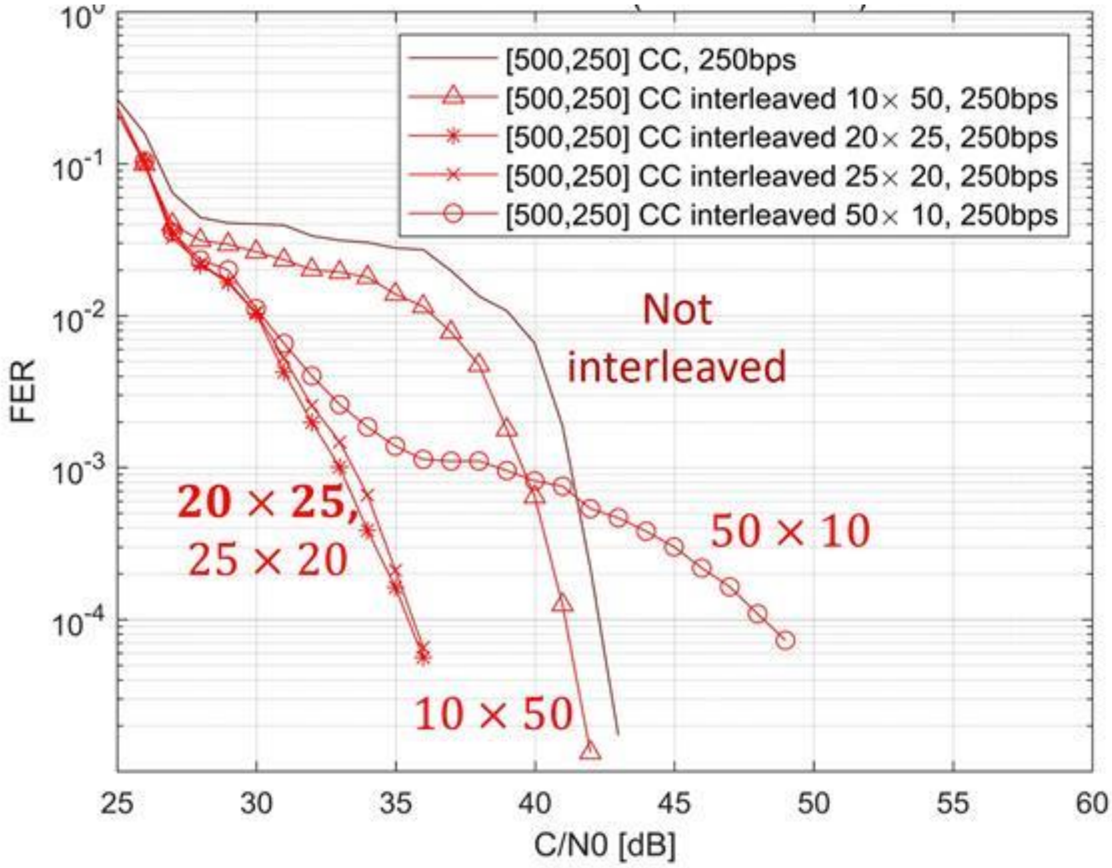
Global Navigation Satellite Systems (GNSS), including Galileo, face challenges in urban environments where multipath effects and obstructions cause fading and burst errors. Galileo currently uses convolutional codes (CC) with a block interleaver to improve reliability. In this study, we analyze the effects of different interleaving configurations and compare the frame error rate (FER) performance of CC with a block interleaver and LDPC with a block interleaver.

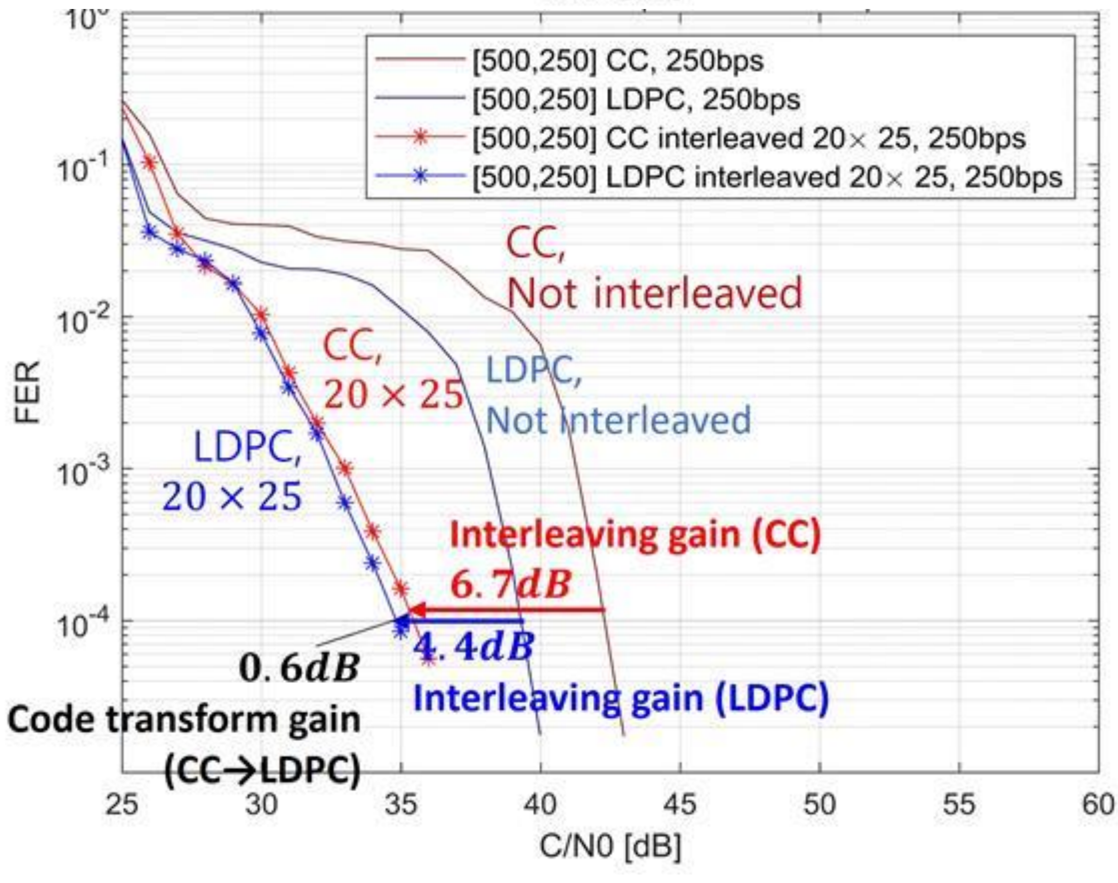
We conduct simulations using the DLR simulator [1], which supports satellite-to-urban channel models. All experiments use codes with a code length of 500 and a message length of 250. The CC used in the simulations is based on a (171, 133) design in octal notation. Through these simulations, we evaluate FER performance under various interleaver configurations. Fig. 1. shows that block interleaver with shallow depth (for example, configuration of 50×10) results in worse FER performance, while block interleaver with narrow width (for example, configuration of 10×50) leads to the appearance of an error floor. These findings suggest that careful tuning of both interleaver depth and width is necessary for better FER performance.

To further explore the impact of coding schemes, we include LDPC codes in the simulations. The LDPC codes are designed using the progressive edge-growth (PEG) algorithm [2]. Fig. 2. shows that LDPC with a block interleaver achieves approximately a 0.6 dB improvement in FER performance compared to CC with a block interleaver for configurations such as 20×25.

[1] B. Krach, A. Lehner, and A. Steingass,
Technical note on the implementation of the land mobile satellite channel model-Software usage, 2005.

[2] X. Y. Hu, E. Eleftheriou, and D. M. Arnold, ``Regular and irregular progressive edge-growth tanner graphs,'' IEEE Transactions on Information Theory, 51(1), pp. 386--398, 2005


[500,250] CC, 250bps
[500,250] CC interleaved 10× 50, 250bps
[500,250] CC interleaved 20× 25, 250bps
[500,250] CC interleaved 25× 20, 250bps
[500,250] CC interleaved 50× 10, 250bps
Not interleaved
20 × 25,
25 × 20
50 × 10
10 × 50
FER
C/N0 [dB]


[500,250] CC, 250bps
[500,250] LDPC, 250bps
[500,250] CC interleaved 20× 25, 250bps
[500,250] LDPC interleaved 20× 25, 250bps
CC, Not interleaved
CC, 20 × 25
LDPC, Not interleaved
LDPC, 20 × 25
Interleaving gain (CC)
6.7dB
4.4dB
Interleaving gain (LDPC)
0.6dB
Code transform gain (CC→LDPC)
FER
C/N0 [dB]

Evolution of Precise Navigation Products at ESA

Zimmermann F[1], Sermanoukian Molina I[2], Gini F[1], Schönemann E[1], Springer T[3], Otten M[3], Dilssner F[3], Mayer V[4], Traiser B[4]
[1]ESA/ESOC - Navigation Support Office, [2]VisionSpace Technologies GmbH, [3]PosiTim UG, [4]LSE Space GmbH

Biography:
Frank Zimmermann is a Navigation Engineer at the Navigation Support Office at ESA/ESOC. He holds a Dr.-Ing. in Aerospace Engineering from University of Stuttgart. He is project manager of the Geodetic Reference Service Provider (GRSP) project at ESA in support of the Galileo program. Before he joined ESA, he worked for many years in space industry, where he was responsible for development projects in the satellite navigation domain and supported startups in the development of navigation applications. He is Deputy Chairman of the German Institute of Navigation DGON.

The Navigation Support Office of the European Space Agency (ESA) is located at the European Space Operations Centre (ESOC) in Darmstadt. It produces high-accuracy navigation products independently for multiple Global Navigation Satellite System (GNSS) constellations and Low-Earth Orbit (LEO) satellites, such as Geodetic and Sentinel satellites. Previous studies demonstrated the performance improvement achieved by the Combination On the Observation Level (COOL) e.g. in the orbit determination system through the inclusion of LEOs in the GNSS processing. This integration at the observation level, combined with the GNSS station network, significantly strengthens the global parameter estimation, among others enhancing the accuracy of the Precise Orbit Determination in terms of satellite orbit overlaps (for both GNSS and LEOs) and station position repeatability before and after ambiguity fixing.
The Navigation Support Office is reviewing its processing setup with the target to exploit the full advantages of combining all available space observations on observation level. This is a necessary step to fully exploit the benefits of the GENESIS mission. A pivotal development in this effort is the integration of LEOs in the GNSS processing and the inclusion of Satellite Laser Ranging (SLR) observations on GNSS and LEOs. SLR provides highly accurate, independent measurements that complement GNSS data by reducing systematic biases and improving orbit accuracy. GENESIS represents a transformative step toward a multi-satellite, multi-technique navigation system, combining GNSS with other geodetic techniques, such as SLR, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and Very Long Baseline Interferometry (VLBI), fostering a unified and robust geodetic framework.
This paper outlines our strategy, presenting the latest results and technical achievements, particularly in the integration of LEOs in the GNSS processing and the combination of the GNSS and SLR observations in a joint processing. It highlights the future roadmap for multi-satellite and multi-technique development within ESA's navigation infrastructure.

Galileo High Accuracy Service: Exploring Atmospheric corrections and Phase Biases for PPP Performance

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[1]Technical University of Munich, [2]Universität der Bundeswehr München, [3]Industrieanlagen-Betriebsgesellschaft mbh (IABG)

Biography:
Camille Parra is currently a Ph.D. candidate at the Technical University of Munich. She received a Master's degree in Geomatics and Geodesy from the École Nationale des Sciences Géographiques in France. Nowadays, she focuses her research on GNSS positioning, and in particular on High Accuracy Services and Galileo utilization.

Galileo High Accuracy Service (HAS) provides free corrections to improve Precise Point Positioning (PPP). The service is divided into two levels: the first level, available globally, provides corrections for satellite orbits, clocks, and code biases, while the second level, limited to Europe, will incorporate atmospheric corrections. Our work focused first on evaluating the current state of HAS and then on assessing its potential future performance by generating atmospheric corrections and phase biases.
To verify the current HAS corrections, a PPP analysis was conducted using data from 132 EUREF reference stations across Europe, from DOY 92 to 153 of 2023. This evaluation employed a dual-constellation setup (GPS and Galileo) in static mode with 30-second data sampling, float ambiguities, and uncombined measurements. The computations relied on the current HAS corrections, including ephemeris and clock corrections, and code biases. As shown in Table 1, the analysis demonstrated good performance, achieving a 68% accuracy level, with horizontal and vertical errors of 4.5 cm and 4.9 cm, respectively, over 24-hour sessions.
Building on these results, atmospheric corrections were generated by interpolating PPP ionospheric and tropospheric delays from 34 selected stations among the ones of the network. These corrections were then applied as constraints in kinematic PPP positioning for 64 additional EUREF stations during 3-hour sessions, maintaining the same dual-constellation approach and time period.
The inclusion of atmospheric corrections significantly improved positioning performance (Table 2): horizontal accuracy increased by 43%, vertical accuracy by 47%, and horizontal convergence time was reduced from 127 minutes to 60 minutes.
These results highlight the benefits that the second service level could offer. In addition to the atmospheric corrections, the impact of phase biases on PPP performance with HAS is currently being analysed.

ACKNOWLEDGEMENTS
We would like to acknowledge Munich Aerospace for the scholarship that made this study possible.

Horizontal Accuracy [cm]		Vertical Accuracy [cm]		Convergence Time at 68% [minutes]	
68%	95%	68%	95%	Horizontal (=15cm)	Vertical (=20cm)
4.4	8.4	4.7	9.0	18	9

Table 1: Static PPP processing performance for 132 stations over Europe . From DOY 92 to 153, 24-hour sessions.

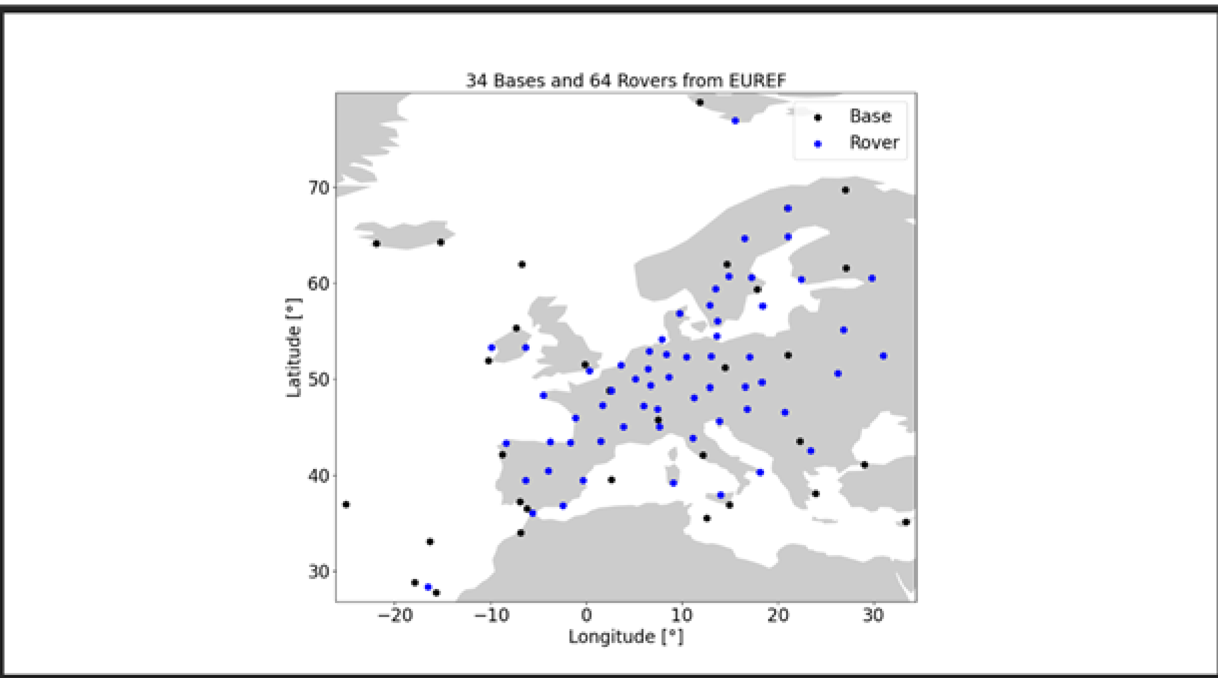

Figure 1: Networks of the Bases and Rovers among EUREF stations
From DOY 92 to 153, Year 2023.

Atmospheric corrections?	Horizontal Accuracy [cm]		Vertical Accuracy [cm]	
	68%	95%	68%	95%
No	14.6	30.7	16.3	39.2
Yes	8.3	16.1	8.6	18.4

Table 2: Accuracies of PPP with atmospheric corrections.

From DOY 92 to 153 of year 2023.

Transmission of ionospheric parameters in Galileo HAS Phase 2

Willems T[1], Fernandez-Hernandez I[1], Winkel J[1], O'Driscoll C[1], Mattis M[1], Zoccarato P[3], Juan J[2], Sanz J[2], Rovira A[2], Timoté C[2]
[1]European Commission DG DEFIS, [2]Universitat Politècnica de Catalunya, [3]European Commission Joint Research Centre

Biography:
Tom Willems obtained a PhD degree from Ghent University in 2006. From 2006 to 2021, he worked as embedded software engineer in GNSS signal processing and as system engineer at Septentrio and Antwerp Space. At both companies, he was deeply involved in the Galileo Test User Receiver projects for ESA. Next, he started working as an independent consultant. Since 2024, he is employed as Senior Consultant at CGI where his current assignment is to provide advisory services to the EC.

The Galileo High Accuracy Service (HAS) has been operational since January 2023, offering good and stable performance. The next phase of HAS is currently being implemented, offering enhanced performance and new functionalities. The HAS enhanced service declaration is foreseen for Q3 2026.

One of the improvements in HAS Phase 2 will be the provisioning of ionospheric parameters to users in the European Coverage Area (ECA). Phase 2 will provide ionospheric vertical delays (IVDs) and ionospheric vertical accuracies (IVAs). IVDs and IVAs will be provided for ionospheric grid points (IGPs) which receivers in the ECA area can see down to 10° elevation. Data for two ionospheric layers (at 270 km and 1600 km) is planned to be provided, for a total of 899 IGPs. Apart from the ECA mask, other IGP masks can also be supported.

Transmitting these ionospheric parameters for a vast number of IGPs requires a significant amount of bandwidth. HAS Phase 2 introduces the new Message Type 2, which will include an IVD and an IVA block. To conserve bandwidth, various encoding schemes were evaluated, with a focus on lossless compression of the IVD block. This analysis was supported by a large dataset of IONEX (Ionosphere Map Exchange) files containing TEC and RMS maps at 5 minute intervals for both layers.

The details of the selected encoding scheme will be presented together with results based on historical data spanning 108 days. Compared to raw encoding of the IVDs using a fixed number of bits, the results show an IVD block size reduction between 12% and 38% and a mean size reduction of 27%. The encoding scheme will be evaluated further during the HAS Phase 2 implementation.

Quality of orbit predictions for real-time GNSS solutions

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[1]Wrocław University of Environmental and Life Sciences, [2]Geodetic Observatory Pecný

Biography:
Krzysztof Sośnica graduated from the University of Bern, Switzerland, in 2014, obtaining a Ph.D. degree in Physics. He is now a full professor of satellite geodesy. His activities include precise orbit determination of GNSS and geodetic satellites, reference frame realizations, Earth's gravity field recovery, and the enhancement of the consistency between GNSS and SLR solutions.

The high-quality orbit predictions are crucial for many GNSS applications, including real-time solutions or the tracking of GNSS satellites by Satellite Laser Ranging stations. In this study, we discuss the current performance of the orbit prediction strategies for GPS, Galileo, GLONASS, BDS-3, and QZSS satellites. We test the length of the orbit fit for the 1-day, 4-day, and 9-day predictions, as well as the optimum orbit parameterization, i.e., the number of empirical orbit parameters of the ECOM model and using the a priori box-wing model.

We found that fitting an initial 2-day orbit arc is the optimal solution for all analyzed navigation satellite constellations. When official satellite construction metadata are available, e.g., for Galileo and QZSS, the hybrid strategy of combining both empirical and physical models leads to the best results, i.e., using the extended Empirical CODE Orbit Model (ECOM2) with box-wing models. However, the optical surface properties in metadata for GPS, BDS-3, and GLONASS are inaccurate or derived empirically; therefore, using a priori box-wing model has a marginal impact on the quality of orbit predictions for these constellations. Moreover, using stochastic pulses for the orbit fit always leads to inferior quality of orbit predictions and, thus, should be avoided.

When employing the most effective prediction strategy, the median 3D position errors after the 1st day of prediction are equal to 6, 7, 10, 8, and 15 cm for satellites GPS-IIF, Galileo-FOC, GLONASS-M, BDS-3 SECM, and QZSS, respectively. Thus, despite the much lower mass of the Galileo-FOC compared to other GNSS satellites, the orbit predictions are of a very high quality due to metadata that allows for a proper adjustment of the impact of the solar radiation pressure that is the main non-gravitational perturbing force.

GRIPP: an Open-Source and Portable SDR Oriented GNSS/SBAS Receiver

Fayon G[1], Castel N[2], Circu C[2], Weiler R[1], Sobreira H[1], Bni Lam N[1], Meersman M[1], Nummisalo L[1], Hahn J[1], Wallner S[1], Sirikan N[1]

[1]European Space Agency, [2]European Space Agency

Biography:

Mr. Gaëtan Fayon holds an engineering degree from IMT Atlantique (2014) and a Ph.D. from the University of Toulouse (2017), both in space communication systems. After 5 years working as system integration and validation engineer in space and automotive industries in France, he joined in 2022 the European Space Agency (ESA) to work on the Galileo project. His main role today focuses on Galileo system integration, validation and qualification, but he is also involved in the Digital Transformation, supporting new processes and tools deployment in the aerospace sector.

Global Navigation Satellite Systems (GNSS) and Satellite-Based Augmentation Systems (SBAS) are today widely used in various domains, from automotive applications to safety of life. Due to their rapid evolutions, constantly aiming to improve the accuracy and robustness of the PVT (Position, Velocity and Time) solutions offered, a constant wave of applications conception, development and updates is experienced.

In the light of this, opening the access to the PVT algorithms is needed. It can ease not only the development of such applications by navigation engineers, but also introduce GNSS and SBAS technology in a ludic way to students and general audience. As usage of industrial mass-markets and professional receivers is limited by their non accessible proprietary algorithms, the use of open-source solutions, like GNSS-SDR or FGI-GSRx, has to be encouraged. Yet, such solutions can be sometimes difficult to tame, in terms of code understanding and tools deployment, at software and hardware level. They can also limit for junior engineers and students the opportunity to code by themselves a GNSS/SBAS receiver.

The development of the GRIPP (GNSS/SBAS Receiver, Independent and Portable PVT) equipment aims to satisfy these goals. This system (Figure 1) is composed of:
- Raspberry Pi, acting as a PVT solutions computer and datastore,
- Pocket SDR device and associated open-source software. This SDR (Software Defined Radio) is specifically designed to retrieve GNSS RAW data,
- dual or triple-band L-band antenna.

This system, compatible with Galileo E1, E5 and E6 and GPS L1, L2 and L5 frequency bands, hosts an open-source software based on the Pocket SDR one. This software (Figure 2) aims to store several hours of RAW navigation messages and compute its own PVT solutions through a configurable algorithm. This one, in development, can segregate live or recorded signals received depending on the constellation and/or satellites in view.

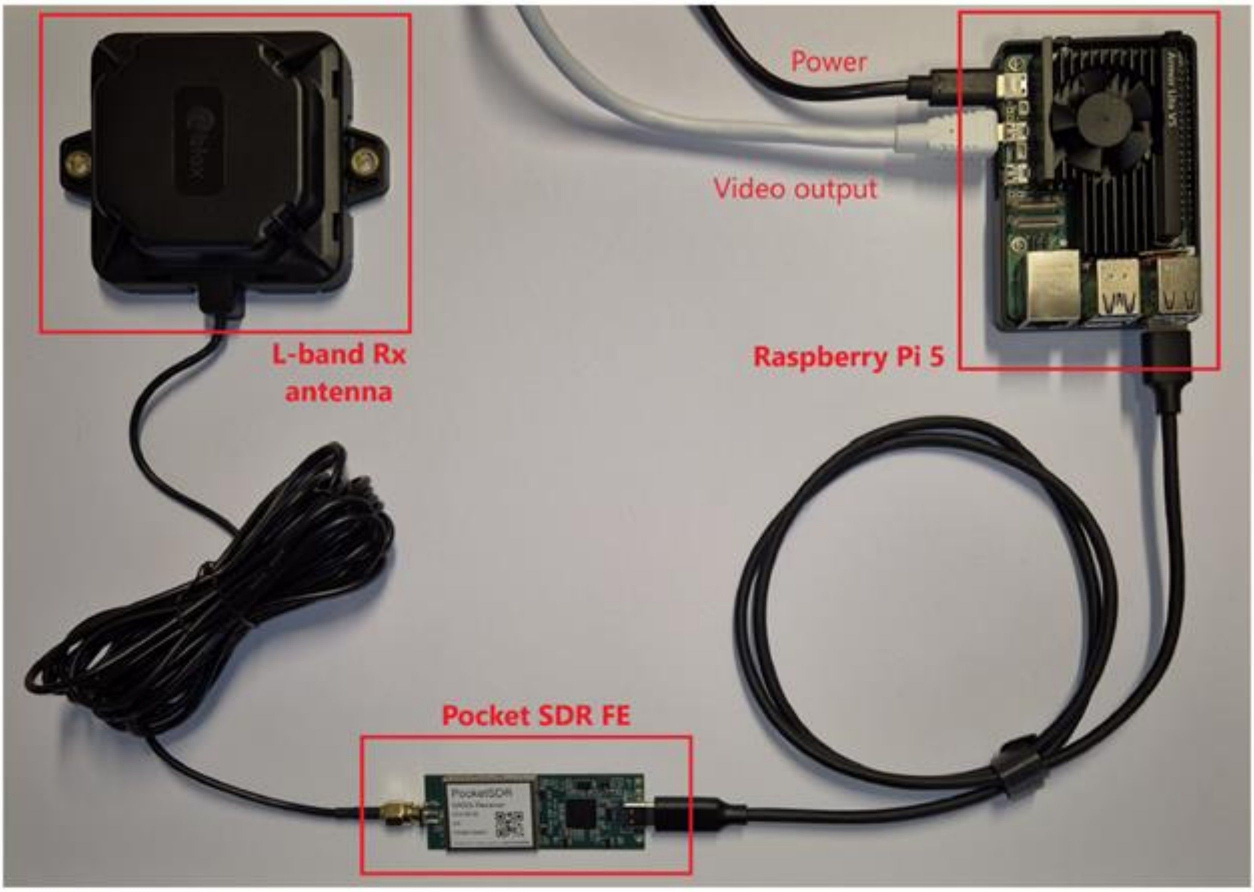


Figure 1: GRIPP hardware prototype

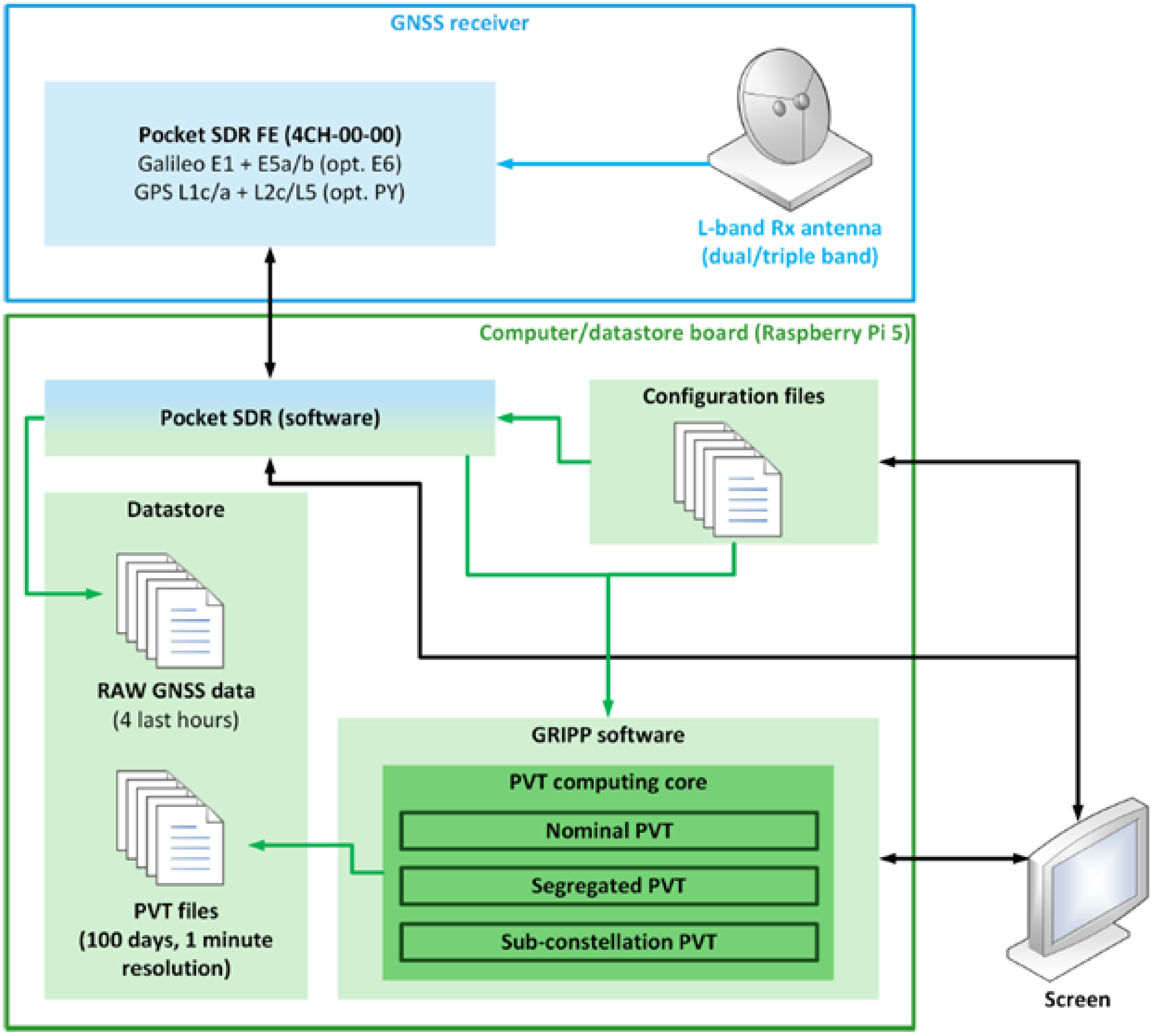


Figure 2: GRIPP software architecture

On the context-aware GNSS navigation: training and test of a K-Nearest Neighbors in different environments

Cappello G[1], Angrisano A[2], Gioia C[3], Maratea A[4], Gaglione S[1,4]
[1]International PhD Programme, UNESCO Chair "Environment, Resources and Sustainable Development", Department of Science and Technology, University of Naples "Parthenope", [2]Department of Engineering, University of Messina, [3]European Commission, Joint Research Center, [4]Department of Science and Technology, University of Naples "Parthenope"

Navigation for the Mass Market, Conference Room A, May 21, 2025, 4:30 PM - 5:50 PM

Biography:
Salvatore Gaglione is Full Professor of Geomatics at the Science and Technology Department of the University of Naples "Parthenope" and scientific director of the PArthenope Navigation Group (PANG) Laboratory. From 2019 He is the Programme Coordinator of the Bachelor Degree in "Ship Technical Management" at same University. On 2010 he was Visiting Academic at "Department of Geomatics Engineering" at the University of Calgary. In the last Academic year, he gives lecture in field of: Radio Navigation and Inertial and Integrated Navigation.
Professor Gaglione is; Vice-President of the International Association of Institutes of Navigation (IAIN); member of the Italian Institute di Navigation" (IIN) and its delegate in European Group of Institutes of Navigation (EUGIN. His research activities are focused on GNSS positioning and integration with other sensors (INS, Camera etc.) for several applications.

GNSS (Global Navigation Satellite System) navigation can be challenging in urban environment, especially using low-cost devices since numerous outliers can lead to inaccurate PVT (Position, Velocity, Time) estimates. Among the possible solutions, recently, Machine Learning (ML) solutions to improve the GNSS positioning became popular, being applied at various levels: LOS (Line-Of-Sight) and NLOS (Non-LOS) signal classification; context recognition; interference detection and so on.
In this contribution, a ML algorithm for automatic context determination is proposed. The PDOP (Position Dilution Of Precision) and visibility variation on a short time-window, and C/N0 (Carrier-to-Noise Ratio) differences among couple of satellites are used to train a K-Nearest Neighbors (KNN) classifier.
This research aims to develop a fast-to-train classifier able to identify the scenario around the receiver with pre-PVT features. The context information can be exploited to apply ad-hoc strategies, at the measurement-level, when an urban canyon context is detected, with the aim to improve the PVT accuracy.
The proposed algorithm was tested using GPS and Galileo data collected with a low-cost GNSS receiver in different conditions and in static and kinematic modality.
The training performance were assessed in terms of confusion matrix, accuracy percentages and ROC (Receiver Operating Characteristic) curve.
The KNN classification performance were demonstrated in multiple static tests, where the a-priori context information is known, in terms of accuracy percentage. Then, also the kinematic mode was evaluated despite the rapid context variation allows a qualitative assessment of the classification performance. Additionally, the computational efficiency of a positioning algorithm, with and without the context classification layer, will be analyzed to evaluate the possibility to adopt the proposed approach for real-time applications.
The results highlighted the KNN potential: more than 90% of accuracy has been obtained in the training phase, while an accuracy of about 80% has been obtained in the test phase.

Development and Validation of GNSS Environmental Context Indicator for Smartphone Raw GNSS Data Processing

Park B[1], Park K[1,2], Kim M[1,2], Lee J[1]
[1]Inha University, [2]PPSOL Inc.

Biography:
Bong-Gyu Park received his B.S. degree in Geoinformatic Engineering and Electronics Engineering from Inha University, South Korea, and he is currently an M.S. student in the Department of Geoinformatic Engineering at Inha University.
His research interests include RTK algorithm development, smartphone GNSS, and deep learning.

The Global Navigation Satellite System (GNSS) signals taken from Android smartphones are being actively studied to meet the high demand for mobile positioning. To ensure users receive high-quality, real-time location data, it is essential to guarantee reliability and consistent accuracy. However, it is difficult to achieve high accuracy with smartphones due to inherent limitations. In this study, aiming to overcome these shortcomings, the GNSS Environmental Context Indicator (ECI) was developed as an index for predicting observation quality and positioning accuracy.

To evaluate signal reception sensitivity and satellite geometry, the Carrier-to-Noise Density Ratio (C/N0) and Position Dilution of Precision (PDOP) were utilized. The logarithmic scale of PDOP was calculated, and this scale, which varies significantly depending on satellite arrangement, was adjusted to align with the scale of C/N0. Additionally, the average Z-score of C/N0 was employed. Finally, weights for each parameter and a scale factor for adjusting the ECI size were implemented.

The experiment was conducted with both stationary and walking tests. Observation data were collected from open-sky environments, urban areas, and indoors. The ECI computation and its probability in addition to the number of visible satellites were analyzed. As a result, it was confirmed that ECI can quantify quality changes according to the observation environment in all test cases. In the semi-indoor situation, the number of visible satellites decreases, and the signal reception sensitivity is low. Thus, the ECI index increases up to the maximum value of five. Whereas the ECI decreases down to the lowest value of one as the user moves to the open sky environment. It increases again to three or four as one enters the urban area. In particular, the ECI temporarily increases as it passes through the signal-obstructed area and the density of surrounding buildings has a direct effect on the ECI computation.

Performance assessment of GNSS Positioning with Receiver Clock Modelling in Different Urban Areas

Zhang L[1], Zhang G[1], Steffen S[2]
[1]The Hong Kong Polytechnic University, [2]Leibniz Universität Hannover

Biography:
Liyuan Zhang is currently a PhD student in the Department of Aeronautical and Aviation Engineering, The Hong Kong Polytechnic University. His research interests include 3D mapping-aided GNSS positioning and GNSS receiver clock modelling in urban canyons.

In recent years, the demand for accurate positioning solutions based on the global navigation satellite system (GNSS) in civilian applications has grown significantly, driven by advancements in intelligent transportation systems and location-based services. As an unknown parameter estimated alongside the position, appropriate modeling of the receiver clock bias can improve positioning performance, particularly when the number of observations is limited. However, in urban areas where most applications operate, the GNSS signal can be easily reflected by buildings with an extra path delay, introducing multipath or non-line-of-sight (NLOS) errors that significantly degrade the performance of receiver clock modeling. This study aims to evaluate the GNSS clock modelling performance in different urban areas. A standard Kalman filter will be used to model the receiver clock bias during positioning, in which the clock modelling accuracy in different urbanization-level environments will be assessed, to evaluate its correlation with urbanization, especially the multipath effects and NLOS receptions. Besides the performance assessment, the potential of receiver clock modelling in improving urban positioning accuracy will be investigated. More specifically, a ray-tracing method simulates NLOS propagation paths based on 3D building models and ground-truth positions to estimate NLOS extra delay, thereby correcting pseudorange measurements. Then, the NLOS error rectified measurements will be applied with the preceding positioning method, to evaluate the potential of employing an appropriate receiver clock modelling to improve urban GNSS positioning accuracy. The contributions of this paper are summarized as follows: 1) assess the performance of GNSS receiver clock modelling in different urbanization level environments; 2) evaluate the potential of incorporating receiver clock modelling to improve GNSS positioning performance in dense urban areas; 3) investigate the potential of employing receiver clock modelling to improve the positioning algorithm relying on master satellite selection.

Experimentation of an integrated Vision-aided Inertial Navigation System with Orthophoto Matching on a fixed-wing UAV

Sivalingam B[1], Hagen O[1]
[1]Norwegian Defence Establishment

Biography:
Baheerathan Sivalingam is a senior researcher at the division of Defence systems, Norwegian Defence Research Establishment. Mainly working with UAV related projects. Research interests are in the area of image analysis, pattern recognition, and image-aided navigation. Presenting Experimentation of an integrated Vision-aided Inertial Navigation System with Orthophoto Matching on a fixed-wing UAV.

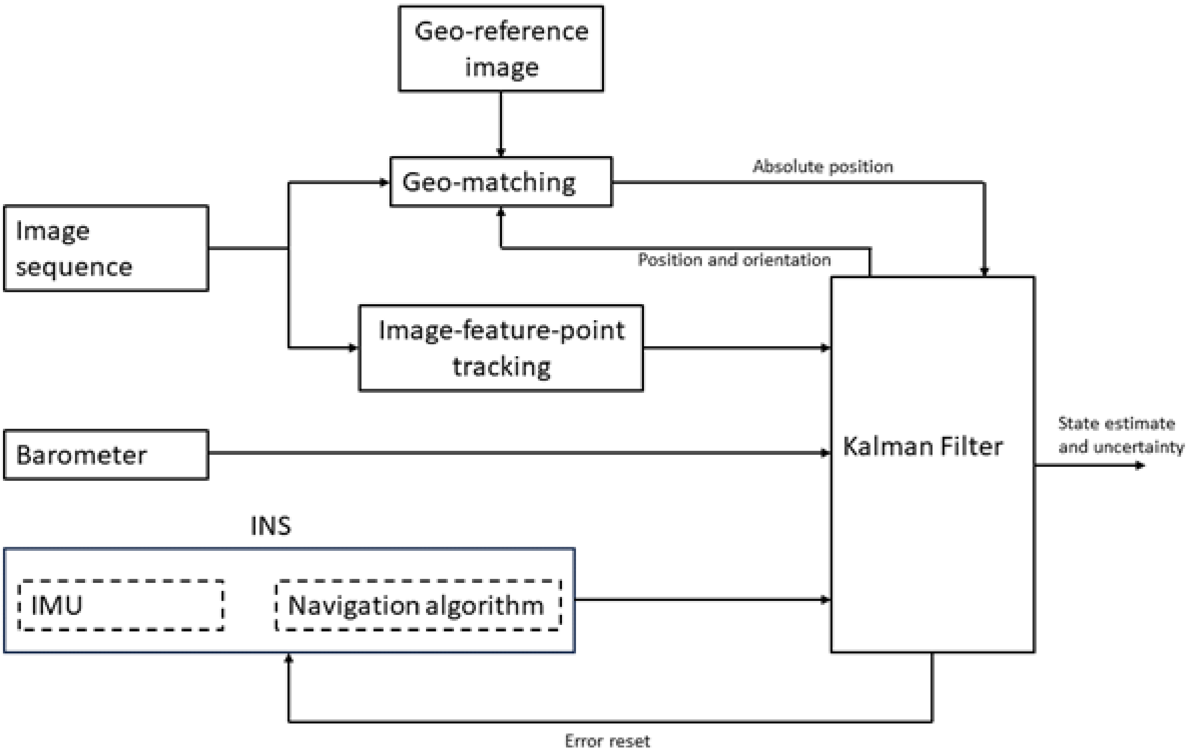
Unmanned aerial vehicles (UAVs) rely on Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU) for navigation, but small UAVs often use low-grade IMUs, causing significant drift during GNSS outages. Image-aided navigation offers a possible solution. The Norwegian Defence Research Establishment (FFI) has developed a real-time Vision-aided Inertial Navigation System (VaINS) that tightly integrates IMU data with image feature points in an extended Kalman filter (EKF). It was tested on a fixed-wing UAV with varying camera pitch angles, improving navigation accuracy.

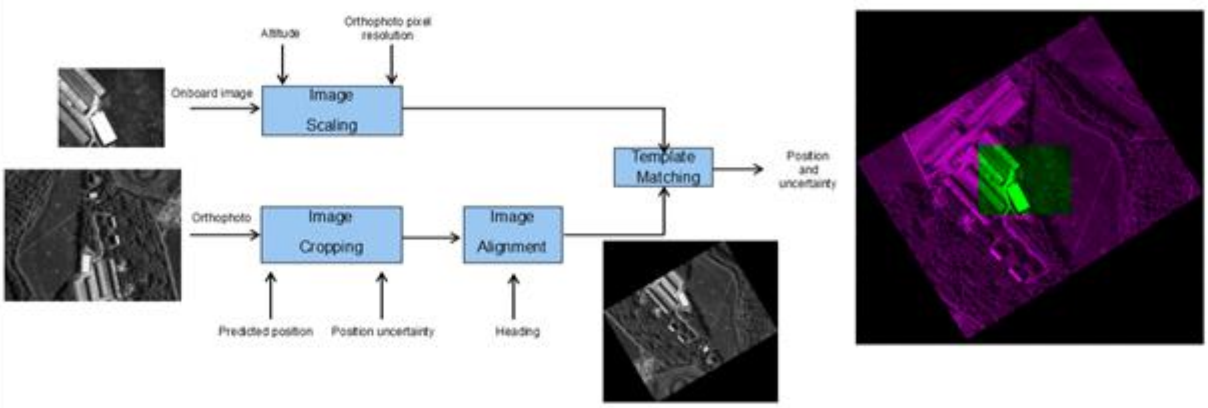
The navigation solution from VaINS still experiences drift over time, requiring compensation. This study integrates an orthophoto-matching algorithm, that matches onboard nadir images with geo-referenced orthophotos using normalized cross-correlation. The following figures illustrate the integration of the orthophoto-matching module with VaINS. VaINS provides initial position and orientation estimates to the orthophoto-matching module, which updates the EKF with its global position estimate upon a reliable match. To integrate this global position, the accuracy and validity of the estimates must be established. This study proposes a 2D generalization of Zucker's algorithm using a simplified stochastic model.

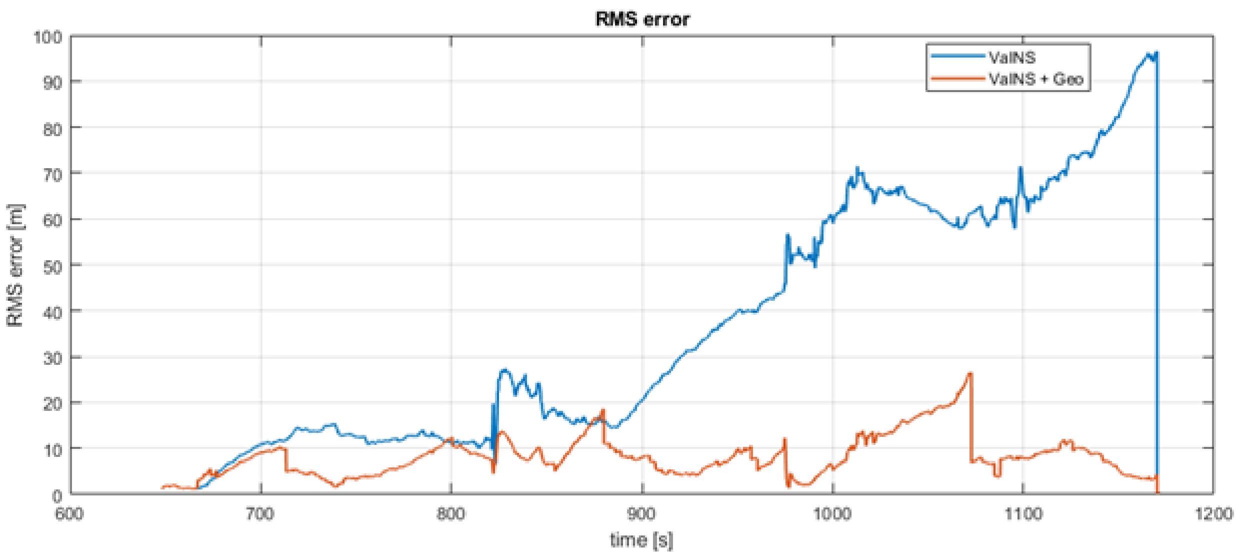
The integrated navigation solution and VaINS are independently compared to the reference solution during simulated GNSS-denied intervals to evaluate performance. This is measured by the root-mean-square (RMS) error between each solution and the reference. Two data sets are analyzed.

The following figures show the RMS plot for the two data sets. The blue line represents RMS plots for the VaINS solution, and the red line represents integrated solution.

The integrated solution showed significantly better performance than VaINS alone. The orthophoto-matching performed well in areas with man-made structures and produced some reasonable matches in areas of vegetation and lake and river shores. This study is preliminary, and further experiments with alternative Orthophoto-matching methods will be conducted in the future.


Geo-reference image
Geo-matching
Absolute position
Image sequence
Position and orientation
Image-feature-point tracking
Barometer
Kalman Filter
State estimate and uncertainty
INS
IMU
Navigation algorithm
Error reset


Altitude
Orthophoto pixel resolution
Onboard image
Image Scaling
Template Matching
Position and uncertainty
Orthophoto
Image Cropping
Image Alignment
Predicted position
Position uncertainty
Heading


RMS error
ValNS
ValNS + Geo
RMS error [m]
time [s]
0
10
20
30
40
50
60
70
80
90
100
600
700
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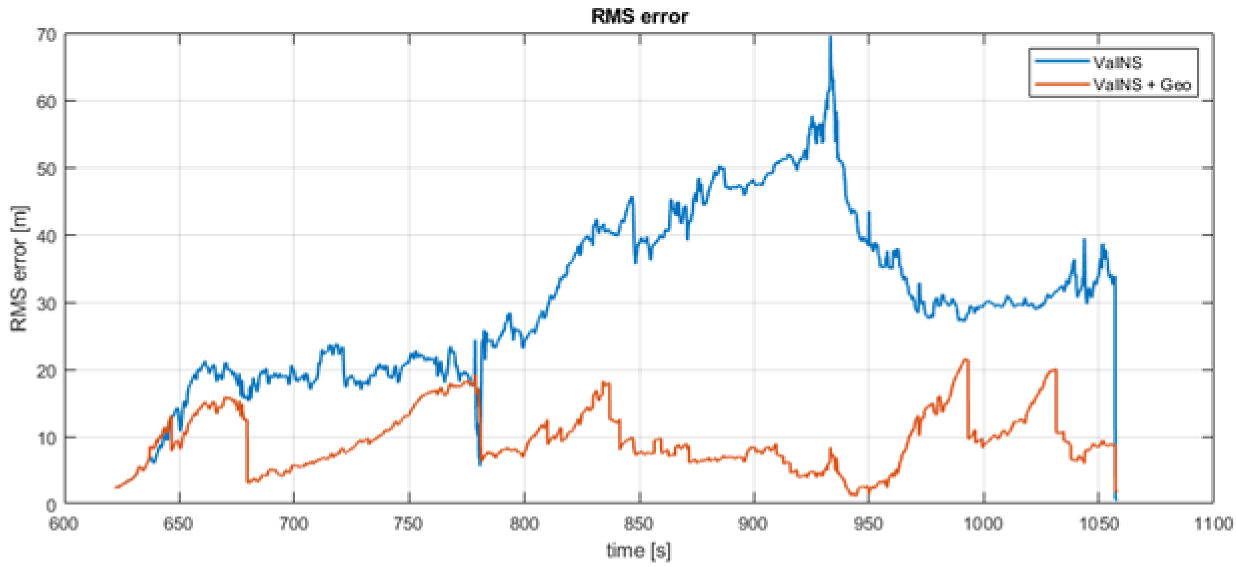
900
1000
1100
1200



RMS error
VaINS
VaINS + Geo
RMS error [m]
time [s]
0
10
20
30
40
50
60
70
600
650
700
750
800
850
900
950
1000
1050
1100

Using Signals of Opportunity for Robust PNT based on LEO Satellites

Navarro P[1], Tobías G[1], Sobrero F[1]
[1]GMV

Biography:
Pedro Navarro Madrid has a Master of Science in Mathematics from the University of Murcia (Spain). He has worked at GMV since 2002 in different GNSS projects related to precise orbit determination and user positioning, including safety-critical applications.

PNT (Positioning, Navigation and Timing) services based on GNSS MEO constellations are a key (and often critical) component in many applications. However, in recent years, the usage of jamming and spoofing techniques in extensive geographical areas is posing an important threat to the users, especially for safety-critical applications. The consequences of outages of the GNSS services or attacks from malicious actors could be very damaging. Hence, alternative ways of providing PNT solutions are needed to increase the robustness and resilience of the systems that use them.

The candidate technology explored in this paper takes advantage of the many LEO satellite constellations deployed for different applications, especially communications. It uses the RF signals transmitted by non-PNT LEO satellites, which are often more robust than GNSS ones, due to the higher received power given the lower orbit compared to MEO, and the higher frequency diversity. They can be used as Signals of Opportunity (SOOP), providing a candidate technology for integration within Alternative PNT (AltPNT) systems.

This work describes and studies the concept of a positioning system that processes signals from communication LEO satellites to deliver positioning capabilities during periods of GNSS denial., The system has a network of monitoring sensors that acquire and process RF signals from multiple LEO satellite constellations to generate Frequency-Difference-Of-Arrival (FDOA) and Time-Difference-Of-Arrival (TDOA) observations.

The paper presents the analysis run by GMV with the use of simulated TDOA and FDOA observations for different network configurations and LEO constellations. The paper shows the results of the experimentation and the associated assessment of achievable performance, both in terms of orbit determination and user positioning accuracy.

Quantum Time Transfer and Resilient PNT Architecture Simulation Model

Mitlyng D[1], Page C[1]
[1]Xairos UK Ltd, [2]Xairos Systems, Inc., [3]KISPE Ltd

Biography:
Carlo Page, Lead Quantum Scientist leads quantum time transfer algorithm and simulation model development at Xairos. His expertise spans application domains including satellite quantum technologies, quantum network synchronisation and secure communications. Carlo has a Master's degree in Physics from the University of Bristol and a PhD in Quantum Optics from the University of Bath. Carlo will be presenting recent simulation work outlining a space deployable quantum time transfer system for resilient PNT architectures.

Xairos has developed quantum time transfer (QTT) system that uses heritage entangled photon hardware for very secure time transfer at sub-nanosecond precision. The basics of this QTT system were presented at the 2024 ENC.
Since then the design and a high-fidelity simulation model has progressed under ESA NAVISP funding. The simulation model has been used to further advance the QTT algorithm, add in security features to detect man-in-the-middle and spoofing attacks, and simulate various design architectures. The initial architecture under development is a resilient timing distribution implemented on a low Earth orbit (LEO) satellite with QTT to ground links. But the model is also capable of evaluation other architectures, including MEO, GEO, and HEO orbits; inter-satellite links for synchronizing satellites in a constellation and formation flying; and terrestrial time distribution from high-altitude platforms, UAS, aircraft, and other mobile vehicles or stationary sites.
This presentation will describe the basics of the QTT design, the simulation model, the design elements and resilient PNT architectures in development, and the roadmap for using this simulation model to develop a commercially-viable system that can augment timing from GNSS.

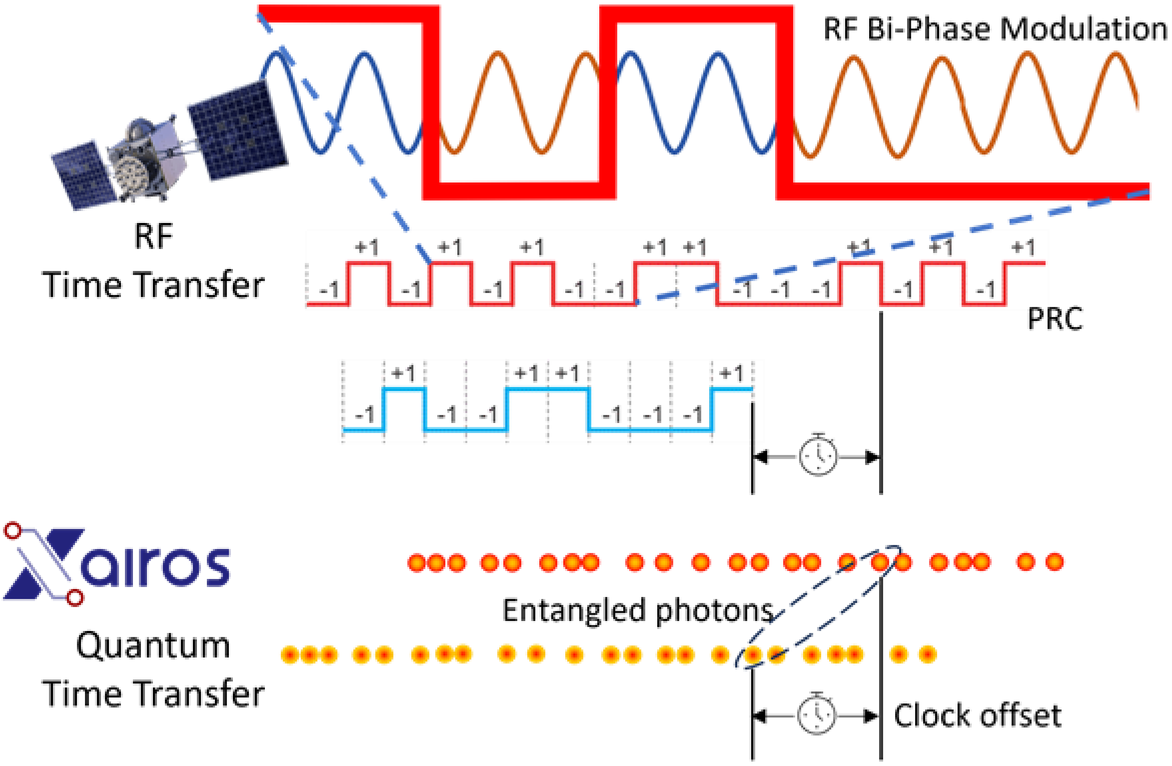


Figure: Quantum vs. RF Time Transfer

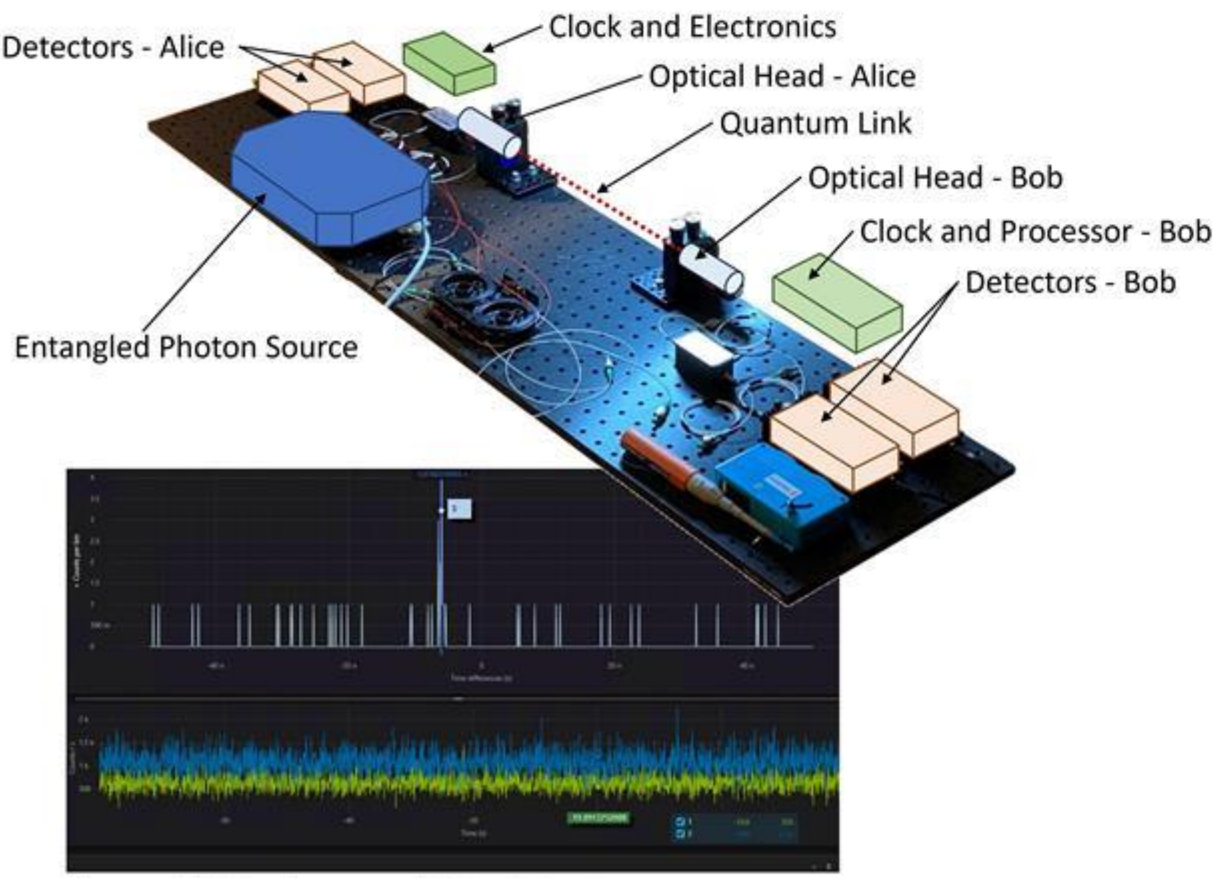


Figure: QTT Hardware and Data Output

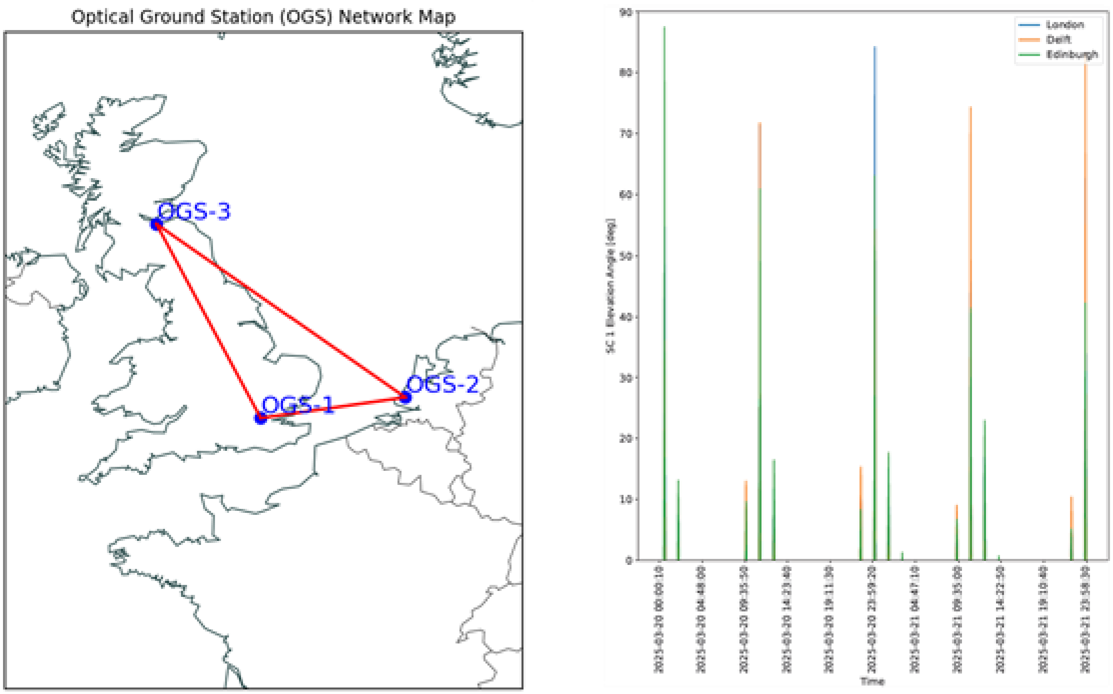


Figure: QTT Simulation Model for LEO Passes over Three Ground Sites

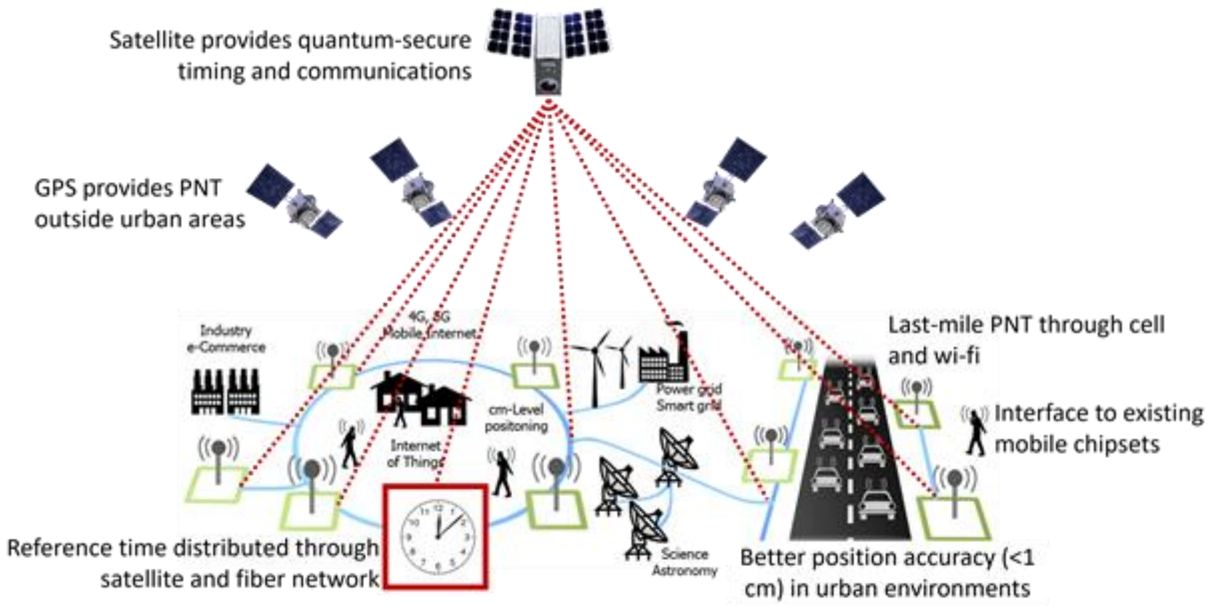


Figure: SuperGPS Architecture that Incorporates QTT Architecture

GNSS Receiver with Advanced PULSAR Enhancements (GRAPE): Increasing Resilience and Performance using LEO PNT Signals

Williams C[1], Macleod M[1], Davies N[1], Marathe T[2], Pant A[2], Gala M[2], Reid T[2], Leclère J[2]
[1]QinetiQ, [2]Xona Space Systems

Biography:
Cian Williams is an Associate Systems Engineer at QinetiQ in the UK, and is the Technical Lead for QinetiQ's contribution to project GRAPE. He holds a Master's degree in Aerospace Engineering from the University of Bath, where he specialised in designing avionics systems for autonomous uncrewed aircraft. His work at QinetiQ involves developing resilient high-performance PNT systems, with a particular focus on utilising and augmenting QinetiQ's Q40 GNSS receiver design. His presentation will describe an ongoing project that aims to integrate the new LEO PNT signals being developed by Xona Space Systems into the Q40 GNSS receiver.

Position, Navigation and Timing (PNT) information is fundamental to many aspects of modern life including for demanding applications in Critical National Infrastructure. The availability and performance of Global Navigation Satellite System (GNSS) signals mean that their use has become ubiquitous. However, increasing demands for positioning performance, PNT availability and resilience has highlighted the need for robust/resilient complementary sources of PNT. New Low-Earth Orbit (LEO) signals are designed to provide enhanced PNT performance and, with increased signal strength can deliver increased availability and resilience in challenged environments such as indoors or in the presence of interference/jamming. PULSAR is a LEO constellation designed as the first global, complementary PNT system that is independent from but able to also work in conjunction with extant GNSS services.

This paper will introduce the Xona PULSAR constellation and signals and the technical innovations that enable it to deliver high performance, resilient PNT services to complement GNSS and other PNT sources.

PULSAR's signals operate within existing GNSS bands and utilise similar structures to modernised GNSS services, but feature notable differences inherent to LEO operation. To deliver global coverage, PULSAR must employ many more satellites than MEO GNSS. This complicates initial acquisition as the receiver must search for a greater number of satellites to determine which are in view. Efficient search strategies are required that leverage the design of PULSAR to achieve fast acquisition times. Similarly, processes for selecting signals for improved geometry must handle the increased number of satellites in view and their faster transit times. This work will describe newly developed satellite search and signal selection strategies.

Finally, the paper will present initial results for the added resilience offered by the PULSAR X1 signal.

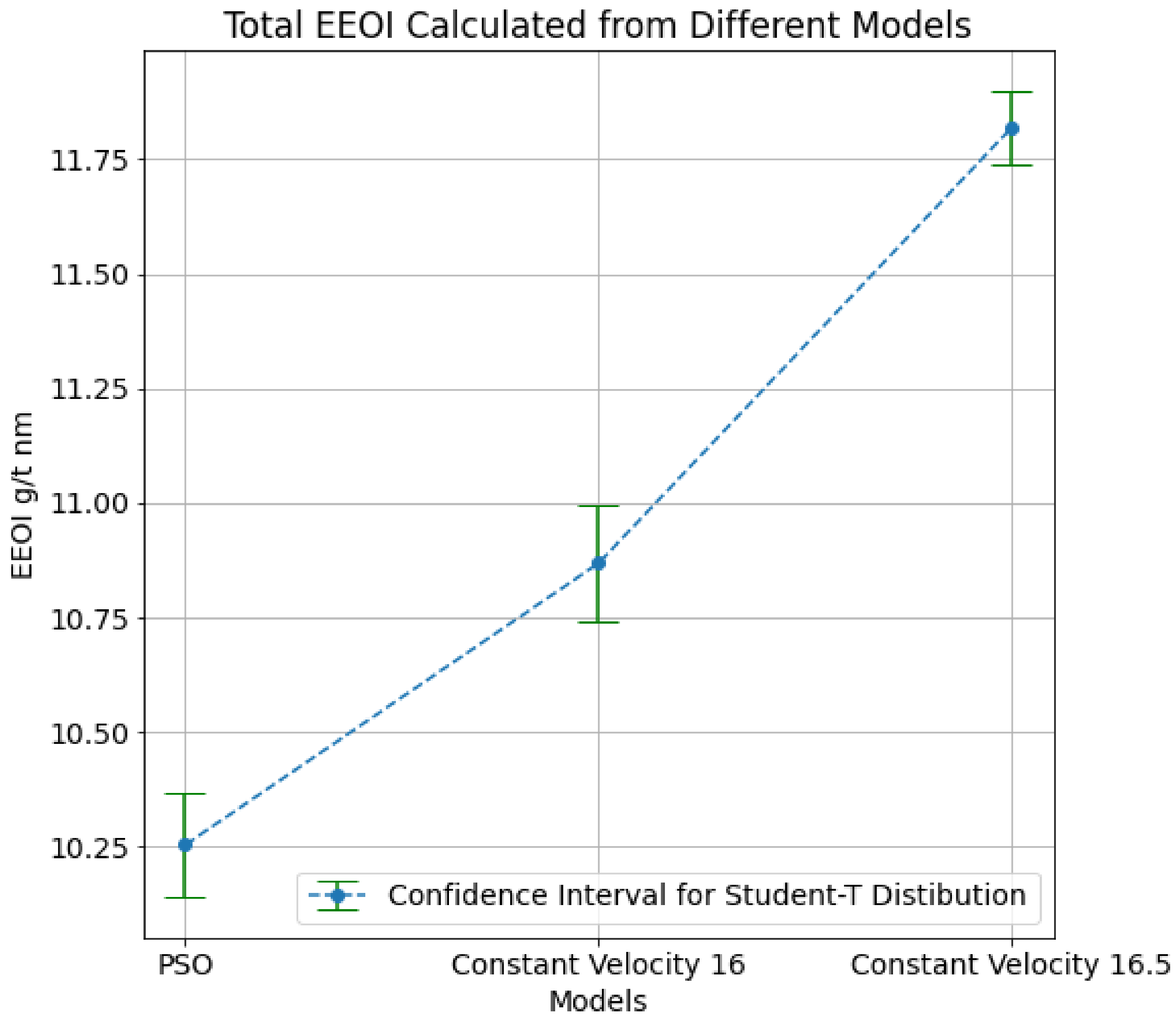
This paper reports work being undertaken within the NAVISP Element 2 GRAPE project supported by UK Space Agency and European Space Agency.

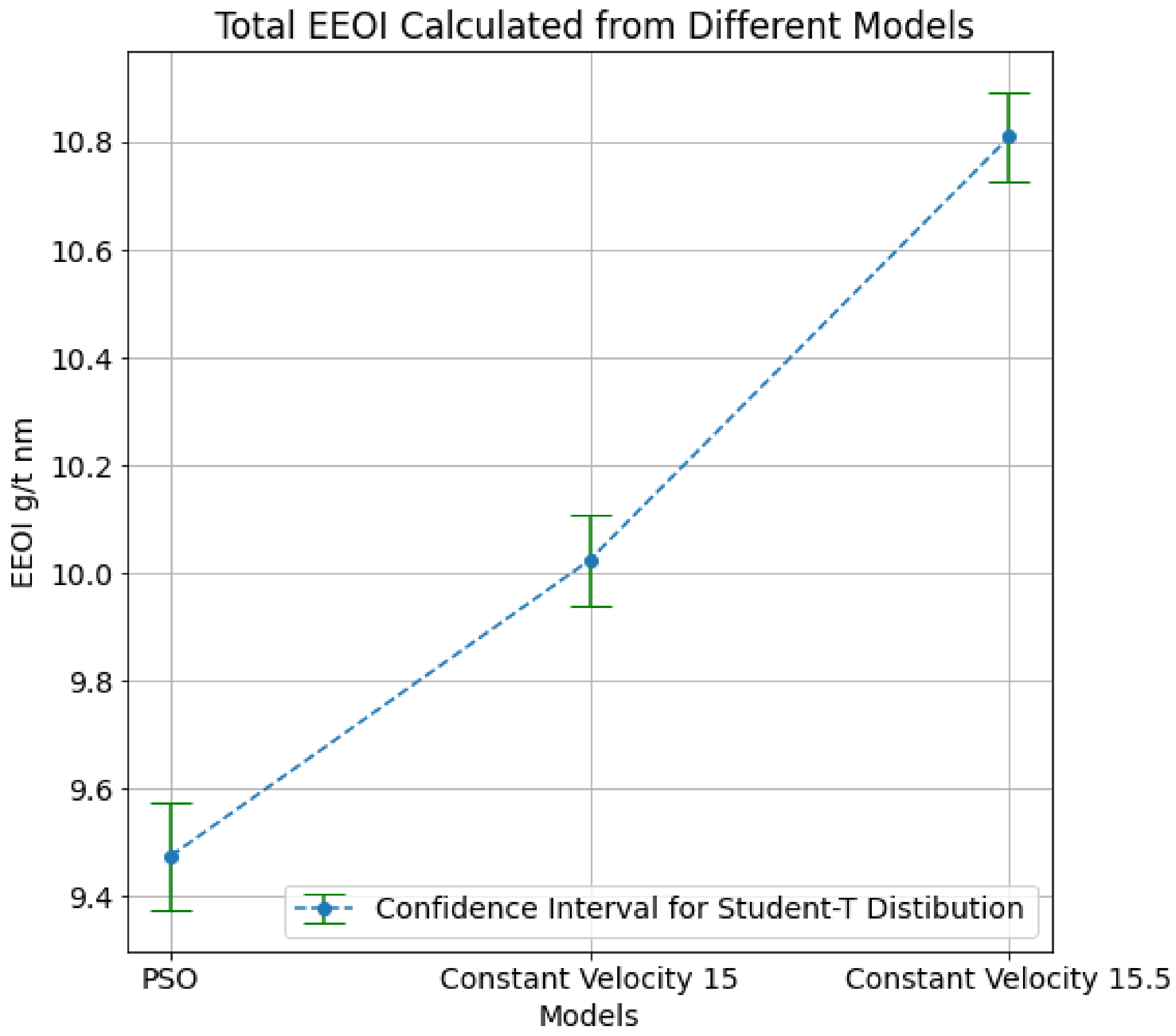
A Dynamic Approach for Operational Efficiency Improvement Using Adaptive Particle Swarm Optimization

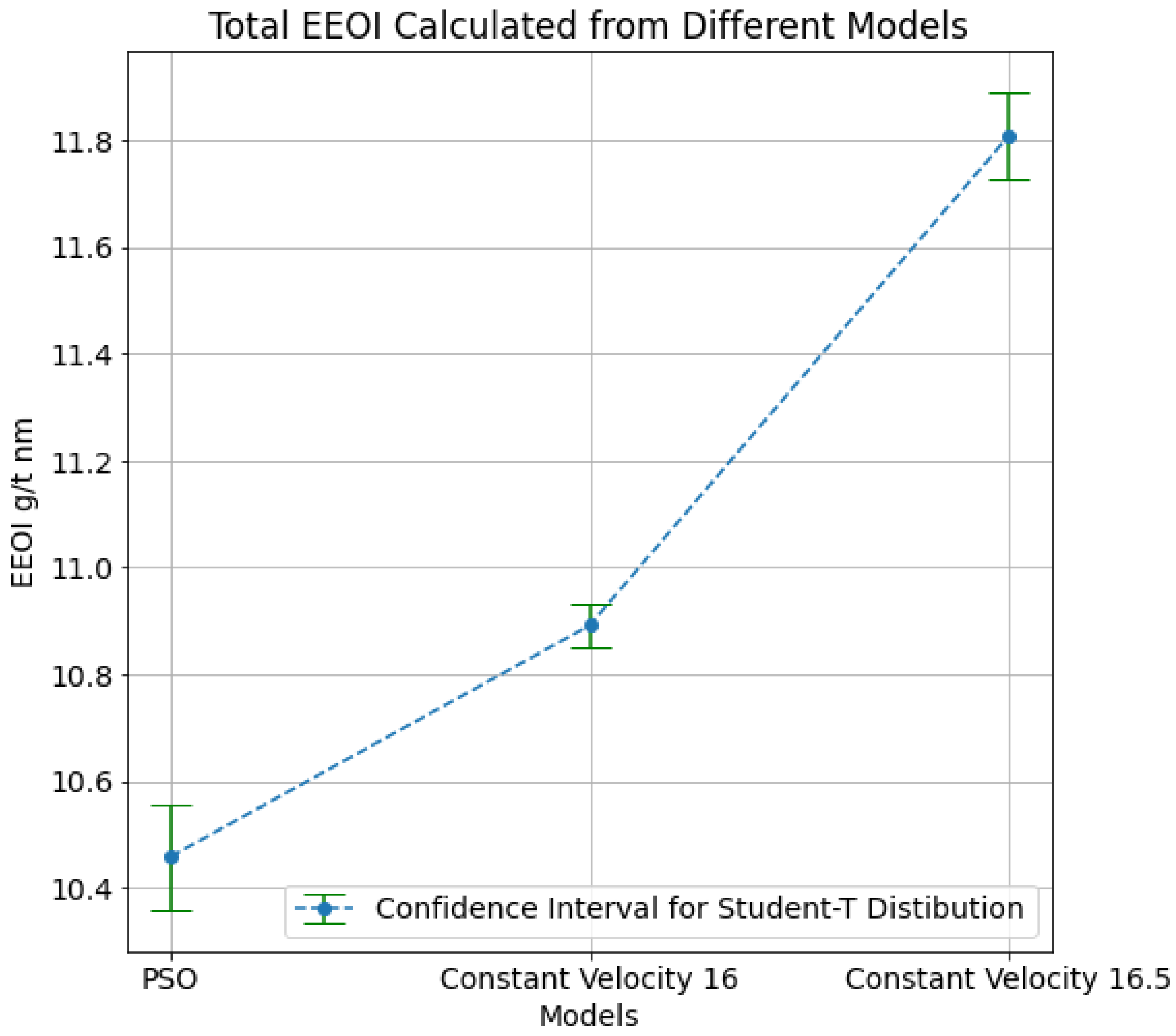
Mahadevan H[1], Kumar A[1]
[1]Fraunhofer Center for Maritime Logistics and Services

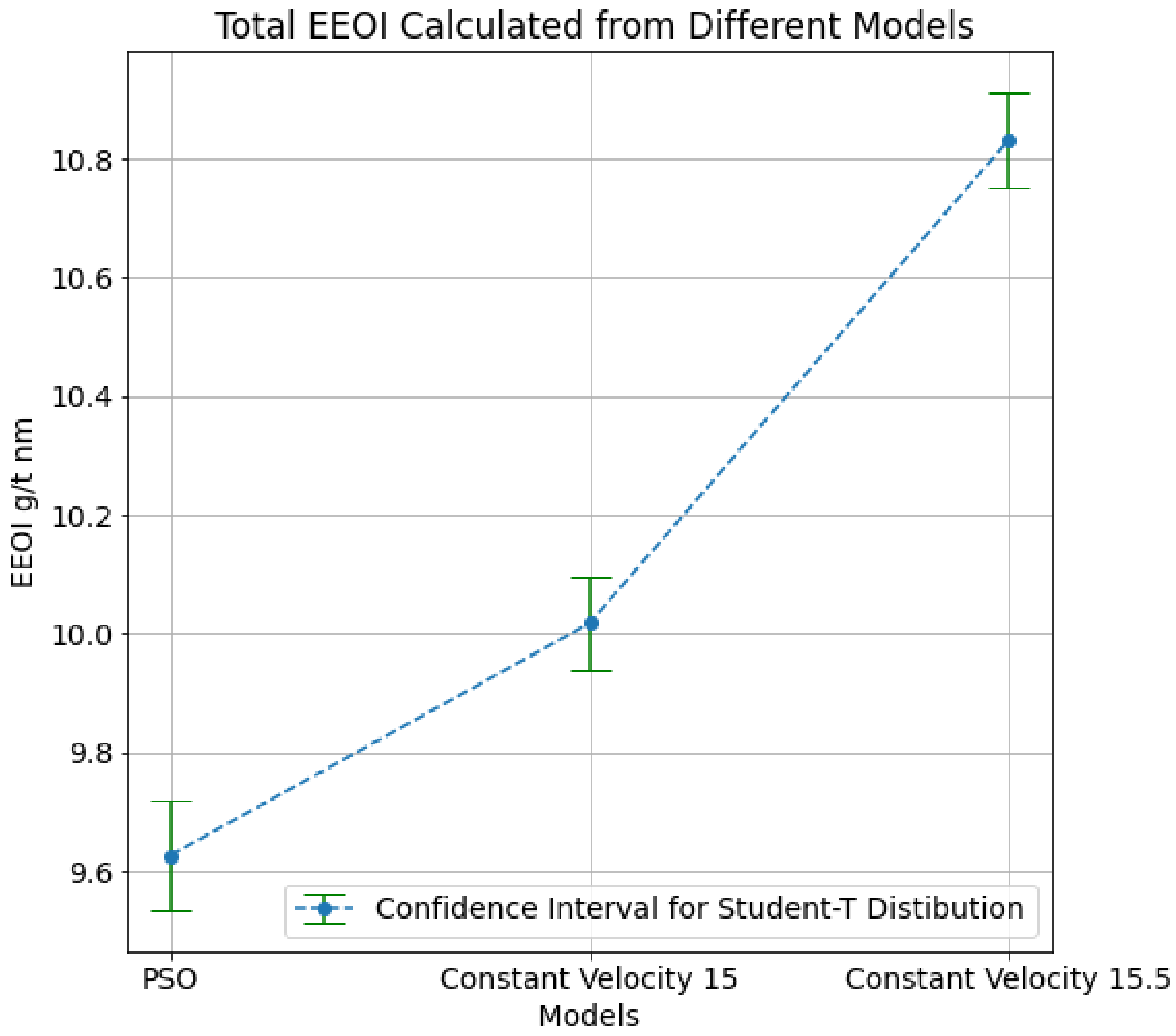
Biography:
I am a Research Associate at Fraunhofer CML, specializing in the Sea Traffic and Nautical Solutions department. I hold a master's degree in Information and Communication Systems from Technical University of Hamburg, with a focus on communication networks, digital communication, and security. My current research involves ship-to-shore communication, maritime simulator networks, and situational awareness assessments. With a passion for advancing maritime technologies, I strive to contribute to innovative solutions that enhance safety and efficiency in maritime operations.

The maritime industry is experiencing significant growth due to globalized trade, but this expansion has led to increasing environmental concerns. Studies project that the sector could contribute up to 17% of global CO2 emissions, posing a major environmental challenge. Stringent environmental regulations from international organizations and government agencies necessitate the maritime industry to find effective solutions to reduce its greenhouse gas (GHG) emissions and improve energy efficiency. This research proposes a methodology for dynamically calculating optimal ship speed to enhance energy efficiency and reduce GHG emissions. By leveraging real-time environmental data (e.g., weather forecasts, sea state information) and operational parameters (e.g., ship characteristics, cargo load), the study utilizes an Adaptive Particle Swarm Optimization based on Velocity Information (APSO-VI) to predict optimal Speed Over Ground (SOG) in real time. The study utilizes the Energy Efficiency Operational Index (EEOI) as a performance metric. EEOI is a widely employed measure in the maritime industry that quantifies the grams of CO2 emitted per tonne-nautical mile (g CO2/t nm) of transport work. The effectiveness of the proposed dynamic optimization model (APSO-VI) is assessed by comparing its performance with constant velocity models through extensive simulations, showing a 5-12% reduction in EEOI with the optimized speed model. The results demonstrate significant reductions in fuel consumption and emissions, supporting the adoption of such technologies for a more sustainable maritime industry. Future research may explore integrating machine learning techniques and advanced weather forecasting models for even more robust optimization strategies.


Total EEOI Calculated from Different Models
EEOI g/t nm
11.75
11.50
11.25
11.00
10.75
10.50
10.25
Confidence Interval for Student-T Distibution
PSO
Constant Velocity 16
Constant Velocity 16.5
Models


Total EEOI Calculated from Different Models
EEOI g/t nm
10.8
10.6
10.4
10.2
10.0
9.8
9.6
9.4
Confidence Interval for Student-T Distibution
PSO
Constant Velocity 15
Constant Velocity 15.5
Models


Total EEOI Calculated from Different Models
EEOI g/t nm
11.8
11.6
11.4
11.2
11.0
10.8
10.6
10.4
Confidence Interval for Student-T Distibution
PSO
Constant Velocity 16
Constant Velocity 16.5
Models


Total EEOI Calculated from Different Models
EEOI g/t nm
10.8
10.6
10.4
10.2
10.0
9.8
9.6
Confidence Interval for Student-T Distibution
PSO
Constant Velocity 15
Constant Velocity 15.5
Models

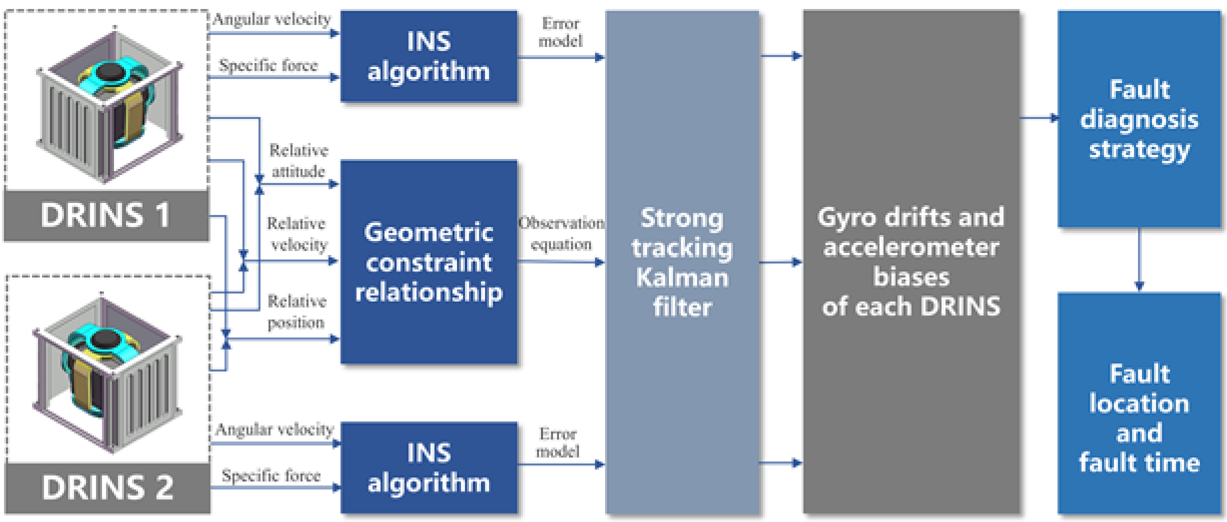
Fault diagnosis algorithm for redundant dual-axis RINSs based on geometric constraint observation

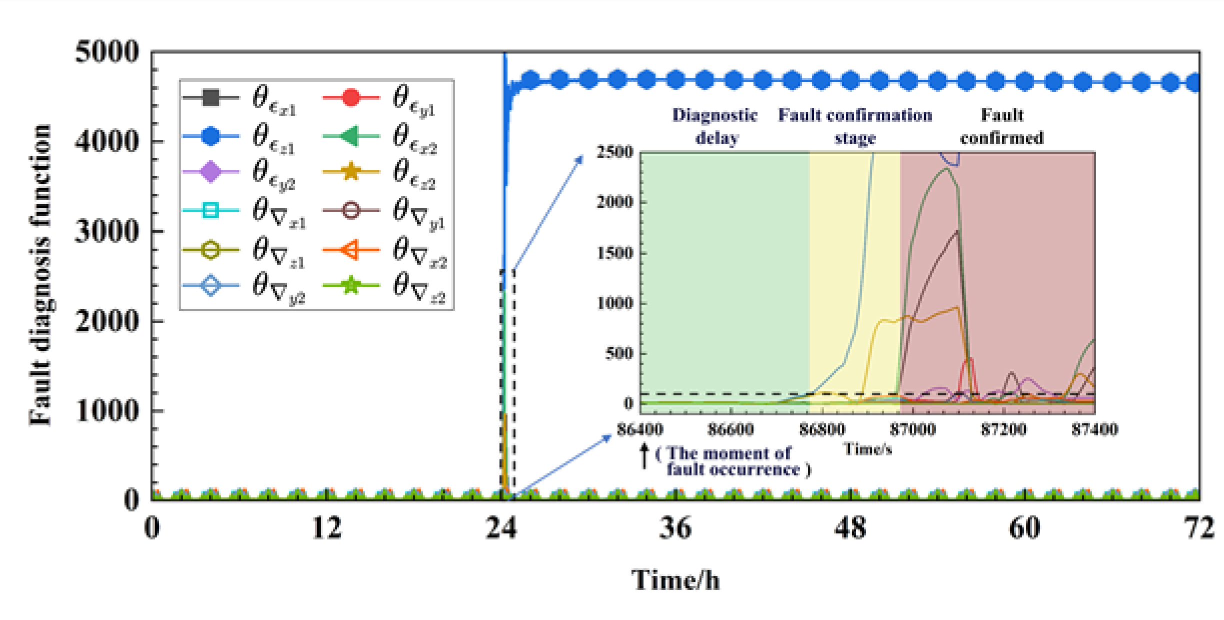
Liang Z[1,2], Liao Z[1,2], Luo H[1,2], Wang Y[1,2], Mu P[1,2], Wang L[1,2], Honggang G[1,2]
[1]College of Advanced Interdisciplinary Studies, National University of Defense Technology, [2]Nanhu Laser Laboratory, National University of Defense Technology

Dual-axis rotational inertial navigation system (DRINS) has been widely applied in marine navigation due to its high accuracy. For system reliability reasons, the long-endurance ships are always configured with redundant DRINS. However, the long-term works of DRINS for tens of days puts forward a significant challenge to its reliability. Usually, fault diagnosis algorithms are essential to detect the DRINS fault. In traditional fault-tolerant marine navigation frameworks, fault diagnosis algorithms are generally achieved with global navigation satellite system (GNSS) aided. Whereas, the raliability of redundant DRINSs cannot be guaranteed in GNSS-denied environments, which deteriorates the navigation safety of ship.

To address this challenge, a fault diagnosis algorithm for redundant DRINSs based on geometric constraint observation is propose. First, the error models and kinematic equations of dual DRINSs are constructed. Then, the geometric relationships, including relative attitude, relative velocity and relative position between the dual DRINSs are employed to construct the observation equation of the filter. Based on the observability analysis, an asynchronous rotation strategy is presented, and the gyro drifts and accelerometer biases of each DRINS become observable. The strong tracking filter is used to estimate the gyro drifts and accelerometer biases of the dual DRINSs. Furthermore, the fault diagnosis strategy is designed for the dual DRINSs based on the estimated values of the error states.

The physical experiments with dual DRINSs are conducted to verify the effectiveness of the proposed algorithm. The experimental results show that the proposed algorithm can effectively estimate the error states of the inertial devices, and the proposed fault diagnosis algorithm can accurately diagnose the faults when the inertial device fails. The repeated experiments with different fault amplitudes and fault times have demonstrated that the diagnosis accuracy is higher than 99%. The proposed algorithm could effectively enhance the reliability of the navigation system in GNSS-denied environments.





Fault diagnosis function
Time/h
Diagnostic delay
Fault confirmation stage
Fault confirmed
Time/s
(The moment of fault occurrence)

Demonstrating the broadcast of authenticated AIS messages using VDES while retaining backwards compatibility

Hargreaves C[1], Safar J[1], Wimpenny G[1], Vastardis N[1]
[1]GRAD

Biography:
Chris Hargreaves works as an R&D Engineer for GRAD: the Research & Development Directorate for the General Lighthouse Authorities of the UK & Ireland.
His specialism is resilient position and navigation and he worked for many years on the UKs eLoran programme.
Today, he is presenting the work of two of his colleagues who have created the capability to digitally sign Marine AIS messages so that their origins can be authenticated, thus preventing the misleading broadcast of spoofed messages.

The spoofing of VDES (VHF Data Exchange System) messages, including those sent using the Automatic Identification System (AIS; a component of VDES), may have consequences ranging from causing a minor nuisance to significant threats to safe maritime navigation. For example, we show a malicious actor could transmit spoofed messages to alter or "hijack" the characteristics of AIS AtoN (Aid to Navigation) transmissions being broadcast by legitimate maritime authorities. This issue is particularly critical in the case of Virtual AtoN (VAtoN), where visual confirmation of the VAtoN character is not feasible, thereby exacerbating the potential risks.

To prevent spoofing, the authors have developed a VDES authentication system based on PKC (Public Key Cryptography) that is both open source and fully backwards compatible with the mariners' existing use of the AIS. Using this technique, the 'live', over-the-air broadcast of authenticated AIS messages is demonstrated; namely the broadcast of an authenticated AIS VAtoN, so giving categoric proof the VAtoN was broadcast by a legitimate authority (in this case, by the General Lighthouse Authorities of the UK and Ireland) and not an imposter.

The technique demonstrated is an improvement upon earlier work by the authors in that PKC digital signatures are carried in the VDE (VHF Data Exchange) component of VDES, rather than the AIS component. This prevents additional channel loading on the AIS, so keeping the two AIS channels free for their original purposes, and offers greater flexibility. This also allows the same technique, used here to authenticate AIS messages, to authenticate VDES messages sent via the ASM (Application Specific Message) and VDE components.

Atmospheric Corrections for Network Operations and Simulations

Plenary Room, May 22, 2025, 10:00 AM - 11:00 AM

On RTK rover algorithm innovation to ensure robust RTK during the Solar Cycle 25 maximum

Kleijer F[1], Vaseur C[1], Vaseur C[1], Arash M[1]
[1]Septentrio

Compared to Solar Cycle 24, the amount of navigation satellites has more than doubled. In addition, the majority of navigation satellites provide up to three carriers featuring modern modulations. As such, the maximum of Solar Cycle 25 provides an excellent opportunity to evaluate innovation in high accuracy positioning algorithms by exploiting this significant increase of both satellites and frequencies.

This abstract describes the innovation in the robustness of the Septentrio RTK (Real-Time Kinematic) positioning technology in terms of maintained availability and accuracy during periods of high ionospheric activity based on rover-only technology: the innovation is designed to not rely on network processing, thus ensuring the freedom of RTK users regarding selection of correction providers.

Ionosphere activity related to challenging GNSS receivers includes at least three distinct physical disruptive phenomena: a) increased residual ionospheric delay over the RTK baseline, b) rapidly changing ionosphere conditions on both ends of the RTK baseline and c) scintillation-causing ionosphere plasma bubbles moving over the rover within the RTK network. These phenomena apply to both physical and virtual baselines as forecasting disruptive ionosphere activity without latency is challenging for RTK networks.

The positioning engine innovations mentioned in this abstract are based on a) early and accurate detection of scintillating carrier phase measurements on a per satellite basis, b) an adaptive physical model of the differential ionosphere delay per satellite to improve the RTK state estimation exploiting the increase in available carriers per satellite and c) geometric ROT (Rate Of TEC) prediction over the baseline geometry relying on available information on relative satellite motion and the solar wake trajectory as function of time of day.

Septentrio’s positioning engine improved RTK availability and accuracy is presented using Solar Cycle 25 field data from both equatorial and high latitude scintillation in context of local Phi60 and S4 data.

High Latitude Ionospheric Gradient Characterization in Support of Network Operations

Sokolova N[1], Morrison A[1], Jacobsen K[2]
[1]SINTEF , [2]Norwegian Mapping Authority (NMA)

Biography:
Nadezda Sokolova received her PhD degree in Telecommunications from Norwegian University of Science and Technology (NTNU). She also holds a MSc degree in Geomatics Engineering from University of Calgary, Canada, and a MSc degree in Space and Aeronautical Engineering from the Arctic University of Norway. Currently, she works as a senior research scientist at SINTEF Digital focusing on high integrity resilient navigation systems.

Accurate and reliable information about the spatial variation of the radio propagation delay due to the ionosphere (ionospheric gradient) is an important parameter in both high precision and high integrity GNSS augmentation systems. Reliable monitoring and modelling of the ionospheric gradient variation during anomalous ionospheric events remains a challenging research topic. It requires understanding of the local phenomena and knowledge of the travelling ionospheric disturbance key characteristics including spatial scale size, orientation, and propagation velocity.
This article presents results from a two year long monitoring campaign carried out in 2021-2022 in Norway, where a cluster of thirteen receivers centred at 69.5°N, 19°E was used to study spatial variation of the ionospheric delay on a multi-scale network (baselines from 1.35–75km). Data captured by this receiver cluster was analyzed for the presence of ionospheric gradients between stations, with each of the detected events characterized in terms of the front slope, width and propagation velocity. This analysis is complemented by observations made using the same receiver cluster during an intense geomagnetic storm that took place on 10-12 May 2024.
The key conclusions of this study are that ionospheric gradient events seen in this region are spatially small-scale irregularities with estimated widths of 60km or less ranging from quasi-static to moving at velocities of 2000 m/s. Nearly all observed ionospheric front slope values were under 150 mm/km. Gradient observations made during the geomagnetic storm were almost always accompanied by scintillation.
Spatially small-scale irregularities can be difficult to observe with large scale networks as the isolated regions of disturbance can pass undetected between station pairs. This might pose challenges to systems/services where interpolation of the atmospheric residuals is done based on observations from a larger scale network/cluster, or concepts using a set of monitoring stations at longer baselines to assist real-time ionospheric gradient threat monitoring/detection.

Realistic Tropospheric Delay Modeling Based on Machine Learning for Safran's Skydel-Powered GNSS Simulators

Carbillet T[1], Mezencev Y[2], Tamazin M[3], Le Véel P[1]
[1]Safran Electronics and Defense, [2]Ecole Centrale de Nantes, [3]Safran Electronics and Defense

Biography:
I am Theo Carbillet, currently employed as GNSS Engineer at Safran Electronics & Defense in Nantes, France. My main activities are focused on advanced research and development on GNSS signal processing for Safran's simulation product line. Topics I am working on are multipath signals modelling, signal processing and advanced filter design, SDR testing and validation, GNSS system architecture and robust navigation algorithms.

Accurate modeling of tropospheric effects on GNSS signals is essential for achieving high-precision positioning, as the troposphere can delay pseudorange signals by up to 30 meters in Standard Point Positioning applications. While empirical models, such as the Saastamoinen model, are commonly used to simulate tropospheric delay by separating it into the hydrostatic (ZHD), and wet (ZWD) components, these models often lack the realism needed to model the highly variable ZWD accurately.
To address this limitation, Safran Electronics & Defense has developed an advanced machine learning-based model to enhance the realism of the unpredicted ZWD simulation within the Skydel-powered GNSS simulators. The model incorporates a feedforward neural network with two hidden layers, integrated with empirical methods for ZHD computation, resulting in a robust hybrid framework. The model is trained on a comprehensive 20-year dataset (2004-2024) collected from 221 GNSS stations worldwide, and further refined using meteorological data from Open Meteo to ensure accurate input parameters.
This innovative hybrid approach significantly enhances the realism of tropospheric delay modeling for Safran’s Skydel GNSS simulation software. Performance evaluations show a significant reduction in simulation errors across all tested stations, especially under complex and dynamic weather conditions. The paper details the new model’s design, training, and optimization processes, emphasizing the seamless integration of machine learning techniques within the Skydel simulator architecture.
By delivering more realistic simulations, this methodology enhances the fidelity of GNSS signal modeling and establishes a new benchmark for the integration of machine learning into reliable GNSS simulators.

Boar Wars: The Forest Strikes Back Against Signal Transmission (Topic: Human and Animal Navigation)

Kaczmarek A[1], Rohm W, Smolak K, Bogusławski P, Shepel A, Cwynar P, Sierny J, Pusz W, Hulewicz K, Łyskawa M

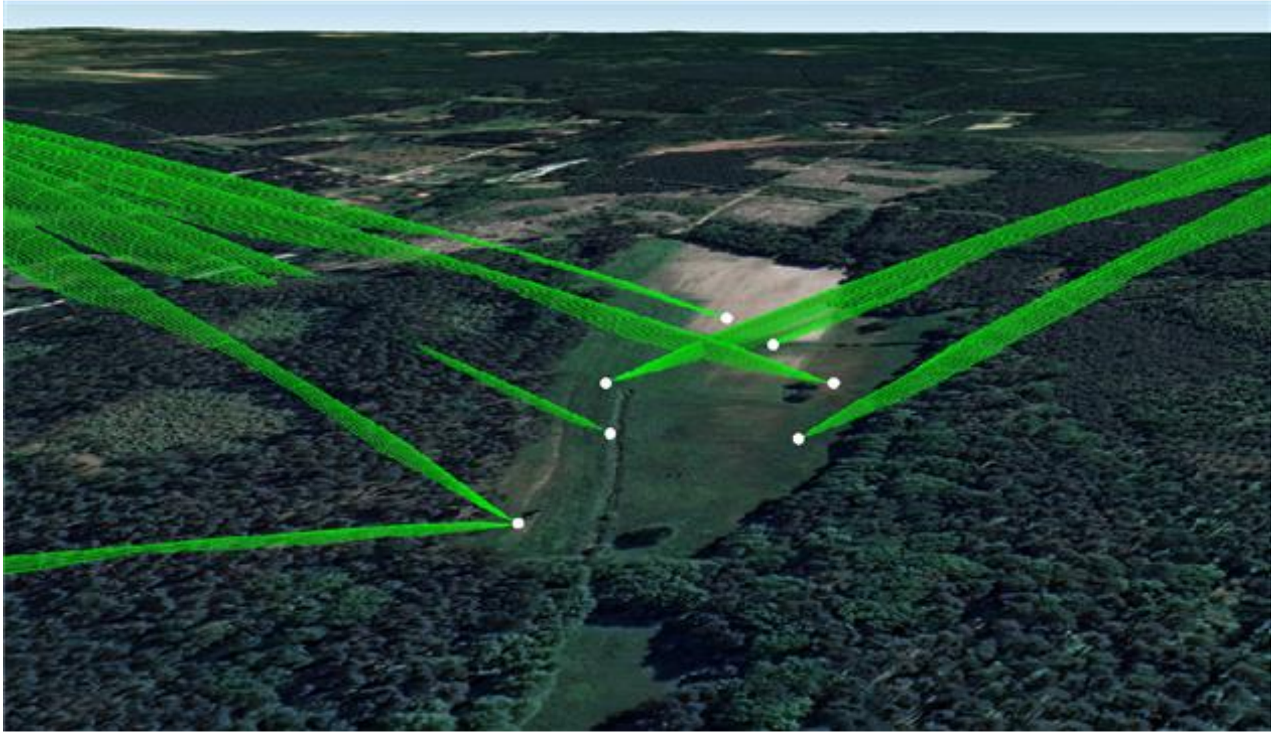
[1]Wroclaw University Of Environmental And Life Sciences, Institute of Geodesy And Geoinformatics

Biography:

Adrian Kaczmarek works at the Institute of Geodesy and Geoinformatics of the Wrocław University of Environmental and Life Sciences as an assistant professor. He deals with the integration of various navigation sensors and prototyping electronic devices related to GNSS positioning.

Wild animal movement tracking and modeling are essential for understanding the spread of infectious diseases, habitat use, and human–animal interactions. A prominent example is African Swine Fever (ASF), which is transmitted by wild boars through their body fluids, respiratory gases, feces, and meat, posing a significant threat to pig farms. In response, safety and sanitary zones have been implemented in affected regions. To improve monitoring, disease modeling, and protection, we employ ear tags equipped with GNSS receivers and radio transmission modules to obtain near–real-time location data for selected wild boars—ultimately covering entire herds. However, tracking in forested areas presents challenges such as GNSS signal attenuation and data transmission degradation. Our current solution relies on low-power wide-area network (LPWAN) communication protocols (e.g., Sigfox), which can theoretically reach up to 10–15 km in open terrain but often drop to 4–5 km in forested areas, leading to frequent signal interruptions. Existing signal propagation models provided by manufacturers tend to overestimate performance in real-world conditions. In this study, we analyze empirically measured signal propagation in forest settings based on Received Signal Strength Indication (RSSI) from devices attached to wild boars. We integrate a digital terrain model, a digital land cover model, and Fresnel zone calculations (Fig. 1) to evaluate energy propagation along the transmitter–receiver path, while also examining the influence of meteorological conditions. These findings highlight critical challenges in GNSS IoT-based wildlife tracking and offer practical solutions for enhancing data reliability under complex environmental conditions.

Fig. 1 Example of obstacles 1st Fresnel zone (green ellipsoid) between transmitters (ear tags: white dots) and receivers (base stations) - map background: Google Earth.



A System Architecture for the GNSS-enabled Provision and Exploitation of Accurate Digital Road Wear Maps

Vallet García J[1], Liaquat M[1], Bhuiyan M[1], Havas G[2], Csepinszky A[2], Ladstätter S[3], Luley P[3], Lesjak R[3], Solmaz [4], Novak T[5], Allmer G[6], Tijink J[6], Körber S[7]
[1]Finnish Geospatial Research Institute (FGI), [2]MoTeRe Nonprofit Kft, [3] JOANNEUM RESEARCH Forschungsgesellschaft mbH, [4]Virtual Vehicle Research GmbH, [5] FH OO Forschungs & Entwicklungs GmbH, [6]ASFINAG Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft, [7]Evolit Consulting GmbH

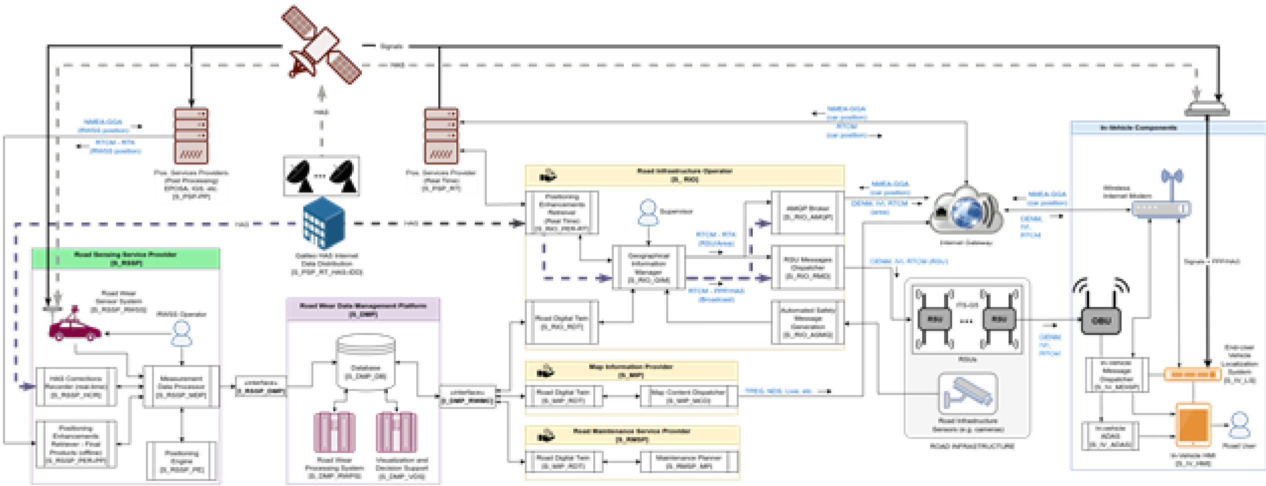
Biography:
Dr. José M. Vallet García is a research manager in the Navigation and Positioning Department of the Finnish Geospatial Research Institute (FGI). His research interests revolve around high accuracy GNSS-based positioning and resilience, and include all aspects pertaining their testing and characterization, including prototyping, systems integration, automation, testing, and performance assessment.

We present an architecture for a system especially designed to create, maintain and exploit accurate digital road wear maps in a flexible and interoperable manner. It relies on global navigation satellite systems (GNSS) for positioning, and is designed to fully leverage the potential of real-time kinematic (RTK) and precise point positioning (PPP) as enabled by Galileo High Accuracy Service (HAS) in both ends, the road sensor and the vehicles of end users. The architecture decouples a) the collection of the raw data necessary to create the map, b) the creation, storage, maintenance and distribution of its content, and c) its consumption by diverse entities for different applications. This decoupling and the assurance of interoperability allows the necessary flexibility to promote the creation of companies providing and exploiting the maps in a future competitive market.

As an example of possible data consumers we will present the case of Cooperative Intelligent Transport Systems (C-ITS) infrastructure operators. These entities take actions to maintain a safe traffic flow of human driven and autonomous vehicles. In this context, C-ITS is used to deliver messages to vehicles (e. g., Decentralized Environmental Notification (DENM) and In-Vehicle Information (IVI)) via Road Side Units (RSUs), and Internet using an Advanced Message Queuing Protocol (AMQP) broker (as specified in the C-ROADS standard). As a novelty, the proposed architecture encompasses the delivery of also Radio Technical Comission for Maritime Services (RTCM) messages used in RTK and PPP positioning. We also present the standards upon which the architecture relies, the identified gaps, and the interfaces that need development.

The work is framed in the EUSPA/H2020 funded ESERCOM-D project [1] (GA No. 101180176), where a fully working solution at a technology readiness level of 8 (TRL8) will be implemented and demonstrated aiming at a future commercialization.

[1]- https://esercomd.eu/



Innovative Applications of Low-Cost GNSS Receivers: Advancing Geodesy, Meteorology, and UAV

Marut G[1], Hadas T[1], Kazmierski K[1], Kaczmarek A[1], Lackowski M[1]
[1]Wrocław University of Environmental and Life Sciences

Biography:
Grzegorz Marut received his Master's degree in 2021 from the Wrocław University of Environmental and Life Sciences, Poland. He is a Ph.D. student at the same university. His main scientific interest is improving the performance of low-cost GNSS receivers. He is involved in the development of low-cost receivers built at the Institute of Geodesy and Geoinformatics and the development of software to manage their work. He is also a scholar in an international project in cooperation with the University of Stuttgart. During the talk he will present the main results of the implementation of low-cost devices in different geodetic applications.

The advent of low-cost GNSS receivers on the mass market has triggered progressive changes in many scientific fields such as surveying, remote sensing and environmental monitoring. The latest devices available are capable of delivering highly accurate and precise positioning, navigation and timing (PNT) products, while significantly reducing the cost of using satellite technologies.
We demonstrate the prototype of a low-cost GNSS device tailored for high-precision applications and continuous operation. The design was preceded by a detailed analysis of the performance of several low-cost GNSS antennas and selected characteristics of GNSS chipsets, i.e. signal-to-noise ratio and multi-frequency signal noise. A simple but effective method for field calibration of low-cost antennas was also developed, providing results with centimetre-level accuracy relative to external calibrations, while significantly improving positioning results, i.e., bringing them closer to those of geodetic grade equipment.
The experiments carried out showed that the low-cost GNSS receivers provide positioning accuracies of a few millimetres and a few centimetres for post-processing and real-time respectively. When using the Galileo High Accuracy Service (HAS), the PNT results obtained with low-cost GNSS receivers are comparable to those of geodetic grade receivers, also in terms of convergence time. We also demonstrate the kinematic experiment with real-time tracking of the Unmanned Aerial Vehicle (UAV). Finally, a local network of 15 low-cost receivers was installed in the city of Wroclaw, Poland, and used to determine the integrated water vapour (IWV). By comparing the estimated IWVs with the water vapour radiometer and the numerical weather prediction (NWP) model, it was confirmed that low-cost GNSS receivers meet the requirements of the E-GVAP programme, i.e. they provide measurements that can be assimilated into NWP models.

Conference Room B, May 22, 2025, 10:00 AM - 11:00 AM

Integrity of an inertial-vision data fusion for a civil aircraft during a precision approach

Thys G[1,2], Macabiau C[2], Jarraud R[1], Lesouple J[2], Vézinet J[2], Martineau A[2]
[1]Safran Electronics & Defense, [2]Fédération ENAC ISAE-SUPAERO ONERA, Université de Toulouse

Biography:
PhD student at Safran Electronics & Defense, affiliated with the Fédération ENAC, ISAE-SUPAERO, and Université de Toulouse, specializing in the integrity of inertial-vision hybridization.

In civil aviation, the development of Performance-Based Navigation (PBN) precision approaches, enabled by the emergence of Satellite-Based Augmentation Systems such as WAAS and EGNOS, is complementing traditional Instrument Landing System approaches However, this development is disturbed by the increasing proliferation of RF interference to GNSS, such as jamming and spoofing. As a result, GNSS might no longer be relied upon for airliners guidance even in environments where states are making best efforts to secure the RF environment.

Navigation-grade Inertial Measurement Units are commonly employed to ensure reliable orientation for aircraft control. However, they cannot independently satisfy the stringent positional accuracy and integrity requirements of PBN Category I operations during extended coasting periods, due to their susceptibility to drift. To address this challenge, this paper proposes a hybrid navigation system that combines inertial data with vision-based measurements to mitigate this position drift while containing integrity requirements within the allowed bounds. Specifically, the navigation camera measures the line of sight of the aircraft relative to known visual landmarks on the runway during the final approach phase. This measurement can be related to parameters of the aircraft trajectory.

To ensure the continuity of the precision approach procedure, the navigation system must maintain stringent requirements for both accuracy and integrity, even when GNSS experiences a loss of continuity service. Integrity is a critical concept in civil aviation, providing the level of confidence in the navigation data provided by the system, and enabling timely warnings when the performance is not suitable for the intended operation. This paper focuses on the integrity aspects of the proposed system, addressing the following objectives:

1. Design a system architecture capable of achieving the required integrity levels for PBN Category I operations.

2. Present initial integrity performance results, demonstrating the system’s capability to support precision approaches under challenging conditions.

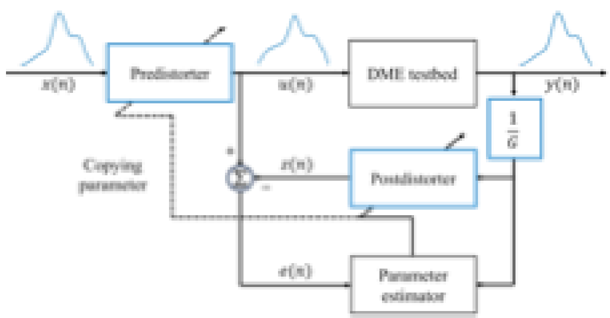
Transforming Legacy Gaussian Pulse based DME to High Accuracy DME using Alternative Pulses

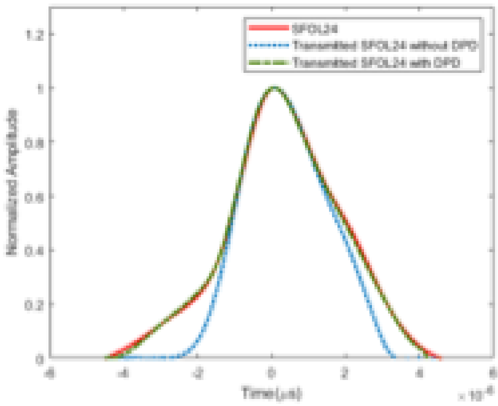
Kim E[1]
[1]Hongik University

Biography:
Euiho Kim is an associate professor in the department of Mechanical & System Design Engineering in Hongik University, Seoul, Republic of Korea. His current research areas are satellite based navigation, aircraft navigation using ground nav-aids, indoor navigation, and robotics. Dr. Kim completed his Ph.D. and master's degree in the department of Aeronautics and Astronautics at Stanford University. He finished his undergraduate degree in the department of Aerospace engineering at Iowa State University.

The Stretched-Front-Leg (SFOL) pulse is an advanced high-accuracy Distance Measuring Equipment (DME) pulse, offering approximately five times greater ranging accuracy than conventional Gaussian pulses. A commercial SFOL pulse-based DME has been developed, and successful transmission tests have demonstrated that the transmitted SFOL pulse meets ICAO DME/N pulse shape and spectrum requirements. Additionally, lab tests using the commercial SFOL-based DME confirmed its superior multipath mitigation performance. Beyond its high ranging accuracy, the SFOL pulse is designed for backward compatibility with legacy DMEs, enabling an easy transition from Gaussian pulse-based DMEs with minimal software and hardware modifications. The commercial SFOL pulse-based DME was adapted from an existing Gaussian pulse-based system. This paper introduces the key signal processing algorithms required to enable SFOL pulse transmission using legacy Gaussian pulse-based DMEs with varying transmitter characteristics.

Transmitting the SFOL pulse from a legacy DME without software modifications results in significant distortion, preventing compliance with DME pulse shape and spectrum requirements. The primary issue stems from the low-grade power amplifiers in the DME transmission unit. To mitigate these distortions, digital predistortion (DPD)techniques can be employed as an effective solution. While DPD allows successful SFOL pulse transmission in low-power mode, it often fails to meet ICAO spectrum requirements in high-power mode due to the narrow spectral margin of the SFOL pulse against ICAO DME/N regulations. To address this challenge, advanced DPD with singular value decomposition (SVD) and variant SFOL pulse shapes are recommended for high-power mode operation. This paper further explores these algorithms and their role in enabling ICAO-compliant high-power SFOL pulse transmission.




SFOL24
Transmitted SFOL24 without DPD
Transmitted SFOL24 with DPD
Normalized Amplitude
Time(μs)
1.2
1
0.8
0.6
0.4
0.2
0
-6
-4
-2
0
2
4
6

GNSS interference along a highway near an aircraft approach lane: A 5-month study

Hauser J[1], Lesjak R[1], Kavousi Ghafi H[1]
[1]Joanneum Research

Biography:
Julia I.M. Hauser, doctorate in applied mathematics
Currently employed at the research institute Joanneum Research in the group Telecommunications, Navigation and Signal Processing with the focus on Navigation
The main areas of activity are numerical simulations and data analysis
The presentations will focus on the results of a five-month study of the types of interferences monitored along a section of highway near an airport runway, specifically a highway located directly under an aircraft approach path.

Intentional and unintentional GNSS interferences can greatly affect the performance of precise timing and localization needed in areas such as automated driving or airport traffic. Nevertheless, we see that jamming occurs near many European airports that are located close to a highway or in heavy industry areas due to interfering signals that are broadcasted there.
In order to assess the impact of such potential risks, we investigated interferences occurring on a section of highway that is located both near an airport and close to logistic centers as part of the Austrian Security Research Program project CATCH-IN. This section of highway is of particular interest as the highway runs in parallel to the approach lane of aircrafts and crosses the approach lane 3.7 km before the aircraft touches down (the flight altitude is only 200 m above the ground).
For this experiment, we distributed six Septentrio Mosaic x5 GNSS receivers as sensors along the highway and monitored this section for five months. We analyzed the data with AGC monitoring, CN0 monitoring and baseband sample monitoring to identify interferences along the highway that could in turn affect the sensors along the descending flight trajectory. During the period of this experiment, we saw events that could cause potential safety risks and problems for aviation safety. In the analysis, we focused on the statistical evaluation of the temporal repetitions, in particular on the times of day that see more interference and on frequencies at which more interference occurs. Additionally, we analyzed the performance of these different algorithms for dealing with large data sets .
The results provide new insight into potential monitoring stations near airports and raise awareness of potential risks and vulnerabilities in aviation safety as well as automated driving along highways .

Improved Urban Navigation for Autonomous Driving: A Collaborative Multi-Agent Multi-Sensor RTK Approach

Schaper A[1], Schön S[1]

[1]Leibniz University Hannover, Institut für Erdmessung

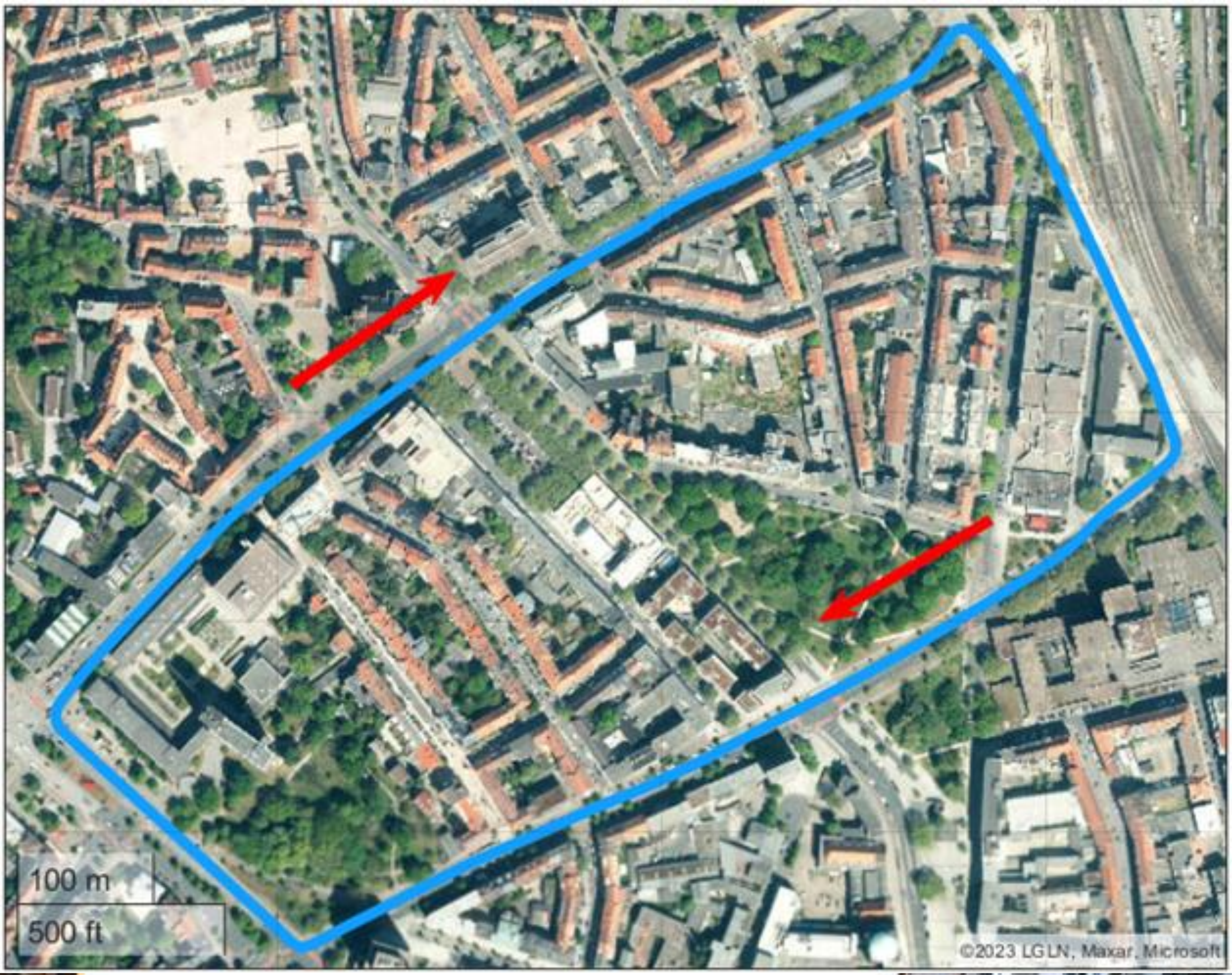
Biography:

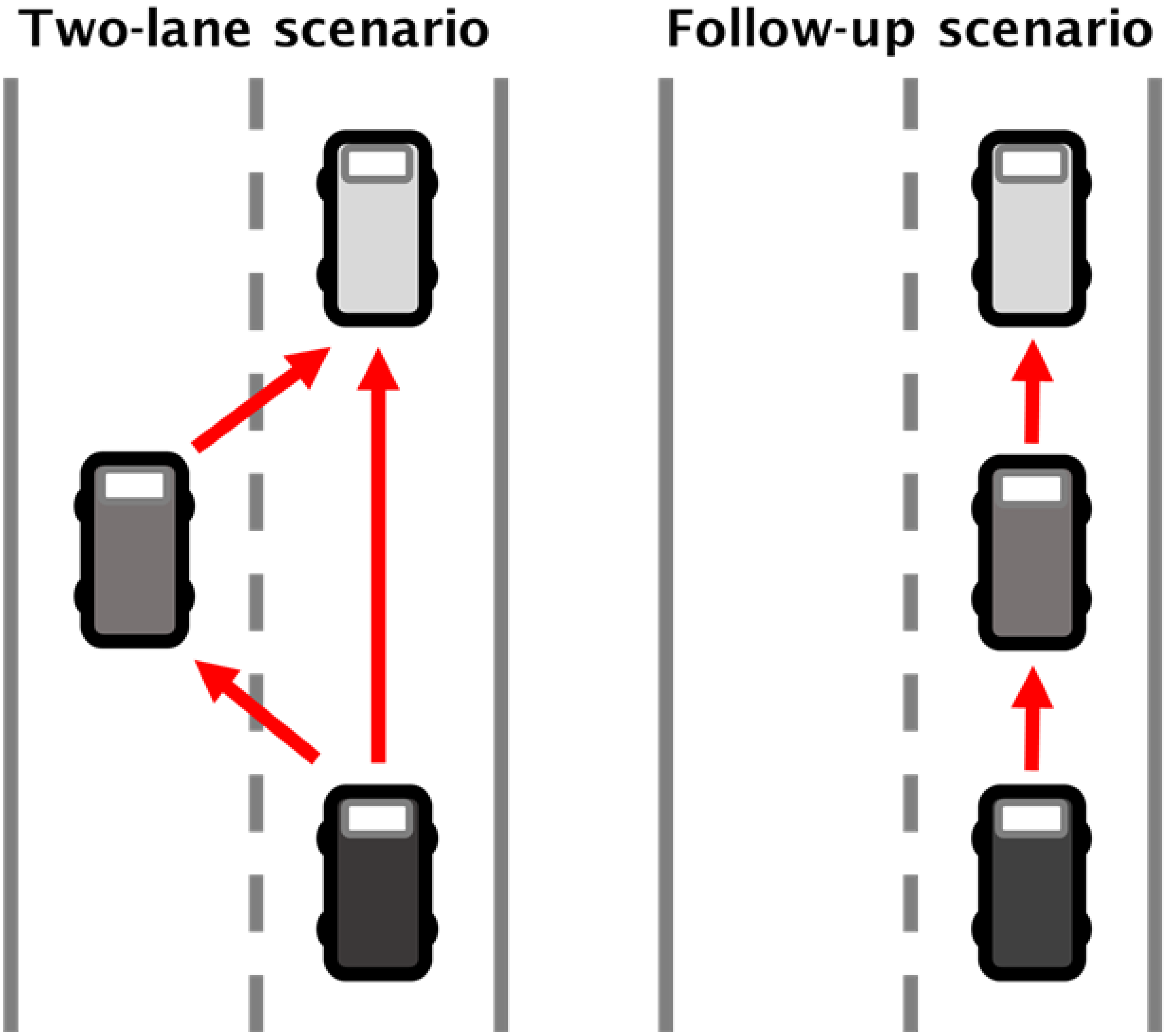
Anat Schaper received her B.Sc. and M.Sc. degree in Geodesy and Geoinformatics from Leibniz University Hannover (LUH) in 2020 and 2021, respectively. She is a Ph.D. candidate in the positioning and navigation research group at the Institut für Erdmessung (IfE) at LUH since 2022. Her research interests are GNSS signal modeling and collaborative navigation in urban areas.

High-accuracy positioning with GNSS in urban environments is challenging – buildings, trees and other obstacles cause GNSS signal diffraction, reflection, or even complete interruptions, resulting in position errors that are too large for the application of autonomous navigation. Several alternatives to conventional stand-alone GNSS positioning, such as Real-Time Kinematic (RTK) or multi-sensor fusion, have been proposed in the past years. In this contribution, we present our multi-agent multi-sensor collaborative RTK (C-RTK) algorithm, which builds a network between neighbouring traffic participants. We conducted a large-scale kinematic and static experiment in the urban environments of Hannover, Germany, to test our algorithms. Three vehicles were equipped with both mass-market and geodetic GNSS and IMU systems, front-facing stereo cameras and LiDAR. Additionally, barcode markers were attached to the vehicles to extract Vehicle-to-Vehicle (V2V) information.

In previous work, we have investigated the theoretical potential of our C-RTK algorithm for a static dataset.

To this end, the original satellite and vehicle geometry from the experiment is used. The GNSS and V2V observations (inter-vehicle coordinate differences) are replaced by perfect observations with random Gaussian noise. For this contribution, we extend our work by incorporating Monte-Carlo runs to reduce the impact of single random vectors. We consider a kinematic dataset composed of 7 rounds on the same trajectory (Figures 1&2). The three vehicles were driving either follow-up or two-lane scenarios (Figure 3) in order to investigate the impact of the network geometry on the C-RTK performance. We also examine the effects of network size, V2V precision, the number of V2V and GNSS observations, and robustness against outliers. We demonstrate the achievable accuracy of V2V observations, derived from triangulation from stereo images, through the application of coordinate system transformations and lever arms within the network. The performance of the C-RTK algorithm is compared with a single-vehicle GNSS-only RTK.


100 m
500 ft
©2023 LGLN, Maxar, Microsoft


Two-lane scenario
Follow-up scenario

CORS and Space Services Integration for Connected and Autonomous Vehicles

Zheng Y[1], Rejon M[1], Benedetti E[1], Sainz A[1], Hancock S[2], Navarro P[1]
[1]GMV, [2]Ordnance Survey

Biography:
Dr. Yuheng Zheng is a Senior Navigation Engineer at GMV-UK with extensive experience in designing, developing, and testing GNSS and PNT algorithms. He has led numerous high-profile projects, including CORSICA, PLATONIC, and MM-PP, focusing on integrating GNSS with various systems for enhanced positioning and integrity. Dr. Zheng holds a Ph.D. in GNSS, Geodesy, and Navigation from University College London and has published extensively in the field. His expertise spans GNSS/INS integration, PPP, RTK solutions, and safety-critical applications for transportation systems.

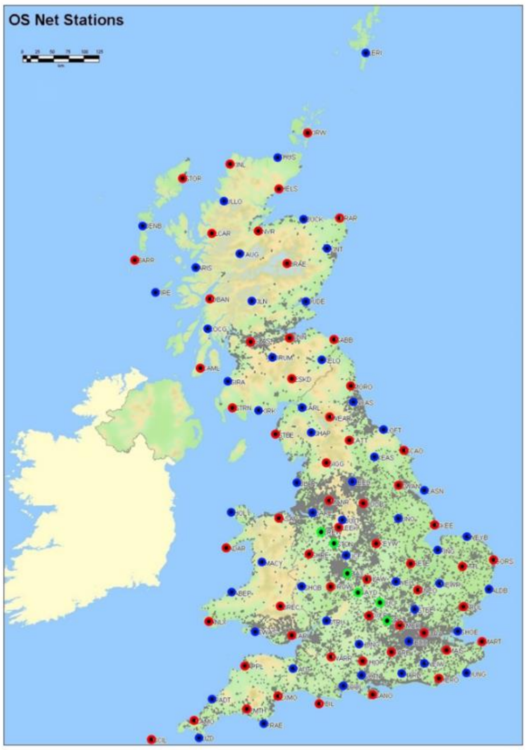
The CORs and Space services Integration for Connected and Autonomous vehicles (CORSICA) project aims to enhance the accuracy and assurance of Global Navigation Satellite System (GNSS) data for transport and logistics, focusing on autonomous transport applications. By integrating the Ordnance Survey (OS) OSNET network of continuous operating GNSS reference stations (CORS) with the GMV GSharp® Precise Point Positioning (PPP) corrections service, the project significantly improves GNSS PPP correction data density and quality across the UK. This integration addresses the critical need for high precision and integrity in applications such as autonomous driving and drone delivery services. The project involves the calibration and integration of OSNET stations into the GMV GSharp® datacenter, enhancing the ionospheric slant delay computations and overall positioning performance. Static and dynamic tests conducted across various UK locations demonstrate the benefits of this integration, particularly in challenging environments with lower network density. The combined network of OSNET and GMV stations shows improvements in achieving sub-decimeter precision in reduced time, highlighting the advantages of network densification.

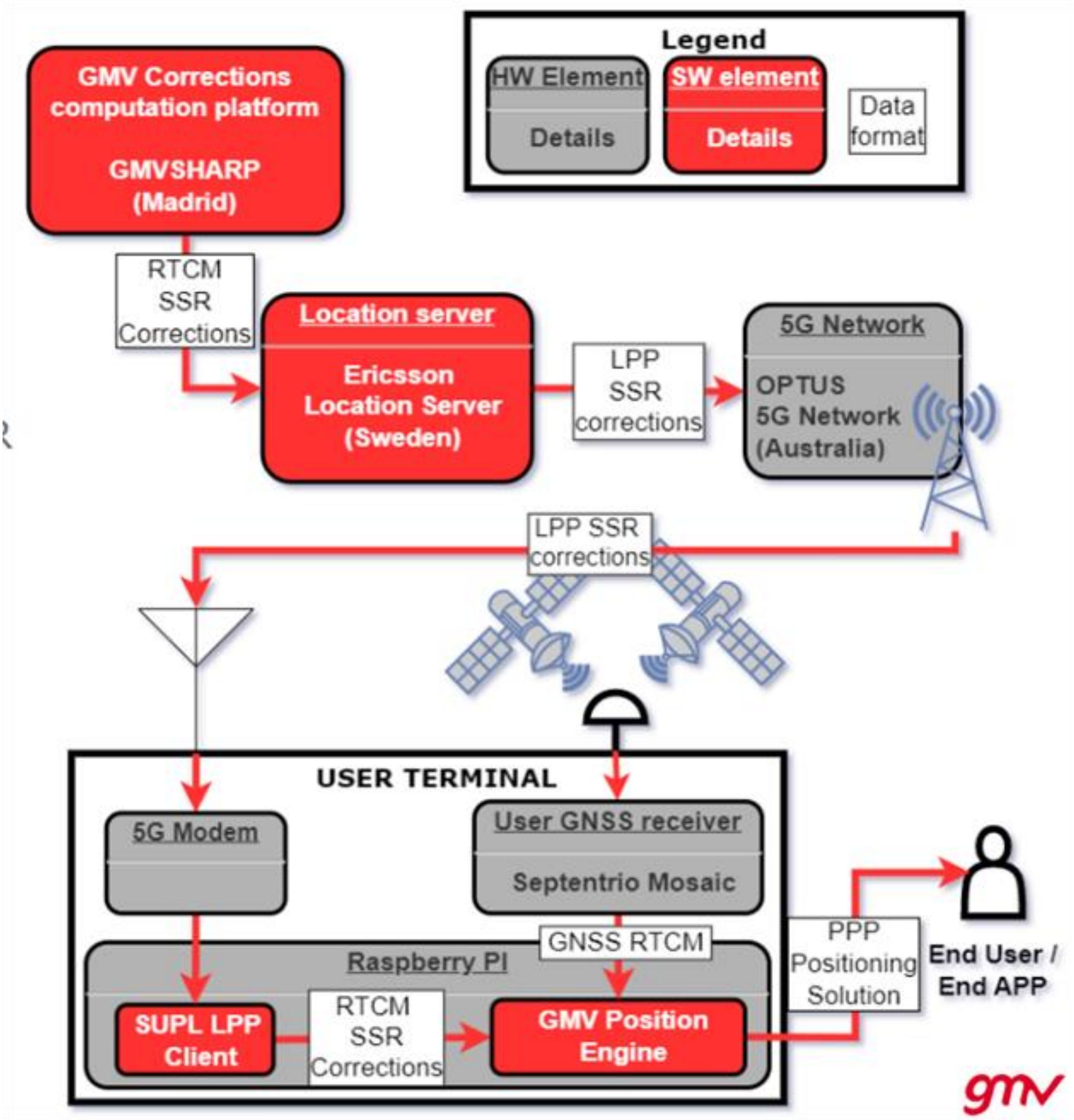
Figure 1: Map of Ordnance Survey OSNET GNSS reference stations in Great Britain

Key findings include the successful integration of OSNET data, resulting in enhanced positioning accuracy and data integrity for safety-critical environments and applications. The GMV GSharp® system generates redundant solutions using different GNSS reference stations, ensuring robust and reliable navigation services.

Figure 2: GMV GSharp PPP Architecture

In conclusion, the CORSICA project demonstrates a significant step towards providing a high-value, safe, and accurate navigation service for autonomous transport applications. The integration of OSNET with GMV GSharp® has proven to enhance GNSS positioning accuracy and reliability, particularly in challenging environments. This advancement supports the development of autonomous driving and drone delivery services, contributing to the broader goals of the UK National Space Strategy.


OS Net Stations

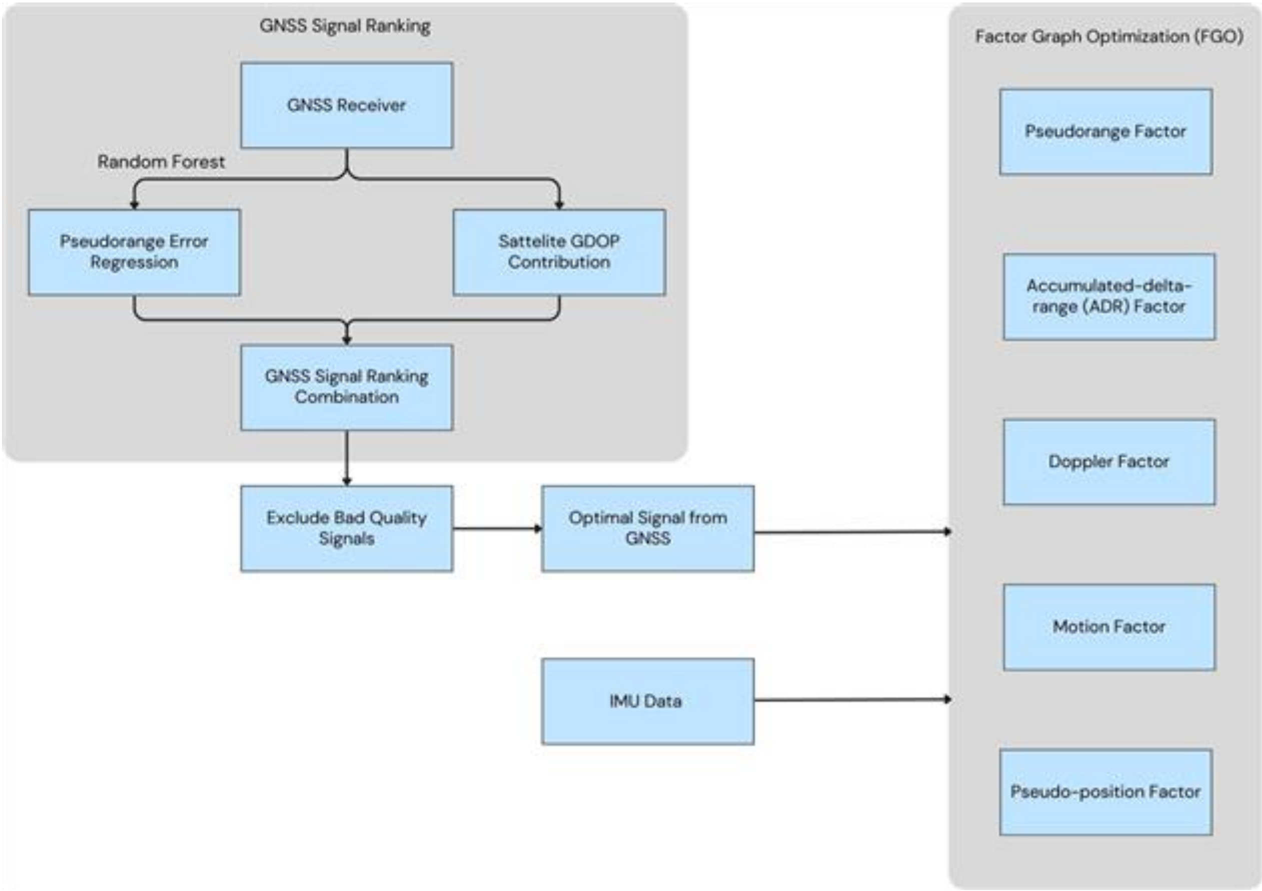

Legend
HW Element
Details
SW element
Details
Data format
GMV Corrections computation platform
GMVSHARP (Madrid)
RTCM SSR Corrections
Location server
Ericsson Location Server (Sweden)
LPP SSR corrections
5G Network
OPTUS 5G Network (Australia)
LPP SSR corrections
USER TERMINAL
5G Modem
User GNSS receiver
Septentrio Mosaic
GNSS RTCM
Raspberry PI
SUPL LPP Client
RTCM SSR Corrections
GMV Position Engine
PPP Positioning Solution
End User / End APP

Signal Quality-aware Factor Graph Optimization for GNSS/INS Fusion in Urban Environments

Fang W[1], Li T[1], Xu Z[1], Sun M[1], Saha C[1], Petrunin I, Kim S[2], Roberts W[2]
[1]Cranfield University, [2]GMV

Biography:
Ivan has extensive knowledge and experience in the area of Digital Signal Processing for Autonomous Systems which covers sensor technologies, perception, data and information fusion, and decision-making for Cyber-Physical Systems. Applications for these developments include vehicle health management, communication and surveillance solutions and, more recently, Position, Navigation and Timing (PNT) for aerospace and ground-based Autonomous and Intelligent Systems.
Ivan is involved in and actively supporting the development and operation of several research facilities, such as the instrumentation of Muti-User Environment for Autonomous Vehicle Innovation (MUEAVI), Research and Innovation Timing Node, PNT simulation facility.

Global Navigation Satellite System (GNSS) positioning in urban environments is often degraded due to signal blockages, multipath effects, and non-line-of-sight reception. Integrating GNSS with Inertial Navigation Systems (INS) can significantly improve positioning performance. However, traditional Kalman filter-based methods struggle to handle the non-linearities and non-Gaussian errors inherent in urban navigation scenarios. Factor Graph Optimization (FGO) has shown great potential in multi-sensor fusion for navigation applications. FGO can not only efficiently integrate information from different sensors, but also deal with various uncertainties to improve the accuracy and robustness of the navigation system. This work proposes leveraging GNSS signal ranking techniques to further improve positioning accuracy within the FGO framework, particularly in harsh urban environments. Instead of using all available GNSS signals in the conventional FGO framework, this work proposes to selectively incorporate only high-quality signals. The GNSS signal quality is assessed based on two key aspects: the accuracy of pseudorange measurements and the quality of satellite geometry (e.g., the number of visible satellites and their spatial distribution). GNSS signal ranking has been demonstrating promising results in the previous works of the authors, therefore, it was expected that a combination of GNSS signal ranking and FGO, which was not explored before, can bring performance benefits, achieving improved accuracy and resilience to GNSS outages. Experiments will be conducted based on "UrbanNav", a real-world dataset collected in urban canyons, to compare the performance of the proposed algorithm with other state-of-the-art FGO-based approaches. This work highlights the potential of GNSS signal ranking and FGO methods for robust navigation in autonomous vehicles and other applications requiring reliable localization in challenging environments.


GNSS Signal Ranking
GNSS Receiver
Random Forest
Pseudorange Error Regression
Sattelite GDOP Contribution
GNSS Signal Ranking Combination
Exclude Bad Quality Signals
Optimal Signal from GNSS
IMU Data
Factor Graph Optimization (FGO)
Pseudorange Factor
Accumulated-delta-range (ADR) Factor
Doppler Factor
Motion Factor
Pseudo-position Factor

Genesis Mission: co-locating geodetic instruments in space for the benefit of navigation and science

Waller P[1], Fusco G, Gidlund S, Morlet C, Perez Lissi F, Sakalauskaite E, Enderle W, Schoenemann E, Berton J, Gini F, Navarro V
[1]Esa/estec

Biography:
Pierre Waller is responsible for payload and instruments of the Genesis Project in the Navigation Directorate of the European Space Agency in Noordwijk, The Netherlands. Prior to that, he was RF and timing expert in the ESA Directorate of Technical and Quality Management. He received the M.Sc. and the Ph.D. degrees in Physics from the University of Paris, France.

Genesis is an ESA-approved mission dedicated to GNSS Science whose primary objective is the contribution to the improvement of the ITRF accuracy (1mm) and long-term stability (0.1mm/year). Secondary objectives include the contribution to a high number of other earth science disciplines [1].
The Genesis Space Segment includes a single spacecraft in MEO (6000km altitude, 95° inclination) co-locating for the first time in space the four geodetic instruments used for the realisation of ITRF: a GNSS receiver, an SLR reflector, a VLBI transmitter and a DORIS receiver. The Ground Segment is composed of a Mission Control Centre (including Ground Station) and will make use of the existing ground infrastructure operated by the Scientific Community. The scientific mission data will be managed by ESA's Data PROcessing, Archiving and Delivery facility (PROAD), under the responsibility of the Navigation Support Office and the GNSS Science Support Centre, in close collaboration with the scientific community.
On the industrial side, the company OHB Italia has been contracted by ESA as prime for the development, qualification, launch and 2 years operation of the mission, with a launch date in 2028 [2]. Antwerp Space (B), as the major sub-contractor of OHB-I, oversees the payload and geodetic instruments. Industrial activities were kicked-off in April 2024, the System Requirements Review was successfully closed-out in Q4 2024, and work is on-going towards a Preliminary Design Review in Q4 2025.
On the scientific side, a Genesis Science Team structure has been set-up and members appointed, including representatives of all geodetic institutes and associated services. The Genesis Science Team has been actively supporting the mission development (in particular consolidation of requirements) and will play a key role in its future exploitation.
The paper will provide a detailed description of the scientific objectives, system overview, and a programmatic status of the Genesis Mission.

[1]: Delva et al. Earth, Planets and Space 75, 5 (2023)
[2]: https://www.esa.int/Applications/Satellite_navigation/ESA_kicks_off_two_new_navigation_missions
[3]: https://www.esa.int/Applications/Satellite_navigation/The_geodetic_community_meets_Genesis

Navigating the Moon: Advances in Lunar PNT Simulation

Verdeguer Moreno R[1], Acosta Bayona I[1]
[1]Spirent Communications PLC

Biography:
Ricardo Verdeguer Moreno works as Product Line Manager at Spirent Communications providing Positioning, Navigation and Timing solutions for defence and space applications.
He is an aerospace engineer, who graduated with honours from Cranfield University with an MSc in Autonomous Vehicle Dynamics and Control. His expertise encompasses market insights and technical proficiency in GNSS-based autonomous systems.

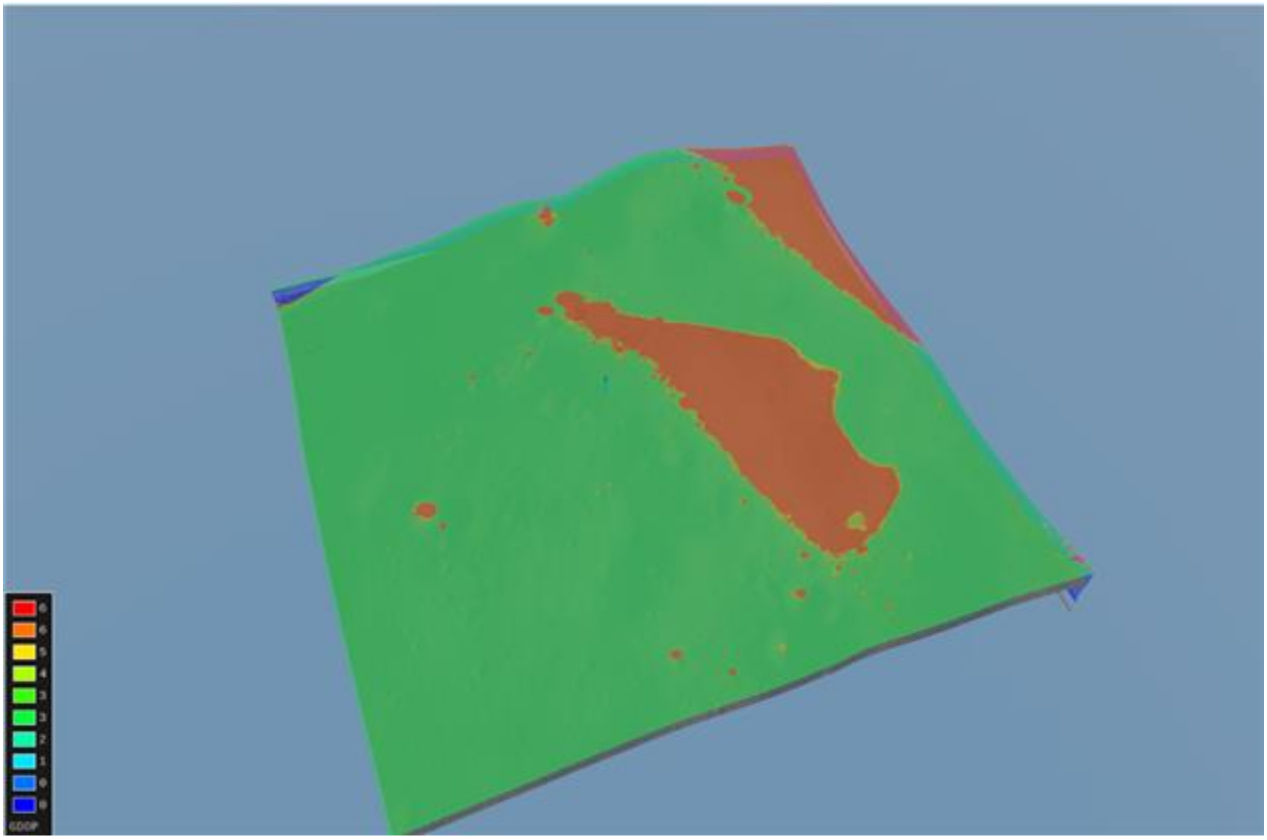
Ivan Acosta Bayona is a Product Line Manager at Spirent Communications, specializing in GNSS and PNT testing. His work focuses on developing advanced 3D and enhanced-realism testing environments, as well as automating GNSS and PNT testing processes to improve efficiency and accuracy.
Ivan holds a Bachelor's in Aerospace Engineering from Universidad de León and is completing his Master's in Aeronautical Engineering at Universidad Politécnica de Valencia.
Ivan is based in Valencia, Spain.

As humanity prepares for sustained lunar exploration, the development of robust Positioning, Navigation, and Timing (PNT) systems suitable for Moon applications becomes critical. This presentation will explore the state-of-the-art in lunar PNT simulation, a cornerstone in the design and validation of these systems. By simulating the unique challenges posed by the Moon's environment, including the constellation orbits definition, its highly variable terrain, and signal propagation impairments, researchers can refine navigation architectures and optimize signal design.

Spirent will showcase the latest developments in lunar PNT simulation frameworks, highlighting advancements in multi-domain modelling that integrates orbital dynamics, signal propagation, and lunar surface interactions. This capability is vital for testing concepts such as Earth-based GNSS extension, lunar satellite constellations, and hybrid solutions combining ground-based and orbital systems.

Our presentation will also feature initial results from an ongoing collaboration with a space agency. Specifically, we will unveil preliminary heatmaps of PNT signal reception across the lunar surface, including locations such as Connecting Ridge, Shackleton Rim and Peak near Shackleton; all generated through high-fidelity 3D simulations. These heatmaps provide crucial insights into coverage patterns, signal availability, and performance variations due to lunar topography, satellite orbits and mission-specific operational constraints.

By combining these simulations with our PNT expertise, we aim to inform the design of resilient PNT systems that can support diverse lunar operations, from crewed landings to robotic exploration and resource extraction.


5
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GDOP

Assessment of lunar users’ PVT performances tightly coupling Moonlight signal with IMU

Audet Y[1], Ceresoli M[2], Melman F[1], Oduber J[1], Wadsworth B[1], Psychas D[1], Swinden R[1], Stallo C[1], Ventura-Traveset J[3]
[1]Esa ESTEC, [2]Department of Aerospace Science and Technology, Politecnico di Milano, [3]European Space Agency (ESA)/CST

Biography:
Yoann Audet joined ESA in 2022 to support interplanetary pnt projects such as Moonlight and MARCONI focusing on system engineering and assessing user performances and ODTS of the systems

The increasing interest in the Moon, highlighted by the rapidly growing number of planned lunar missions for the next decade, presents a significant challenge for ensuring reliable communications and navigation. Space agencies worldwide are developing communication and navigation constellations to provide services that enable missions to achieve their objectives. To support its exploration vision, the European space agencies have proposed the Moonlight program to develop a constellation for navigation and communication. This initiative is part of a global effort to create interoperable systems under the LunaNet framework [1].
In this contribution, the performances of the 4 satellites Moonlight constellation will be updated compared to previous works [2], [3], by presenting results assuming the user is equipped with an IMU. This study will first present a high-fidelity modelling of the IMU sensor and of its errors (such as noise and bias terms, scale factors, non-orthogonality and quantization) as well as its integration within the navigation filter. The analyses will then focus on two scenarios, one involving a moving surface rover and the second on a lunar landing trajectory. Sensitivity analyses to assess the impact of the IMU grade on the user positioning performances will also be performed. Finally, a test case scenario involving IMU measurement faults will be analysed to assess the reliability enhancements that the additional Moonlight measurements can provide to the navigation filter and whether their usage can successfully prevent catastrophic failures such as those of the Mars Schiaparelli probe.

[1] NASA; ESA; JAXA, “Draft 5 LunaNet Interoperability Specifications"
[2] Y. Audet, “Positioning of a Lunar Lander using a dedicated Lunar Communication and Navigation System assuming realistic ODTS performances,”
[3] Y. Audet et al., “Positioning of a lunar surface rover on the south pole using LCNS and DEMs,” Advances in Space Research

Introducing Two-Way Measurements for Lunar Navigation with Moonlight Initial Operational Capability

Audet Y[1], Melman F[1], Petri S[1], Oduber J[1], Wadsworth B[1], Swinden R[1], Stallo C[2], Pettitt D[2], Ventura-Traveset J[3]
[1]Esa ESTEC, [2]European Space Agency (ESA)/ECSAT, [3]European Space Agency (ESA)/CST

Biography:
Yoann Audet is a Radio navigation system engineer who joined esa in 2022, first a young graduate trainee. He is supporting the interplanetary pnt initiative of the agency such as the Moonlight programme and MARCONI where is he focusing on the ODTS and user performance assessment

The growing interest in the Moon, exemplified by the fast-growing number of lunar missions planned for the coming decade, poses a major challenge for communications and navigation to ensure reliability. Space agencies worldwide are working on communication and navigation constellations to provide a service that enables missions to ensure their objectives. To support its exploration vision, the European Space Agency has proposed the Moonlight program to develop a constellation for navigation and communication. This effort is part of a global effort to have interoperable systems under the LunaNet framework [1].
Albeit a constellation with 4 navigation satellites is foreseen, during the IOC (Initial Operation Capacity) only one navigation satellite and one communication satellite will be put in orbit around the end of the decade. To enhance the positioning performance, a concept of using Two-Way measurements (TWM) is considered. This article proposes to introduce the concept of TWM for the Moonlight constellation both in terms of concept of operation but also in terms of modelling of the observables including modelling of the SISE and preliminary error budget. This work will also introduce a mathematical model for the two-way measurements (processing time, latency, etc.) of the Moonlight constellation and how to handle them in a navigation filter. A sensitivity analysis of the error budget will be performed to assess the impact of the error budget on the two-way pseudorange error. Finally, a first glance at the results will be presented for a rover scenario, showing how the TW measurements can help to solve the PVT problem. This analysis will use the current lunar ESA simulator and navigation filter (Extended Kalman Filter with and without batch processing) presented in previous work [2], [3], [4].

For references see image 1

[1] NASA; ESA; JAXA, "Draft 5 LunaNet Interoperability Specifications," 2025.

[2] Y. Audet, F. T. Melman, D. V Psychas, R. D. Swinden, and J. Ventura-Traveset, "Positioning of a Lunar Lander using a dedicated Lunar Communication and Navigation System assuming realistic ODTS performances," 2023. doi: 10.3390/0.

[3] Y. Audet *et al.*, "Positioning of a lunar surface rover on the south pole using LCNS and DEMs," *Advances in Space Research*, vol. 74, no. 6, pp. 2532–2550, Sep. 2024, doi: 10.1016/j.asr.2024.06.022.

[4] F. T. Melman, P. Zoccarato, C. Orgel, R. Swinden, P. Giordano, and J. Ventura-Traveset, "LCNS Positioning of a Lunar Surface Rover Using a DEM-Based Altitude Constraint," *Remote Sens (Basel)*, vol. 14, no. 16, 2022, doi: 10.3390/rs14163942.

Enhancing Multi-GNSS clock combination for Precise Point Positioning

Białas J[1], Zajdel R[1,2], Sośnica K[1]
[1]Wrocław University of Environmental and Life Sciences, Institute of Geodesy and Geoinformatics, Grunwaldzka 53, 50-375 Wrocław, Poland, [2]Research Institute of Geodesy, Topography and Cartography, Geodetic Observatory Pecný (GOP)

Biography:
Mr Jakub Białas is a second year PhD student in the field of satellite geodesy at the University of Environmental and Life Sciences in Wrocław. His research focuses on the study of satellite clocks in GNSS constellations, with particular emphasis on stochastic modelling of satellite clocks to improve the accuracy of Precise Point Positioning. In today's presentation, he will discuss his work on combining multi-GNSS clock products and their impact on the Precise Point Positioning method.

Positioning, navigation and time synchronisation in Global Navigation Satellite Systems (GNSS) require highly stable and accurate orbit and clock products. These are regularly provided by the International GNSS Service (IGS) from different Analysis Centres (AC). However, there is still no unified multi-GNSS clock product including GPS, GLONASS, Galileo, and BeiDou. Our research aims to develop a multi-GNSS clock product combination tailored for user applications using the Software for Precise Orbit and Clock Combination (SPOCC). This approach seeks to enhance the reliability, consistency, and accuracy of multi-GNSS positioning, particularly improving the precision of Precise Point Positioning (PPP).
To mitigate inter-system biases (ISBs) and inconsistencies in orbit and clock modelling among IGS Analysis Centers (ACs), we first align the clock products to a selected stable AC, and then perform an ISB alignment of all constellations to the GPS reference constellation. The radial orbit correction is applied to clock products because of the correlations with the clock component. Subsequently, the aligned clock products are combined using an iterative weighted mean with the weights determined by the least-squares variance component estimation (VCE).
We perform several clock product combinations by varying the reference AC, switching the reference constellation from GPS to Galileo, and testing different AC weighting schemes. We assess the stability of different combined GNSS clock products by employing Modified Allan Deviations and examining other characteristics related to the inter-epoch stability of combined multi-GNSS clock products. Finally, we utilize the multi-GNSS clock products to compute Precise Point Positioning (PPP) solutions in both static and kinematic modes. This allows us to study the impact of different combination strategies on the accuracy of the clock parameters and the determined coordinates.

Enhancing real-time PPP solution through receiver clock modeling

Mikoś M[1], Sośnica K[1], Kazmierski K[1], Schön S[2], Hadas T[1]
[1]Wrocław University of Environmental and Life Sciences, Institute of Geodesy and Geoinformatics,
[2]Institut für Erdmessung, Leibniz University Hannover

Biography:
Marcin Mikoś received his Master of Engineering in Geodesy and Cartography from the Wroclaw University of Environmental and Life Sciences in 2022 and is currently a Ph.D. student. His main task includes multi-GNSS positioning with clock modeling.

The International GNSS Service (IGS) network includes over 500 stations, with those equipped with hydrogen maser (HM) clocks achieving the highest level of stability. In Precise Point Positioning (PPP), independently estimating receiver clock parameters at every observation epoch introduces additional noise into the calculated station coordinates. We propose a strategy that applies Markov stochastic process modeling to receiver clock parameters using a random walk process introduced to the sequential least-squares adjustment. Testing this approach with identical clock correction constraints on GNSS receivers equipped with HM clocks improves the stability of clock estimates compared to a reference solution without additional constraints. This research focuses on real-time orbit and satellite clock products, including Galileo High Accuracy Service (HAS), IGS, and Centre National d'Études Spatiales (CNES) products, with additional analyses based on the final products from the Center for Orbit Determination in Europe (CODE), in both static and kinematic solutions. This stochastic modeling of the receiver clock parameter significantly enhances the solution, yielding more stable PPP coordinate estimates when using either the real-time HAS, CNES, and IGS products, or CODE post-processing products.

Deep Learning Assisted Composite Clock: Robust Timescale for GNSS through Neural Network

Mudrak A[1], Fayon G[2], Sobreira H[2], Castillo A[2], Nummisalo L[2]
[1]European Space Agency, [2]European Space Agency

Biography:
Mr. Gaëtan Fayon holds an engineering degree from IMT Atlantique (2014) and a Ph.D. from the University of Toulouse (2017), both in space communication systems. After 5 years working as system integration and validation engineer in space and automotive industries in France, he joined in 2022 the European Space Agency (ESA) to work on the Galileo project. His main role today focuses on Galileo system integration, validation and qualification, but he is also involved in the Digital Transformation, supporting new processes and tools deployment in the aerospace sector.

Clock synchronization is vital for navigation systems that require a stable, available, and resilient common time reference to ensure the positioning and timing performance for all users. The composite clock approach, adopted by systems such as GPS (Global Navigation Satellite System) and EGNOS (European Geostationary Navigation Overlay Service), addresses these needs by ensembling multiple physical clocks through Kalman filters. Such algorithm can efficiently detect anomalies in individual clocks and can then adapt each clock's contribution to the overall system time. Yet, while clock behaviour can be seen as non-linear, non-Gaussian and non-stationary, conventional filtering methods implemented today often assume the opposite. There are also significant challenges related to the initialization of such filters and handling the clock ensemble reconfiguration.

To address these challenges, this study proposes to introduce the concept of deep learning assisted GNSS composite clock, leveraging supervised learning methods to dynamically estimate filter parameters in real-time and non-linear environment, also considering partial information. Based on recent advances (see Figure 1 and Figure 2, based on Revach et al., KalmanNet: Neural Network Aided Kalman Filtering for Partially Known Dynamics, 2022), the proposed approach embeds a dedicated recurrent neural network within existing composite clock filters enhancing their ability to capture complex clock behaviours and ensemble reconfigurations.

By comparing the performance of traditional filtering methods with this novel deep learning integrated system, it will be demonstrated how this hybrid approach can yield more reliable, precise, and robust timescale. The resulting composite clock solution not only mitigates the limitations of the classical Composite Clock algorithms, but also provides a powerful tool for dealing with uncertainties in clock dynamics. Ultimately, this work highlights the potential of machine learning to enhance clock ensembling strategies, opening the usage of artificial intelligence in next-generation navigation systems.

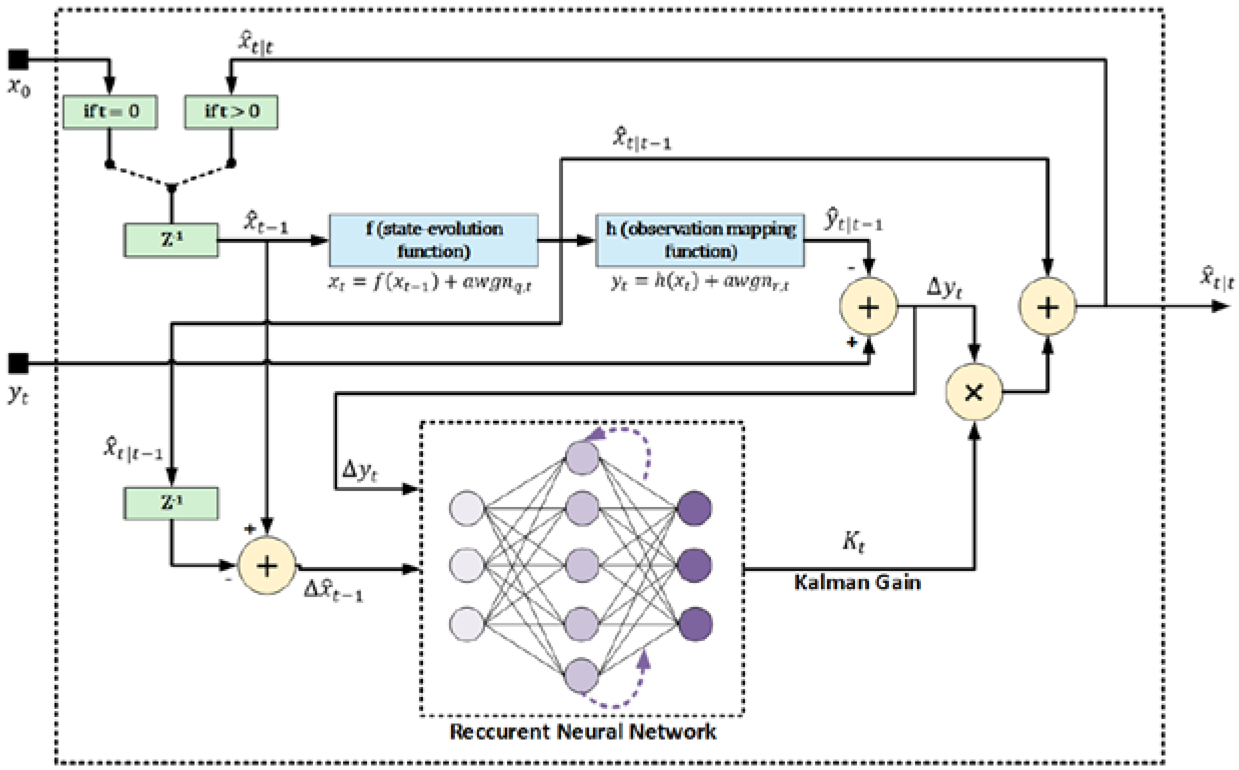


Figure 1: Example of Kalman filter where gain is computed through recurrent neural network. Inputs considered: innovation difference Δy_t and forward update difference $\Delta \hat{x}_{t-1}$ (difference between the posterior state estimation and the prior state estimation)

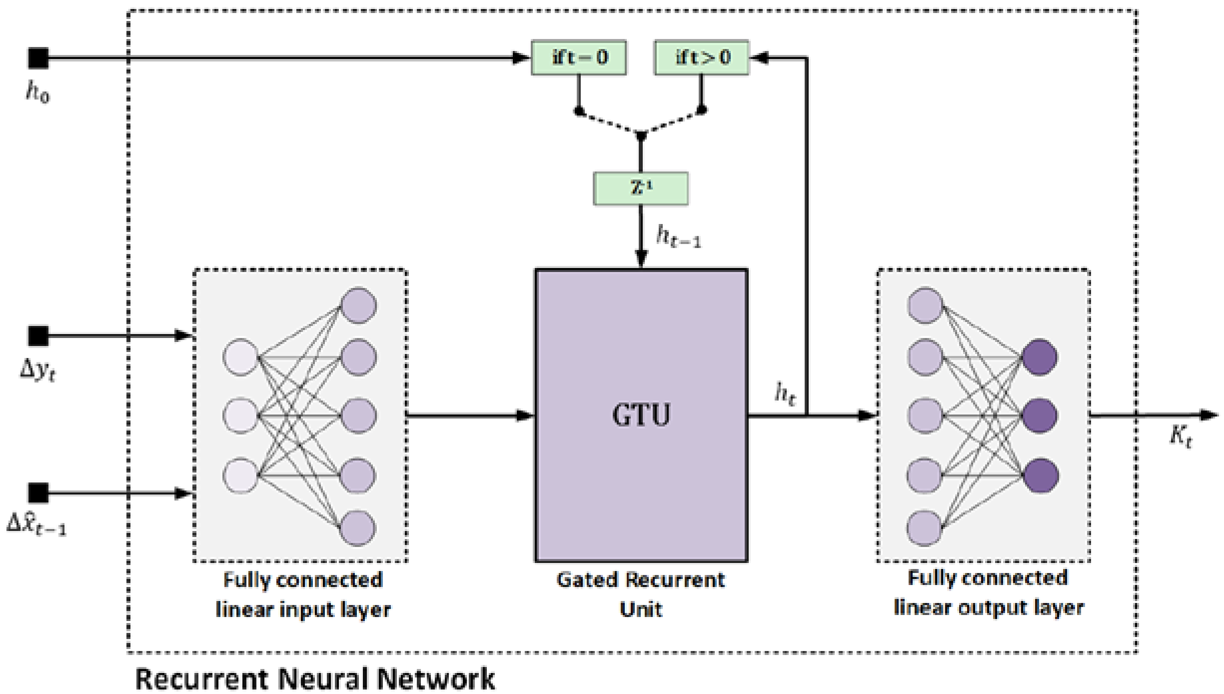


Figure 2: Recurrent neural network architecture in the context of Kalman filter gain computation. Inputs considered: innovation difference Δy_t and forward update difference $\Delta \hat{x}_{t-1}$) (difference between the posterior state estimation and the prior state estimation)

Reinforcement learning-driven GNSS observation selection for enhanced PPP accuracy

Tena A[1], Chamorro A[1], Benedetti E[2], Gonzalez Sainz A[1], Díaz A[3], Rodríguez V[3], Crespo M[1]
[1]GMV, [2]GMV NSL, [3]Universidad Politécnica de Madrid

Biography:
María Crespo Estrada holds a double MSc in Aerospace Engineering by the Technical University of Madrid and Computational Software and Techniques in Engineering by Cranfield University. She has worked as an Advanced Engineer for five years in GMV in the field of GNSS high accuracy positioning with a high focus in GNSS Integrity. She is currently leading the development and integration GMV GSharp Safe and Accurate Positioning Engine in Autonomous Driving Application for automotive customers.

This paper presents a reinforcement learning (RL) framework integrated into the GMV GSharp® Precise Point Positioning (PPP) algorithm to optimize Global Navigation Satellite System (GNSS) measurement processing. The RL agent, originally developed to reduce multipath effects, has evolved into a decision-making tool that evaluates the usefulness of GNSS measurements, improving positioning accuracy. This change was necessary to address various challenges in GNSS measurement processing, including multipath interference, measurement noise, and other factors that affect PPP performance.

The RL model processes GNSS observations utilizing a set of features derived from GNSS measurements, such as pseudoranges, signal-to-noise ratios, elevation angles, and residuals. These features are critical as they provide the necessary data for the RL agent to assess the quality and reliability of each measurement, thereby informing its decision-making process. We designed the action space as a binary decision framework, where the agent determines whether each measurement should be included in the solution. We designed a reward function to encourage decisions that reduce positioning errors. It assigns higher rewards for actions that improve accuracy and penalizes those that undermine the solution's stability.
Training data includes GNSS raw observations that we collect across diverse environments, such as urban canyons, suburban areas, and open spaces. This diversity ensures that the RL agent is exposed to multiple real-world conditions, crucial for developing a robust model capable of handling challenges in GNSS measurement processing. Broad validation demonstrates that the RL-enhanced PPP algorithm achieves significant accuracy improvements compared to the baseline GSharp® solution, even under adverse conditions.

This work shows the potential of RL to evolve the processing of GNSS measurements. The agent's ability to adaptively manage observation quality and relevance offers a robust and precise positioning solution, facilitating next-generation GNSS applications for complex environments.

Conference Room B, May 22, 2025, 11:40 AM - 1:00 PM

Current Status and Plans of Galileo Signal Authentication Service

Fernandez-hernandez I[1], Winkel J[1], O'Driscoll C[1], Willems T[1], Cancela S[2], Ramirez A[2], Terris-Gallego R[3], Lopez-Salcedo J[3], Seco-Granados G[3], Caparra G[4], Blonski D[4], Motella B[1], Galan A[5], Simon J[6]
[1]EC, [2]GMV, [3]UAB, [4]ESA, [5]KU Leuven, [6]EUSPA

Biography:
Tom Willems obtained a PhD degree from Ghent University in 2006. From 2006 to 2021, he worked as embedded software engineer in GNSS signal processing and as system engineer at Septentrio and Antwerp Space. At both companies, he was deeply involved in the Galileo Test User Receiver projects for ESA. Next, he started working as an independent consultant. Since 2024, he is employed as Senior Consultant at CGI where his current assignment is to provide advisory services to the EC.

Galileo Signal Authentication Service (SAS) is the next new feature to be offered by Galileo, the European GNSS. Its signal-in-space initial capability is expected already in the first months of 2025, starting with the L3 elliptic satellites.
Galileo SAS uses the existing Galileo E6C signal, to be encrypted, in combination with OSNMA (Open Service Navigation Message Authentication), through the so-called semi-assisted authentication concept. In this concept, future portions of the E6C are re-encrypted with OSNMA future keys and published in a server. The concept allows signal authentication as a free and open service, and without private key management by users. In exchange, the time between authentications is 30s, inherited from OSNMA, and introduces a latency between the E6C signal reception and its authentication down to a few seconds.
This work will present the status of Galileo SAS. It will present its latest technical definition, already shared preliminarily in previous publications. It will also present the latest testing results, including, if possible, results from the signal-in-space testing, and results from the MMARIO (Message and Measurement Authentication Receiver for Initial Operations) project, aimed at developing the first SAS server and receiver platform. Finally, the work will outline the Galileo SAS plans for the near future, up to the initial service declaration.

The Design and Test of an Array Based GPS Anti-Spoof System

O'Brien C[1], Lai E[1], Harding-Jones P[1], Wharton S[1], Cowan A[1]
[1]Chelton

Biography:

Cian O'Brien is a UK based Senior DSP and Algorithm Engineer at Chelton, where he works on GNSS Anti-Jam and Signal Intelligence. Before joining Chelton, he received a PhD degree from the Centre for Vision, Speech and Signal Processing at the University of Surrey, where he worked on source separation and analysis of audio and music signals. His presentation will be about Cheltons recent development of an array based spoofing detection and mitigation system.

Spoofing attacks are an important and growing threat to the reliability of modern Global Navigation Satellite Systems (GNSS). Unlike jamming attacks, spoofing attacks tend to be low power, making detection and mitigation challenging. The amount of reported spoofing attacks has risen sharply in recent years, with one source reporting over 41,000 incidents in a one-month period alone. While modern GNSS receivers are equipped with some signal monitoring capabilities (e.g. Receiver Autonomous Integrity Monitoring), receiver based Anti-Spoof solutions are limited.

Here we describe the design and development of an array based Anti-Spoof prototype, based on Chelton’s DACU4c Anti-Jam platform. While attackers can carefully match signal level features such as code delay and Doppler profile, they are unable to mask the fact that all spoofing signals originate from a single source. The prototype uses a novel algorithm to detect correlations in the received signals (post de-spreading), indicative of a single spoofing source, and steers a null in the direction of the detected spoofer using the DACU4c’s beamformer. The system can also provide additional information such as satellite reliability estimates and estimated spoofer direction in order to aid situational awareness. We report the results of an open sky spoofing trial using several commercial GPS receivers, during which the prototype was subjected to a selection of high fidelity spoofing attacks. For an unprotected system, it was demonstrated that the receivers could be successfully captured even without an initial jamming stage. With Anti-Spoof protection, the receivers were protected in all scenarios.

Fugro Satguard: Protection against spoofing and Jamming

Visser H[1], Wen X[1], de Vries R[1], Erik E[1]
[1]Fugro

Biography:
Hans Visser is a Geodesist working on GNSS for 35 years as technical manager, monitoring GNSS and Product Manager Satguard.

Fugro Satguard: Protection against spoofing and Jamming.

Global Navigation Satellite System (GNSS) satellite position spoofing by modifying the broadcast ephemeris has become a significant issue in the last years as can be seen by aircraft being spoofed in the eastern Mediterranean and east Baltic Sea. Also, for the maritime environment during hydrographic surveys position spoofing is becoming a problem.

Fugro is a leading GNSS orbit and Clock correction services provider for professional users. More than 100 GNSS reference stations are used to calculate orbit, clock, and bias corrections for GPS, Galileo, BeiDou, and GLONASS. This data is transmitted to GNSS receivers via six geostationary communication satellites and the internet, enabling centimeter-level positioning accuracy.

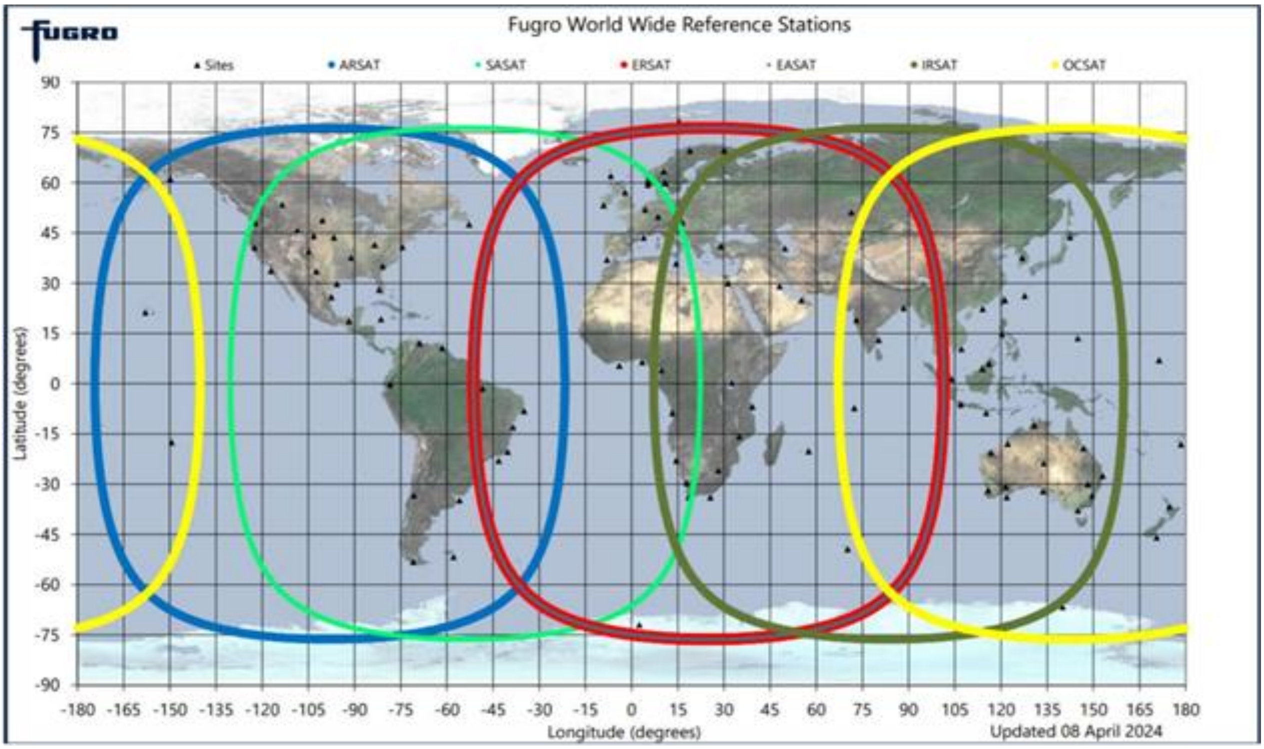
Satguard offers protection against jamming and spoofing through navigation Message Authentication, Spatial Integrity monitoring (SIA), robust RAIM techniques, and anti-jam antennas.

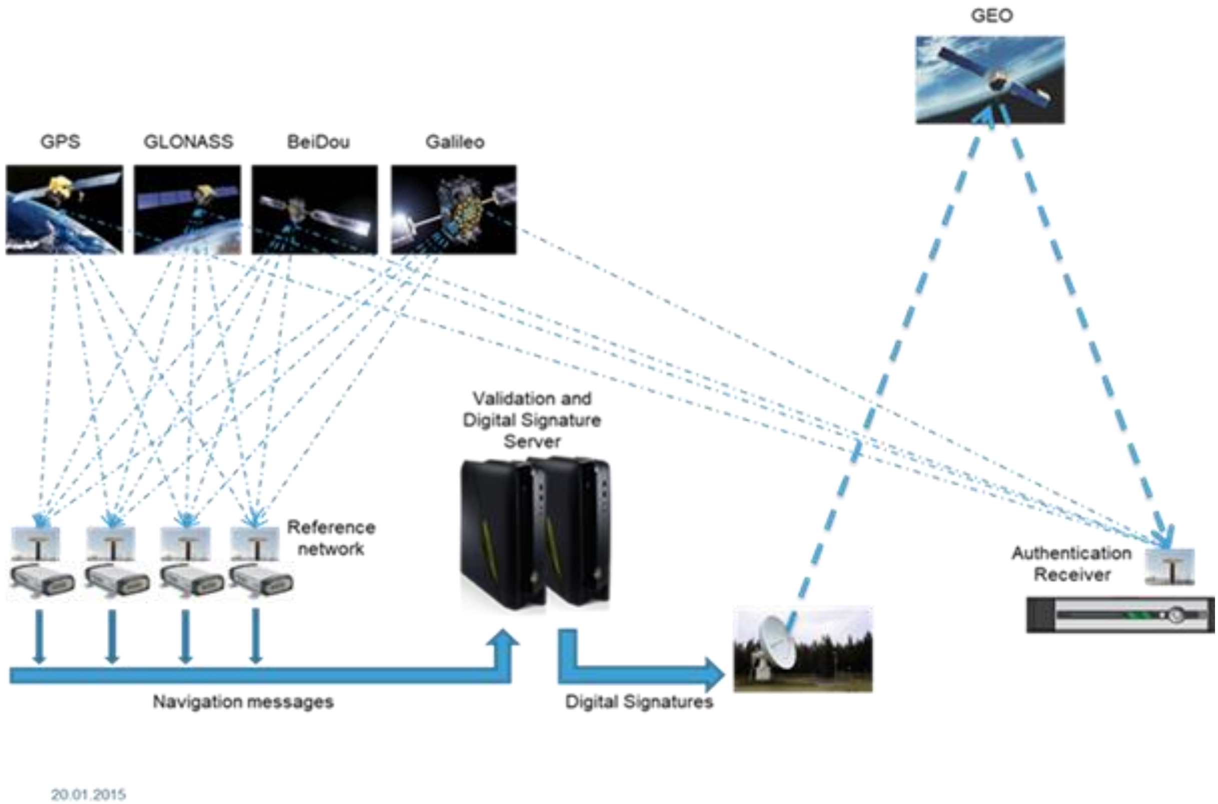
We explain the implementation of Navigation Message Authentication (NMA) using GPS, Galileo, BeiDou, and Glonass, and the authentication of broadcast orbit and clock (BMA) corrections. NMA position information is provided in three modes: flag, relaxed, and strict.

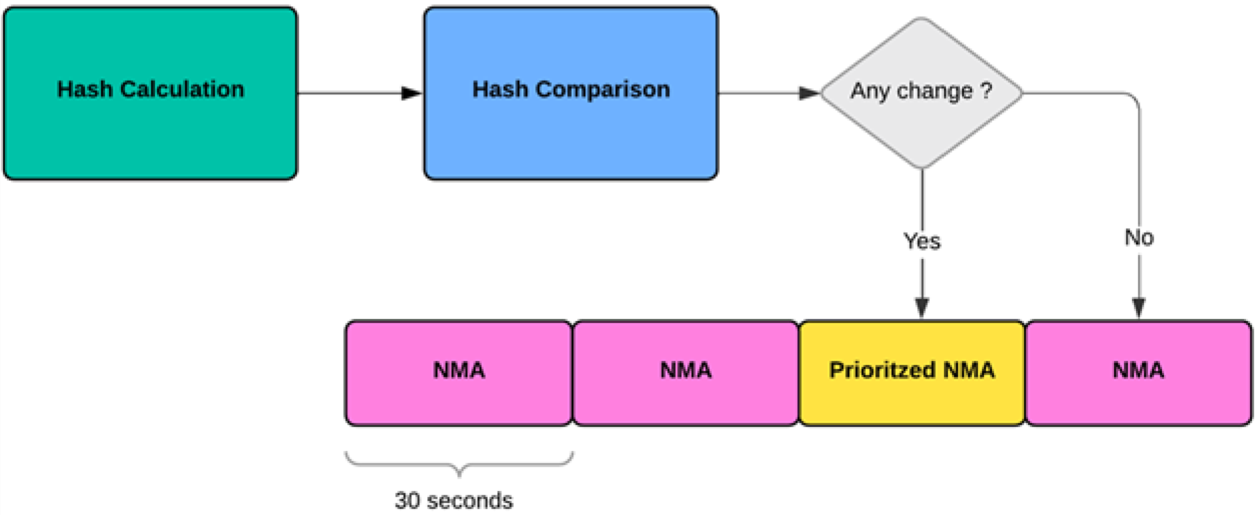
Multiple antennas are used to calculate relative baselines between the antennas. These antennas are deployed with Oceanstar on large vessels with baselines of several hundred meters and on small vessels to determine the attitude.

Using RAIM techniques pseudorange manipulation (Meaconing) is addressed. RAIM with Precise Point Positioning, four constellations, and triple frequencies, combined with authenticated ephemeris and with sufficient GNSS satellites makes spoofing very difficult.

Satguard is implemented in Seastar 9410-Aut for the dynamic positioning market, Starpack GNSS receivers for offshore operation,s and unmanned survey vessels. Satguard is also implemented in AtomiChron, Fugro’s sub-nano timing accuracy solution, to protect against time spoofing. Additionally, Satguard can be used by third-party OEMs to integrate in their own GNSS solutions.


FUGRO
Fugro World Wide Reference Stations
Sites
ARSAT
SASAT
ERSAT
EASAT
IRSAT
OCSAT
Latitude (degrees)
Longitude (degrees)
Updated 08 April 2024


GEO
GPS
GLONASS
BeiDou
Galileo
Validation and Digital Signature Server
Reference network
Authentication Receiver
Navigation messages
Digital Signatures
20.01.2015


Hash Calculation
Hash Comparison
Any change ?
Yes
No
NMA
NMA
Prioritzed NMA
NMA
30 seconds

A Frequency-Cross-Validation Approach for Pseudorange Fault Detection in GNSS Relative Positioning

Li Z[1], Wang D[1], Wu J[1]
[1]National University Of Defense Technology

Biography:
Dingjie Wang is an associate professor at the College of Aerospace Science and Engineering at NUDT. He received his Ph.D. degree in aeronautical and astronautical science and technology from NUDT in 2018. His current research interests mainly focus on inertial navigation and GNSS/INS integration.

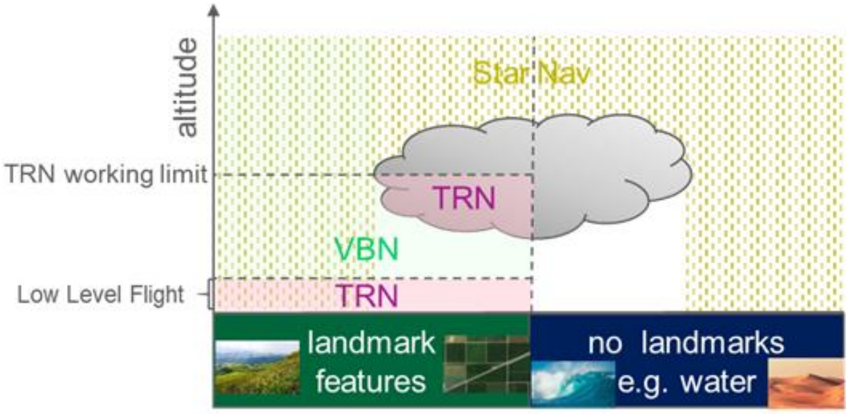
In this paper, we propose a novel pseudorange fault detection method based on frequency-cross-validation (FCV). The method begins with the estimation of the baseline vector between two receivers using least squares method, leveraging single-difference pseudorange observations from a single frequency across multiple channels. Subsequently, the single-difference pseudorange observations between two receivers are predicted for another frequency, on a channel-by-channel basis. Test statistics are then constructed by comparing these predicted values with corresponding actual single-difference pseudorange observations. If the test statistics exceed the predefined thresholds, it indicates the presence of a fault in the pseudorange observations, which should be excluded from further processing. Compared to conventional fault detection methods, the proposed FCV approach exhibits lower false alarm and missed detection rates, as well as enhanced independence between different frequency points. Through a series of experiments where faults are artificially introduced into the pseudorange observations, it is demonstrated that FCV method achieves higher accuracy in estimating the relative position vector between the two receivers using dual-frequency single-differenced pseudoranges, compared with the classical detection method. The results validate the effectiveness and superiority of the FCV method in GNSS relative positioning applications.

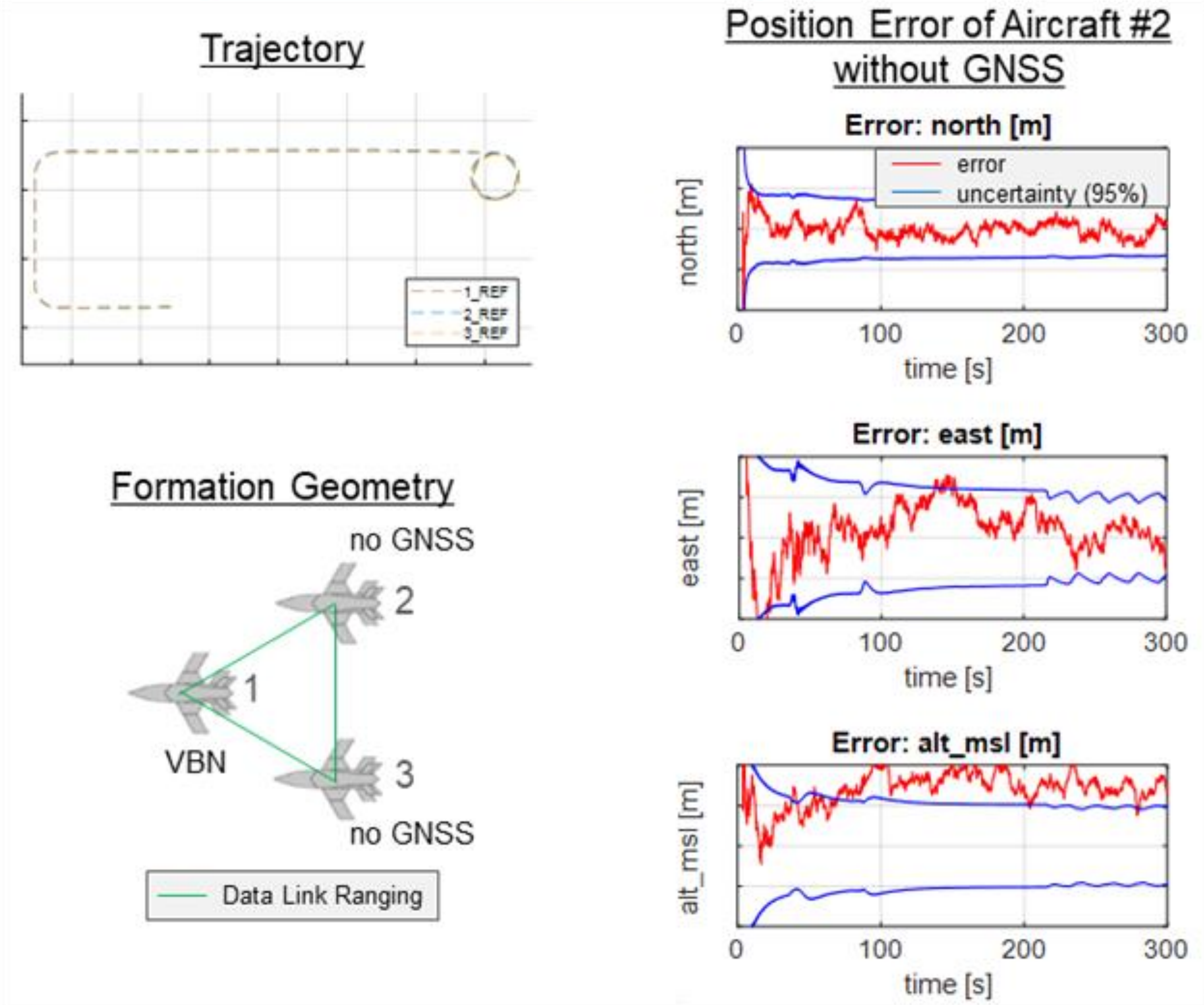
A Solution to GNSS-denied Navigation for Aeronautics – combining GNSS-denied Navigation Means and Collaborative Navigation

Neuhauser T[1]
[1]Airbus Defence And Space

Biography:
Name: Tobias Neuhauser
Affiliation: Airbus Defence and Space, Manching (Munich area)
Main Area:
- Since 2016 active in Research and Technology in the field of GNSS-denied navigation and Collaborative Navigation for military aircrafts
- This includes GNSS-denied navigation means such as Vision-based Navigation and Star Navigation
- Collaborative Navigation using for instance data link ranging to obtain state estimations with high relative accuracy between collaborating aircrafts
- Maturation of these technologies end-to-end with focus on sensor fusion
Topic:
- How the combination of different GNSS-denied Navigation means and Collaborative Navigation can address the challenge of GNSS-denied navigation for aeronautical applications

The vulnerability of GNSS became obvious more than ever in the Ukraine conflict. Massive electronic warfare renders GNSS useless. Unfortunately, there is not the “one” GNSS-denied navigation method which alone can substitute GNSS in all aspects such as worldwide operability and excellent position accuracy.
All onboard autonomous GNSS-denied navigation means have in common that they correlate sensor data with environmental features. The availability and performance largely depend on the existence of environmental features and capability to sense these environmental features. For example, a camera of Vision-based Navigation (VBN) system may not “see” environmental features (although physically present) in foggy conditions.
Therefore, complementary GNSS-denied navigation means need to be combined to cover the wide range of environmental conditions. Figure 1 depicts the approach of Airbus Defence and Space by combining VBN, Terrain-Referenced Navigation (TRN) and Star Navigation (StarNav). The environmental conditions are divided by the availability of landmarks, visibility conditions (e.g. obstruction by clouds) and altitude. VBN is operational if visibility to landmarks is given. StarNav is complementary to VBN as no landmarks are required but visibility to the stars is mandatory. Last but not least TRN completes the GNSS-denied navigation system for operation in low-visibility conditions.
In the era of systems of system Collaborative Navigation becomes part of the solution for GNSS-denied navigation, although it does not directly contribute to it. What marks collaborative navigation is its high relative accuracy which may be achieved by data link ranging between collaborating platforms. The relative accuracy is essential that accurate absolute navigation information can spread within the formation. Figure 2 showcases this for a formation of three aircrafts for which aircraft “1” has an operational VBN system while aircrafts “2” and “3” have neither GNSS nor GNSS-denied navigation capabilities. Nonetheless, aircraft “2” shows an absolute position accuracy comparable to aircraft “1”.


altitude
Star Nav
TRN working limit
TRN
VBN
Low Level Flight
TRN
landmark features
no landmarks e.g. water


Trajectory
1_REF
2_REF
3_REF
Formation Geometry
no GNSS
2
1
VBN
3
no GNSS
Data Link Ranging
Position Error of Aircraft #2 without GNSS
Error: north [m]
error
uncertainty (95%)
north [m]
0 100 200 300
time [s]
Error: east [m]
east [m]
0 100 200 300
time [s]
Error: alt_msl [m]
alt_msl [m]
0 100 200 300
time [s]

Integrity monitoring for positioning through graph-based SLAM optimization

Bekkers S[1]
[1]NLR

Biography:
Sam Bekkers is an R&D Engineer at Royal NLR - Netherlands Aerospace Center in Amsterdam. He obtained a MSc Robotics at Delft University of Technology in 2024. His main work topics focus on implementing multi-sensor SLAM solutions aimed to increase the navigation robustness, in GNSS availability or denial.

This paper addresses the issue of integrity monitoring in visual Simultaneous Localization and Mapping (SLAM) systems, with a focus on graph optimization techniques. Despite the significant advances in SLAM research, integrity monitoring remains a crucial aspect that has received limited attention. While some research has been conducted on Extended Kalman Filter (EKF)-based SLAM approaches, literature shows limited documentations of research towards integrity monitoring of graph optimization techniques.
Our method proposes a chi-squared failure detector to identify inconsistencies in the position estimation process. By analysing the residual reprojection error, our detector can identify potential failures and provide a measure of the system's integrity. Additionally, a Fault Detection and Exclusion (FDE) method is incorporated and its performance is evaluated through comparison to a commonly utilized Random Sample Consensus (RANSAC) outlier rejection scheme. The proposed approach is designed to detect failures in real-time. Moreover, we look into the applicability of our failure detector in multimodal sensor fusion algorithms. This is essential for ensuring the reliability of localisation systems based on multi-sensor SLAM solutions, which is a critical characteristic in various applications such as robotics and (autonomous) navigation.
The effectiveness of our approach is evaluated through experimental data, demonstrating its ability to detect failures and provide accurate integrity estimates. The results of this research contribute to the development of more robust and trustworthy SLAM solutions, enabling their deployment in safety-critical applications and ensuring timely warnings to users when integrity is low. Our method provides a step forward in addressing the integrity monitoring challenges associated with graph-based SLAM as the proposed chi-squared failure detector has the potential to become a standard component in multi-sensor SLAM systems.

A resilient navigation system for autonomous urban air mobility using low-cost hardware

Maier M[1], Klink D[1], Topp T[1], Hobiger T[1]
[1]Institute of Navigation, University of Stuttgart

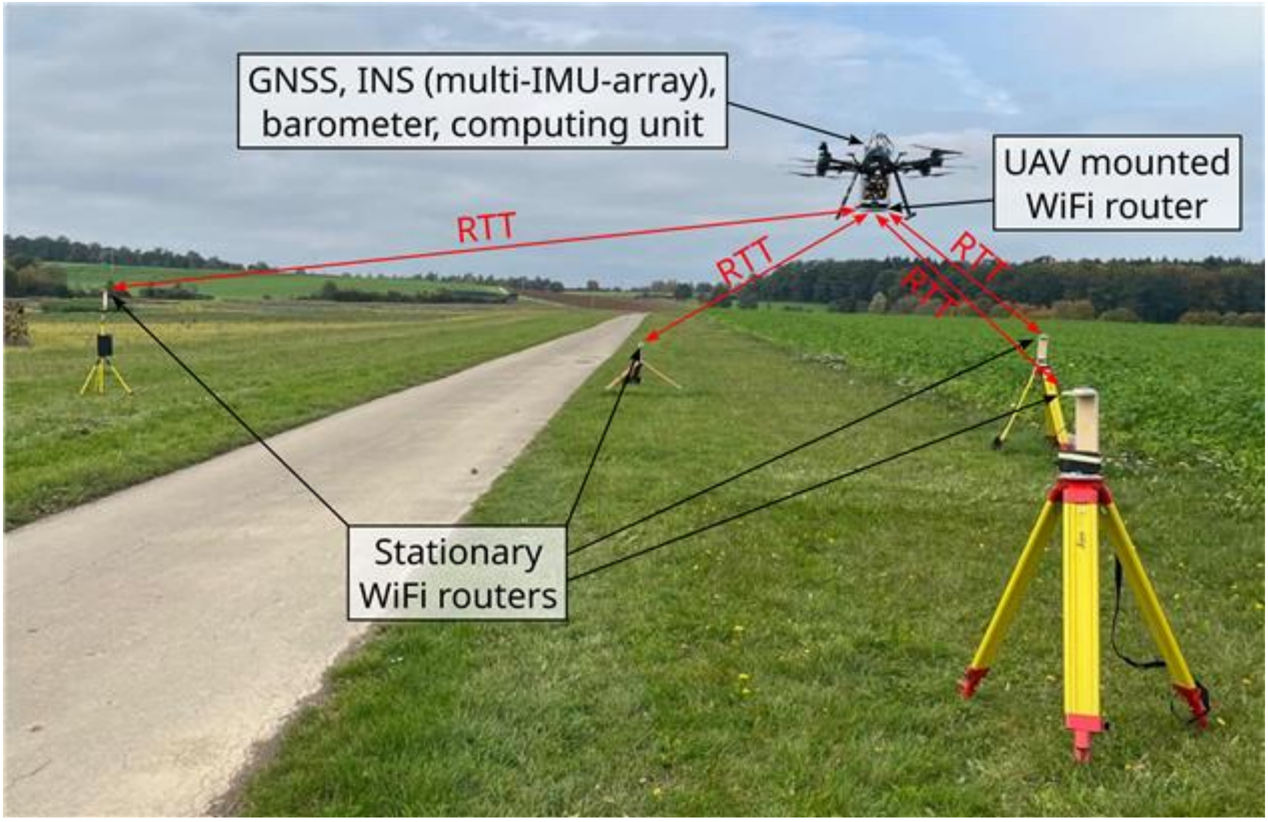
Biography:
Marcel Maier is a PhD student and research associate at the Institute of Navigation at the University of Stuttgart, Germany. His main area of research is focused on robust navigation algorithms for autonomous flight. The topic he intends to treat is an integrated navigation system that uses a WiFi positioning system and a barometer to complement GNSS/INS-fusion.

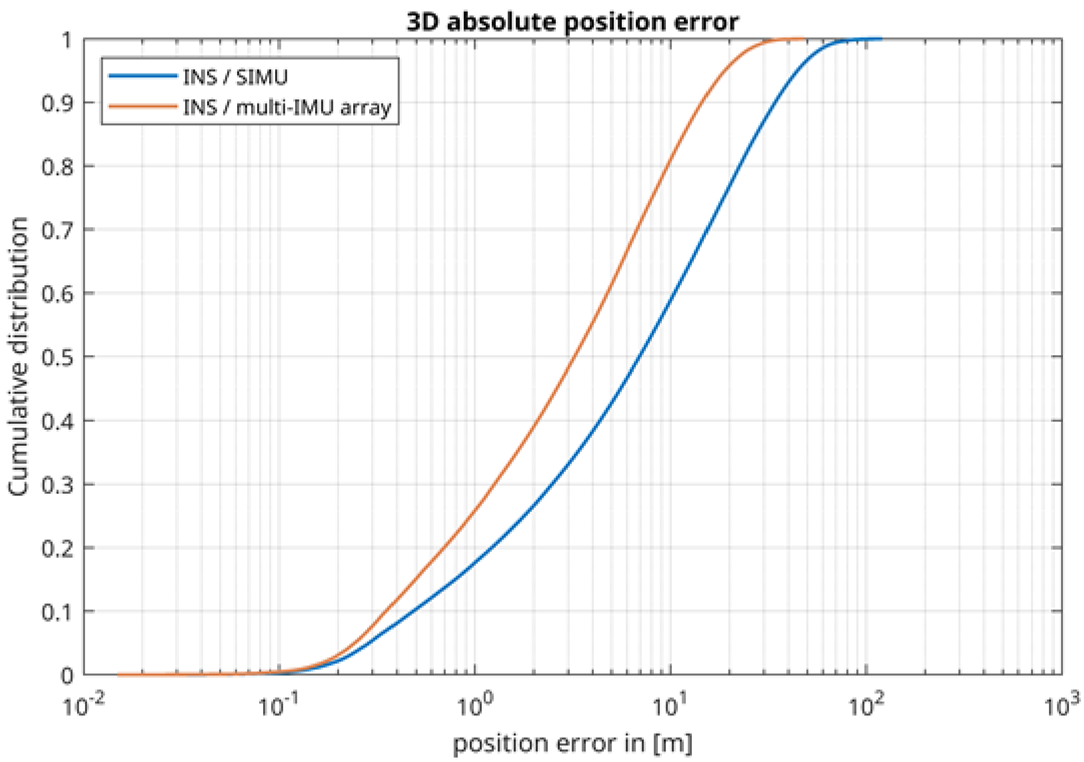
Constrained by tight cost calculations and relatively small payload capabilities, we propose an integrated navigation system for urban air mobility flight operation using low-cost hardware. Our concept features a WiFi-based Positioning System (WPS), which complements GNSS, a barometer and an Inertial Navigation System (INS), which makes use of multiple Inertial Measurement Units (IMUs). These four sensor systems are fused using a loosely coupled Kalman filter. Compared to basic GNSS/INS-fusion, our approach has an improved robustness and accuracy.

The WPS consists of an off-the-shelf WiFi router mounted to an Unmanned Aerial Vehicle (UAV) and a set of stationary WiFi routers. If the positions of the stationary routers are known, Round Trip Times (RTTs) to the UAV mounted router can be used to calculate the position of the UAV (see figure 1). Flight tests have shown that the WPS's position accuracy is comparable to GNSS code-phase positioning. The WiFi routers are also used as a bidirectional data link, providing the UAV with measured RTTs and telemetry and enabling down-streaming of the navigation solution for monitoring purposes.

The INS makes use of a multi-IMU array, in which specific forces and angular rates of an arbitrary number of Single IMUs (SIMUs) are fused consistently in a B-spline Kalman filter. The B-spline fusion model acts as a low-pass filter which allows to separate actual dynamic motion from sensor noise. In general, this concept provides redundancy and has a better precision than a SIMU (see figure 2).

The proposed integrated navigation system is implemented in the open-source software framework INSTINCT (Institute of Navigation, Stuttgart, Toolkit for Integrated Navigation Concepts and Training). The potential of this approach is validated by simulations and flight tests and the results will be summarized in our presentation.


GNSS, INS (multi-IMU-array), barometer, computing unit
UAV mounted WiFi router
RTT
RTT
RTT
RTT
Stationary WiFi routers

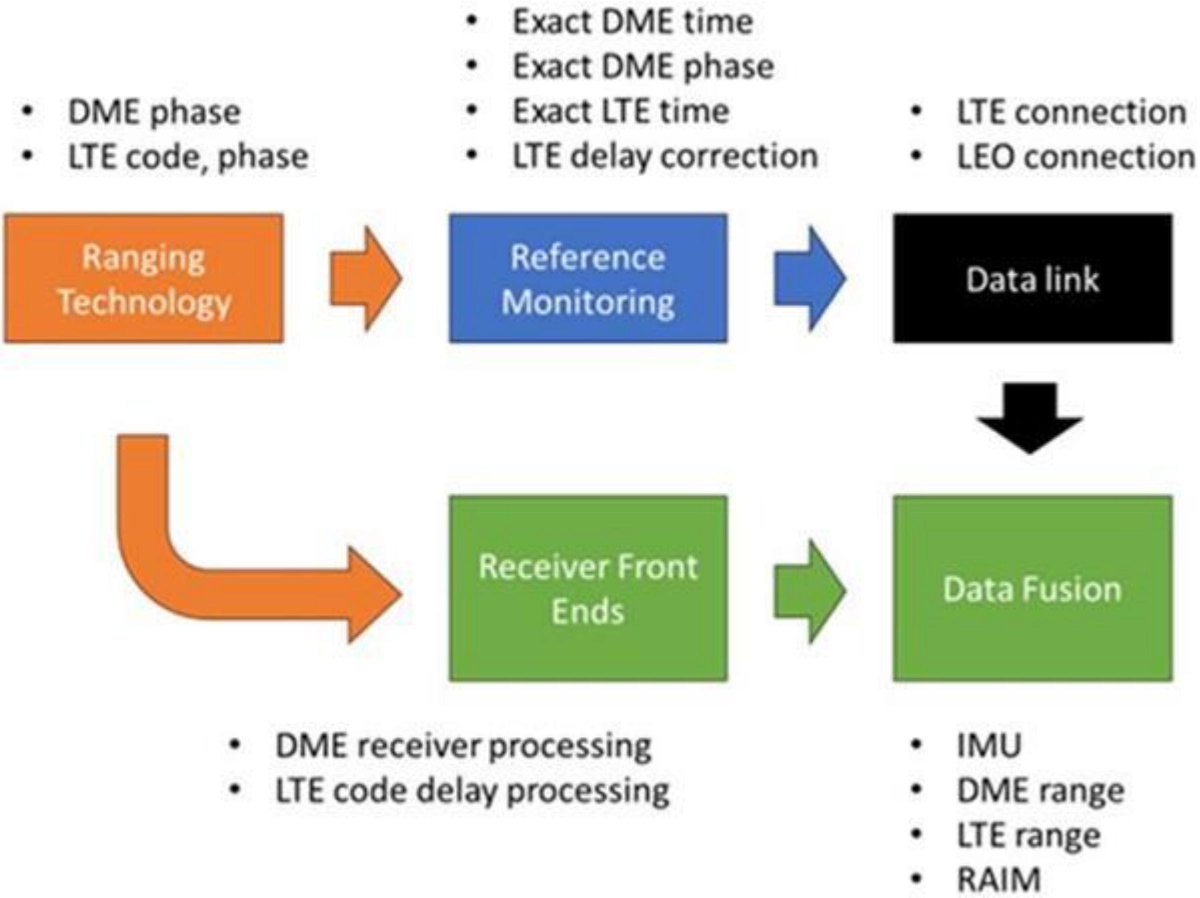

3D absolute position error
INS / SIMU
INS / multi-IMU array
Cumulative distribution
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
position error in [m]

Robust Autonomous Navigation using Carrier Phase of ARNS Signal for Unmanned Aircraft Systems

Tiwari S[1], Peltola P, Lavin B, Bransby M, Yin J, Arora T, Petrunin I, Tsourdos A, Budianu A, Salgueiro F
[1]Telespazio Uk, [2]Faculty of Engineering and Applied Science, Cranfield University, [3]European Space Agency (ESA)

Biography:
Ivan has extensive knowledge and experience in the area of Digital Signal Processing for Autonomous Systems which covers sensor technologies, perception, data and information fusion, and decision-making for Cyber-Physical Systems. Applications for these developments include vehicle health management, communication and surveillance solutions and, more recently, Position, Navigation and Timing (PNT) for aerospace and ground-based Autonomous and Intelligent Systems.
Ivan is involved in and actively supporting the development and operation of several research facilities, such as the instrumentation of Muti-User Environment for Autonomous Vehicle Innovation (MUEAVI), Research and Innovation Timing Node, PNT simulation facility.

Unmanned Aerial Vehicles (UAV) regulatory frameworks are progressing to where autonomous flight and operations Beyond Visual Line-Of-Sight (BVLOS) are a possibility, thus driving the need for reliable navigation services to complement or act as a back-up to existing ones (mainly GNSS). However, all GNSSs are vulnerable to natural interference, deliberate and accidental jamming and spoofing. In urban canyons they can have a limited view of the satellites and hence have trouble calculating a position. Clearly this is unacceptable when operating a safety critical service. Such are equally many situations when operating UAV in public areas. Trusted PNT solutions must be developed to tackle the challenges that congested airspace brings, such as the safety of autonomous flight in populated areas or avoiding in-flight collisions. It is also important that traffic management systems of the future have the right tools for safe operations. Such systems require reliable positioning and route information for decision making and for communicating information to the UAVs. The aim of this activity is to develop an effective A-PNT solution based on the carrier phase of ARNS signals and, telecommunication SOOP, hybridised with dead-reckoning (with barometer), to complement the current adopted GNSS/ SBAS-based PNT solution for Unmanned Aircraft Systems. LTE phase measurements are fused with GNSS and DME phase measurements using double-differenced observations. Inspired by Theunissen's research we use multiple frequencies adaptation into a double-differenced fusion solution. Here the PVT fusion is agnostic to the source of the phase measurements. Continuous phase needs to be measured at both the drone and a reference station. Double differenced observations need a communications link in any real-time implementation of our post-processed testing. The system was tested using simulation of LTE, DME and GNSS measurement and further with a real drone setup. The figure below depicts the overall procedure of the working system.



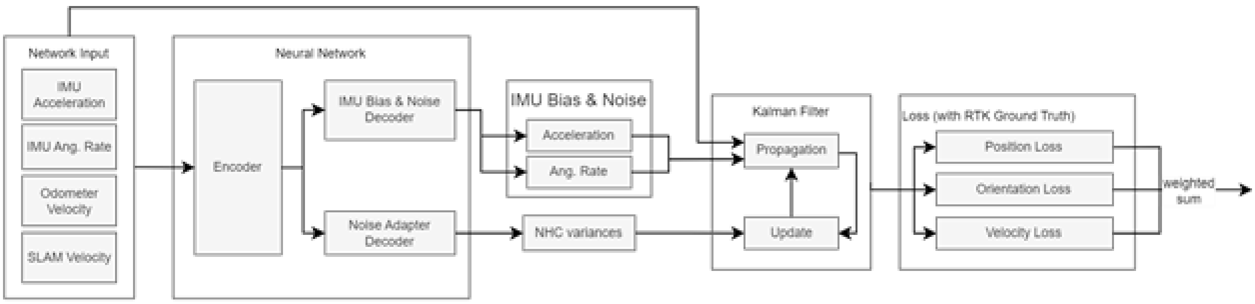
DME phase
LTE code, phase
Exact DME time
Exact DME phase
Exact LTE time
LTE delay correction
LTE connection
LEO connection
Ranging Technology
Reference Monitoring
Data link
Receiver Front Ends
Data Fusion
DME receiver processing
LTE code delay processing
IMU
DME range
LTE range
RAIM

Multitask Deep Neural Network for IMU Calibration, Denoising and Dynamic Noise Adaption for Vehicle Navigation

Schmid F[1], Fischer J[1]
[1]ANavS GmbH

Biography:
Frieder Schmid is a Software Engineer at ANavS GmbH in Munich, Germany. The focus of his work at ANavS is the navigation of moving objects.
He completed his master's degree in Geodesy and Geoinformatics at the University of Stuttgart in 2024, with his degree in the field of navigation, parameter estimation and sensor fusion.
Today, he will present an approach to IMU Calibration and Kalman filter noise adaption with deep learning.

In the context of intelligent vehicle navigation, especially in scenarios where GNSS signals are unavailable or unreliable, accurate and efficient sensor data processing is critical for maintaining robust performance. Classical calibration methods, including discrete and system-level calibration, have traditionally been used to correct Inertial Measurement Unit (IMU) errors, despite lacking either time-varying characteristics or the ability to account for nonlinear and non-Gaussian noise. In Kalman filter-based state estimation, a major challenge is defining the variance-covariance matrix for measurement noise, which classical methods often assume to be constant, leading to a suboptimal choice for the measurement noise in changing environments. These limitations have led researchers to adopt deep learning techniques to develop more effective and adaptive methods for both the IMU calibration and dynamic noise adaptation. This paper presents a novel approach of IMU calibration with dynamic noise adaptation for Kalman filtering in vehicle navigation. In contrast to existing approaches the proposed system uses a Multitask Deep Neural Network (MTDNN) architecture and makes use of additional sensor data — such as odometry information— alongside the raw IMU signals to the network. This way the network achieves better generalization and less overfitting while with the reduced computational overhead through parameter sharing, enable deployment on resource-constrained systems such as a Raspberry Pi. The network is trained using ground truth data derived from post-processed RTK trajectories under simulated GNSS outages, emphasizing high accuracy in GNSS-deprived conditions. A custom dataset for the network training was collected using a high precision RTK module, equipped with a tactical-grade FOG-IMU and visual sensors, covering diverse driving scenarios including urban, highway, and rural environments. Results demonstrate the system's superior generalization, computational efficiency, and real-time capability, marking a significant step forward in IMU calibration and dynamic noise adaptation for vehicle navigation. This work was conducted under the EU-funded DREAM project.



Feasibility of AI Feature Recognition Aided PNT in GNSS-Challenged Environments

Gabela J[1], Majic I
[1]Vienna University Of Technology, [2]University of Vienna

Biography:
Jelena currently works in the Engineering Geodesy division of the Vienna University of Technology. She completed her doctoral degree at the University of Melbourne, Australia in 2021 on cooperative integrity monitoring in GNSS-challenged environments.
Her main area of activity revolves around GNSS-challenged and denied environments including estimation theory, indoor positioning and integrity monitoring.

Many safety-critical Positioning, Navigation, and Timing (PNT) applications, such as autonomous vehicles or Intelligent Transport Systems, require the capability to achieve high accuracy and satisfy stringent integrity monitoring requirements. Sensor fusion and cooperative approaches are often proposed as PNT solutions for such applications in the Global Navigation Satellite System (GNSS) challenged and denied environments. These approaches ensure measurement redundancy in areas where GNSS cannot be relied on and can often be separated into Peer-to-Peer (P2P) solutions that imply communication and measurements between dynamic nodes in the network with unknown positions, and Peer-to-Infrastructure (P2I) solutions that imply communication and measurements between those dynamic nodes and anchor (i.e., infrastructure) nodes with known positions. Many current methods rely on infrastructure nodes equipped with additional sensors such as Ultra Wide Band radios or a detailed 3D map of the environment, both of which can be costly to set up.

With the rapid development of Artificial Intelligence (AI), many tasks that were previously slow and cumbersome are now readily solved in real-time. Instead of relying on large map databases to extract features, AI-based vision models, such as Meta AI's Segment Anything Model (SAM), can quickly and efficiently segment distinct objects in any image. In combination with other foundational AI models, segmented features can be recognised. This lowers the barrier for including new Signals of Opportunity in integrated navigation systems, such as visual recognition of features and landmarks. This paper investigates the feasibility of combining AI methods with traditional sensor fusion and cooperative positioning approaches based on estimators such as the Extended Kalman Filter and Particle Filter. Consequently, the case study assesses the capabilities of AI-based segmentation and feature recognition from the visual data in integrated navigation systems.

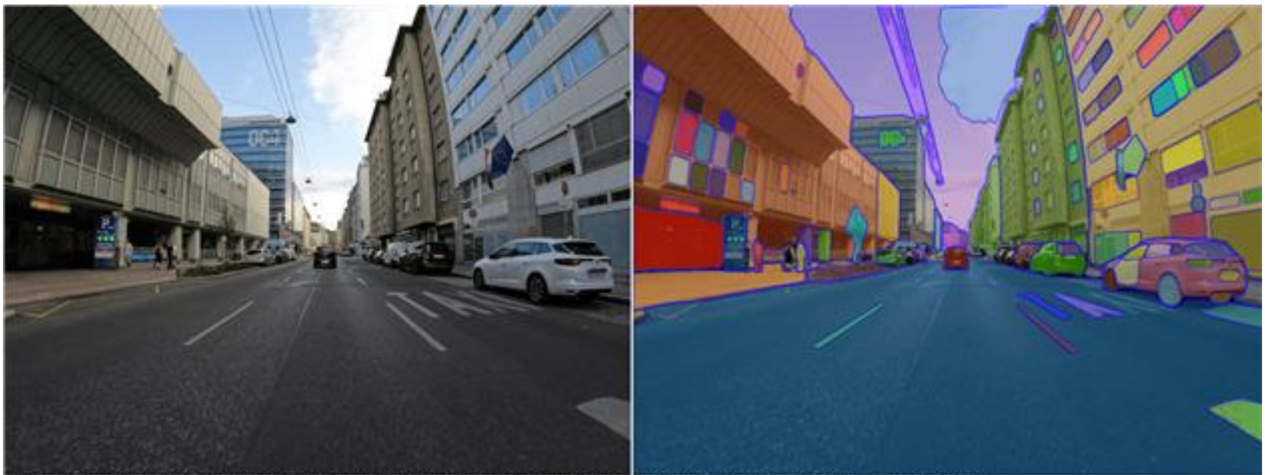


Figure 1. Demonstration of Meta AI's SAM. Recognition of roads, lanes, and other vehicles.

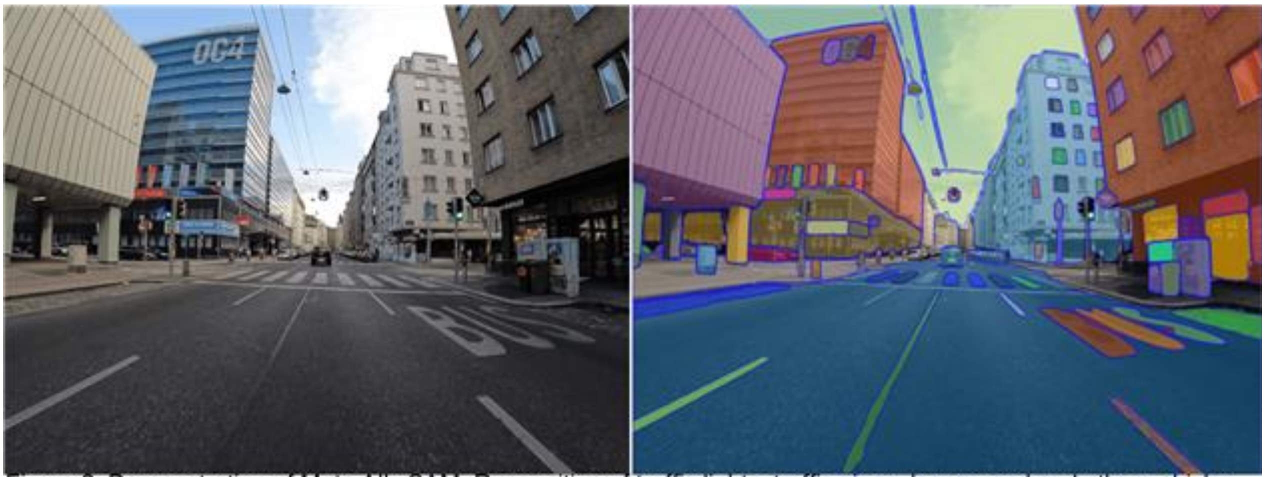


Figure 2. Demonstration of Meta AI's SAM. Recognition of traffic lights, traffic signs, lanes, road and other vehicles.

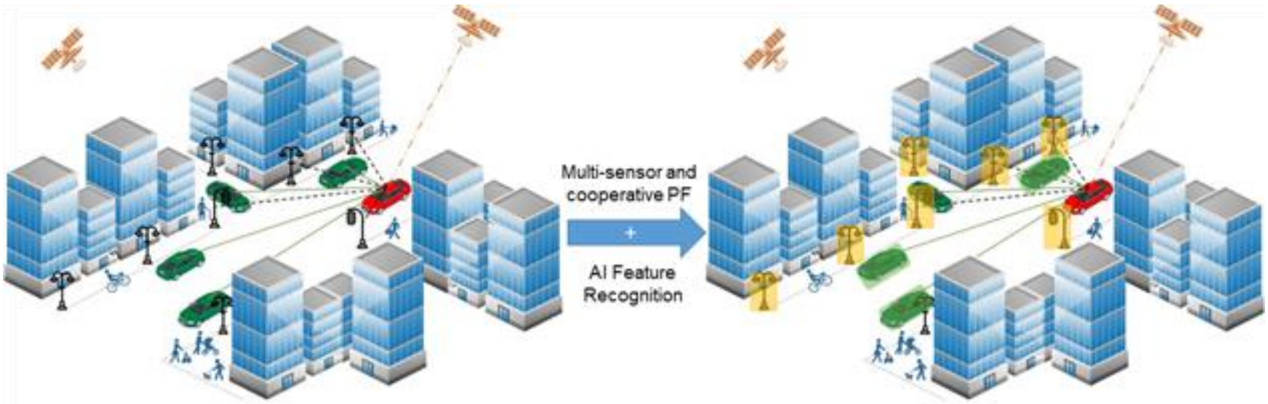


Figure 3. From traditional multi-sensor and cooperative positioning to AI aided PNT

Combination of autonomous vehicle and mobile mapping technologies for the production of high-definition maps

Colomina I[1], Blázquez M, Caevalho F, Pratra R, Billy A, de la Riviere J, Kaartinen H, Hyppa J, Joseph-Paul K, Skaloud J, Pölzbauer F, Lambauer K, Solmaz S, Hashimy L
[1]GEONUMERICS

Biography:
Dr. Ismael Colomina is the Chief Executive and Scientist of GEONUMERICS. With a background in Applied Mathematics, and after a long experience in practical mapping, photogrammetry and geodesy at the ICGC, he spent 15 years in academia. Since 2015 he is with GEONUMERICS where his main interest is in sensor fusion for positioning, attitude determination and robust navigation, with and without GNSS. He ius the coordinator of GAMMS.

The production of the maps to support autonomous vehicles (AVs) is a challenge as they must be accurate, up-to-date and fully cover large areas. These maps, called high-definition (HD maps), are produced in different ways, one of them being a combination of crowd-sourced semi-professional geodata collection and professional mapping with mobile mapping systems (MMSs). Professional mobile mapping produces base maps that are continuously updated with crowd-sourced data. From time to time, the base maps must be redone. The research reported in this contribution delves in the production of the base maps.
Terrestrial MMSs are commonly installed on vans driven by humans. In this case, humans are collecting data that later will be transformed in cartographic information for robots, the AVs. However, while AVs are equipped with low-grade instruments, MMSs are equipped with geodetic-grade ones. We may ask ourselves: can we combine the AV technology with the MMS motion sensing devices, so the AV-MMS combination becomes an MMS mapping robot? Or, in other words: can the higher-grade instruments of an MMS replace the geoinformation of an HD map so the AV-MMS combination can autonomously collect geodata in unmapped areas or in areas where HD maps are obsolete? Or to what extent is this possible to significantly reduce costs. The European Commission (EC) and European Union Agency for the Space Programme (EUSPA) project “Galileo-based autonomous mobile mapping system” (GAMMS) is trying to answer the previous questions by integrating miniature atomic clocks and satellite positioning and navigation, inertial navigation, visual odometry, laser scanning and vehicle dynamic models into (i) a navigation system (to feed the AV autopilot for real-time positioning) and (ii) a post-processing system to derive a higher-accuracy solution for mapping.
We will describe the said multi-sensor system in more detail, the sensor-fusion strategy, the results of the first project test campaign.

Adaptive Pods positioning solution based on reception context and vehicle movement

Chaiben Y[1], Ambellouis S[1], Marais J[1]
[1]Université Gustave Eiffel

Biography:
Yasmine Chaiben is a research engineer at the Université Gustave Eiffel since Feb. 2025. She received an Engineering Degree from the National Engineering school of Sousse in nov. 2024. She is working on context aware navigation solutions for the EU Pods4Rail project.

The transport world needs to address challenges as climate change, for environmental protection, or urbanisation. The Pods4Rail project, funded by Europe's rail (ERJU) aims at promoting sustainable and flexible solutions for transporting people and goods. Its goal is to promote a concept for a door-to-door transport chain based on rail.
The proposed system integrates the concept of intermodality with a digitalised, decentralised mobility service and multimodal interfaces to different transport modes.
The railway-based intermodal pod system (figure 1) will be a new kind of mobility system composed of pods and specific carrier units. It will be a-based rail transport, using railway infrastructure in combination with other modes of transport, like road or ropeway. This will improve the quality of life in urban and rural areas and contribute to a more sustainable and efficient future of mobility.
A Pods localisation Is a required input for various applications: traffic management, Pods tracking and passenger information. As for many land transport applications, the use of a GNSS receiver is a cheap and basic equipment. However, it is well-known that GNSS signal reception faces many degradations due to masking obstacles, multipath or signal interferences that is reducing its performance and its usability.
The Pods vehicle will travel in various types of environments: open sky areas, urban canyons, areas with trees and bridges. All will disturb performance in different ways. Moreover, the Pods will be carried by different transport modes, each of them following a different dynamic behaviour.
The paper will introduce the concept of context-aware localisation and present comparative studies of state-of-the-art approaches for context detection.
Considering the environmental constraints and dynamic of each Pods, we will investigate an adaptive positioning solution relying, as a first step, on the context and behaviour detection.

Collaborative Indoor Positioning: Integrating UWB Systems and Smartphone Sensors

Masiero A[1], Toth C[2], Grejner-Brzezinska D[3], Kealy A[4]
[1]University Of Padua, [2]The Ohio State University, [3]University of Wisconsin-Madison, [4]Swinburne University of Technology

Biography:
Andrea Masiero is Associate Professor of Geomatics at the Research Center of Geomatics of the University of Padua. His research interests range from Geomatics, Mobile Mapping, Positioning and Navigation, Machine Learning to Computer Vision and Remote Sensing. In this work he is going to talk about indoor collaborative indoor positioning based on smartphone sensors, such as inertial sensors, and UWB radio signals.

While Global Navigation Satellite Systems (GNSS) generally perform well outdoors, providing reliable positioning across various conditions, they face significant limitations indoors, where effective positioning is not guaranteed. To address these challenges, alternative positioning sensors are often employed, including inertial sensors, radio transceivers, cameras, and LiDAR (Light Detection and Ranging) sensors, typically integrated into hybrid systems.
Recent advancements in SLAM (Simultaneous Localization and Mapping) methods, leveraging cameras and LiDARs, have demonstrated promising results. However, these vision-based strategies often entail high power consumption, making them less suitable for portable devices with limited battery life. Consequently, this study focuses on RF and inertial sensors, which offer lower power consumption. Inertial sensors are standard in most smartphones, and UWB (Ultra-Wideband) transceivers have recently been incorporated into select high-end devices, making them viable alternatives to camera- and LiDAR-based systems.
UWB-based positioning traditionally relies on trilateration, using range measurements between moving devices and static UWB nodes with known positions. While static nodes enable absolute device positioning, reducing the reliance on such infrastructure is desirable to minimize system implementation and maintenance costs.
This work explores a collaborative indoor positioning approach that reduces the need for static UWB nodes. It employs UWB ranging between multiple moving devices and leverages affordable inertial sensors embedded in smartphones. The study provides a comparative performance analysis, highlighting the potential of this method to achieve effective positioning with reduced infrastructure requirements.

Comparative Analysis of Factor Graph Models for Carrier Phase-Based Precision Navigation

Dome T[1], Russell T[1], Ortiz Rejón M[1], Zheng Y[1], Benedetti E[1], Li T[2], Sun M[2], Petrunin I[2]
[1]GMV, [2]Cranfield University

Biography:
Dr. Tibor Dome is a Software Engineer at GMV, specializing in satellite-based positioning systems. He focuses on developing innovative navigation algorithms that enable reliable, high-accuracy, and safe applications across industries. His work combines advanced algorithms and statistical techniques to enhance real-time GNSS performance and post-processed positioning solutions. In his presentation, he will address key advancements in precise navigation technologies and their applications.

Kalman filtering has long been the preferred method for GNSS-based state estimation due to its simplicity, computational efficiency, and the suitability of GNSS observation models for linear approximations with Gaussian errors. However, the factor graph framework has emerged as a powerful alternative, particularly in challenging environments and when integrating additional sensors. The locality property of factor graphs has demonstrated advantages across robotics and autonomy applications, including mapping, visual and inertial odometry, motion planning, trajectory estimation, and deep learning. While most sensor modalities in these fields already adopt factor graphs for state estimation, GNSS has yet to fully capitalize on their potential. This study addresses a gap in the literature by presenting a comparative analysis of factor graph formulations for high-precision GNSS positioning, focusing on techniques like Precise Point Positioning (PPP) and Real-Time Kinematic (RTK). We examine the construction of pseudorange and carrier phase factors and evaluate trade-offs of different factor graph architectures (see Fig. 1). We consider the integration of Ambiguity Resolution (AR) factors into the graph to enhance accuracy and fully leverage recent advances in PPP-AR. We highlight the flexibility of factor graph-based plug-and-play navigation for operation across a wide range of scenarios, including low- to high-dynamics environments and low- to high-cost equipment, as well as platforms ranging from small drones to large vehicles. Our study emphasizes the benefits of factor graphs over Kalman filtering for GNSS positioning, including improved accuracy and reliability in light urban areas and under tree canopies, reduced PPP convergence times, and increased AR fix rates. Combining these advances with innovations from the robotics and autonomy communities holds the promise of robust positioning for safety-critical autonomous applications in deep urban environments. The work is carried out under ESA NAVISP Element 1, which is devoted to the development of innovative PNT, systems, technologies, algorithms and techniques.

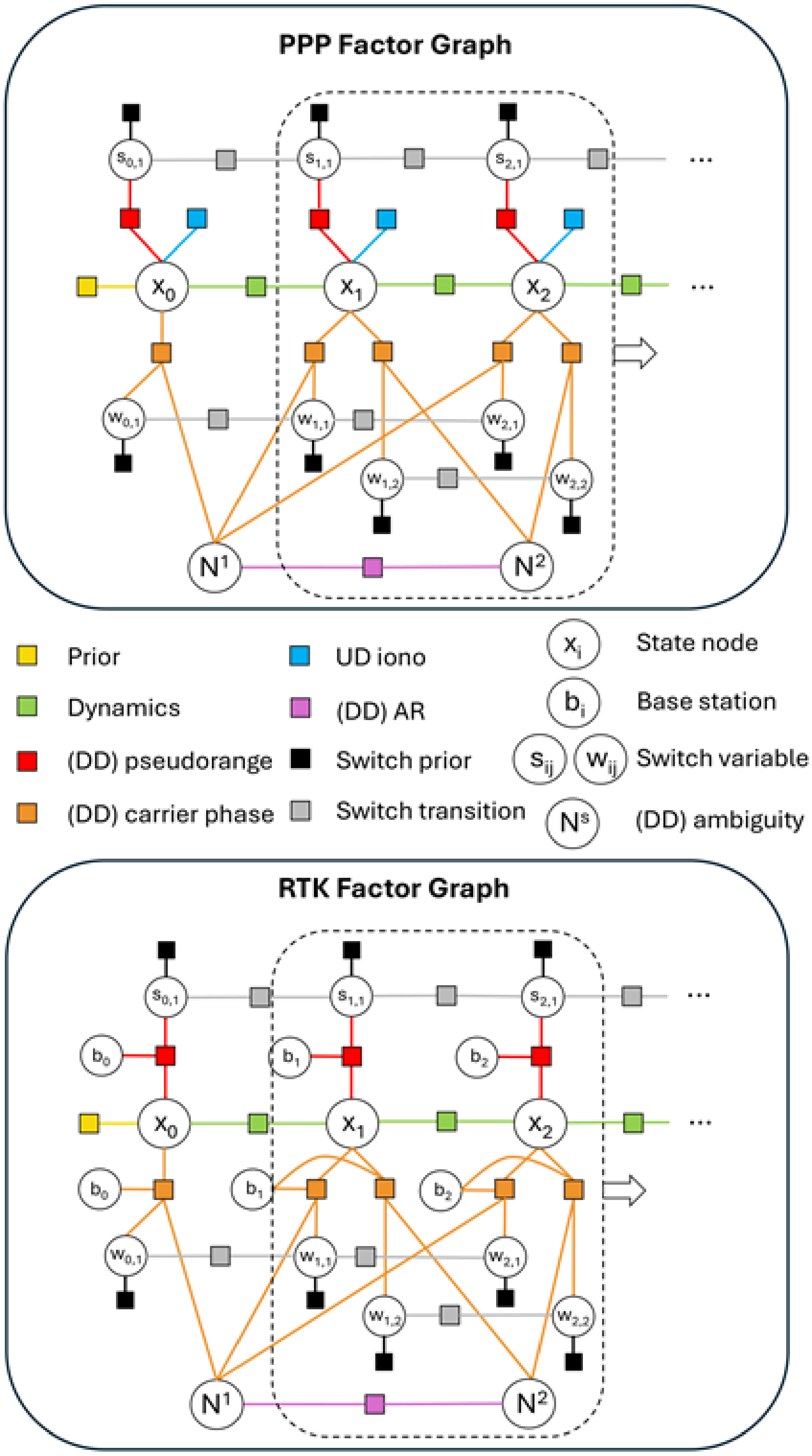


Figure 1: Simplified factor graphs for potential PPP (top) and RTK (bottom) solvers with two in-view satellites, each having one channel. Pseudorange factors (red; double-differenced [DD] for RTK), carrier phase factors (orange; DD for RTK) and undifferenced (UD) ionospheric delay factors (blue, PPP only) constrain the state vertices. For clarity, only one pseudorange factor and one UD ionospheric delay factor (PPP only) are shown per state vertex. Switch variables have associated prior factors (black) and are connected by switch transition factors (grey). State transition factors (green) link the state vertices. Carrier phase factors are further connected to (DD) ambiguity variables, pairs of which can be constrained upon successful AR.

Algorithms for Close-Range Nonlinear Mixed-Integer Location Estimation

Uziel O[1], Toledo S[1]
[1]Tel Aviv University

Biography:
Ophir Uziel is a computer science MSc student in Tel Aviv University, working on nonlinear mixed-integer location estimation. Ophir obtained his BSc in physics and computer science from the Hebrew University of Jerusalem in 2019.

Since the 1990s, algorithms for mixed-integer least-squares minimization have enabled centimeter-level GNSS localization using carrier-phase observations, primarily using the RTK approach. The maximum-likelihood estimator yields a nonlinear least squares minimization problem with both integer and real variables. The first step in the dominant solution method, LAMBDA, linearizes the Euclidean distances around an approximate solution, to obtain a linear mixed-integer least squares problem. Due to the huge range to MEO satellites, the linearization is very accurate.

We consider the same problem, but when the emitters (satellites) are much closer, as might be the case with terrestrial or indoor pseudolites, as well as with LEO satellites operating in the X band and above.

We show that the LAMBDA approach fails on such problems because the linearization is not accurate enough.

We propose and investigate three methods for solving these challenging minimization problems. At this early stage, we focus on range constraints without nuisance parameters.

The first method uses a squaring-and-differencing algorithm, superficially similar to closed-form GNSS code-phase solvers. The algorithm resolves ambiguities that are squares of shifted integers, not integers, but we show that the Schnorr-Euchner search algorithm can handle these ambiguities. By correctly de-correlating the constraints and by using a linear approximation to one constraint, the one that we subtract from the others, we correctly resolve the ambiguities down to ranges of 10m.

The second method uses double differencing in multi-epoch (RTK-type) problems to eliminate the squared integers from the squared constraints. The algorithm requires dropping constraints, so it is less robust than the first method, but faster.

The third method uses a computational geometry approach to enumerate the so-called Voronoi cells (geometically-consistent assignments of integers). We show that the number of cells is polynomial, not exponential. The implementation depends on a computational-geometry library, which currently can only handle 2D problems.

High-Precision In-Motion Alignment Method for SINS Based on Two-Dimensional LDV

Tian M[1]
[1]National University Of Defense Technology

Biography:
The author, Tian Ming, is from Hunan, China. He is employed at the National University of Defense Technology. His research interests include multi - sensor information fusion and inertial navigation algorithms.

The accuracy of initial alignment directly affects the navigation performance of the Strapdown Inertial Navigation System (SINS). High-precision, rapid, and convenient initial alignment methods are essential for SINS. This paper proposes a method for achieving fast and high-precision in-motion alignment by integrating a Laser Doppler Velocimeter (LDV) to assist the SINS. In existing LDV-assisted SINS in-motion methods, only one-dimensional velocity from LDV is utilized, with the vehicle's vertical and lateral velocities derived through non-holonomic constraints (NHC). However, when the vehicle experiences bumps, the NHC assumption of zero vertical velocity is violated, which reduces the accuracy of the measurement model and the alignment precision. To address this, this paper uses two-dimensional velocity from the LDV to enhance SINS in-motion alignment. First, based on the optical path structure of the LDV, the two-dimensional vehicle velocity (forward and vertical) is obtained. Next, a measurement model is constructed using this two-dimensional velocity data, and an adaptive unscented quaternion estimator is employed to estimate the SINS attitude. This estimator avoids the singularities and norm constraint issues that are commonly encountered in quaternion-based applications. The proposed method is validated through field tests, where experimental results show that it provides accurate attitude estimates and meets the requirements for in-motion alignment. Within 300 seconds of alignment time, the heading error converges to within 0.1°.

Jamming Mitigation Performance Analysis of a State-of-the-Art Multi-Band Receiver Module

Heijnen S[1], Sleewaegen J, Heijnen S
[1]Septentrio NV

Biography:
Samuel Heijnen is a DSP engineer at Septentrio. He holds a master's degree in electrical engineering, specializing in signal processing and information systems, which he earned at KU Leuven in 2024.

In this presentation we discuss the impact of a variety of jamming signals on GNSS reception and analyze the improvement achieved by active interference mitigation on a Septentrio multi-frequency multi-constellation land grid array (LGA) module.

First, we present the automated test system we developed. This system is capable to inject a combination of jamming waveforms into the GNSS signal, anywhere in a 500 MHz frequency span. The signals in the jamming waveform database are based on field recordings and represent actual chirp jammers, PRN jammers and narrowband interference. The power of the jamming signal is precisely calibrated and referenced to the input of the antenna LNA, yielding metrics, which are independent of antenna gain and cabling.

We will then introduce the module used in the test and discuss its capabilities to mitigate interferers, leveraging a powerful assembly of digital interference mitigation circuits.

After this we are ready to present the measurements, showing how C/No loss evolves as a function of jamming power incident to the antenna, for a representative set of jamming scenarios. This is done both for a legacy narrowband signal (GPS L1C/A) and a modern wideband signal (GALILEO E5a). For each of these signals we compare results for a module with active interference mitigation and one without. This provides insight into the benefit of interference mitigation and addresses the contribution of GNSS signal design.

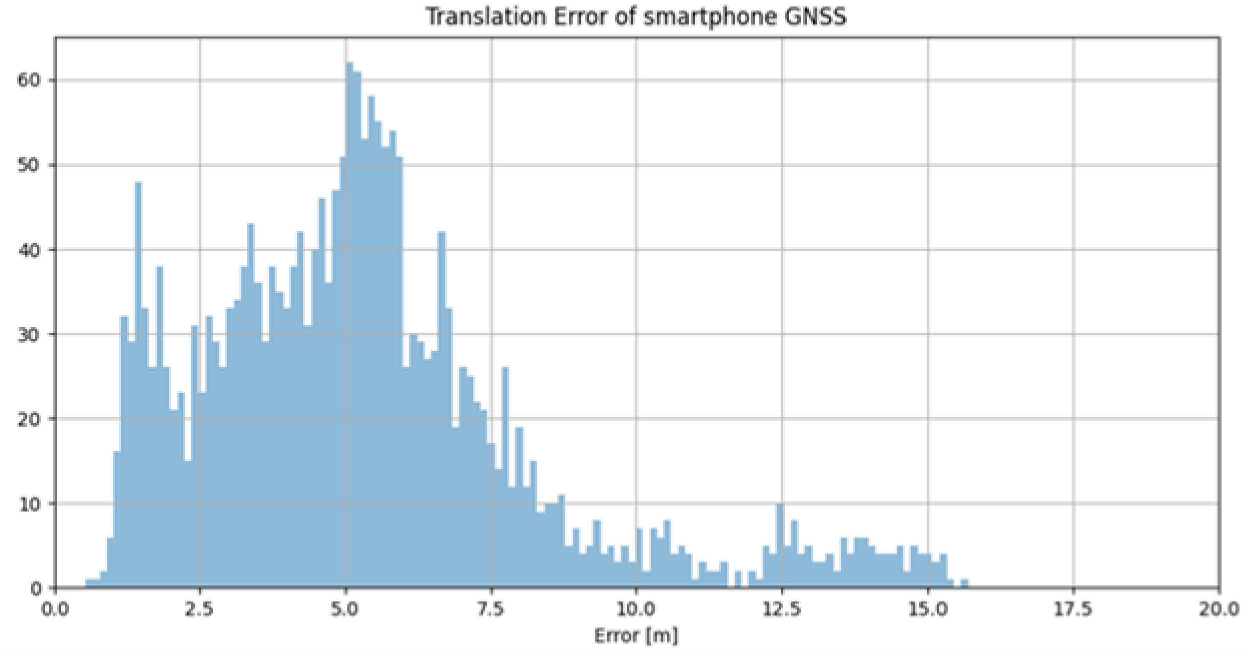
Finally, we discuss the impact on positioning, listing the maximal jamming power level for which the receiver can achieve a cold position fix and the level up to which it can still maintain a fix. This is done for a number of jamming scenarios and receiver configurations.

The role of visual localisation in future navigation systems: a complementary approach

Vultaggio F[1,2], Loeper Y[1], Schörghuber M[2], Colomina I[3], Fanta-Jende P[2], Gerke M[1]
[1]Technische Universität Braunschweig, [2]Austrian Institute of Technology, [3]GeoNumerics

Biography:
Francesco Vultaggio is a PhD candidate at TU Braunschweig in collaboration with the Austrian Institute of Technology. His area of research is in Visual Localization and is currently exploring strategies to scale the technology. He will present a work carried out within the Egeniouss project on how to integrate Visual Localization in a complete localisation framework.

Navigation relies on two complementary approaches: incremental relative position estimation (e.g. using IMUs or cameras) and absolute position estimation (often GNSS signals). These components are combined through sensor fusion algorithms, which integrate absolute pose data to correct for the drift incremental estimates by accounting for sensor errors and estimates uncertainty. However, GNSS signals degrade in urban areas due to obstructions, interference, and multipath effects, see Figure 1.
Visual Localisation (VL) offers an alternative to GNSS by localising a query image in preexisting maps of the environment such as georeferenced meshes or 3D models. While traditional VL can obtain accurate pose estimates it depends on costly ground imagery. Aerial imagery enables scalable, city-wide VL at lower costs. In our previous work we showed how aerial mesh based VL, see Figure 2c, can achieve decimetre level accuracy. However, city scale meshes are impractical to store on an edge device. To enable offline deployment, we introduced a lightweight approach using 3D CityGML models, see Figure 2a, which are freely available for many cities worldwide and require minimal storage. In another work we demonstrated that pose estimation with CityGML models converges near true solutions despite limited texture and geometry.
In this contribution, we present a complementary navigation framework that leverages multiple sensors in low-cost devices (e.g. consumer smartphones) by integrating mesh and CityGML-based visual localisation with visual odometry and IMU data for real-time, accurate, and scalable positioning. The IMU serves as the primary navigation sensor, providing high-frequency position, velocity, and attitude (PVA) estimates, while other sensors correct and calibrate its output. The framework can be extended with optional augmentations such as High-Accuracy Service (HAS) to enable navigation in GNSS-denied, disconnected, intermittent, and low-bandwidth (GNSS-DDIL) environments.


Translation Error of smartphone GNSS
60
50
40
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0
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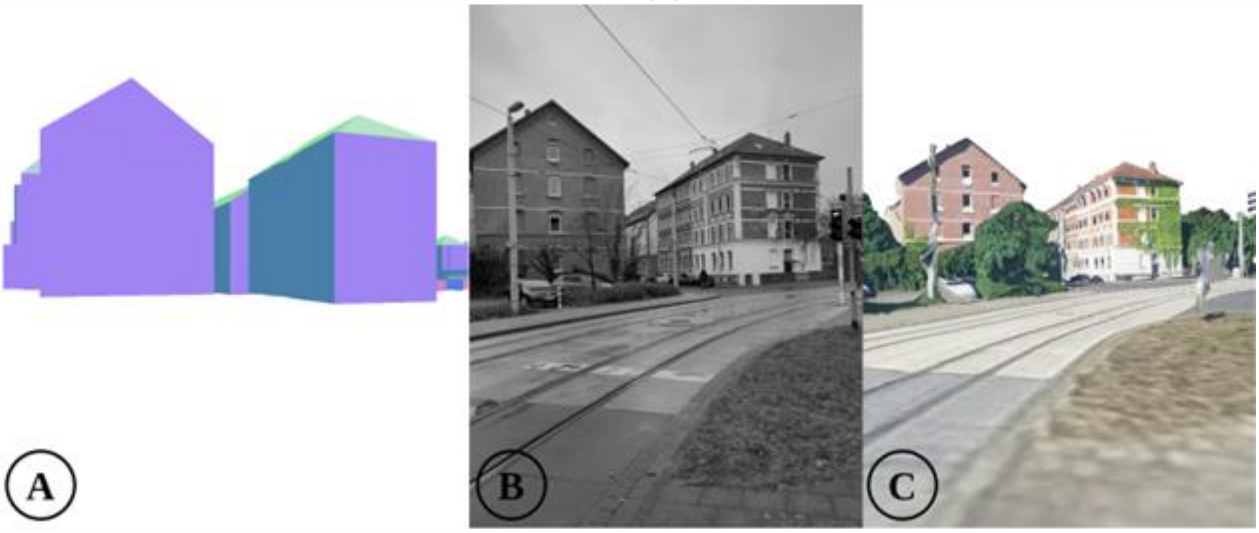
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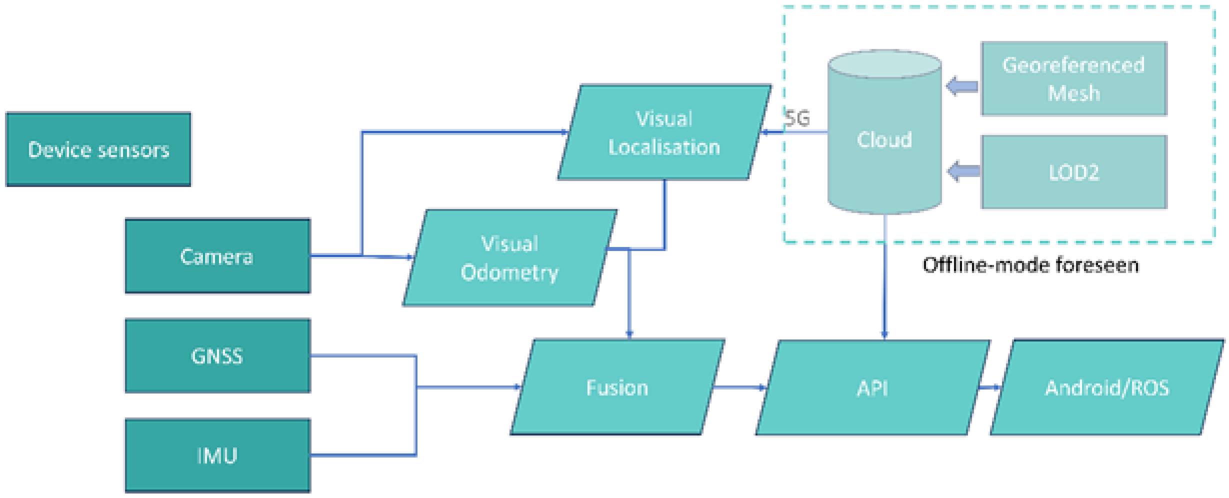

Device sensors
Camera
GNSS
IMU
Visual Localisation
Visual Odometry
Fusion
API
Android/ROS
5G
Cloud
Georeferenced Mesh
LOD2
Offline-mode foreseen

Parametric error model of GNSS pseudorange differencing for resilient cooperative train positioning

Saura E[1], MINETTO A[3], DOVIS F[3], MARAIS J[2]
[1]Ikos Consulting, [2]Université Gustave Eiffel, [3]Politecnico di Torino

Biography:
Enki Saura received the engineering degree from École supérieure des techniques aéronautiques et de construction automobile in 2022 and is currently pursuing a Ph.D. degree in electronics from Université Gustave Eiffel, France. Since 2022, he has been an innovation consultant with IKOS Consulting, a consultancy firm specializing in engineering for the railway and energy sectors. He is currently involved in cooperative GNSS performance analyses and enhancement in land transport environments.

In Europe, most train passengers use only a small portion of the railway network. In France, capillary lines make up 42% of the network but account for only 10% of the commercial offer. Despite their importance for urban development, traditional rail solutions are often uneconomical for low passenger traffic, leading to the decommissioning of thousands of kilometers of tracks. To create a sustainable solution, lighter infrastructure is essential.

A promising approach is replacing costly Train Detection Devices (TDD) located on tracks with GNSS-based on-board systems. While GNSS could reduce infrastructure costs, its use in passenger rail is hindered by safety standards and non-predictable errors like multipath and interference. To address these, recent research focuses on multi-sensor GNSS solutions to ensure safety and performance for rail applications. However, for lighter railway systems, that usually consist of single tracks, the absolute position of the trains is not the actual necessary data for collision avoidance systems but more inter distance between trains. We explore then the use of pseudorange differencing ranging. This technique is expected to be more resilient, easier to certify and a more cost-effective approach than the multi-sensor approach. However, direct ranging with pseudorange differencing in the railway industry is not usual and statistical error models are still to be determined.

Pseudorange differencing error model varies based on factors such as speed, baseline length, dilution of precision and multipath. In a previous work, we characterized the impact of those parameters on baseline errors. In this paper, we intend to use the data collected during a previous simulation campaign of over 205 hours to propose a parametric error model. This model is designed to be later integrated into an integrity monitoring algorithm for trains. Its performance will be validated on a test track in a subsequent paper.

Experimental Testbed and Measurement Campaign for Multi Constellation LEO Positioning

Fernández I Temprado M[1], Reus-Bergas A[1], López-Salcedo J[1,2], Seco-Granados G[1,2]
[1]Institut Estudis Espacials De Catalunya, [2]Universitat Autònoma de Barcelona (UAB)

Biography:
Marc Fernandez Temprado
Research Assistant,
Marc Fernandez Temprado is a undergrad student in Telecommunications at UPC Barcelona Tech, specializing in satellite positioning and signal processing. His research focuses on using Low Earth Orbit (LEO) satellites for Doppler-based positioning, leveraging Software-Defined Radio (SDR) platforms. In his presentation, Marc will introduce a portable testbed for multi-constellation LEO signal processing, exploring its potential for next-generation positioning applications in both outdoor and indoor environments.

The interest in Low Earth Orbit (LEO) satellites has grown exponentially in recent years, driven by the emergence of the NewSpace economy, a global trend fueled by the dramatic reduction in the cost of satellite launch and operation. This cost efficiency has attracted numerous private companies to deploy their own mega-constellations, consisting of thousands of small LEO satellites. The rapid expansion of this new satellite ecosystem has also captured the attention of the positioning, navigation, and timing (PNT) community, which sees LEO satellites as a promising solution to overcome many of the limitations of conventional Global Navigation Satellite Systems (GNSS) that rely on Medium Earth Orbit (MEO) satellites.

LEO satellites provide several compelling advantages such as: i) a much higher receiver signal power, due to smaller propagation losses; ii) better geometry and visibility in urban areas, due to the large number of available LEO satellites; iii) much higher dynamics, thus enabling single-satellite positioning and Doppler-based positioning. These attributes make LEO satellites especially attractive for next-generation positioning applications. However, while dedicated LEO-PNT constellations are still under development, existing LEO satellites present a valuable opportunity to experiment with live signals for positioning purposes.

In this context, the goal of the present paper is two-fold. Firstly, a portable multi-constellation hardware testbed is presented, which has been developed based on the use of COTS and software-defined radio. The testbed allows the simultaneous and synchronous recording of LEO signals from Orbcomm, Iridium, Globalstar and OneWeb, and then a software module is in charge of processing all these signals and providing the positioning observables. Secondly, an exhaustive measurement campaign is presented, where multi-constellation observables are characterized. Both outdoor and indoor scenarios are considered and compared, thus unveiling the potential of opportunistic LEO positioning in the long-awaited satellite-based indoor positioning.

Conference Room C, May 22, 2025, 2:30 PM - 3:50 PM

Addressing Divergence in Least-Squares for LEO-PNT

Van Uytsel W[1], Majorana A[1,2], Janssen T[1], Berkvens R[1], Weyn M[1]
[1]IDLab - UAntwerpen - imec, [2]University of Padova

Biography:
Wout Van Uytsel obtained his Bachelor's degree in Applied Engineering: Electronics-ICT from the University of Antwerp, Belgium, in 2022, followed by a Master's degree in the same field from the same university in 2023. Currently, he is pursuing a PhD at the University of Antwerp within the IDLab - imec research group. His primary research interests include Low Earth Orbit (LEO) satellite communication and indoor positioning using satellite signals.

Positioning, Navigation and Timing (PNT) services serve as the backbone for a wide range of applications. Currently, Global Navigation Satellite Systems (GNSS) provide these PNT services. However, a new trend aims to leverage satellites in Low Earth Orbit (LEO) to provide more robust and diverse PNT information. LEO satellites have the potential to address several limitations of GNSS, while also introducing unique challenges. A typical GNSS receiver uses the Least Squares (LS) algorithm to calculate a position estimate. However, when using solely LEO satellites, the LS algorithm struggles to converge upon a good positioning estimate when initiating the algorithm from the center of the Earth. This paper analyzes and addresses the divergence of the LS algorithm with LEO-PNT satellites, by introducing an Earth step adjustment to ensure convergence. Furthermore, we verified the convergence of the algorithm in a Monte Carlo simulation. The Earth step adjustment reaches a convergence rate of 99.99%, while the unadjusted LS algorithm reaches a convergence rate of 41.46%.

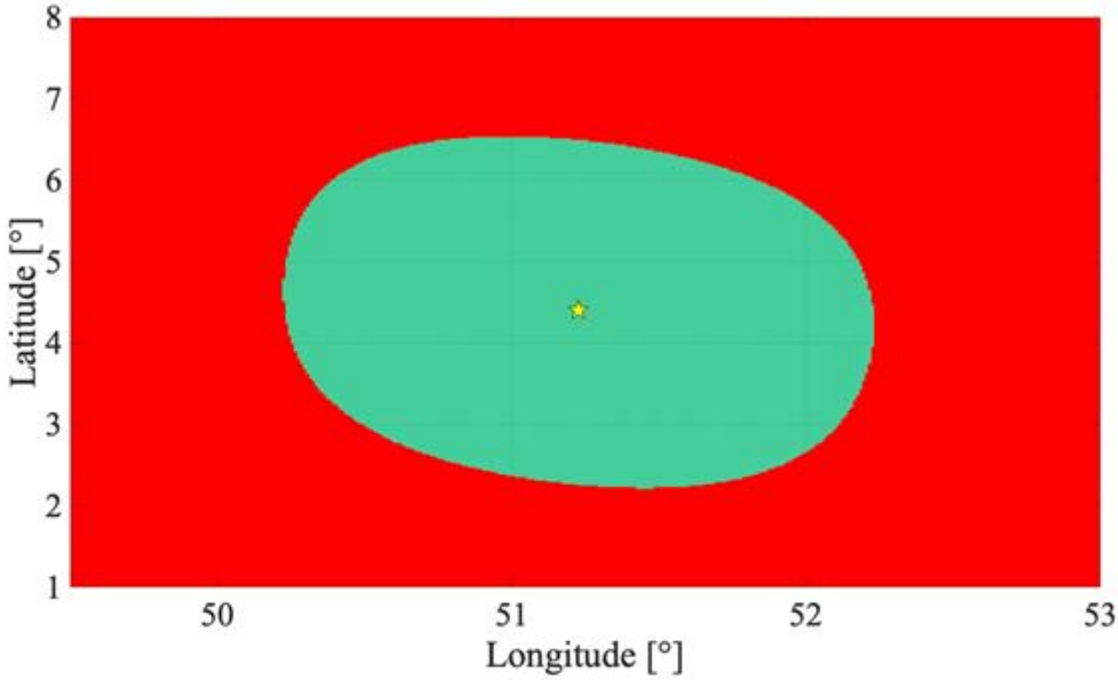


FIGURE 2. Effect of the initialization point on the convergence of LS. The convergence area is green, and the divergence area is red. The star symbol indicates the real receiver's position. The altitude was chosen to be on the surface of the Earth i.e. 0 m.

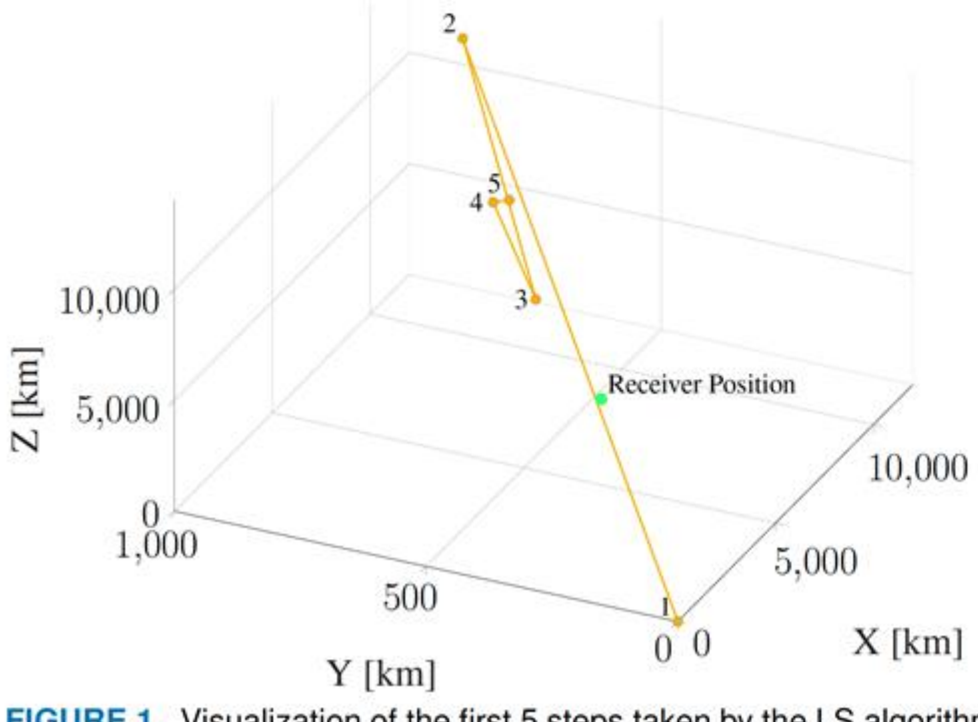
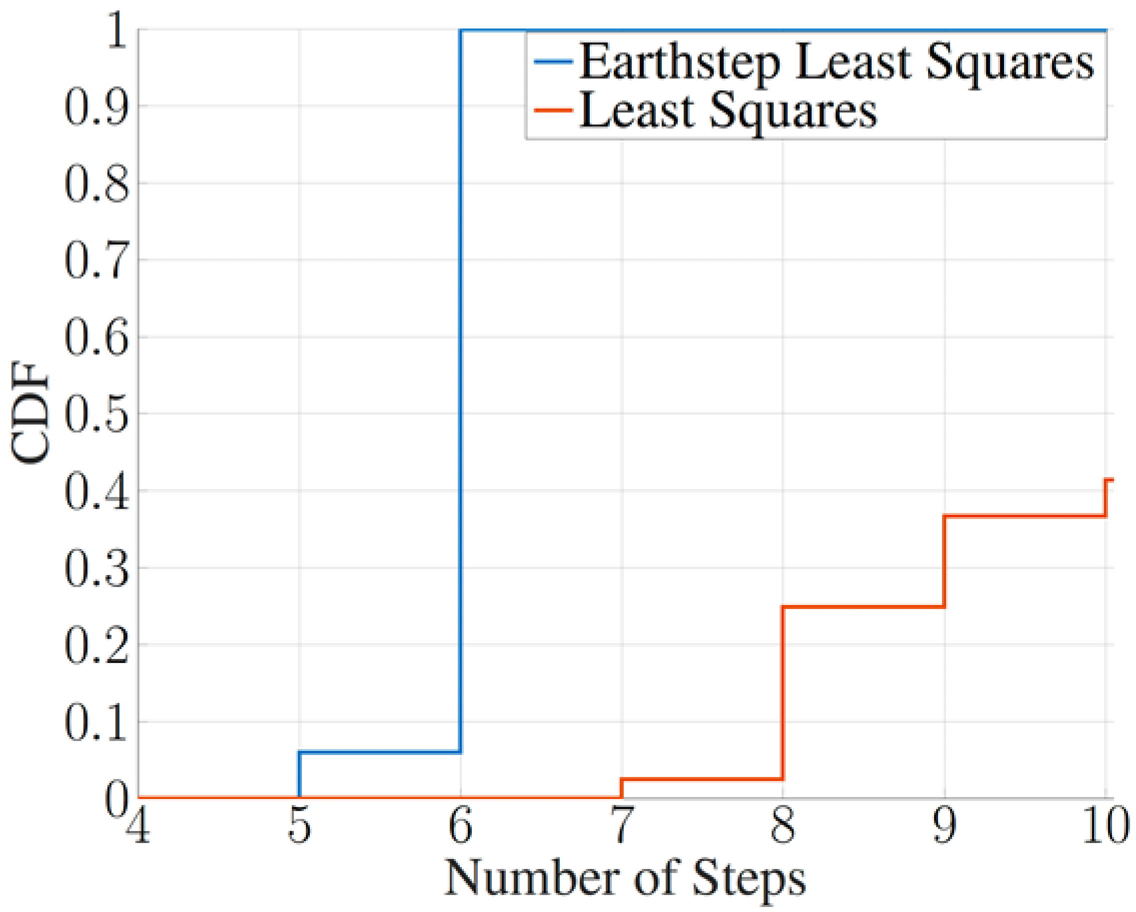


FIGURE 1. Visualization of the first 5 steps taken by the LS algorithm in ECEF with initialization point at the center of the earth and 16 LEO satellites in view.


Earthstep Least Squares
Least Squares
CDF
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
4
5
6
7
8
9
10
Number of Steps

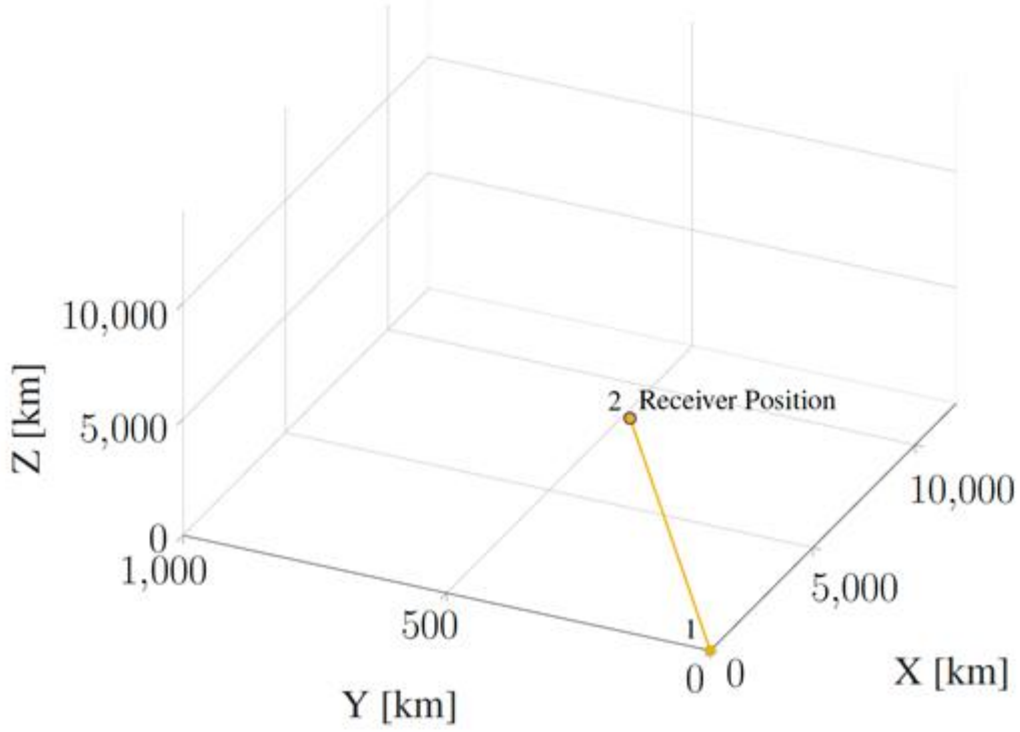


FIGURE 4. Visualization of the steps taken by the adjusted LS algorithm in ECEF with the initialization point at the center of the earth. The Earth step resolves the divergence problem of the algorithm, and the second step almost coincides with the real receiver position. In this figure, we only show the first 2 steps since the other steps almost fully coincide with the second step

Regional network estimation of low Earth orbit systems for positioning, navigation, and timing.

Massarweh L
[1]Delft University of Technology

Biography:
Lotfi Massarweh is a GNSS researcher in the Mathematical Geodesy and Positioning group at TU Delft, and a former Marie-Curie fellow for the H2020 TREASURE program, during which he worked as an aerospace engineer at Deimos Engenharia in Lisbon.
He completed his PhD on mixed-integer models, specializing in integer ambiguity resolution for kinematic precise positioning and orbit determination, along with PPP-RTK user and network estimation.
In this contribution, he will discuss advancements in future LEO-PNT systems, thus emphasizing the anticipated needs and challenges for ground-based estimation of LEO satellite corrections with high accuracy and low latency.

The deployment of low Earth orbit constellations for positioning, navigation, and timing (LEO-PNT systems) represents a major step in the advancement of global navigation satellite systems (GNSS). The rapid geometry changes of LEO satellites are expected to significantly reduce convergence times in precise positioning of ground users. However, users' precise point positioning (PPP) depends critically on the real-time availability of highly accurate satellite corrections, including orbit coordinates, clock offsets, and hardware code/phase biases, especially relevant for PPP with ambiguity resolution (PPP-AR).

Future LEO-PNT systems can leverage existing GNSS constellations to enable on-board precise orbit determination (POD), providing ground users with low-latency satellite products. While satellite orbits can generally be predicted with centimeter-level accuracy over short time periods, the estimation and prediction of clocks pose greater challenges. Thus, a ground tracking network will likely remain essential for enabling real-time PPP/PPP-AR, especially in view of the necessary estimation of satellite (transmitter) hardware delays.

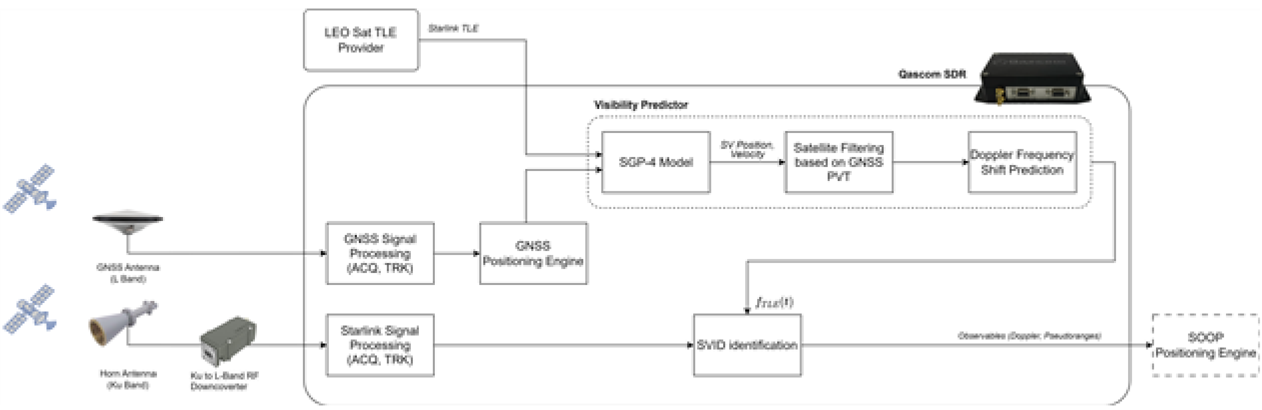
This research focuses on the (regional) network estimation of LEO-PNT satellite corrections, where we assume orbits to be accurately determined on board. Specifically, we investigate the ground estimation of satellite clocks and biases through a regional network over Europe. End-to-end numerical simulations are conducted for both network and user sides, assessing the network distribution necessary to ensure reliable real-time PPP-AR corrections. This is crucial due to the limited coverage of LEO constellations, with satellite tracking arcs shorter than 15 minutes. We adopt an undifferenced and uncombined PPP-AR formulation for network and user models, after removing existing rank deficiencies, thus incorporating integer ambiguity resolution using the recently developed LAMBDA 4.0 toolbox. Ultimately, this numerical analysis allows the generalization of the discussion to multi-frequency scenarios, e.g., beyond traditional L-band signals.

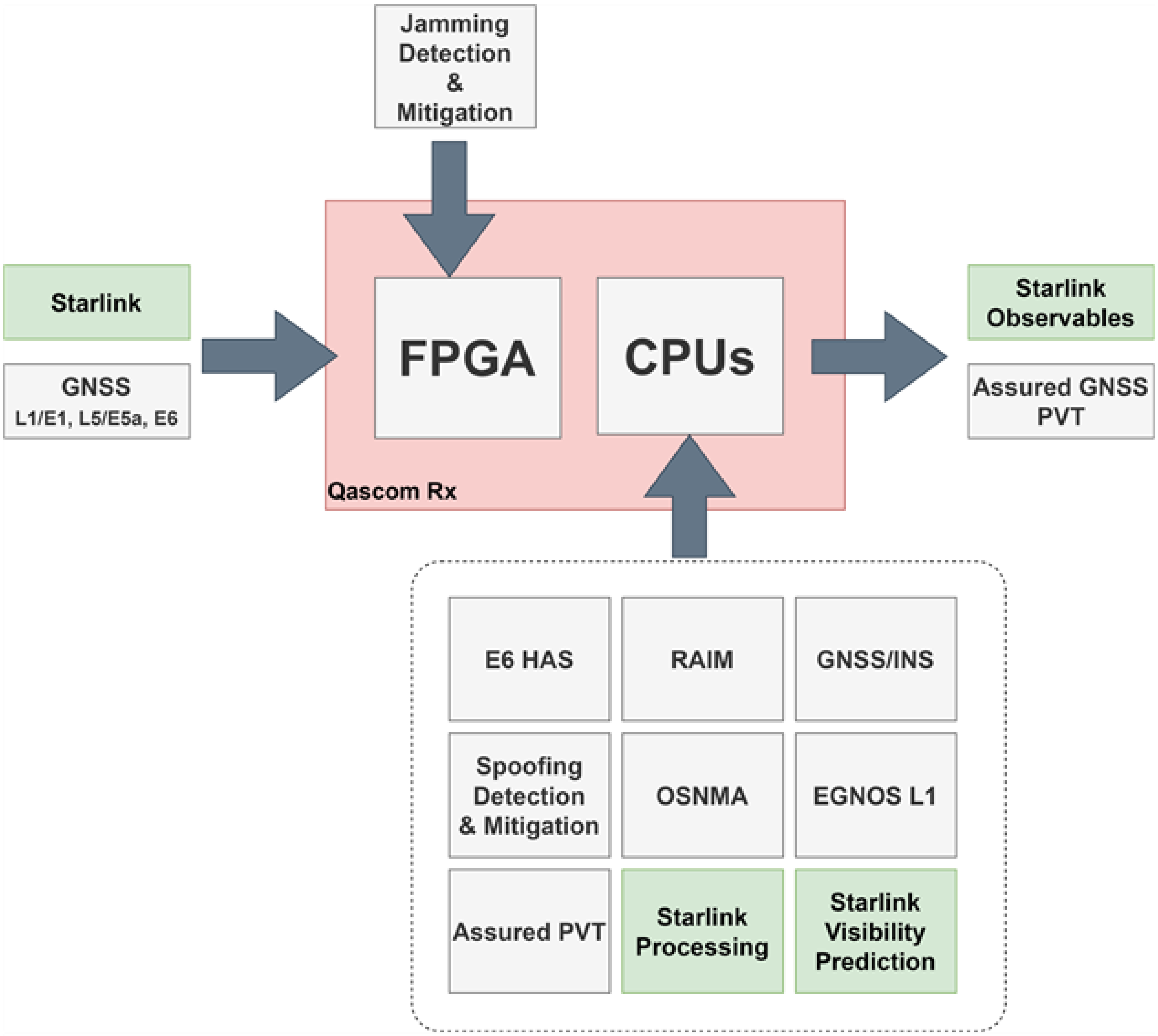
Starlink based Positioning using Qascom SDR Receiver: Design and Demonstration

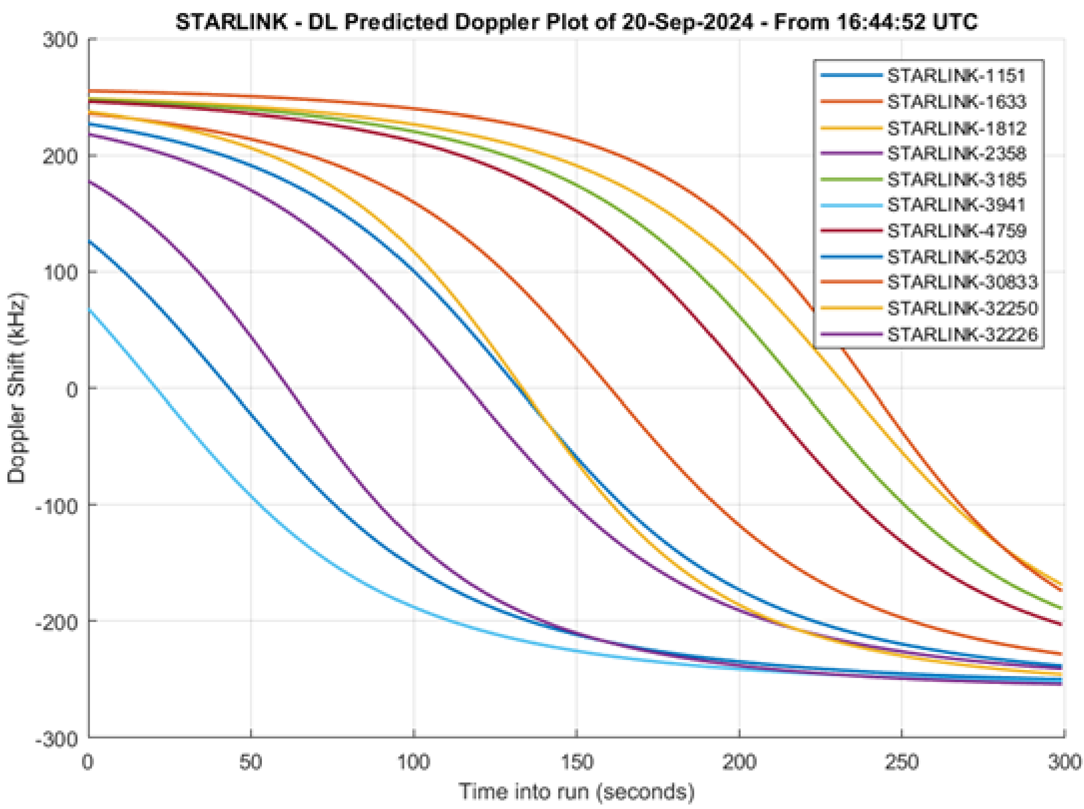
Curzio A[1], Sbalchiero E[1], Fantinato S[1], Crosta P[2], Bni Lam N[2]
[1]Qascom, [2]European Space Agency

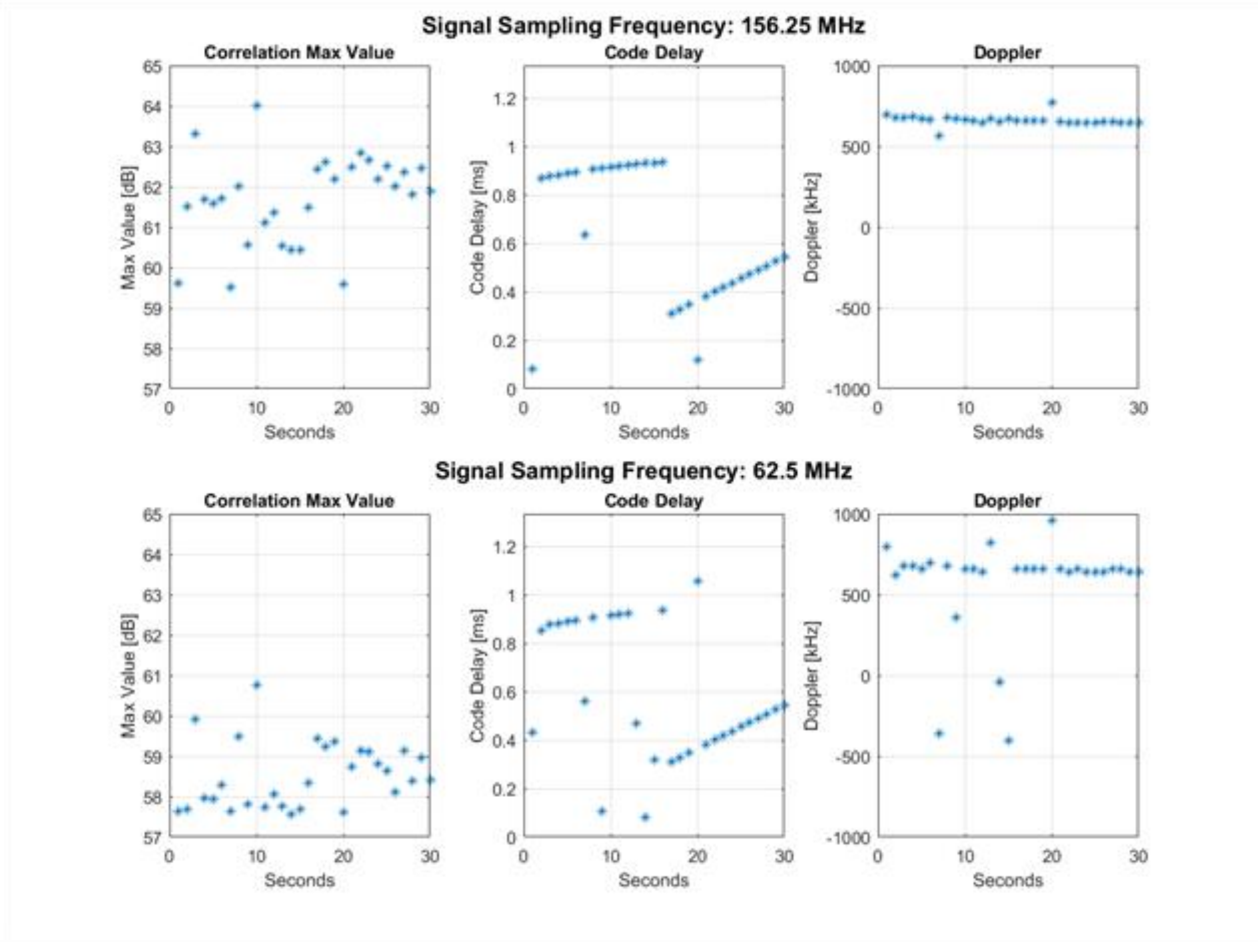
Biography:
Alessio Curzio is a GNSS Receiver and Test Engineer at Qascom, specializing in GNSS, PNT, and signal processing. His work focuses on developing receivers for future dedicated LEO-PNT systems and leveraging signals of opportunity for positioning and navigation. He is also involved in a test user receiver project utilizing Galileo 1st and 2nd generation signals. The topic he plans to cover is "Starlink-based Positioning using Qascom SDR Receiver: Design and Demonstration."

Several studies on the usage of Starlink as Signal Of OPportunity (SOOP) focused on exploiting unmodulated tones within approximately 1 MHz of its bandwidth, with the goal of reducing the receiver complexity [1]. However, recent experiments [2] suggest that this signature is disappearing from the Starlink spectrum, making it no longer relevant for positioning purposes.
As an alternative, this paper presents the design of a Starlink SOOP receiver based on an adaptation of the Qascom receiver, implementing a GNSS-like acquisition technique. The proposed architecture consists of: a) One GNSS antenna, b) One Ku-band horn antenna c) an external LNB for down-conversion to L-band, and d) the Qascom receiver with two RF inputs. The proposed solution has the capability to generate Doppler and range observables from both Starlink and GNSS signals, while the GNSS PVT is only used for Starlink satellite identification through a visibility prediction. Future developments could extend this setup to a hot redundant architecture with multiple antennas and receivers, increasing the number of Starlink satellites to be tracked simultaneously, and allowing for a Starlink-only PVT.
The Qascom GNSS receiver is based on a state-of-art Xilinx processor in Software Defined Radio (SDR), providing modular and highly configurable software architecture (a Core Module and multiple software Applications), that can be easily updated to support Starlink processing.
To demonstrate the adequacy of the hardware resources (i.e., the receiver sampling frequency of 62.5 MHz, against the 240 MHz Starlink bandwidth), the signals presented by [3] were down-sampled, and a non-coherent acquisition was performed using known synchronization sequences [4]. The results obtained reducing the sampling frequency from 156.25 [3] to 62.5 MHz demonstrate successful acquisition, although with a loss in Signal-to-Noise Ratio. To mitigate this, a trade-off analysis on the number of non-coherently integrated Starlink frames is also presented.




Jamming Detection & Mitigation
Starlink
GNSS
L1/E1, L5/E5a, E6
FPGA
CPUs
Qascom Rx
Starlink Observables
Assured GNSS PVT
E6 HAS
RAIM
GNSS/INS
Spoofing Detection & Mitigation
OSNMA
EGNOS L1
Assured PVT
Starlink Processing
Starlink Visibility Prediction


STARLINK - DL Predicted Doppler Plot of 20-Sep-2024 - From 16:44:52 UTC
Doppler Shift (kHz)
Time into run (seconds)
STARLINK-1151
STARLINK-1633
STARLINK-1812
STARLINK-2358
STARLINK-3185
STARLINK-3941
STARLINK-4759
STARLINK-5203
STARLINK-30833
STARLINK-32250
STARLINK-32226



#	Reference
[1]	A. Curzio et al., "Starlink Receiver Prototyping for Opportunistic Positioning," presentation at ENC 2024 Conference, Noordwijk, NL, May 2024. ESA-ESTEC.
[2]	S. Kozhaya, J. Saroufim, and Z.M. Kassas, "Starlink for PNT: a trick or a treat?," in Proceedings of the 37th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2024), September 2024, pp. 3779-3788.
[3]	B. N. Lam and P. Crosta, "Tracking Starlink signals using Luneburg Lens," presentation at NAVITEC 2024 Conference, Noordwijk, NL, Dec 2024. ESA-ESTEC.
[4]	T.E. Humphreys, P.A. Iannucci, Z.M. Komodromos, and A.M. Graff, "Signal structure of the Starlink Ku-band downlink," IEEE Transactions on Aerospace and Electronic Systems, vol. 59, no. 5, pp. 6016-6030, 2023.

Performance Assessment of Multi-RIS-Aided Localization in Terrestrial and Non-Terrestrial Networks

Egea-Roca D[1], Xhafa A[1], López-Salcedo J[1], Seco-Granados G[1]
[1]IEEC-UAB

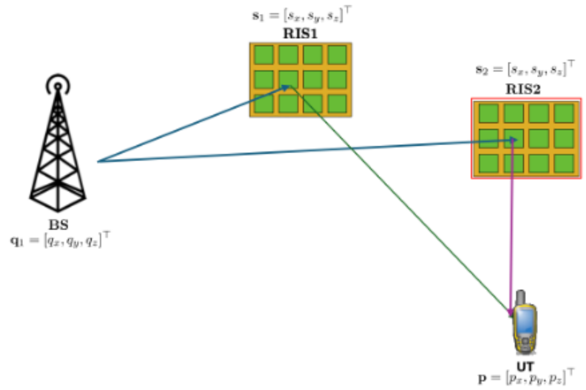
Biography:

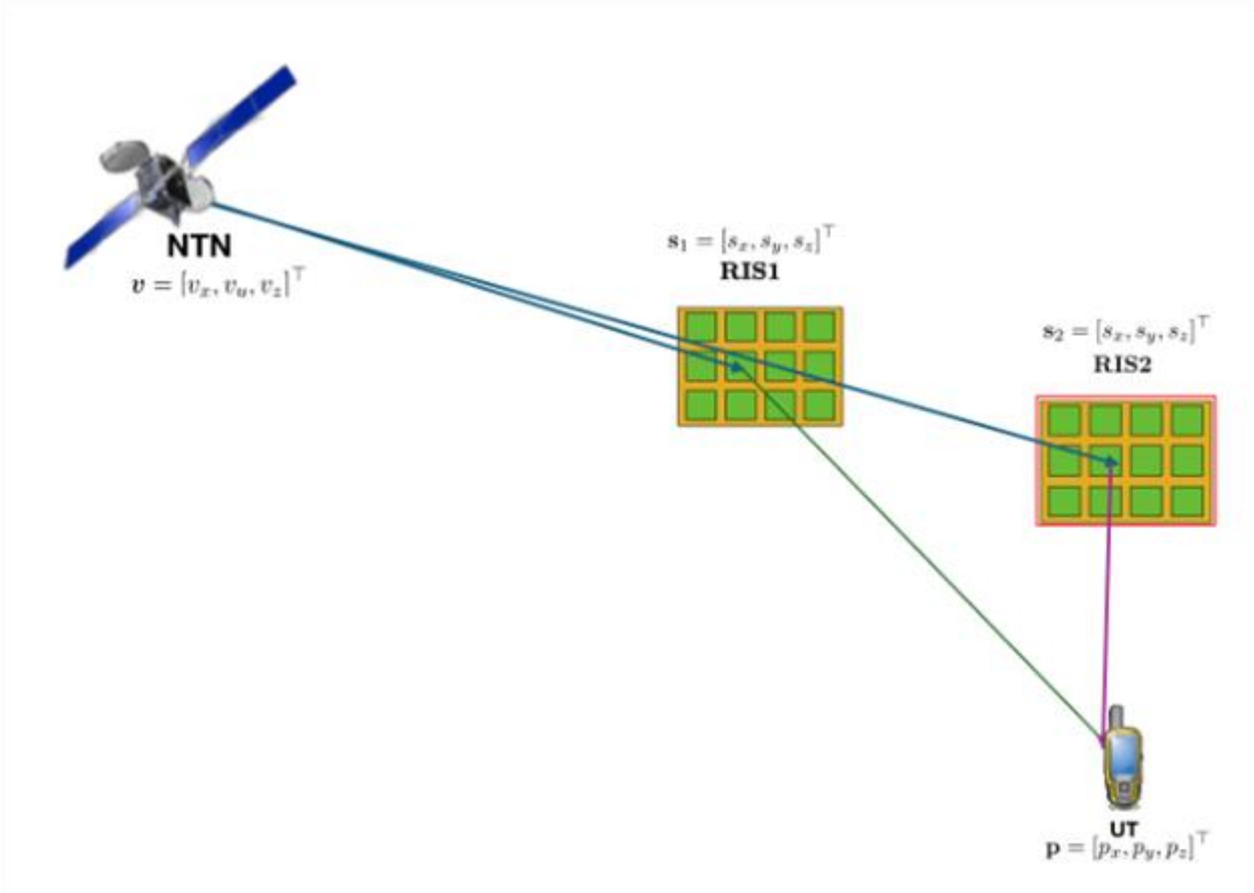
Daniel Egea Roca received the M.Sc. and PhD in Electrical Engineering in 2012 and 2017, respectively, from Universitat Autònoma de Barcelona (UAB). Currently, he is a post-doctoral researcher at the SPCOMNAV group at Universitat Autònoma de Barcelona (UAB), hired by the Institute of Space Studies of Catalonia (IEEC).
His research interests lie in the field of statistical signal processing applied to integrity in GNSS receivers, and signal design and processing for LEO-PNT.
The topic to be presented deals with the use of reflective inteligent surfaces (RIS) to aid localization in terrestrial networks and non-terrestrial (i.e., satellite-based) networks.

The increasing availability of low-Earth orbit (LEO) satellites, alongside the expected deployment of reflective intelligent surfaces (RISs), presents transformative opportunities for localization systems. LEO satellites can complement or serve as alternatives to global navigation satellite systems (GNSSs) [1], while RISs enhance both terrestrial networks (TN) and non-terrestrial networks (NTN) by providing additional, cost-effective location references. Unlike deploying base stations or satellites, RIS installations require minimal infrastructure while significantly improving localization accuracy and coverage.

Current research primarily focuses on RIS-aided localization in TN systems, while its application in NTN-based localization is still in its early stages [2]. In terrestrial systems, studies show that RIS can improve accuracy and coverage, even with one base station and single-antenna equipment [3]. However, the high attenuation of the base station-RIS-user path limits performance over long distances. This challenge can be addressed by deploying multiple RIS, as indicated by several sources on TN [4-6]. For NTN, early works have explored single RIS deployment and provided preliminary accuracy results [7]. However, research on multiple RIS is very little and primarily focuses only on performance bounds [2].

This study conducts a comparative analysis of key performance indicators (KPIs) for RIS-aided TN and NTN localization systems, focusing on the deployment of multiple RIS. The scenarios to be considered are shown in Fig. 1 and Fig. 2, respectively. Our contributions are threefold: (i) introducing a signal model and processing techniques for NTN RIS-aided localization with multiple RIS, (ii) analyzing and comparing different RIS phase profiles for separating RIS contributions and improving localization accuracy, and (iii) evaluating performance metrics such as accuracy, sensitivity, coverage, and dynamic range. Particular attention is given to the trade-offs between these metrics and the number of deployed RIS, as well as the comparative benefits of RIS-enhanced TN and NTN systems.


$\mathbf{s}_1 = [s_x, s_y, s_z]^\top$
RIS1
$\mathbf{s}_2 = [s_x, s_y, s_z]^\top$
RIS2
BS
$\mathbf{q}_1 = [q_x, q_y, q_z]^\top$
UT
$\mathbf{p} = [p_x, p_y, p_z]^\top$


NTN
$\boldsymbol{v} = [v_x, v_y, v_z]^\top$
$\mathbf{s}_1 = [s_x, s_y, s_z]^\top$
RIS1
$\mathbf{s}_2 = [s_x, s_y, s_z]^\top$
RIS2
UT
$\mathbf{p} = [p_x, p_y, p_z]^\top$

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[4]: A. Fadakar, M. Sabbaghian, and H. Wymeersch, "Multi-RIS-Assisted 3D Localization and Synchronization via Deep Learning," *IEEE Open Journal of the Communications Society*, vol. *5*, pp. 3299-3314., 2024

[5]: H. Chen, P. Zheng, M. F. Keskin, T. Al-Naffouri, and H. Wymeersch, "Multi-RIS-enabled 3D sidelink positioning," *IEEE Transactions on Wireless Communications*, 2024.

[6]: K. Keykhosravi, M. F. Keskin, S. Dwivedi, G. Seco-Granados, and H. Wymeersch,. Semi-passive 3D positioning of multiple RIS-enabled users. IEEE Transactions on Vehicular Technology, vol. 70, no. 10, pp. 11073-11077, 2021.

[7]: S. Saleh, M. F. Keskin, B. Priyanto, M. Beale, P. Zheng, T. Y. Al-Naffouri , G. Seco-Granados, "6G RIS-aided Single-LEO Localization with Slow and Fast Doppler Effects", *IEEE GLOBECOM - Positioning and Sensing Over Wireless Networks Workshop*, Dec 08 2024.

Plenary Room, May 22, 2025, 4:30 PM - 5:50 PM

Monitoring Radio Frequency Interference Affecting GNSS using Android Smartphones

Tegedor J[1], Gioia C, Barbero M
[1]Joint Research Center

Biography:
Dr. Gioia received the M.S. in Nautical sciences and the Ph. D. in Topography and Geomatics from Parthenope University, in 2009 and 2014, respectively. Since 2013, he has been working at the Joint Research Centre of the European Commission, providing scientific support to policymakers in the development of EU space policy. Currently, he is Project Officer at the Galileo Sector of the JRC. His research interests are primarily centered around location and navigation with focus on positioning accuracy, reliability, and performance in various environments. His work delves into the development of robust GNSS solutions that address challenges such as signal interference and multipath effects, which are critical for improving navigation systems used in transportation, aviation, and emergency response.

Global Navigation Satellite Systems (GNSS) are exploited in a wide range of applications and its reliability and accuracy are more critical than ever. Received GNSS signals are inherently weak making them extreme susceptible to Radio Frequency Interference (RFI), whether intentional or unintentional. RFI can severely impact GNSS performance, leading to degraded or even denied of service. Traditionally, RFI detection has relied on dedicated, often expensive, hardware, limiting its widespread deployment.

The Joint Research Centre (JRC) has explored the potential of leveraging the ubiquitous presence of smartphones for RFI monitoring. In particular, specific effort has been dedicated to utilizing the Automatic Gain Control (AGC) measurements provided by the last versions of the Android GNSS API.

A proof-of-concept to detect RFI using Android devices has been developed and tested. This approach not only promises a cost-effective alternative to traditional methods but also opens the door to crowdsourced approaches, enhancing the scope and granularity of RFI monitoring. This paper describes the laboratory tests performed to characterize smartphone AGC behaviour in the presence of interference, as well as open-field tests conducted at the JRC campus, and during the Jammertest 2024 in Norway. The laboratory tests characterised AGC measurements under various types of interference, including continuous wave and wideband interference. The open-field tests, on the other hand, involved collecting AGC data in real-world environments and analysing the results to monitor AGC variations in realistic conditions.

The proposed approach demonstrates the potential to detect both intentional and unintentional interference, even in indoor environments, and can also identify spoofing and/or meaconing, as these typically affect AGC levels. However, the approach has limitations, such as small AGC variations that cannot always be linked to GNSS interference, and significant differences between smartphones that must be considered when combining data from multiple devices.

Development of a star classifier for optimal geopositionning purposes using a star-sighting device

Rance G[1], Élie P[1]
[1]Safran Electronics & Defense

Biography:
Guillaume Rance is R&D engineer at Safran Electronics & Defense, and holds a Ph.D. in control systems engineering.
His research activities mainly concern the control of gyrostabilized sights, robotics and space-based applications such as stellar navigation.

In environments where Global Navigation Satellite Systems are denied, a comon solution to recover one's position on the Earth is to use stars as inertial references, as it was done centuries ago by navigators using a sextant. Nowadays, sextants are replaced by star-sighting devices composed of inertial sensors, precise clocks and one or more star sensors, combining the short-term precision of inertial navigation techniques and the long-term precision of celestial ones. In this context, this paper aims at developing a star classifier for geopositionning purposes, i.e. a way to discriminate stars in the sky so that an observer can choose the stars that would provide the most precise estimate of its position regarding the sighting performances of the device used (sensor definition, precision of the inertial sensor, etc.). The star classifier proposed in this paper is based on differential calculations and spherical trigonometry, and leads to closed-form expressions which are easily embeddable to evaluate the potential of a star. These closed-form expressions are then validated on an experimental setup composed of a PASEO XLR® gyrostabilized sight (Image 1).

Wide area GNSS interference source localization using a sparse monitoring network

Morrison A[1], Sokolova N[1]
[1]Sintef As

Biography:
Aiden Morrison is a senior researcher at SINTEF Digital in trondheim Norway. His background includes a bachelor's degree in Eletrical Engineering and a Doctorate from the University of Calgary Geomatics Engineering program. His work in recent years has focused on GNSS Radio Frequency Interference detection and analysis and has contributed to the creation of the largest known database of multi-frequency multi-constellation RFI for which raw sample data has been centrally collected and retained.

This paper discusses the design, development, and initial testing of a distributed monitoring system intended to help detect and localize sources of harmful interference impacting GNSS users over city sized areas using only a small number of monitoring stations to limit cost.
The paper starts with the motivation and background for the work which is rooted in the results of the Advanced Radio Frequency Interference Detection Analysis and Alerting System (ARFIDAAS), a network of GNSS RFI monitors which built the largest known database of multi-frequency GNSS RFI events. Insights gained from this database on factors such as modulations, impacted bands, power-level distributions and other relevant factors are used to inform the design of the source localization system.
The design of the receiver hardware to allow implementation of a distributed time difference of arrival (TDOA) detection and localization system incorporating components of off the shelf radios while supporting dynamic coverage of all L-band signals will be detailed along with the software architecture used to control and operate the individual nodes. Further information is included to describe the design and operation of the software which controls the composite network, including decisions made for the support of mobile detectors and multiple data consumers to allow pursuit of multiple simultaneous sources.
Since the system is designed for detection of sources which are likely below the local noise floor at the participating nodes, the paper will explore the derived operating envelope of the architecture, show examples of measurements produced during controlled field testing at Jammertest 2023, and discuss considerations for the screening of nuisance events likely to be unintentionally generated by incidental devices over a city sized area. Aspects related to the concept of using machine learning techniques for the assessment of and pre-elimination of nuisance low power unintentionally generated sources will be briefly addressed.

PNT as a Service (PNTaaS) Europe Deployment providing a Resilient Alternative to GNSS

Brown A[1], Zuberi A[1]
[1]NAVSYS Corporation

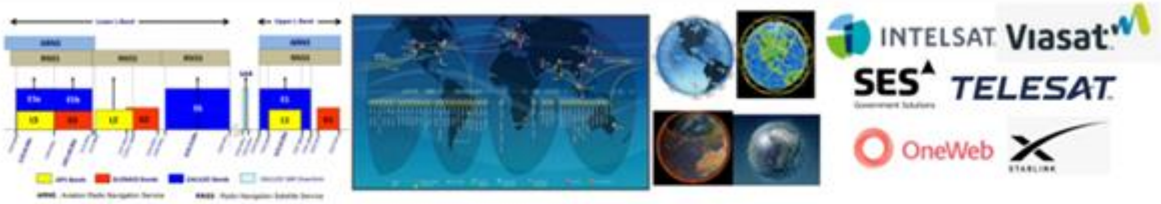
Biography:
Alison Brown is President and CEO of NAVSYS Corporation, which she founded in 1986. She grew up in Edinburgh Scotland and studied engineering at Cambridge University. She graduated MIT with an MS in Aeronautics and Astronautics then UCLA with a PhD in Mechanics and Aerospace. She was elected a member of the National Academy of Engineering for her contributions to research and development of precision navigation and timing technologies, is a Fellow of the Institute of Navigation, an Honorary Fellow of Sidney Sussex College, Cambridge and a member of the Defense Science Board. PNT Resilience and Robustness is her topic.

Global Navigation Satellite Systems (GNSS) signals are vulnerable to jamming and there is now extensive denial of service in part of Europe. To provide resilience, alternative Position Navigation Timing (PNT) solutions are needed separated in frequency from the L-band GNSS signals. The PNT as a Service (PNTaaS) solution developed by NAVSYS allows existing broadband Satellite Communication (SATCOM) satellites, operating in C-band, Ku-band or Ka-band, to be used for PNT as signals of opportunity (SoOP).

In this presentation, the open architecture PNTaaS solution is described. The PNTaaS Cloud Platform provides data services that publish what SATCOM satellite signals are available to be used as SoOP. Users can then subscribe to the PNTaaS services to receive data content snapshots of the broadband SoOP along with the timing and satellite location data needed to use these signals for PNT. By capturing a SoOP signal snapshot at the same time as the published PNTaaS data, PNT observations can be made by processing the received PNTaaS data using a simple Software Defined Radio (SDR).

NAVSYS has been operating the PNTaaS Cloud in the United States and recently deployed PNTaaS infrastructure to Europe on a trial basis for testing with selected partners. In this presentation, we describe the operation of the PNTaaS components, the test results for timing applications using selected SoOP and the plans for further deployment of the service and opportunities for partners to leverage this capability.

For additional information on the resiliency and robustness of the PNTaaS solution, the NAVSYS whitepaper is provided at the following
https://static1.squarespace.com/static/570a836659827e091de14a8a/t/6453e555f6ce8378f12ddeb5/1683219798831/23-04-001+PNTaaS+Providing+a+resilient+Back-Up+to+GPS+by+Leveraging+Broadband+Satellite+Constellations+and+Ground+Infrastructure.pdf



Problem/Opportunity

All GNSS signals are in L-band (1.1-1.6 GHz) and are vulnerable to interference. PNTaaS leverages existing commercial satellite and terrestrial signal sources as SoOP accessing frequency allocations from 3-30 GHz.

Proposed Solution

PNTaaS provides data services to enable use of commercial broadband GEO, MEO and LEO satellite systems as SoOP. Massive constellation size and different frequency ranges provides PNT resilience. Integration with SATCOM partners delivering SATCOM as a Managed Service (SaaMS) or Hybrid SATCOM solutions enables rapid transition to critical theaters

Impact

PNTaaS provides near-term capability for delivering precision PNT when GPS or GNSS are not available. PNTaaS SDRs can provide aiding to DoD's A-PNT devices to bound inertial/clock errors through MOSA interface standards (e.g. ASPN, I-PNT)

Figure 1 PNTaaS Solution Benefits

Multiple providers can publish PNTaaS data services	Multiple constellations can publish signals through PNTaaS	PNTaaS ground services publish time + orbit corrections	PNTaaS SDRs integrated with clock + inertial provides APNT outputs

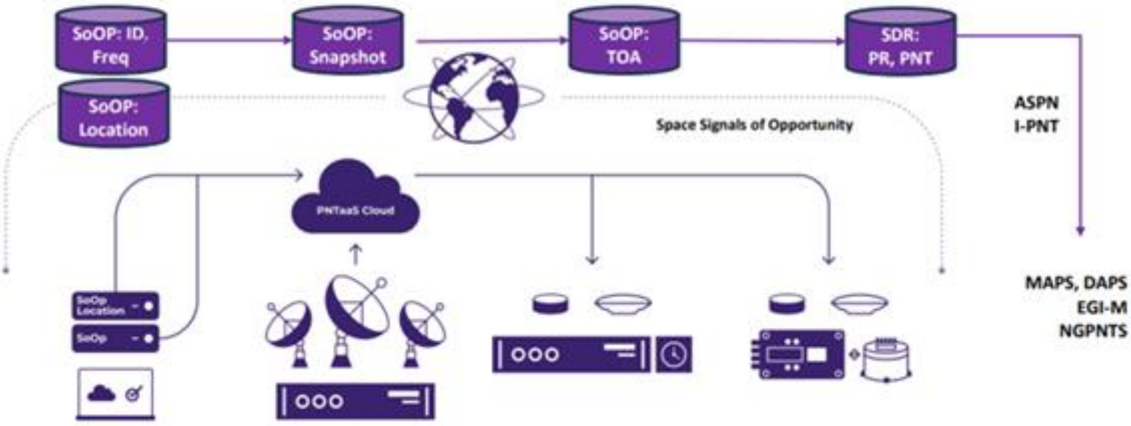


Figure 2 PNTaaS Open Architecture leverages existing space industrial base

NAVSYS with our commercial SATCOM partners plan for rapid deployment of our PNTaaS back-up navigation solution in areas experiencing GPS denial

Figure 3 GPS Jamming today (www.gpsjam.org)

Advancements in Weak GNSS Signal Acquisition for Deep-Space Navigation

Tiwari R[1], Ashforth B[1], Mather C[1]
[1]QinetiQ Uk

Biography:

Dr. Rajesh Tiwari is a senior scientist at QinetiQ, an Associate Fellow of the Royal Institute of Navigation, and an Honorary Fellow of the University of Nottingham, UK. He specializes in GNSS signal processing, navigation modelling, and is an expert in attitude determination using multiple GNSS receivers. Dr. Tiwari is proficient in GNSS signal acquisition Tracking and RTK/PPP and developed an innovative integrity prototype for autonomous vehicle Level-5. Dr. Tiwari has 15 years of experience in GNSS signal processing and sensor fusion, including academic and industrial research.

GNSS (Global Navigation Satellite System) signals are primarily meant to serve the Earth's surface and nearby space applications, with their beam directed nadir, ensuring the main lobe is observable anywhere on the surface of the Earth. However, GNSS main lobe availability is limited in space. The spillover of GNSS broadcast beams, forming secondary lobes, can be detected in deep space. Despite the low signal strength and non-linear dynamics of Doppler shifts, acquisition and tracking these GNSS signals remains interesting, and can serve trans-lunar orbit (TLO) applications. Traditional GNSS acquisition techniques, primarily designed for Earth-based applications, suffer from limited sensitivity, loss of coherence over long integration times, and high Doppler-induced frequency smearing when applied to TLO and deep-space missions. To address these challenges, an Adaptive Pre-Averaging Approach with Modified Windowing, is investigated to acquire GNSS signals in high altitude beyond Earth space. The work integrates two key elements: (1) adaptive pre-averaging based on real-time signal dynamics and (2) a modified windowing function to optimise frequency-domain representation and reduce spectral leakage. Unlike conventional pre-averaging methods that apply fixed-length coherent integration, our approach dynamically adjusts the integration window size based on real-time estimations of Doppler rate, SNR fluctuations, and the coherence time of the GNSS signal. By incorporating orbital models, we predict Doppler variations and select the optimal integration duration, mitigating the risk of phase decoherence over longer periods. The proposed approach enhances GNSS acquisition sensitivity by up to 6 dB, making it feasible to use Earth-based GNSS signals for navigation in lunar transfer orbits. We evaluate the performance of the proposed method through in-house GNSS baseband signal simulation using realistic GNSS signal models and appropriate noise. The results demonstrate a significant improvement in acquisition probability and time-to-first-fix (TTFF) compared to conventional GNSS acquisition techniques.

Novel Approach for Receiver Antenna Calibration: Parameterization of Phase Center Corrections by Hemispherical Harmonics

Kröger J[1], Kersten T[1], Schön S[1]
[1]Leibniz University Hannover, Institut für Erdmessung

Biography:
Johannes Kröger received his M.Sc. degree in Geodesy and Geoinformatics at the Leibniz University Hannover (Germany) in 2018. Since then, he works as a Ph.D. student at the Institut für Erdmessung (LUH). His current interests are absolute GNSS receiver antenna calibration and the analysis of high-sensitivity GNSS equipment. In particular, he investigates and optimizes the calibration procedure and estimation of phase center corrections (PCC) and develops methods to compare different sets of PCC.

To achieve precise positioning, navigation, and timing using Global Navigation Satellite System (GNSS) signals, accounting for Phase Center Corrections (PCC) is crucial. These corrections can be determined either in an anechoic chamber with artificial signals or in the field using a robot and real signals. In the robot-based method for determining PCC, Spherical Harmonics (SH) are usually used for PCC parameterization. However, SH are defined for a full sphere, whereas usable observations for PCC estimation are mainly measured on the upper hemisphere of the antenna, leading to an unstable normal equation system (NES) when no additional restrictions are applied. This instability makes the system highly sensitive to distortions in the observation vector and prevents the calculation of reasonable standard deviations for the estimated PCC.

Our contribution introduces the use of Hemispherical Harmonics (HSH) for PCC parameterization. This approach involves shifting the associated Legendre polynomials to the range of observed incidence angles at the antenna including negative angles encountered during antenna tilting in the calibration process. As a result, a stable NES is obtained that permits the analysis of formal standard deviations for the gridded PCC values. We demonstrate estimated PCC using the novel approach for different antenna types, GNSS and frequencies, considering the standard deviations. The benefits of utilizing HSH are further illustrated through closed-loop simulations. The differences in PCC (dPCC) between the different methods are assessed using previously developed quality measures. It is shown that the maximum deviations at the pattern level are smaller than 0.5 mm, while the condition number of the NES can be reduced from approximately 10^{10} to less than 10^{2}. Additionally, we evaluate the impact of dPCC on geodetic parameters through a standardized simulation approach.

Enhanced DME Carrier Phase Tracking Approach for Alternative PNT in UAV Applications

Yin J[1], Arora T[1], Raza M[1], Petrunin I[1], Tsourdos A[1], Tiwari S[2], Peltola P[2], Lavin B[2], Bransby M[2], Budianu A[3], Salgueiro F[3]
[1]Cranfield Univeristy, [2]Telespazio UK, [3]European Space Agency

Biography:
Dr Ivan Petrunin
Reader in Signal Processing for Autonomous Systems and DARTeC Fellow
Ivan has extensive knowledge and experience in the area of Digital Signal Processing for Autonomous Systems which covers sensor technologies, perception, data and information fusion, and decision-making for Cyber-Physical Systems.Applications for these developments include vehicle health management, communication and surveillance solutions and, more recently, Position, Navigation and Timing (PNT) for aerospace and ground-based Autonomous and Intelligent Systems.

Benefiting from the worldwide infrastructure, the Distance Measuring Equipment (DME) system is considered one of the most promising candidates for APNT to cope with the vulnerability of the Global Navigation Satellites System (GNSS). The method of using the carrier phase of the DME signal allows the distance measurement to achieve a centimeter level of accuracy. However, due to the random emission of the DME pulses and the sparse phase measurement, the carrier phase of the DME signal can hardly be measured using the conventional carrier tracking loop such as the phase lock loop.
The generic procedure of the proposed enhanced carrier tracking loop algorithm is presented in Figure 1
Once the DME pulse pairs are detected within the given interval, a local replica is generated with the initial frequency and phase are estimated through zeros crossing approach and correlation. Then apply the matched filtering process for the detected DME pulse A_i as Eq (1) presented
where t_i and T_i represent the beginning of the pulse and the duration of the pulse respectively. $e^{j(2\pi \hat{f}_c t+\hat{\phi})}$ is the local replica with $\hat{f}_c$ and $\hat{\phi}$ are the estimated pulse carrier frequency and phase. To overcome the arbitrary phase reference for each pulse, a reference pulse approach is used to adjust the successive pulses according to the reference pulse, this process ensures the carrier phase measurements across pulses are consistent.
The performance of the proposed algorithm is validated through a series of UAV tests. The tests are conducted at Cranfield University, UK with testing altitude range varying between 25m to 120m under urban and open sky environments to validate the altitude and environment effect on the tracking algorithm. The testing results presented in Figure 2 indicate that the proposed adaptive enhanced carrier tracking approach maintains a stable tracking performance.

$$y_i = \int_{t_i}^{t_i+T_i} A_i(t)e^{j(2\pi\hat{f}_c t+\hat{\phi})}dt \qquad 1$$

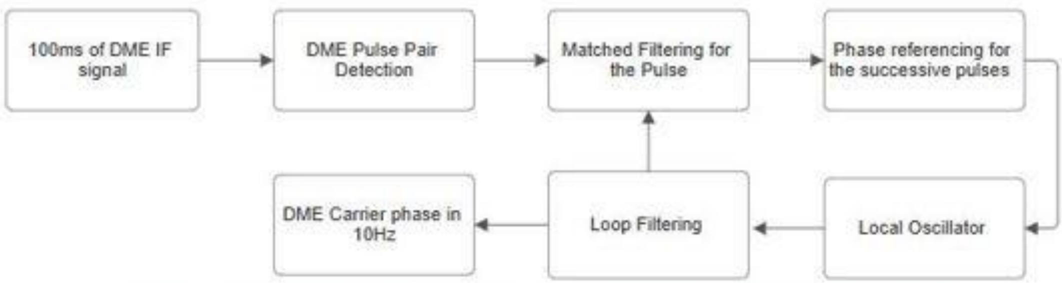


Figure 1 Generic procedure of the Matched filtering-based carrier tracking approach

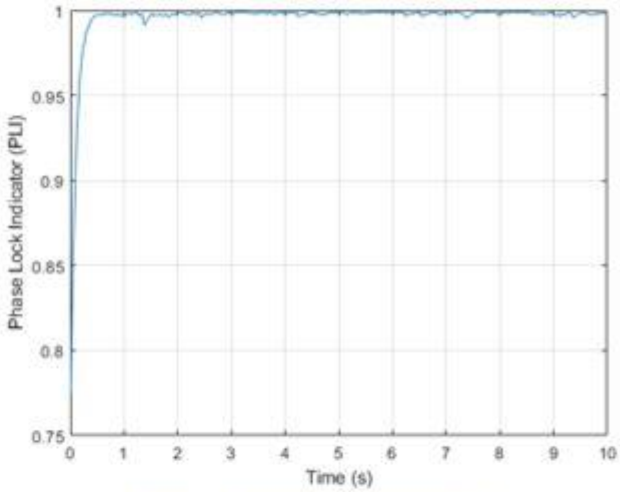


Figure 2 Phase Lock Indicator (PLI)

UAV position tracking with ground cameras

Masiero A[1], Dabove P[2], Di Pietra V[2], Piragnolo M[1], Guarnieri A[1], Toth C[3], Blaszczak-Bak W[4], Gabela J[5], Chiang K[6]
[1]University Of Padua, [2]Polytechnic of Turin, [3]The Ohio State University, [4]University of Warmia and Mazury in Olsztyn, [5]Vienna University of Technology, [6]National Cheng Kung University

Biography:
Andrea Masiero is Associate Professor of Geomatics at the Research Center of Geomatics of the University of Padua. His research interests range from Geomatics, Mobile Mapping, Positioning and Navigation, Machine Learning to Computer Vision and Remote Sensing. In this work he is going to talk about indoor collaborative indoor positioning based on smartphone sensors, such as inertial sensors, and UWB radio signals.

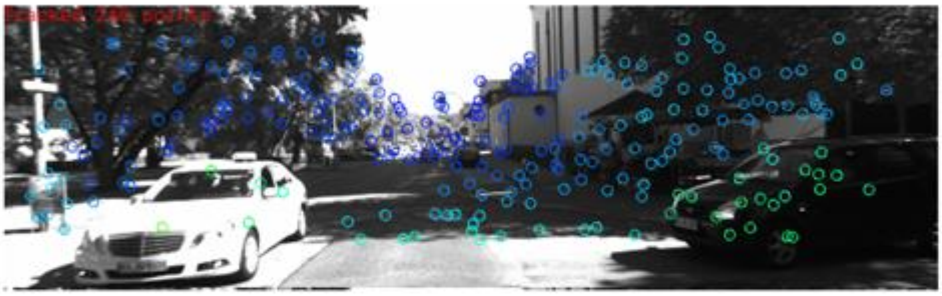
The use of Unmanned Aerial Vehicles (UAVs) has become quite popular in a number of applications during the last few years. Such spread use is motivated by the UAV flexibility of usage and by their ability to automatically execute several tasks, mostly thanks to the availability of Global Navigation Satellite Systems (GNSS), which usually allow reliable outdoor localization of aerial vehicles. However, the extension of task automatic execution also indoors, and in other challenging working conditions for the GNSS, requires an alternative positioning system, able to compensate for the unreliability or unavailability of GNSS in those cases.
To this aim, additional sensors are usually considered. Among them, cameras are probably the most popular ones. The most common case of vision-based positioning system is given by a camera mounted on the moving platform, used to determine its ego-motion in a dead-reckoning approach, i.e. visual odometry. Despite this solution is affordable and not requiring the installation of any infrastructure, it allows to obtain absolute positioning of the camera, i.e. of the UAV, only if certain landmarks, with known position, are visible in the flying area.
Differently, this work considers the use of external cameras, installed in the flying area, to track the UAV movements. This approach is similar to the one implemented in motion capture systems as well, where a set of static cameras are used to triangulate some target positions, using calibrated cameras. Instead, this work investigates the use of vision and machine learning tools to (i) extract the UAV position from each video frame, (ii) estimate its 3D position. Estimation is performed with single and multiple cameras. Performance analysis is provided on a dataset collected at the Agripolis campus of the University of Padua.Performance analysis is provided on a dataset collected at the Agripolis campus of the University of Padua.

Robust real-time automotive Visual SLAM with dynamic object removal

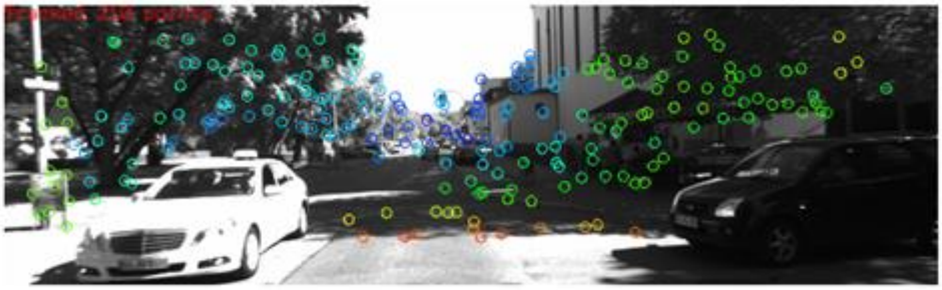
Sachße L[1], Horokh O[1], Fischer J[1], Bensch R[1]
[1]ANavS Gmbh

Biography:
Luka Sachße is a software engineer in the ANavS Computer Vision Team. He graduated in 2019 at TUM from the Geodesy and Geoinformation master's program with a focus on Deep Learning based methods for Computer Vision and Remote Sensing.
Since March 2020, he is working at ANavS where his main task is the integration of Visual SLAM / Odometry in the localization software of ANavS. He contributed to the development of vehicle and robot localization algorithms in multiple research projects.

Visual Simultaneous Localization and Mapping (SLAM) is a technology that relies on visual feature tracking to estimate the camera motion while creating a map of the environment. It is crucial for autonomous navigation of robots, vehicles and drones in GNSS-denied environments (urban canyons, tunnels, indoors).
SLAM algorithms generally assume that features in the observed environment belong to static and rigid objects. Thus, in crowded and dynamic environments such as urban traffic, the algorithm's performance in terms of camera motion estimation is heavily affected by the high amount of dynamic objects observed.
To address this challenge, a real-time method for the detection and exclusion of moving objects in the motion estimation stage of a Visual SLAM frontend is presented.
Our approach integrates an Instance Segmentation Network that produces accurate instance masks that allow the removal of dynamic object features. To overcome real-time limitations due to slow network inference, a mask propagation algorithm is introduced that makes use of sparse optical flow and stereo depth information.
The proposed algorithm runs on an embedded platform and utilizes the GPU for inference.
We implement our method on a real vehicle, evaluate it on multiple public datasets and prove that the removal of dynamic objects leads to increased accuracy and robustness.
This work was conducted under the EU-funded DREAM project.



(i) Keypoints tracked by our baseline Visual SLAM algorithm



(ii) Keypoints tracked by our algorithm after the removal of dynamic object points

Figure 1: Comparison between the baseline and our improved feature tracking algorithm on an image from the KITTI Odometry dataset.

(i) frame at t_0

(ii) frame at t_1

(iii) frame at t_2

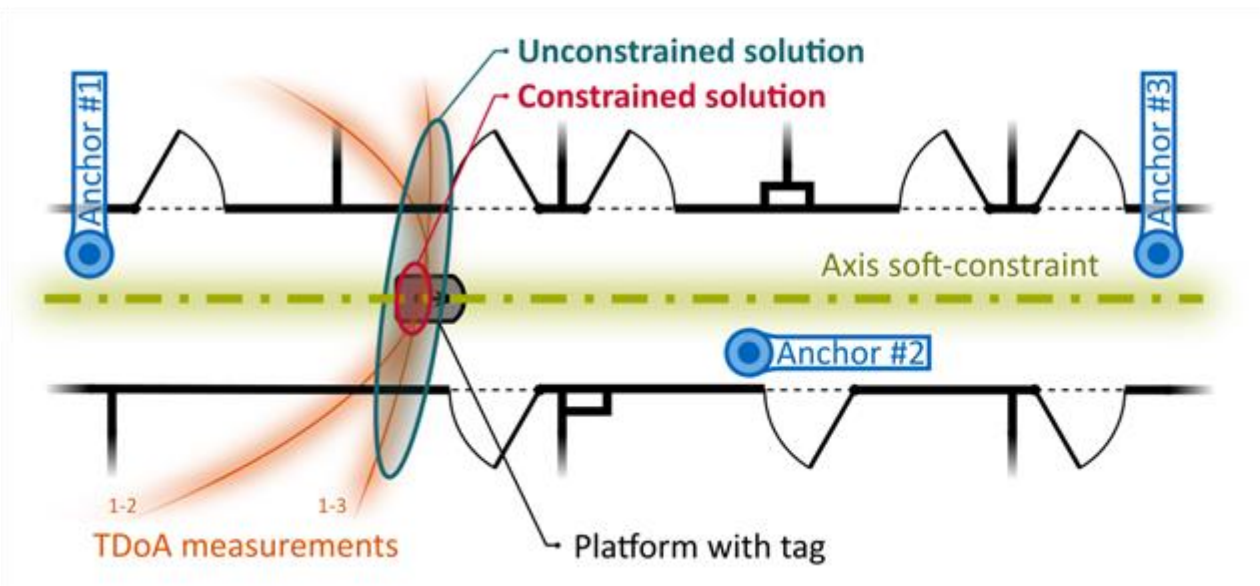
Figure 2: Three consecutive images from sequence 01 of the KITTI Odometry dataset with instance mask overlays that were obtained by a instance segmentation network. In (i) the masks are used to determine the dynamic object points (red). These are excluded while the remaining valid points (green) are used for motion estimation. Dynamic points are tracked from the previous image frame to the current frame (ii) by sparse optical flow. Newly detected keypoints at that frame are shown in blue. At (iii) instance segmentation masks become available again and are used to filter out moving object points.

Constrained 1D localization for downlink TDoA-based UWB RTLS

Navratil V[1], Krska J[1]
[1]Czech Technical University In Prague, Faculty of Electrical Engineering

Biography:
Vaclav Navratil serves as assistant professor at the Czech Technical University in Prague, Faculty of Electrical Engineering. He is the current president of the Czech Institute of Navigation and a the Europe Regional Vice-Chair of CGSIC-IISC. He is focused primarily on positioning algorithms including sensor fusion, utilization of Signals of Opportunity and GNSS precise positioning techniques. He is also interested in RF measurements and instrumentation.

In the radio positioning systems, such as Ultra-Wide Band (UWB) Real-Time Localization Systems (RTLS), the positioning accuracy is affected by several factors. In particular, the anchor (infrastructure nodes) constellation geometry affects the accuracy of tag (user device) localization; the Dilution of Precision (DOP) concept is used to describe and quantify such effect.
In typical UWB RTLS installations, the anchors are mounted in the same height, which yields high values of vertical DOP (VDOP) that implies degraded accuracy in the vertical direction. Such uncertainty can be decreased by introducing a soft-constraint on users' height coordinate. Furthermore, when the anchors are placed in a narrow constellation, e.g. in a long corridor or in a tunnel, the accuracy is hindered in the perpendicular direction (w.r.t. the axis of the corridor). Nonetheless, the along-axis accuracy is only marginally affected. In such scenarios, however, the along-axis accuracy is typically more important than the cross-axis one. Therefore, it is beneficial to constrain the horizontal position estimate on a line along the corridor axis, see Fig. 1. Such approach brings benefits in the overall accuracy, convergence rate, and thus position information availability. It may also provide indoor positioning service with reduced number of deployed anchors or improve the RTLS robustness.
In our paper we propose the application of such constraints in the Extended and Unscented Kalman Filters (EKF, UKF) that serve as the position estimators. The downlink variant of Time-difference of Arrival (TDoA) positioning is utilized, i.e. the position is available on the user platform and can be further utilized in fusion with multiple sensors, rendering it suitable for autonomous robotic platforms. Nevertheless, the proposed approach is applicable for uplink TDoA or TWR-based positioning as well.
We also provide the demonstration and performance assessment based on real measured data from an industrial robotic platform.



Machine Learning-Enhanced Sensor Fusion for Unmanned Ground Vehicles in a GNSS-denied environment

Chicaiza Morocho P[1], Wheeler P[1], Tiwari R[2]
[1]PEMC Research Institute, University of Nottingham, [2]QinetiQ, Malvern Technology Centre

Biography:

Paola Chicaiza received her MSc in Digital Signal Processing from Newcastle University, UK in 2017, graduating with distinction and first-class honours. She is currently a second-year PhD student at the PEMC Research Institute, University of Nottingham, UK, focusing on Unmanned Ground Vehicles operating in GNSS-denied environments, with an emphasis on collision avoidance and safety integrity. Her research integrates sensor fusion techniques using low-cost LiDAR and inertial sensors augmented by Machine Learning to enhance reliability and performance in challenging operational conditions.

Unmanned Ground Vehicles (UGVs) in a Global Navigation Satellite Signal (GNSS)-denied environment face multiple challenges, particularly in acquiring satellite signal for the position, navigation, and timing (PNT) that is a critical element of a highly dynamic vehicular environment. High-resolution sensors such as inertial and LiDAR are employed to overcome these challenges but demand costly solutions, and more operational resources like power consumption, larger data storage, or increased computational capacity. To address these limitations, this research explores an innovative approach to leverage cost-effective sensor integration solutions through Machine Learning (ML) techniques to enhance optimised sensor fusion for reliable PNT solutions. The research study provides the possibility of using sensors with lower spatial and temporal resolution instead of high-resolution options, attempting to maintain equivalent performance in terms of accuracy and reliability for trajectory estimation. This study introduces the development of a simulation implemented in Python to represent UGV performance in a GNSS-denied environment. The simulation analyses three-dimensional position data using inertial and LiDAR high-resolution sensors to estimate the trajectory of the vehicle based on their measurements. The synthetic data generated is downsampled to emulate sensors to establish synchronisation. A comparative analysis process is conducted to assess the performance. Subsequently, ML techniques generate complementary synthetic data from low-resolution sensor data to enhance trajectory estimation. Reduction of sensor data resolution leads to performance degradation; however, an optimised way of selecting sensors before integration produces reliable PNT and is computationally less costly. This research uses the integration of ML to synthetically data generation into the sensor fusion process to explore the critical gaps in sensor resolution; aiming to enhance trajectory estimation, and improve collision avoidance capabilities, which are challenges associated with UGV operation in GNSS-denied environments.

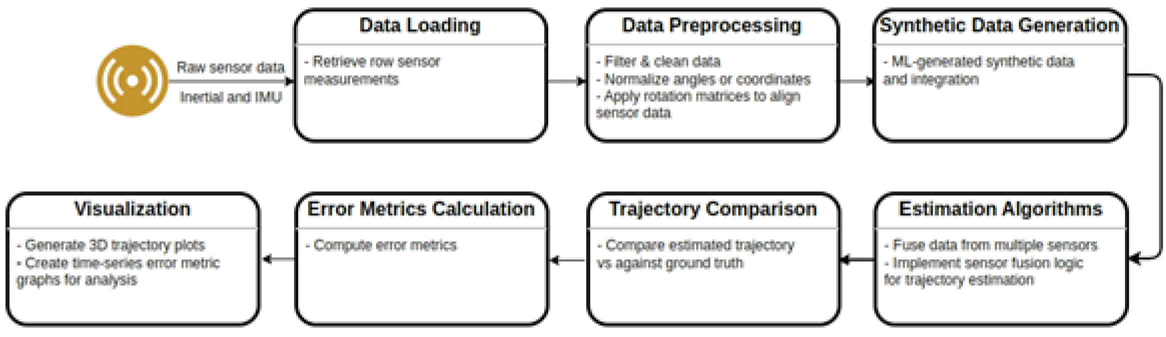


Fig. Functional Workflow

Blender-based simulation and evaluation framework for GNSS-LiDAR sensor fusion

Kalisz A[1], Khalil M[1], Cortes I[1], Urquijo S[1], Overbeck M[1], Miksovsky C[1], Rügamer A[1]
[1]Fraunhofer IIS

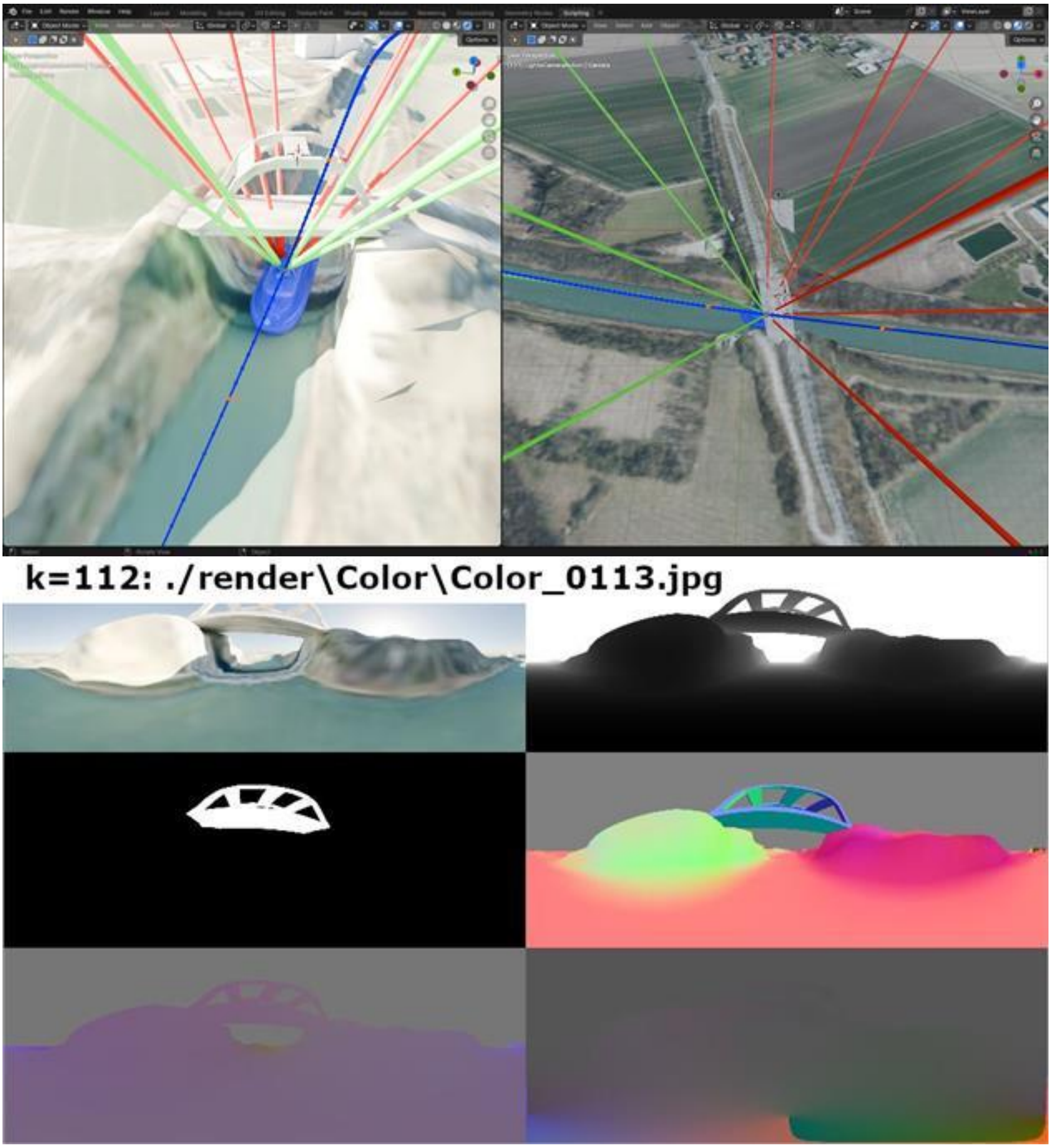
Biography:
Adam Kalisz is a researcher specializing in Visual Simultaneous Localization and Mapping (Visual SLAM) and sensor fusion technologies. He completed his Master's degree in Computer Science at Friedrich-Alexander-Universität (FAU) Erlangen-Nürnberg, Germany, focusing on the integration of GNSS and camera-based systems.
Following his graduation, Adam Kalisz worked as a researcher at the same institution for five years. During this time, his work concentrated on improving open-source Visual SLAM algorithms through comprehensive error modeling, as well as fusing diverse sensors such as GNSS, radar, LiDAR, IMU, and semantics to enhance localization accuracy.

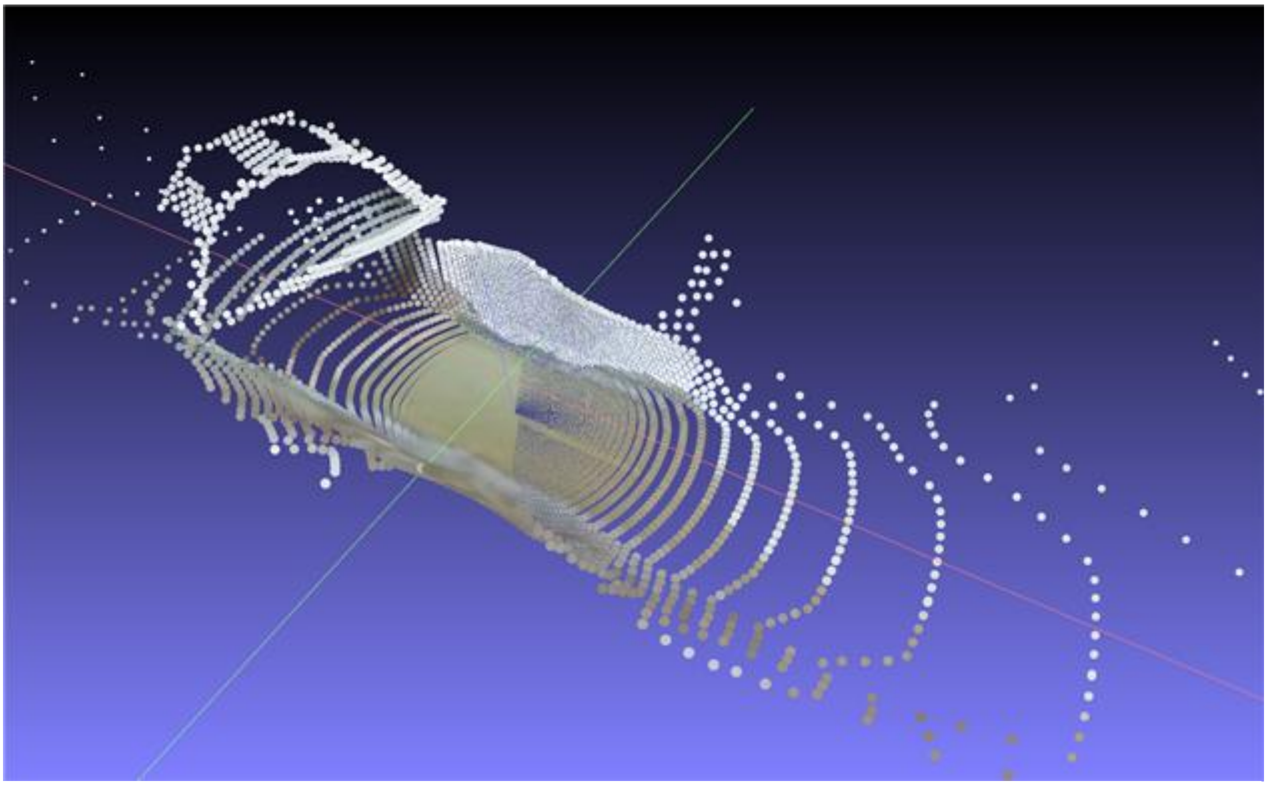
The fusion of Global Navigation Satellite System (GNSS) and Light Detection and Ranging (LiDAR) sensors has emerged as a critical research area for high-precision navigation and mapping applications. While GNSS provides absolute positioning, it is susceptible to multipath errors, signal occlusions, and atmospheric disturbances. LiDAR, on the other hand, offers high-resolution environmental perception but lacks absolute localization and is sensitive to sensor noise and drift over time. To address these limitations, robust sensor fusion architectures are necessary to improve positioning accuracy, reliability, and robustness in diverse environments.

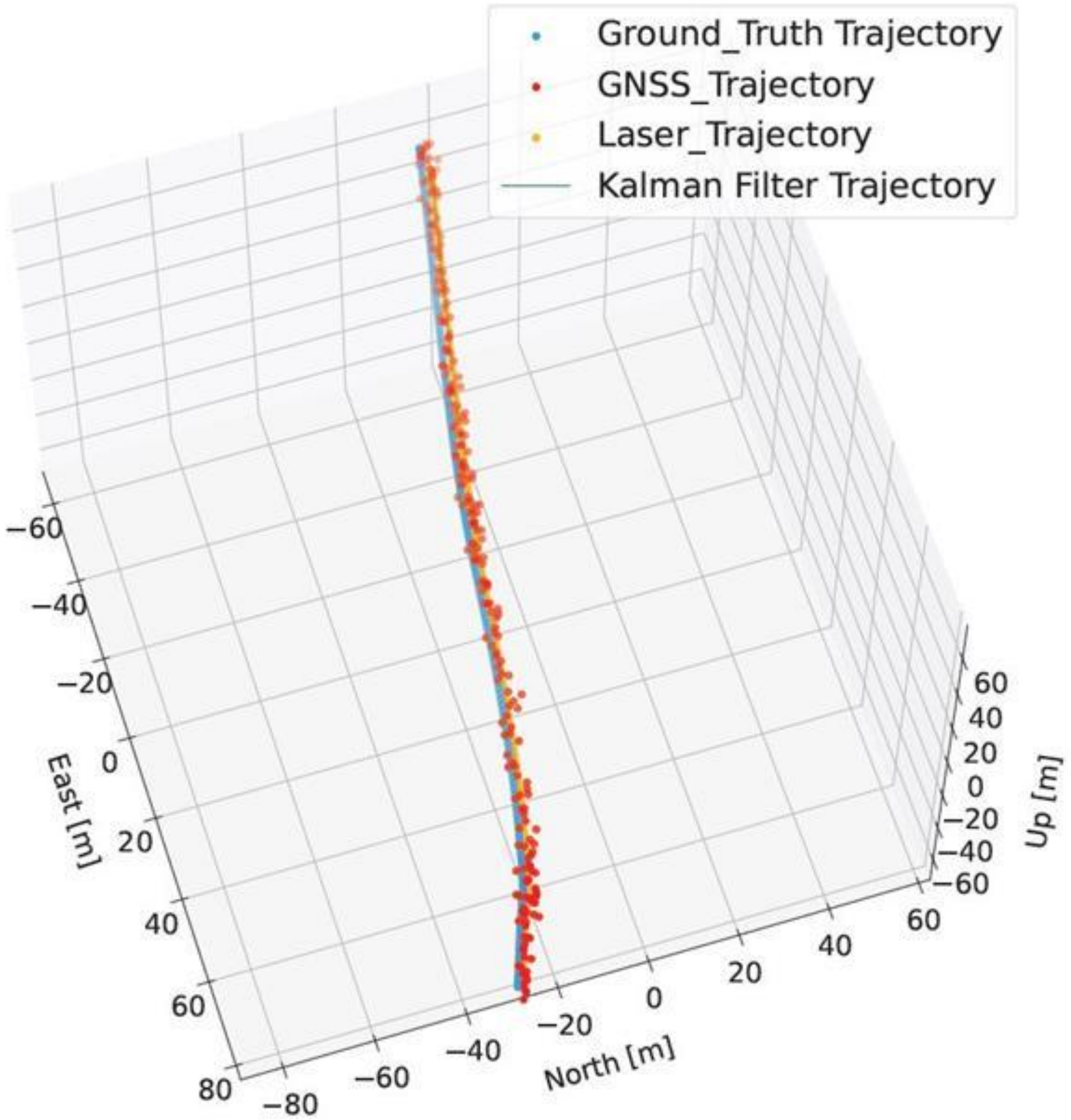
This research focuses on the systematic modeling of GNSS and LiDAR errors to enhance sensor fusion performance. A key aspect of this work is the design of fusion architectures that optimize trade-offs between accuracy, environmental-dependency, and robustness to sensor failures. To this end, this research investigates trajectory alignment, geometric similarity and sensor signal dropouts. Various fusion strategies, including tightly coupled and loosely coupled approaches, are explored to evaluate their effectiveness under different operational conditions.

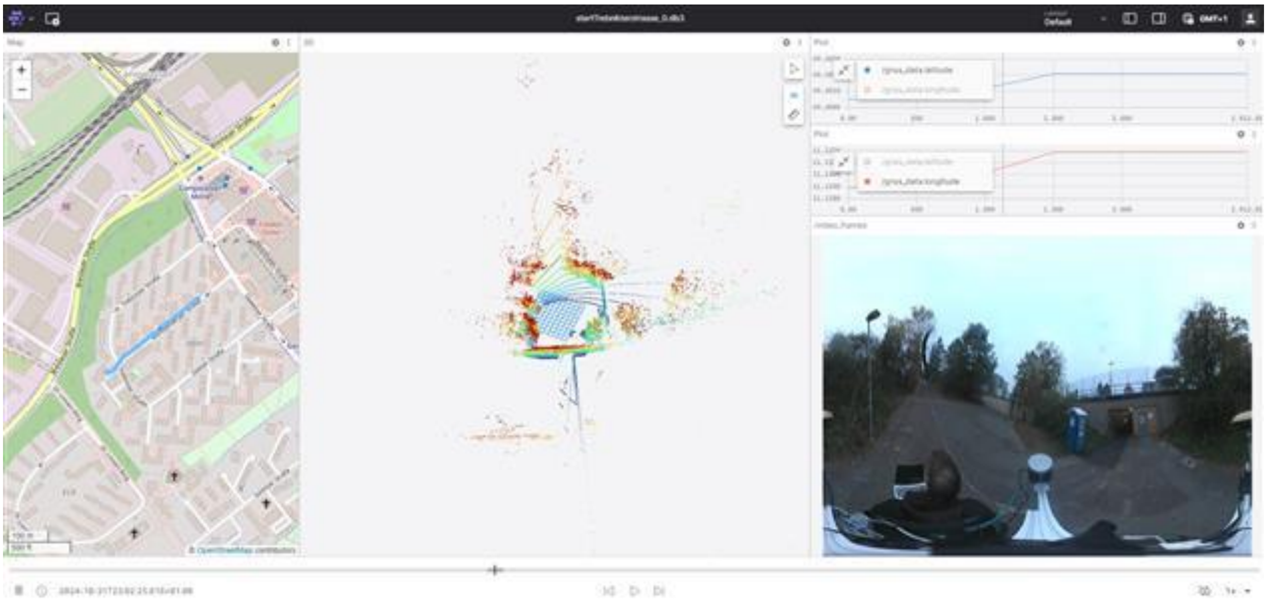
Simulation-based evaluation is a core component of this study, enabling controlled analysis of sensor errors, fusion methodologies, and performance metrics. A custom Blender-based simulation framework has been developed to facilitate reproducible experiments and allow for benchmarking of different fusion strategies. By systematically analyzing fusion performance in terms of accuracy, consistency, and computational cost, this work aims to provide valuable insights into the optimal integration of GNSS and LiDAR for real-world applications. The simulation framework generates a reusable output format in order to demonstrate the flexibility of this methodology by running a selected fusion approach on real data (Sim2Real).

The proposed framework and findings contribute to the research community by providing tools and methodologies for evaluating sensor fusion strategies, fostering advancements in precise and resilient localization solutions for autonomous systems, robotics, and geospatial applications in challenging environments.


k=112: ./render\Color\Color_0113.jpg




Ground_Truth Trajectory
GNSS_Trajectory
Laser_Trajectory
Kalman Filter Trajectory
East [m]
North [m]
Up [m]



Inter-Satellite Link Network Real-Time Ring Dissemination Performance and Robustness

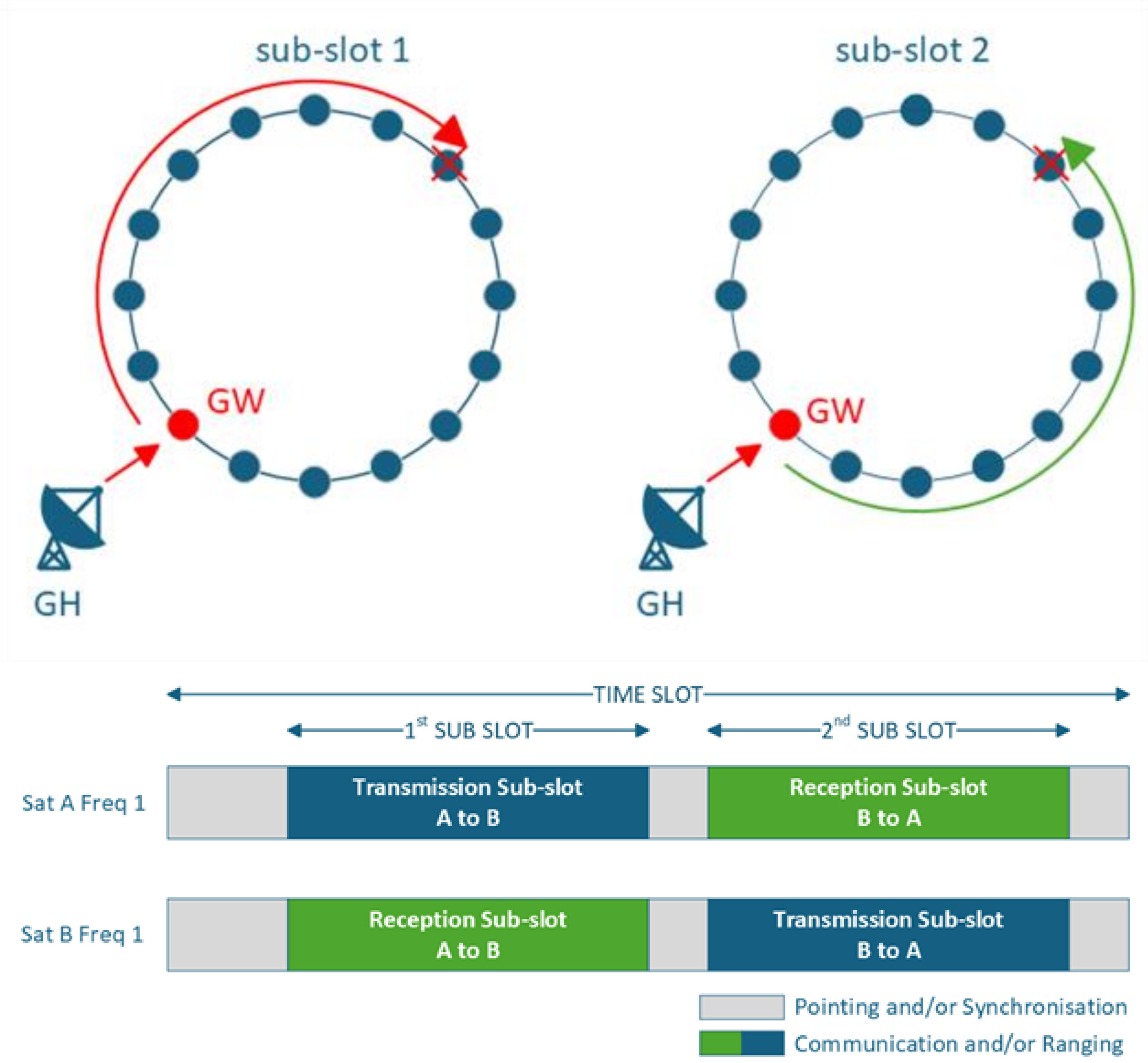
Zini E[1], Wagner C[2], Neto P[3], Morelli A[3]

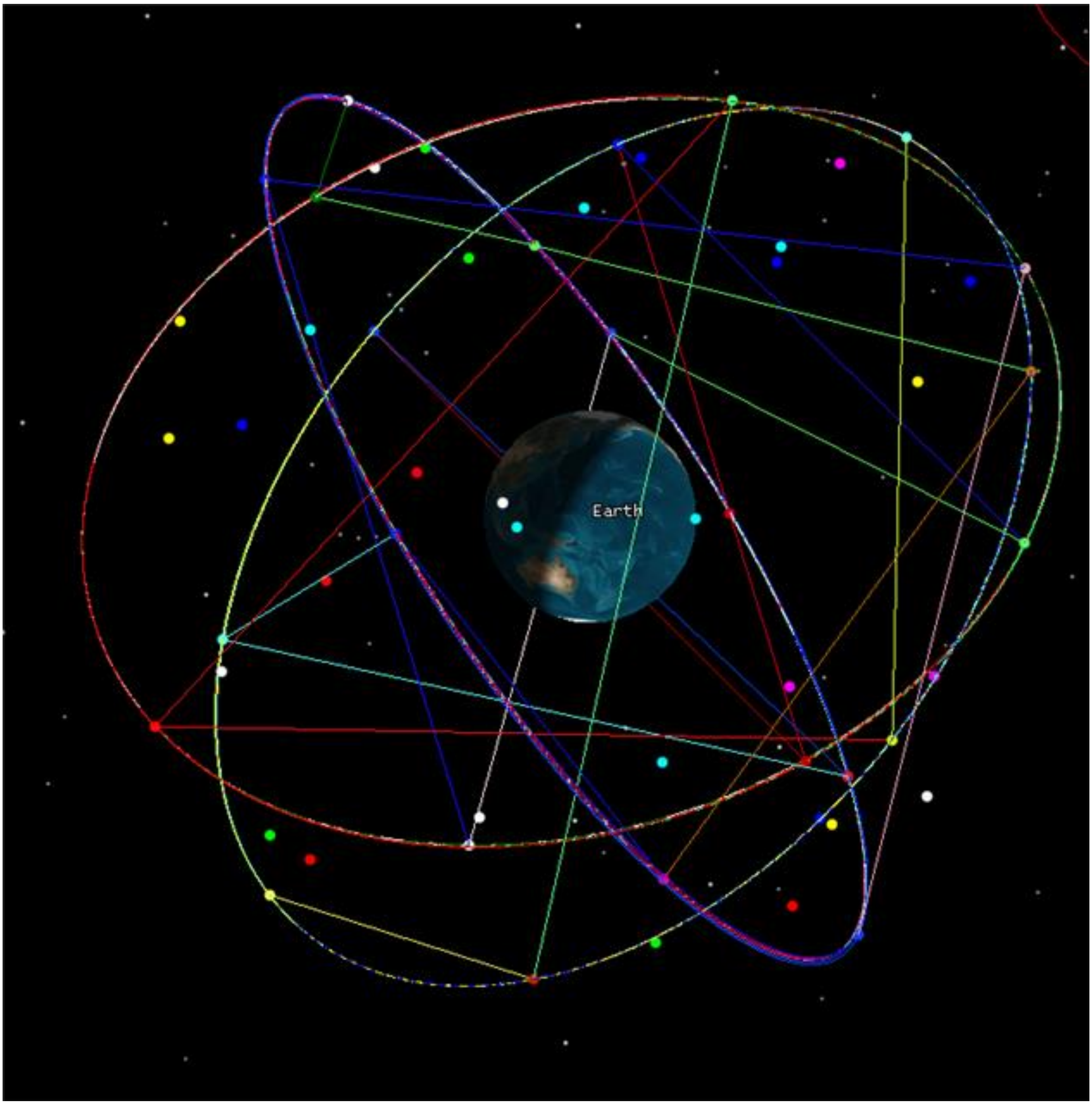
[1]Thales Alenia Space Italia, [2]European Space Agency, [3]WISER srl

Biography:

Edoardo Zini is a Navigation System engineer for Thales Alenia Space. After contributing to the Lunar Radio Navigation System (LRNS) design as system engineer, with particular focus on ODTS aspects, he is currently working on Galileo 2nd Generation System Engineering as technical coordination of the System Design team. His main areas of involvement are ISL, RF Interfaces, Data Dissemination and on-board data handling.
Collocated at ESA/ESTEC premise.

Inter-Satellite Link (ISL) are a key enabling technology for next-generation of GNSS satellites. ISL offers enhanced Monitoring and Control (M&C) and data dissemination capabilities, helps reducing the size of the ground segment network and ultimately leads to better Clock and Ephemeris Data (CED) accuracy thanks to inter-satellite ranging measurements and reduced Signal-in-Space Error (SISE) through faster on-board data refresh rates.
An ISL-enabled constellation operates as a network where nodes (satellites) communicate via a data routing logic. The ground segment interacts with the constellation through designated access points called “Gateways.” Data dissemination can occur either directly (single-hop) or through multiple nodes (multiple-hop). If each node has two active ISL payloads, Real-Time Ring (RTR) transmission is achievable using connection matrices that create single or multiple interconnecting rings.
This network-oriented approach enhances real-time command and monitoring of satellites while increasing bandwidth usage. However, its effectiveness relies on the availability of the ISL payloads; if a link is not active, the rings open and data cannot travel past that node.
Considering that a GNSS constellation will be constituted by satellites at very heterogeneous points of their operative life, the ageing of the ISL payloads is expected to introduce failures over time, either temporarily or permanently.
The present paper analyses the performances of an ISL-capable MEO network exchanging data using a RTR strategy and evaluates its robustness when progressively introducing failures. The benefits of using a half-duplex communication scheme are analyzed.
The effects of failures are analysed firstly assuming no intervention from Ground and then introducing mitigation actions by the ground segment including contact replanning based on failed links and isolation of faulty satellites.
The performance metric considered is the time taken to disseminate data from their generation to when they reach the target satellite. Simulation hypotheses, recommendations, and future work are also presented.


sub-slot 1
GW
GH
sub-slot 2
GW
GH
TIME SLOT
1st SUB SLOT
2nd SUB SLOT
Sat A Freq 1
Transmission Sub-slot
A to B
Reception Sub-slot
B to A
Sat B Freq 1
Reception Sub-slot
A to B
Transmission Sub-slot
B to A
Pointing and/or Synchronisation
Communication and/or Ranging

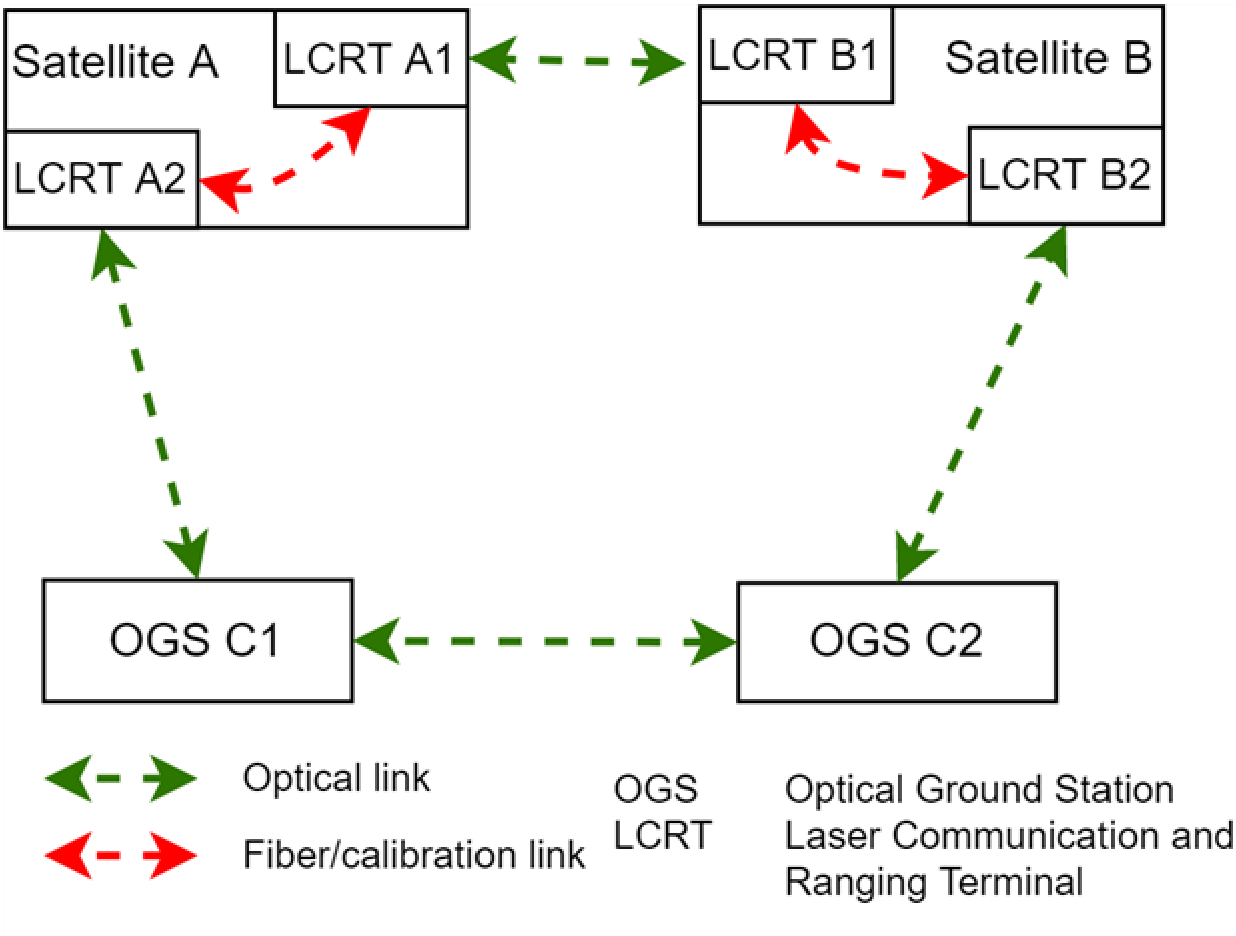

Earth

Optical time transfer accuracy verification via closed-loops inter-satellite and ground-to-satellite links topologies

Dassié M[1], Michalak G[1], Giorgi G[1]
[1]DLR

Biography:
Dr. Grzegorz Michalak received his PhD in Physical Sciences (Astronomy) in 2000 from Wrocław University, Poland. In 2001 he joined orbit determination group at the German Research Centre for Geosciences (GFZ). His main activity was focused on precise orbit determination of GNSS and LEO satellites using real and simulated data. In 2021 he joined the German Aerospace Center (DLR) where he works on Galileo evolution concepts including exploitation of inter-satellite links in GNSS.

The exploitation of Optical Inter-Satellite Links (OISLs) has the potential to provide significant benefits to GNSSs, offering clock synchronization via highly accurate time transfer, precise ranging, robustness against jamming and spoofing, high data rates, and freedom from signal frequency regulations. As with any new technology, it is crucial to conduct in-space experiments to demonstrate the capabilities of OISLs before widespread adoption.
In this work, we present preliminary analyses of an in-orbit demonstrator concept, which is being designed under the name Optical Synchronized Time And Ranging (OpSTAR). It involves two MEO satellites in a trailing configuration, each equipped with two laser terminals. On the ground, we assume two co-located and inter-connected Optical Ground Stations (OGSs). Whenever both satellites are simultaneously visible from the OGSs, an OISL and two additional Optical Ground-to-Satellite Links (OGSLs) are established, forming a closed "measurement loop" (Figure 1).
We first present a detailed procedure for conducting two-way time transfer assuming OISL and OGSL pseudo-range observables. A cross-link clock observable is formed by differencing two one-way pseudo-ranges and, by correcting it with estimated signal flight times, relativistic effects, atmospheric delays and hardware delays, a relative clock offset estimate is obtained. We analyze how modelling errors of these delays impact the estimate accuracy, identifying the relevant ones.
Next, we make use of the core concept of OpSTAR leveraging the fact that the sum of ideal clock differences across a closed measurement loop is null. Since the difference estimates will necessarily be noisy, and possibly biased, we analyze the individual error contributions to establish the minimum requirements for keeping the cumulative error across the loop below the picosecond level. Finally, we propose a mix of measurement link topologies to mitigate the probability of incurring in unobservable biases in the aggregated sum.


Satellite A
LCRT A1
LCRT A2
LCRT B1
Satellite B
LCRT B2
OGS C1
OGS C2
Optical link
Fiber/calibration link
OGS
LCRT
Optical Ground Station
Laser Communication and
Ranging Terminal

Toward an Interpretable Multipath Error Model from GNSS Observables through the Application of Deep Learning

Barbero T[1], Matera E, Ekambi B[1], Chamard J[1], Ekambi M[1]
[1]Abbia GNSS Technologies

Biography:
Thomas Barbero is a R&D engineer at Abbia Group, where he works on performance topics for EGNOS, Factor Graph Optimization applied to Navigation. Additionally, his research activities focus on the integration of Deep Learning algorithms for PNT robustness.
This work presents results regarding the ability to capture correlations between GNSS raw data and multipath using Deep Learning, and focus on the interpretability of the operations of the presented models.

Global Navigation Satellite Systems (GNSS) are integral to many applications relying on precise positioning. However, multipath errors pose significant challenges to achieving high accuracy PVT solutions.
Multiple studies consider the use of Deep Learning to mitigate multipath degradation of the PVT, without focusing on the interpretability aspects tied to the application of Deep Learning.
This article proposes an in-depth analysis of the latent space of an Auto Encoder (AE) to uncover and interpretate intricate relationships between GNSS raw data. Additionally, we investigate the correspondence between specific local structures within the latent space and spatial correlations in the physical world.
By examining latent space, we seek to understand and visualize the reconstruction of a pseudo-geometrical environment and identify the underlying factors influencing multipath errors. We validate our hypotheses through the applications of metrics tailored to our specific use-cases.
The first task involves isolating multipath error from Pseudorange measurements of L1 C\A and L2 GPS modulations, applying the Code Minus Carrier methodology. This is followed by the training and the evaluation of AE models using a combination of multipath measurements and other GNSS observables that shall exhibit significant correlations with the multipath.
A static GNSS receiver was deliberately chosen to simplify the analysis process and leverage the repeatability conditions of GNSS raw data. This controlled setting ensures that the observed patterns and correlations are primarily due to environmental factors rather than receiver mobility.
To generalize our findings, data from several reference stations from the International GNSS Service (IGS) network were analyzed.
We obtained promising results, showing that the higher multipath error components could be identified in specific regions of the AE latent space, forming clusters with similar characterization. Additionally, AE trained over a single reference station kept a moderate increase in the mean reconstruction error for different reference stations without additional training.

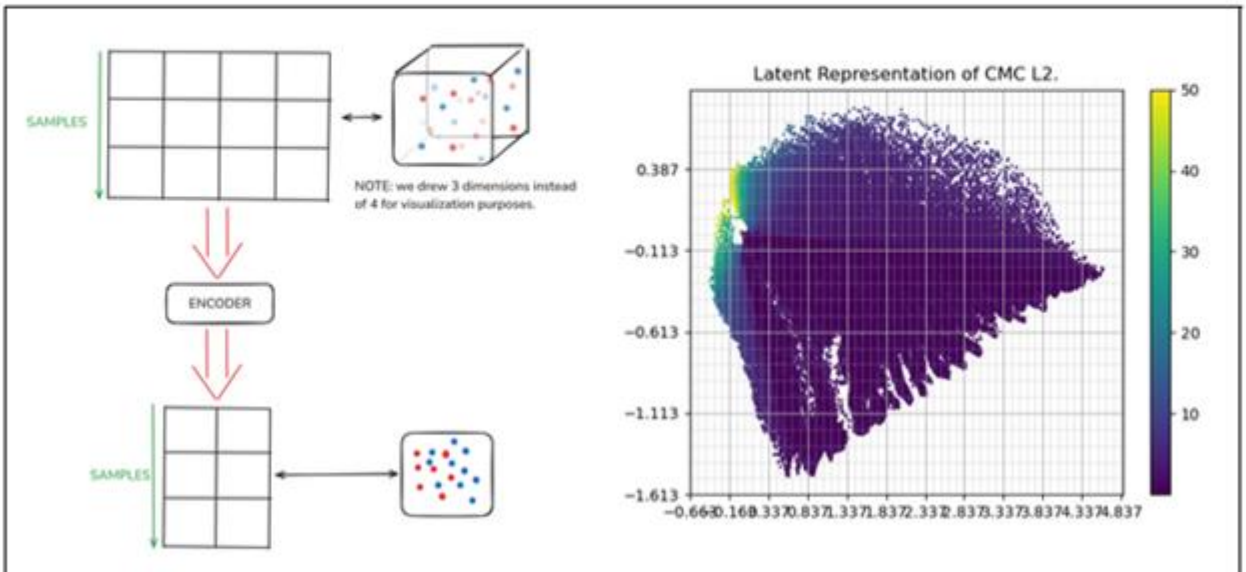


Figure 1: Illustration of the applied methodology on the left, examples of resulting latent space on the right.
The original dimensions of the samples are reduced, enabling the representation of the dataset in a figure.

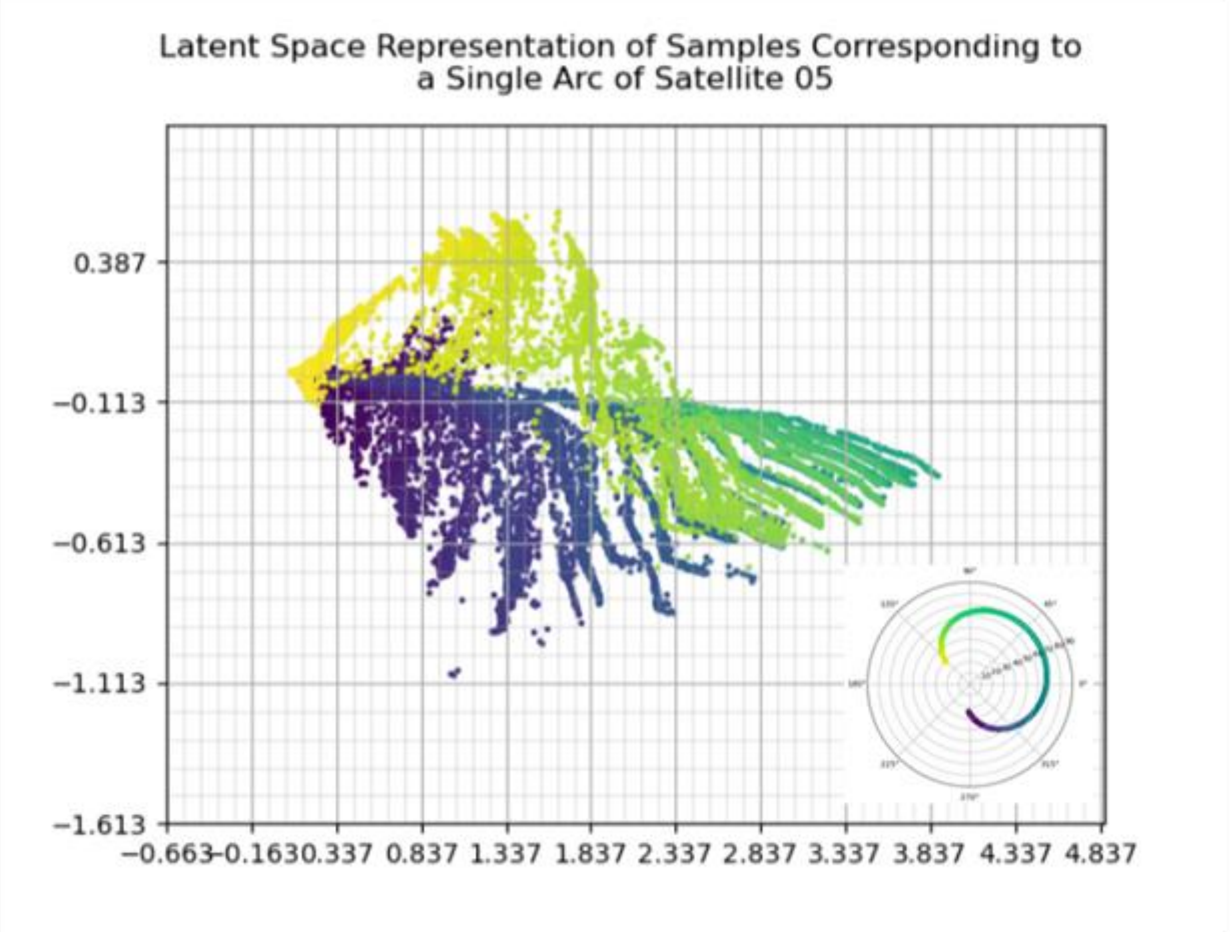


Figure 2: Latent space of an Auto-Encoder for samples corresponding to a single geometrical arc of Satellite 05 over our considered reference station.

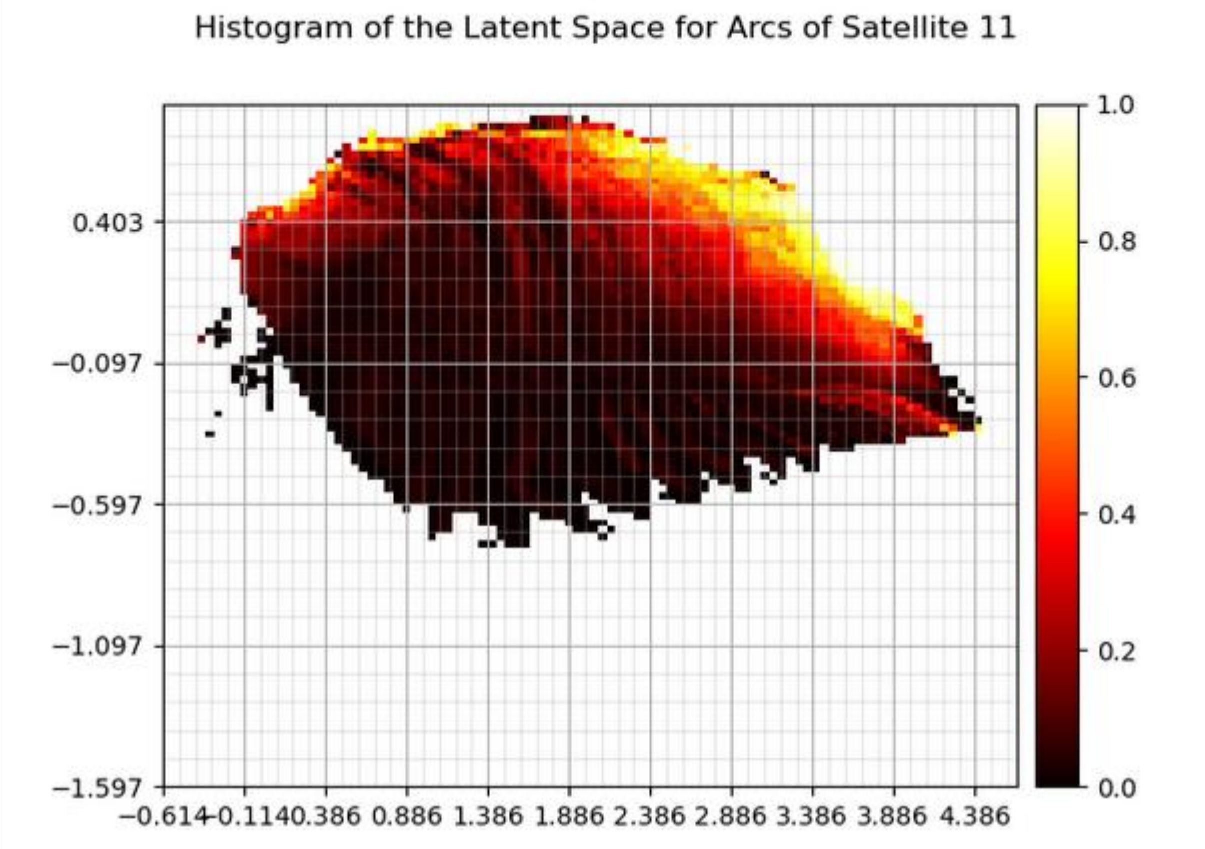


Figure 3: Histogram of the latent space of an Auto-Encoder for samples corresponding to arcs of the same Satellite over our reference station for 100 days.

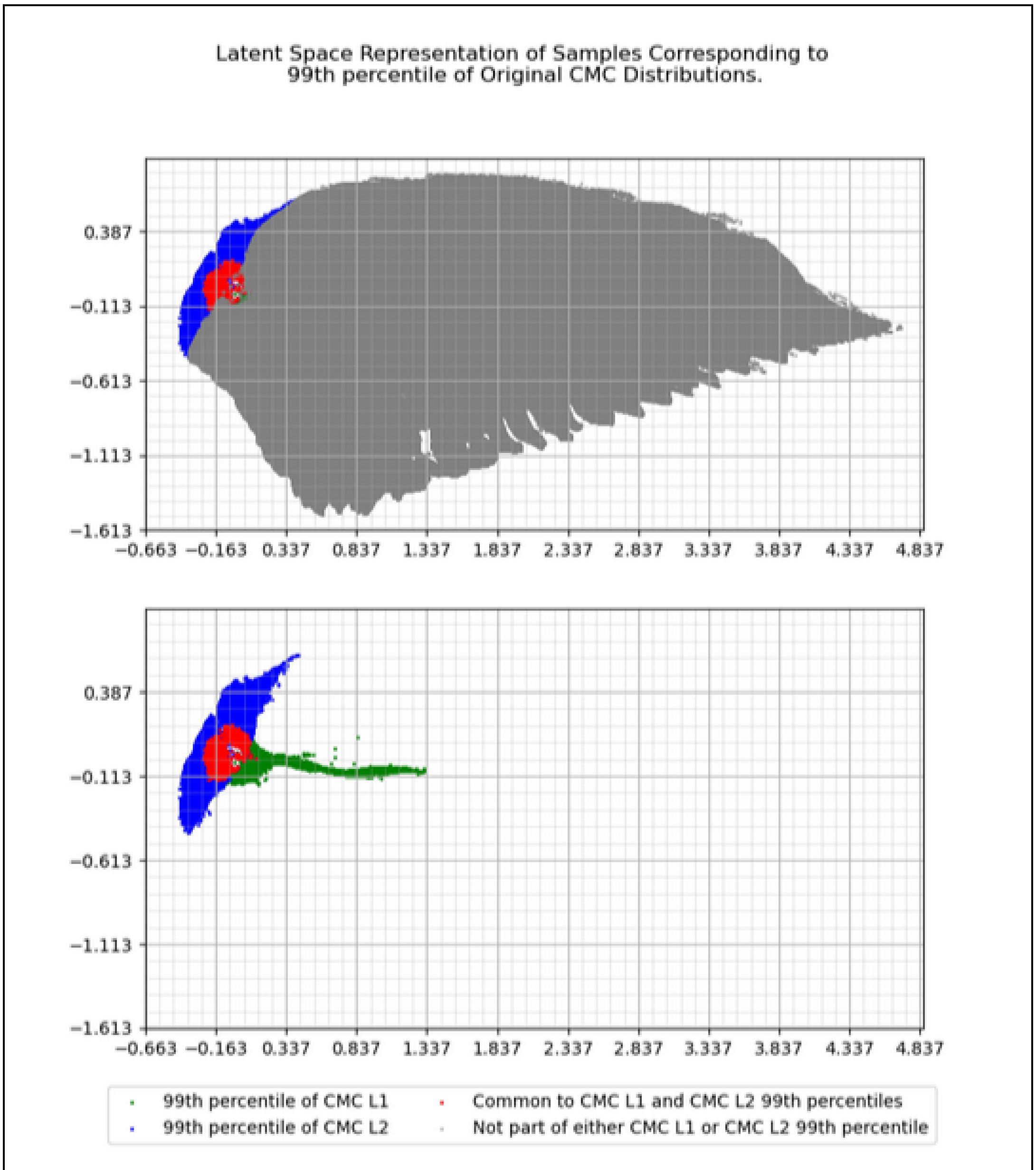


Figure 4: On top: Latent space of an Auto-Encoder displaying samples corresponding to the 99th percentiles of CMC L1 and CMC L2, the intersection of both percentiles and the complement of the union of the percentiles.
On bottom: Latent space of an Auto-Encoder displaying samples corresponding to the 99th percentiles of CMC L1 and CMC L2 and the intersection of both percentiles. The complement of the union of the percentiles is not plotted.

Genesis GNSS Observables: Simulation Methodology and Preliminary Results

Sakalauskaite E[1], Waller P[1], Fusco G[1], Gidlund S[1]
[1]ESA/ESTEC

Biography:
Evelina Sakalauskaite has a MEng in Aerospace Engineering from the University of Sheffield. She joined ESA and the ESA Genesis Project Team in September 2023 as a Young Graduate Trainee in System Engineering for Genesis. She supports preparation for science exploitation and system engineering activities.

Genesis is a European Space Agency (ESA) mission, currently in development within the Directorate of Navigation, aiming to significantly contribute to the accuracy improvement of the International Terrestrial Reference Frame (ITRF) to 1mm and its long-term stability to 0.1mm/year. It will be the first mission co-locating all four space-geodesy instruments - GNSS receiver, SLR reflector, VLBI transmitter, and DORIS receiver - on a single, well-calibrated spacecraft at an altitude of 6000km.

Because the selected orbit lies outside of the classical terrestrial service volume (TSV) (up to 3000km), where GNSS performance is well-established, the mission and instrument designs face significant challenges to ensure the required GNSS visibility and performance. To address this, an early assessment of the expected quality and quantity of GNSS observables in the selected orbit is essential.

To support the mission and instrument design definition, a simulation methodology has been defined and implemented using simulation tools at ESA/ESTEC, aiming to assess GNSS performance at Genesis orbit for different receivers, antenna types, configurations, and environmental parameters. The methodology includes two approaches: simulating GNSS receiver characteristics based on various input parameters and using a hardware simulator to generate physical signals and a representative hardware receiver (“hardware in the loop”). These simulations will provide preliminary raw data for early assessment of POD processing and ITRF-related product generation.

Initially, a realistic scenario was set up using the latest data to simulate GNSS satellites (power levels, antenna patterns, etc.). This scenario was validated using the “hardware-in-the-loop” approach against a well-known GNSS receiver and antenna configuration at a fixed location on Earth. Following this validation, various simulation scenarios were executed to collect preliminary data for analysis.

The paper will provide a detailed description of the simulation scenario parameters, validation process, and initial findings which will be presented at the ENC 2025.

23 May 2025

GNSS RF Monitoring - 2

Plenary Room, May 23, 2025, 10:00 AM - 11:00 AM

Leveraging National Metrology Laboratory UTC Reference for Strengthening GNSS Resilience Against Jamming and Spoofing

Fleming D[1], Fleming D
[1]Timing Solutions

Biography:
David Fleming manages the Time, Frequency and Acoustics Laboratory in the National Standards Authority of Ireland' National Metrology Laboratory (NSAI NML). Holding a PhD. from the Technological University of Dublin, he has worked in the field of Metrology and Calibration in the NSAI NML for 15 years and has extensive experience in calibration, research, collaboration, mentoring, and project management.

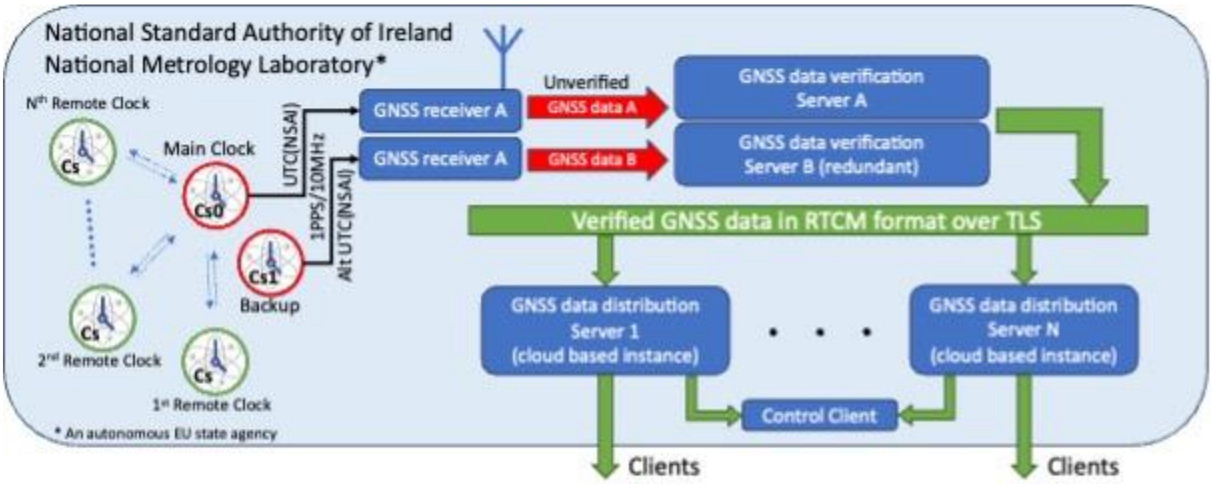
Global Navigation Satellite Systems (GNSS) are essential to critical infrastructure sectors such as transportation, energy, telecommunications, finance, and emergency services, providing precise positioning, navigation, and timing (PNT). However, GNSS signals are inherently vulnerable to jamming, spoofing, and unintentional interference, posing significant risks to operational continuity.

This paper explores innovative strategies to enhance GNSS resilience by leveraging the National Standard Authority of Ireland's National Metrology Laboratory (NSAI NML) UTC reference – UTC(NSAI). Utilising an independent atomic clock, the NSAI NML can verify GNSS navigation data and signals and subsequently distribute them to critical infrastructure sectors, including telecommunications, power utilities, data centres, public institutions, airports, and maritime operations. When combined with GNSS Common View Time Transfer (CVTT) – a technique traditionally used by national metrology institutes to compare atomic clocks – this approach enables accurate time synchronisation, even in environments where GNSS signals are jammed at L1 frequency. The use of independently verified GNSS data allows receivers to cross-check navigation information against a trusted reference, enhancing their ability to detect and mitigate spoofing attacks.

To support these findings, this paper presents measurement results from a controlled jamming and spoofing campaign conducted at the European Space Agency's ESTEC facility. The results illustrate the impact of interference on GNSS receivers and assess the effectiveness of CVTT and verified GNSS data as mitigation strategies. These insights offer a practical evaluation of GNSS vulnerabilities and provide actionable countermeasures.

The adoption of CVTT and verified GNSS data distribution offers a cost-effective and scalable solution for enhancing the resilience of GNSS-dependent systems. As global reliance on GNSS continues to grow, integrating hybrid PNT architectures and resilient receiver designs will be essential for safeguarding economic stability and public safety.

This paper provides a roadmap for industry stakeholders, policymakers, and researchers to strengthen GNSS security and resilience in critical applications.


National Standard Authority of Ireland
National Metrology Laboratory*
Nth Remote Clock
Main Clock
Cs
Cs0
Cs1
Backup
2nd Remote Clock
1st Remote Clock
* An autonomous EU state agency
UTC(NSAI)
1PPS/10MHz
Alt UTC(NSAI)
GNSS receiver A
GNSS receiver A
Unverified
GNSS data A
GNSS data B
GNSS data verification Server A
GNSS data verification Server B (redundant)
Verified GNSS data in RTCM format over TLS
GNSS data distribution Server 1 (cloud based instance)
GNSS data distribution Server N (cloud based instance)
Control Client
Clients
Clients

Bridging Field Data and 3D PNT Simulation: Evaluating Performance in Interference-Rich GNSS Environments

Verdeguer Moreno R, Gomez-Lopez M
[1]Spirent Communications PLC - Positioning

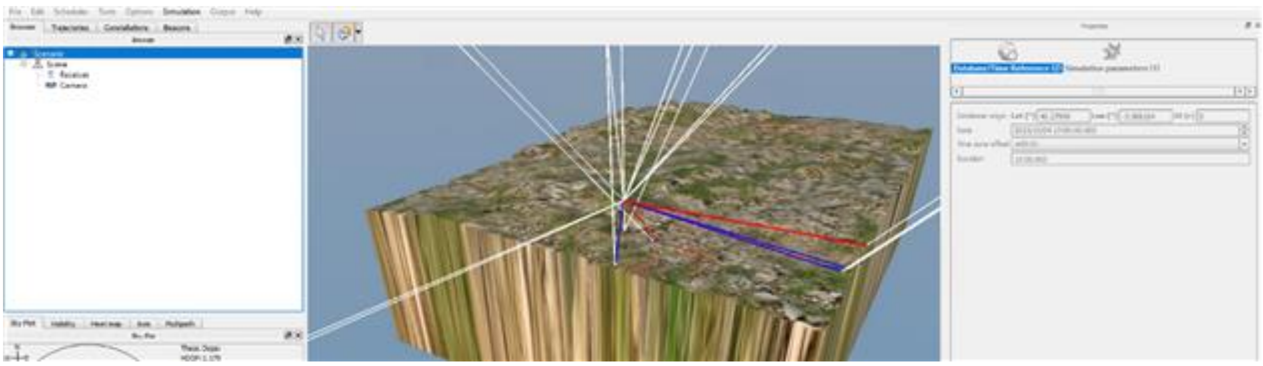
Biography:
Ricardo Verdeguer Moreno works as Product Line Manager at Spirent Communications providing Positioning, Navigation and Timing solutions for defence and space applications.
He is an aerospace engineer, who graduated with honours from Cranfield University with an MSc in Autonomous Vehicle Dynamics and Control. His expertise encompasses market insights and technical proficiency in GNSS-based autonomous systems.
Ricardo will discuss key findings from analysis (co-authored by Miguel Ángel Gómez, Researcher at the Spanish National Institute of Aerospace Technology), illustrating how 3D simulation enables researchers and system developers to anticipate performance degradations, design robust mitigation strategies, and test resilience under controlled, repeatable conditions.

Operating in GNSS-degraded or denied environments, particularly those impacted by jamming, can greatly benefit from advanced simulation tools. These tools accurately replicate complex real-world conditions and provide valuable insights into the behaviour of equipment in these increasingly common scenarios.

Our research focuses on assessing the fidelity of 3D simulation capabilities for replicating GNSS signal behaviour under interference-rich conditions. We conducted fieldwork to record GNSS signals with different power levels and types of interference, capturing real-world vehicle dynamics. These recordings were then used as a benchmark to compare against simulated data. This simulation leverages from 3D modelling tools, and incorporate obscuration, reflection and diffraction effects to all the RF signals generated.

We discuss key findings from this comparative analysis, illustrating how 3D simulation enables researchers and system developers to anticipate performance degradations, design robust mitigation strategies, and test resilience under controlled, repeatable conditions. This approach not only reduces dependence on costly field campaigns and accelerates the development of interference-resilient navigation systems but also ensures repeatability and enables in-depth analysis, as all key parameters can be precisely determined—unlike in field campaigns.

By demonstrating the transformative potential of 3D PNT simulation, this work supports the applications in defence, transportation, and critical national infrastructure (CNI) under GNSS-degraded scenarios.



Error Correction Using Bayesian GRU Network in Hybrid Visual Inertial Navigation System

Tabassum T[1], Negu S[2], **Petrunin I**[3], Rana Z[4]
[1]Cranfield University, [2]Cranfield University, [3]Cranfield University, [4]Prince Mohammad Bin Fahd University

Biography:
Ivan has extensive knowledge and experience in the area of Digital Signal Processing for Autonomous Systems which covers sensor technologies, perception, data and information fusion, and decision-making for Cyber-Physical Systems. Applications for these developments include vehicle health management, communication and surveillance solutions and, more recently, Position, Navigation and Timing (PNT) for aerospace and ground-based Autonomous and Intelligent Systems.
Ivan is involved in and actively supporting the development and operation of several research facilities, such as the instrumentation of Muti-User Environment for Autonomous Vehicle Innovation (MUEAVI), Research and Innovation Timing Node, PNT simulation facility.

Vision-based navigation systems (VINS) are increasingly utilised as an alternative to GNSS for UAVs operating in urban environments, offering a promising solution to address navigation challenges. Performance degradation is attributed to the current state-of-the-art systems in complex scenarios due to visual fault conditions like illumination variation, rapid motion, texture-less environments, and weather effects. While hybrid architectures incorporating Kalman filters and machine learning (ML) improve performance, they lack evidence of providing contingency for non-gaussian error distributions, limiting operational safety. To address these shortcomings, an enhanced hybrid VINS architecture is proposed featuring a Bayesian GRU-based error correction network (B-GRU) providing prediction of error boundary while compensating model errors, as illustrated in Figure 1. To the best of the author's knowledge, this is the first attempt to estimate uncertainty using B-GRU compensator while addressing data uncertainty for VINS applications. The system architecture integrates an Error-State Kalman Filter (ESKF) and the B-GRU, compensating for position errors with uncertainty prediction.

The proposed approach is validated using datasets from Spirent’s SimGEN software utilizing GSS700 and AirSim photorealistic urban environment, replicating the complex fault conditions. The ML-based correction model is trained on various visual failure modes to adapt the variability in the signal patterns during flights. The testing datasets encompass diverse lighting conditions and flight paths. Results demonstrate that the fusion strategy effectively corrects erroneous measurements arising from corrupted sensor data and imperfect models. It achieves 76% accuracy in partly-sunny and 62% in foggy conditions, with 5.13% of points exceeding error boundary on horizontal-axis while capturing complex flight dynamics in unseen locations. Comparative analysis demonstrates the effectiveness of B-GRU in mitigating failure modes with predictive error boundary, achieving a 45% improvement in performance compared to architecture that integrates sensor error compensation. This approach shows a step forward in enhancing positioning accuracy and contingency in challenging urban environments.

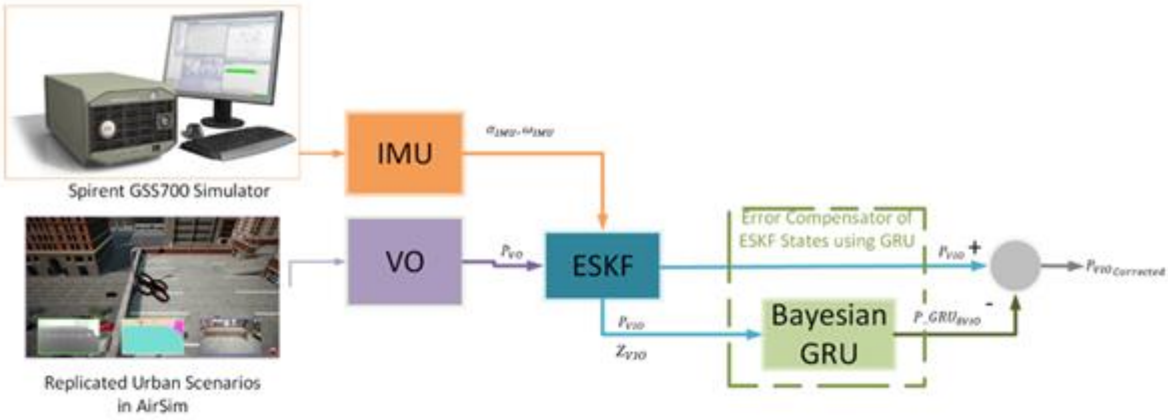
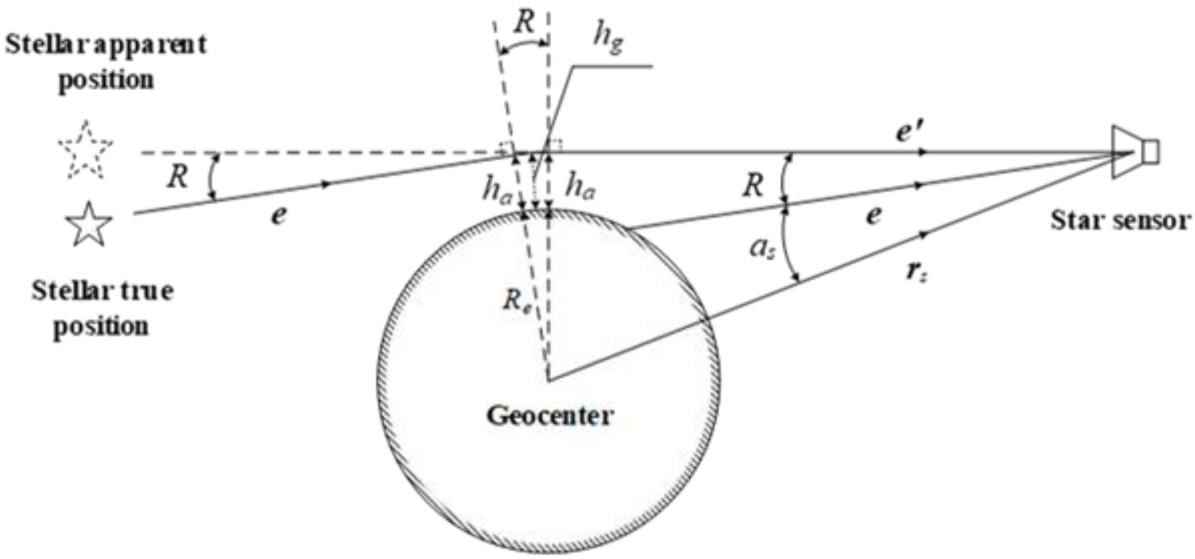


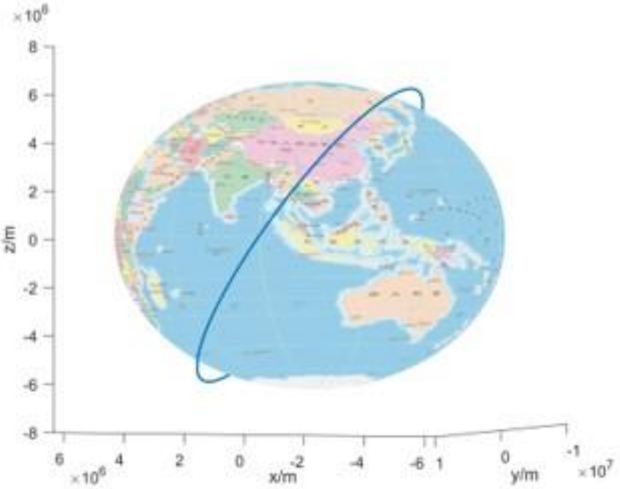
Figure 1 High-level architecture of the proposed hybrid VINS system

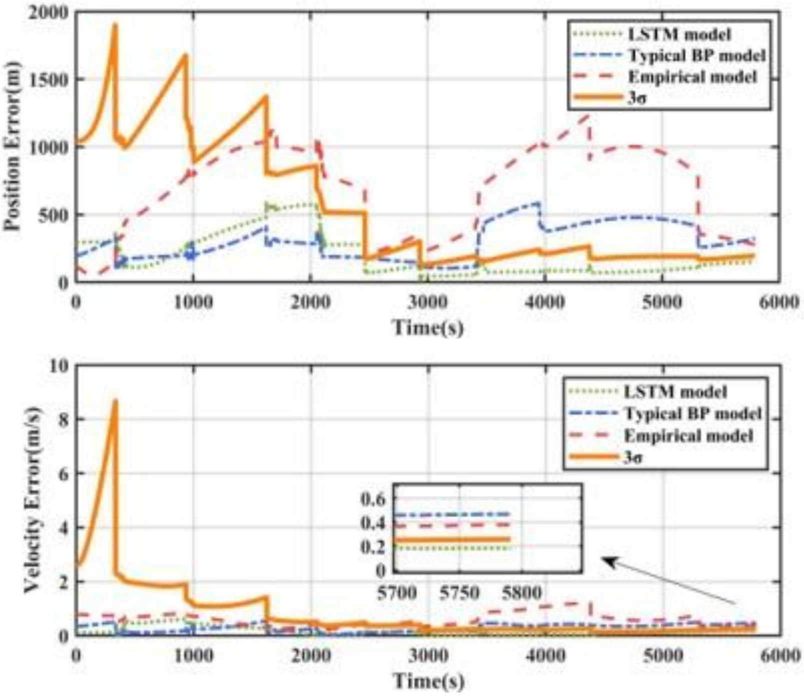
Using artificial intelligence approaches to improve refraction-based autonomous navigation for satellites

Wang D[1], YAN X[1], YANG H[1], ZHANG H[1], Zheng W[1]
[1]National University Of Defense Technology

The stellar refraction navigation accuracy is heavily degraded due to the improper starlight atmospheric refraction model caused by the mismatch between spatiotemporally varying global atmosphere and the assumed model. To address this issue, this paper proposes a hybrid algorithm of both dual-band stellar refraction observations and LSTM learning to estimate and compensate the complicated atmospheric density error. In this algorithm, dual-band starlight refraction observations are used to improve the autonomous navigation accuracy. On the other hand, a well-trained LSTM networks is introduced to compensate for the atmospheric density error in-orbit, which learns the relationship between the actual atmospheric density and multiple factors such as time, latitude, longitude, and altitude beforehand. The simulation results represent that the proposed algorithm can handle the accuracy degradation with effective the atmospheric density error compensation, enhancing SINS/RCNS navigation performance for satellites.





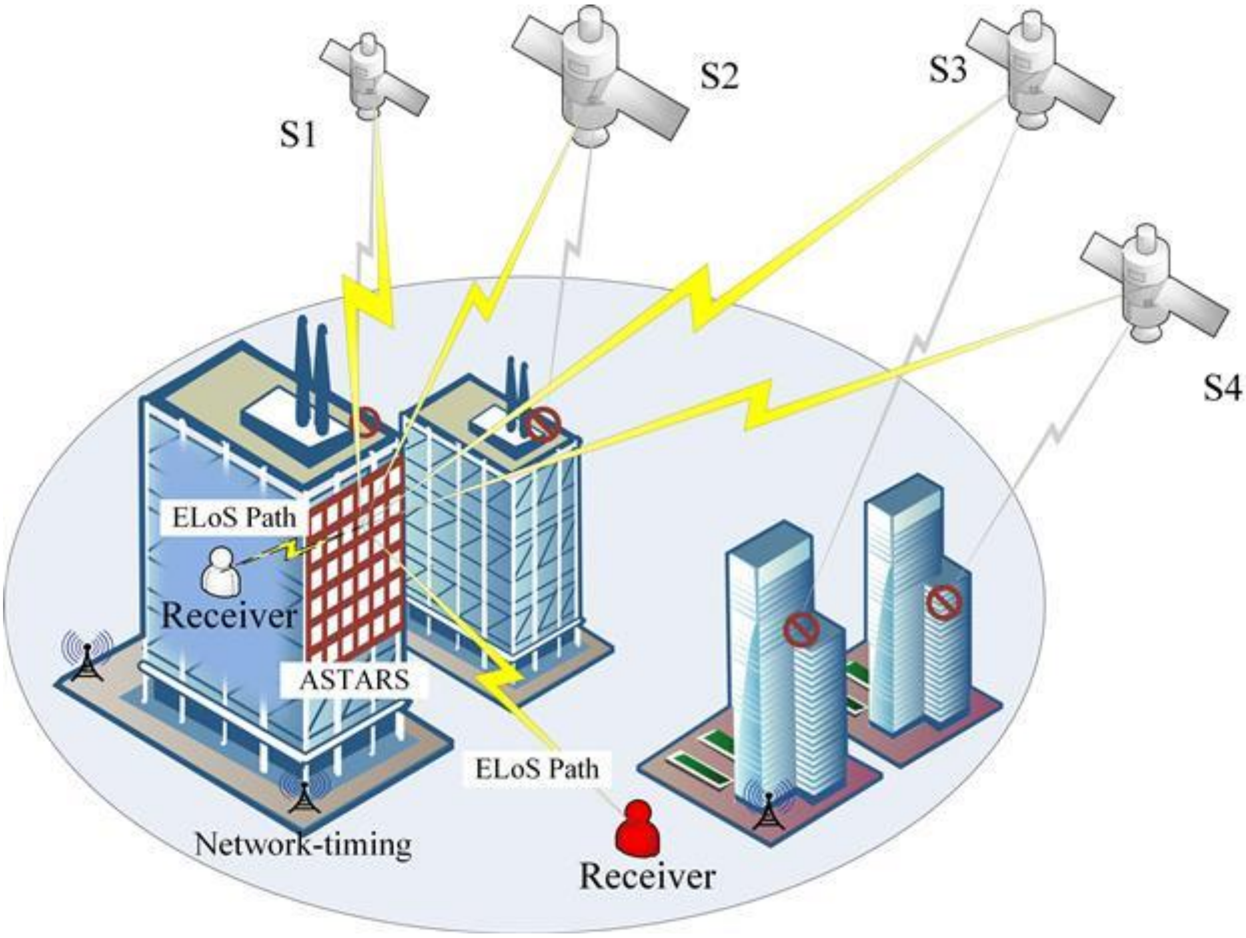


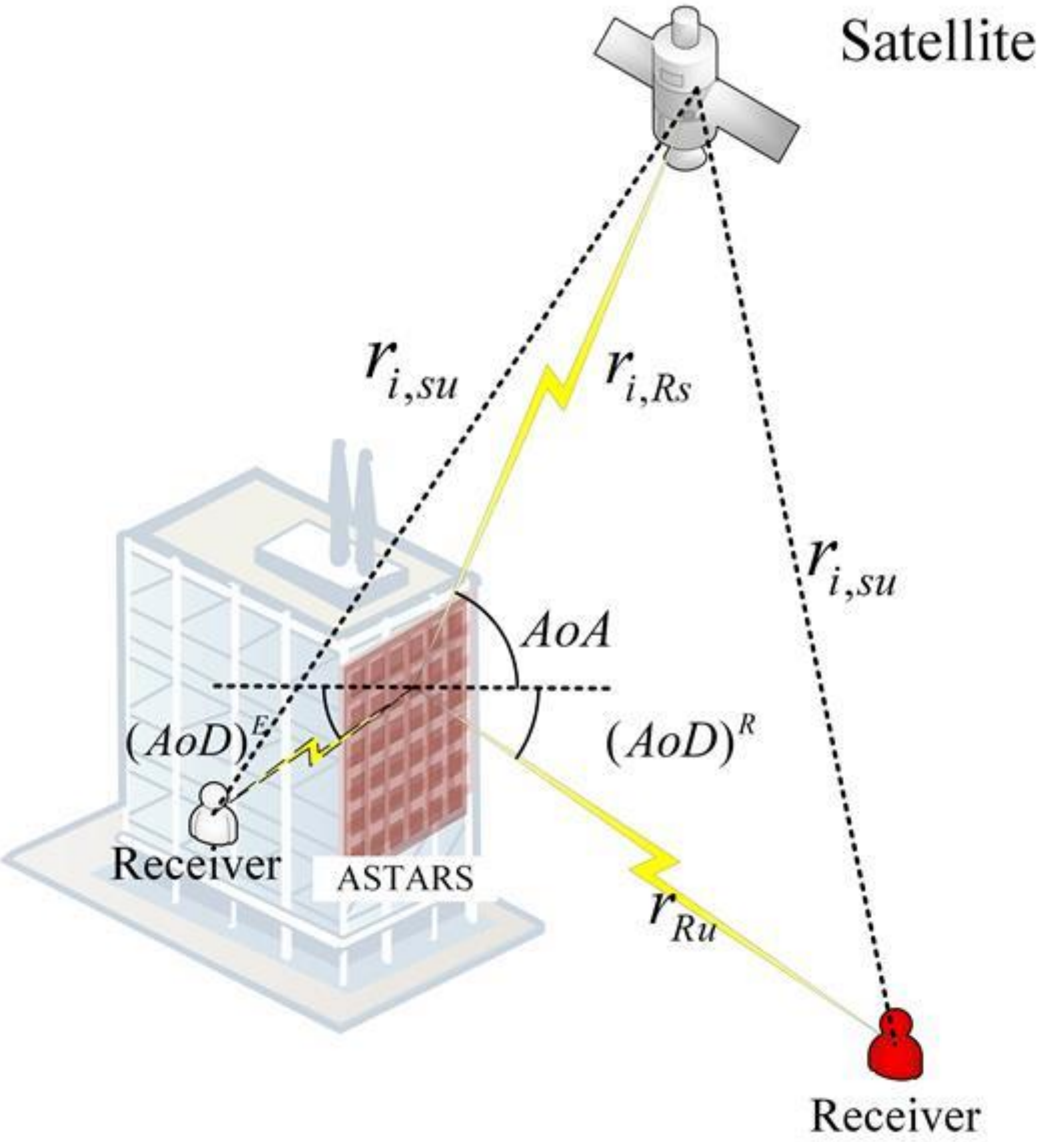
Position Error(m)
Time(s)
LSTM model
Typical BP model
Empirical model
3σ
Velocity Error(m/s)
Time(s)
LSTM model
Typical BP model
Empirical model
3σ

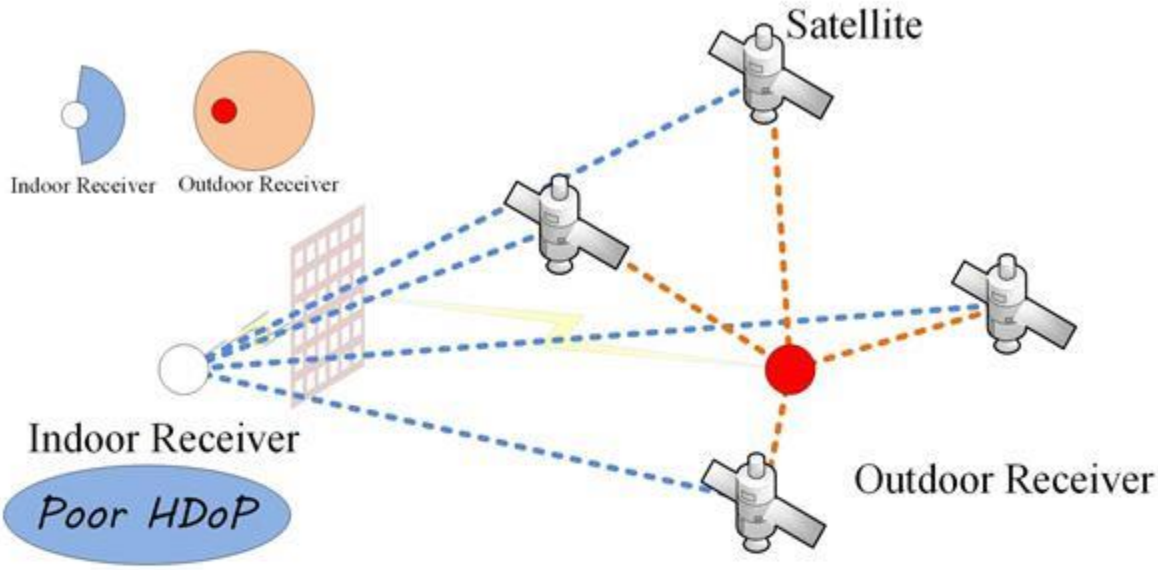
ASTARS empowers satellite navigation in urban canyons and indoor environments, offering a novel positioning approach.

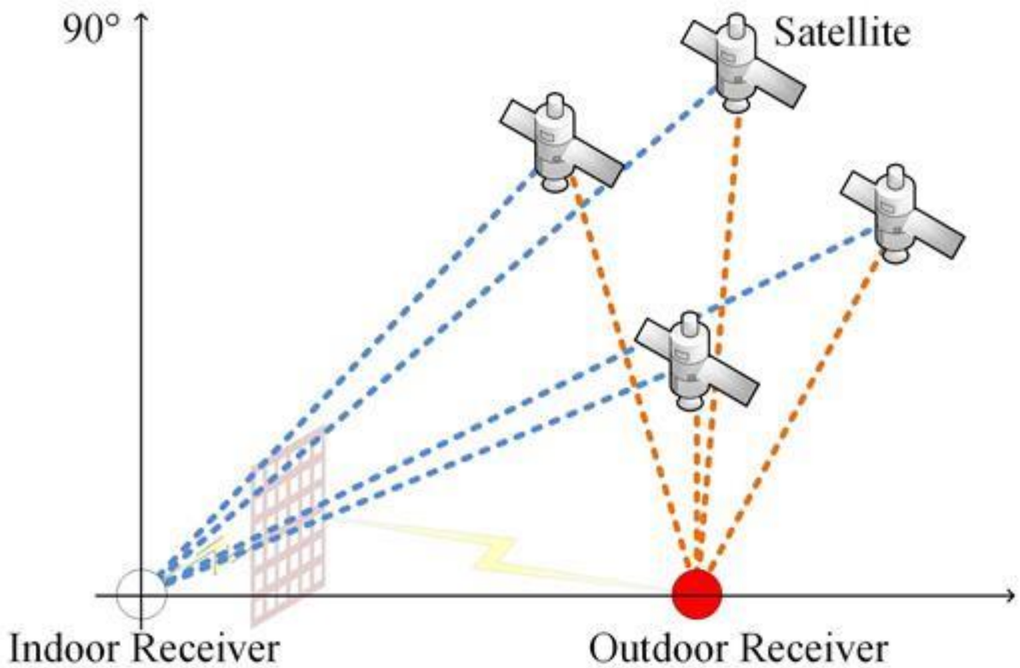
Zhang Y[1], Sun X[1], Hou T[1,2], Li A[3], Pollin S[4], Liu Y[5], Nallanathan A[2,6]
[1]School of Electronic and Information Engineering, Beijing Jiaotong University, [2]School of Electronic Engineering and Computer Science, Queen Mary University of London, [3]School of Computing and Communications, Lancaster University, [4]Department of Electrical Engineering (ESAT), KU Leuven, [5]Department of Electrical and Electronic Engineering, The University of Hong Kong, [6]Department of Electronic Engineering, Kyung Hee University

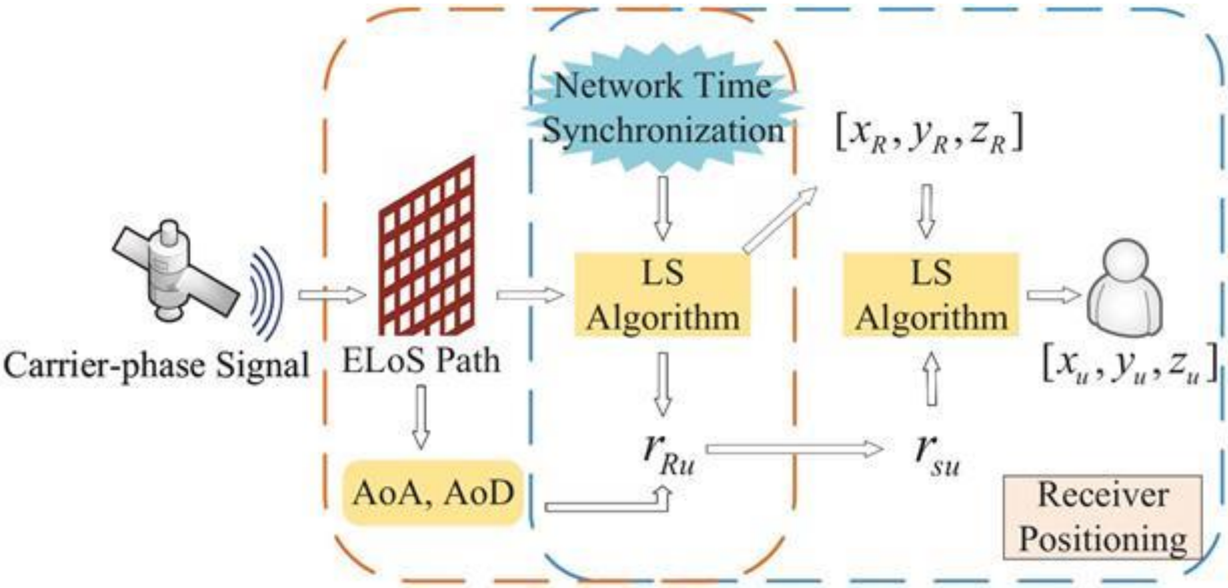
To mitigate the loss of satellite navigation signals in urban canyons and indoor environments, we propose an active simultaneous transmitting and reflecting reconfigurable intelligent surface (ASTARS) empowered satellite positioning approach. Deployed on building structures, ASTARS reflects navigation signals to outdoor receivers in urban canyons and transmits signals indoors to bypass obstructions, providing high-precision positioning services to receivers in non-line-of-sight (NLoS) areas. The path between ASTARS and the receiver is defined as the extended line-of-sight (ELoS) path and an improved carrier phase observation equation is derived to accommodate the new signal path. The receiver compensates for its clock bias through network time synchronization, corrects the actual signal path distance to the satellite-to-receiver distance through a distance correction algorithm, and determines its position by using the least squares (LS) method. Mathematical modeling of the errors introduced by the proposed method is conducted, followed by simulation analysis to assess their impact.
Simulation results show that: 1) in areas where GNSS signals are blocked, with time synchronization accuracy within a 10 ns error range, the proposed method provides positioning services with errors not exceeding 4 m for both indoor and outdoor receivers, outperforming NLoS methods with positioning errors of more than 7 m; 2) the additional errors introduced by the proposed method do not exceed 3 m for time synchronization errors within 10 ns, which includes the phase shift, beamwidth error, time synchronization errors, and satellite distribution errors, outperforming traditional NLoS methods, which typically produce positioning errors greater than 5 m.


S1
S2
S3
S4
ELoS Path
Receiver
ASTARS
ELoS Path
Network-timing
Receiver


Satellite
$r_{i,su}$
$r_{i,Rs}$
$r_{i,su}$
AoA
$(AoD)^E$
$(AoD)^R$
Receiver
ASTARS
r_{Ru}
Receiver


Satellite
Indoor Receiver
Outdoor Receiver
Indoor Receiver
Poor HDoP
Outdoor Receiver


90°
Satellite
Indoor Receiver
Outdoor Receiver

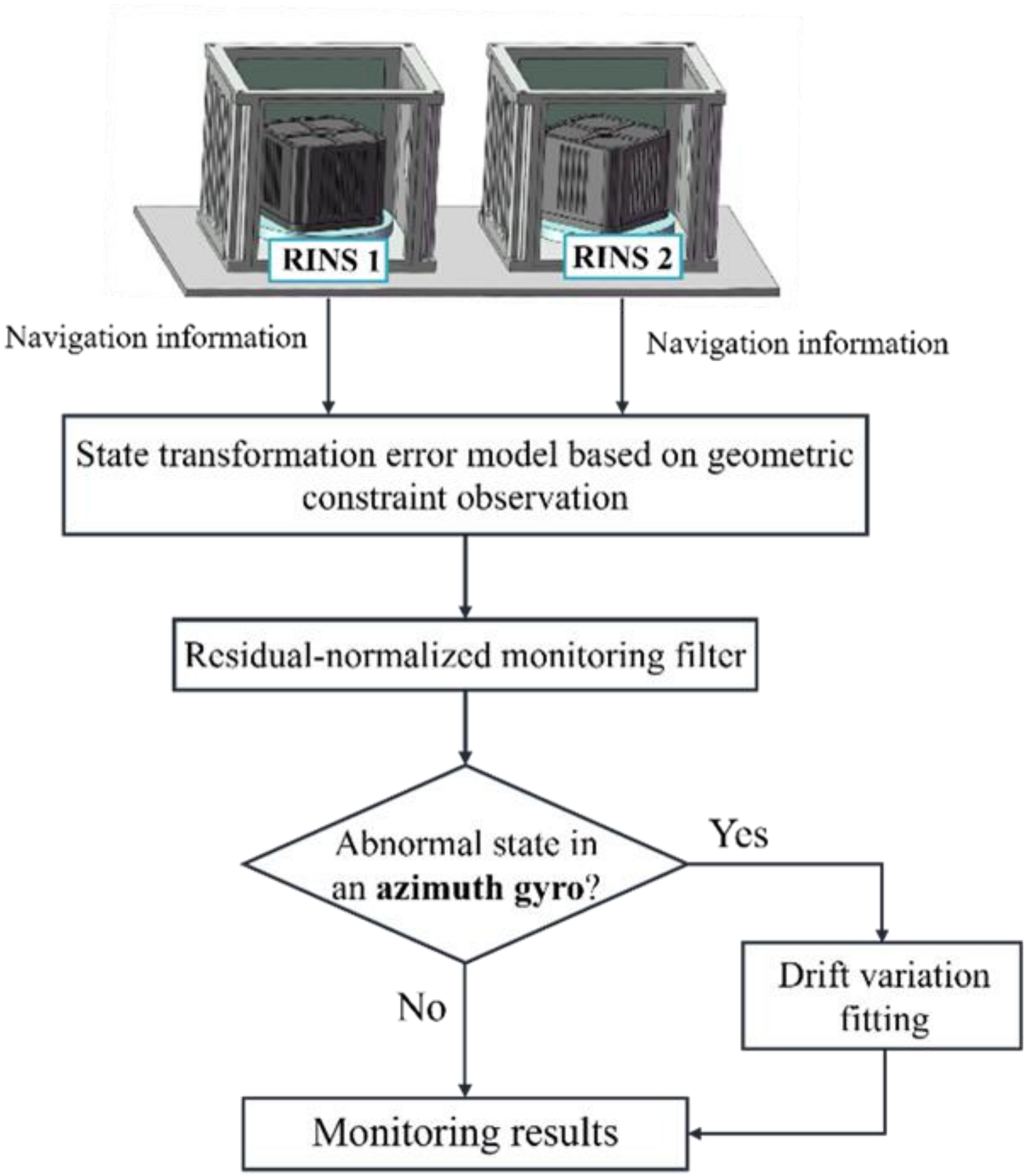

Network Time Synchronization
$[x_R, y_R, z_R]$
LS Algorithm
LS Algorithm
Carrier-phase Signal
ELoS Path
$[x_u, y_u, z_u]$
AoA, AoD
r_{Ru}
r_{su}
Receiver Positioning

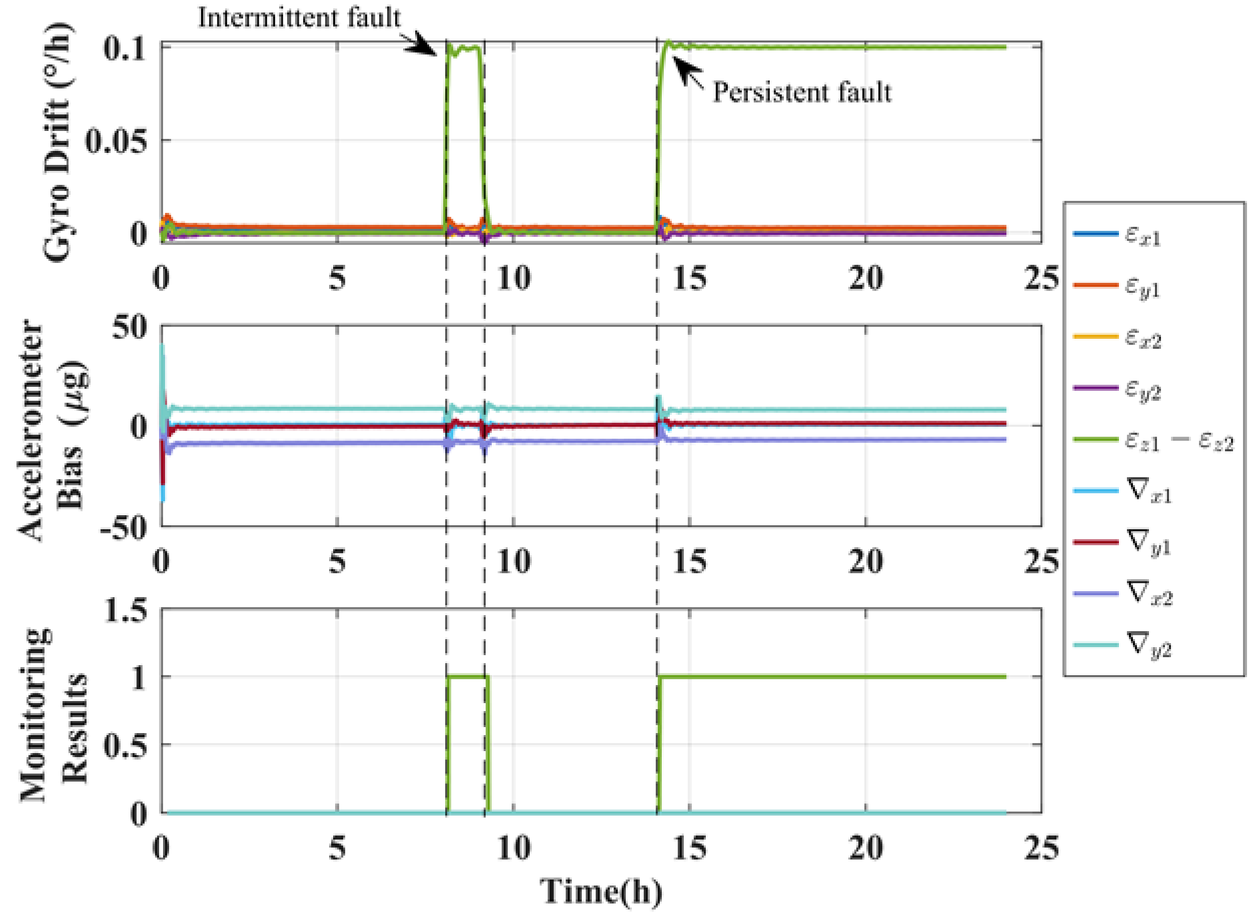
Abnormal performance monitoring algorithm for dual single-axis RINSs redundant system in the reference information absence

Wang Y[1,2], Liao Z[1,2], Liang Z[1,2], Tian M[1,2], Wang L[1,2]
[1]College of Advanced Interdisciplinary Studies, National University of Defense Technology, [2]Nanhu Laser Laboratory, National University of Defense Technology

Biography:
Lin Wang received a Ph.D. degree in control science and engineering from the National University of Defense Technology, Changsha, China, in 2018. He is currently an Associate Research Fellow at the College of Advanced Interdisciplinary Studies, National University of Defense Technology. His research interests include inertial technology, integrated navigation technology, and laser intelligent sensing.

Rotational Inertial Navigation Systems (RINSs) have gained widespread use in various fields due to their ability to overcome the error accumulation issue in traditional Inertial Navigation Systems (INSs). Currently, large ships commonly adopt a redundant configuration of two single-axis RINSs to ensure the reliability and stability. In the absence of external reference information, e.g., in GNSS-denied environment, relying solely on the information provided by these two RINSs for performance monitoring has become a crucial measure to accurately control system status and ensure navigation safety.
To effectively monitor the dual single-axis RINSs redundant system, a novel abnormal performance monitoring algorithm that integrates adaptive filtering with parameter estimation is proposed. Using relative attitude observations from the turntable's optical encoders and relative velocity and position information between two RINSs, state transformation error model founded on geometric constraint observation is established, which avoids the inaccurate calculation in the system matrix. Furthermore, the adaptive residual-normalized monitoring filter based on the error model greatly increases the sensitivity to potential abnormal performance. However, it is insufficient to monitor the abnormal performance in azimuth gyros due to the non-separable estimation of azimuth gyro drifts. Therefore, a novel drift variation fitting mechanism is further proposed to address this challenge. Experiments are conducted with two single-axis RINSs. In these cases, abnormal performance is artificially introduced into the raw data, categorized into intermittent and persistent faults. At this point, the faults have been correctly and promptly detected. To quantitatively analyze the average fault monitoring time, all sensors are grouped into three distinct categories: horizontal gyros, horizontal accelerometers, and azimuth gyros. The corresponding average fault monitoring time has been optimized by 66.57%, 57.94%, and 68.03% compared with our previous research. The experimental results prove that the proposed method can achieve real-time performance monitoring of dual single-axis RINSs.


RINS 1
RINS 2
Navigation information
Navigation information
State transformation error model based on geometric constraint observation
Residual-normalized monitoring filter
Abnormal state in an **azimuth gyro**?
Yes
No
Drift variation fitting
Monitoring results



Intermittent fault
Persistent fault
Gyro Drift (°/h)
0.1
0.05
0
0
5
10
15
20
25
Accelerometer Bias (μg)
50
0
-50
Monitoring Results
1.5
1
0.5
Time(h)
ε_{x1}
ε_{y1}
ε_{x2}
ε_{y2}
$\varepsilon_{z1} - \varepsilon_{z2}$
∇_{x1}
∇_{y1}
∇_{x2}
∇_{y2}

Galileo HAS Receiver for Precise Orbit Determination for LEO and low MEO

Pintor P[1], Lalgudi Gopalakrishnan G[1], Braun B[2], Kunzi F[2], Markgraf M[2], Schmidt M[2]
[1]Spaceopal Gmbh, [2]DLR

Biography:
Pedro Pintor is a GNSS engineer with over 18 years of experience in the space and satellite navigation industry. He holds an M.Sc. in Space Science from Chalmers University of Technology in Gothenburg and an M.Sc. in Electrical Engineering from Universidad Europea in Madrid. Since 2018, Pedro has been part of Spaceopal, where he served as the technical manager for several Galileo HAS projects. Before joining Spaceopal, Pedro worked for the European Space Agency's (ESA), he served as a GNSS consultant for Spain's Air Navigation Service Provider (ANSP) and at the European Satellite Services Provider (ESSP).

The satellite sector has seen significant growth and diversification in recent years, driven by advancements in satellite technology, miniaturization, and the increasing demand for satellite-based services.
Galileo’s High Accuracy Service (HAS) offers an opportunity to enhance onboard Precise Orbit Determination (POD) and navigation payload design for Low Earth Orbit (LEO) and low Medium Earth Orbit (MEO) satellites. Spaceopal, in collaboration with DLR, is developing a novel Galileo HAS receiver tailored for POD and LEO navigation payloads. This receiver provides precise onboard knowledge of a satellite’s orbit in real-time, enabling mission planners to optimize ground operations and enhance navigation data processing. Additionally, the POD receiver facilitates time synchronization for LEO/ low MEO PNT navigation payloads, further boosting mission capabilities.
The receiver is based on an existing prototype and addresses key challenges, including robust signal processing under the dynamic conditions in earth orbit and handling of multi-frequency, multi-constellation GNSS observables. The hardware design focuses on using commercial-off-the-shelf (COTS) components to minimize costs while maintaining reliability, for example by integrating latch-up protection circuits and redundant memories. This approach ensures an affordable, high-quality solution with a compact size, low weight, and decimeter-level navigation accuracy. By integrating Galileo HAS, the receiver delivers enhanced performance without incurring additional costs for premium accuracy services. An optional chip-scale atomic clock supports highly accurate time synchronization with GNSS, crucial for generating navigation signals in LEO/ low MEO PNT payloads.
Testing is executed across diverse operational scenarios including functional, performance and mechanical and environmental.
The Galileo HAS receiver development for POD and LEO/ low MEO navigation payloads represents an advancement in satellite navigation technology, addressing modern mission demands with cost-effective, high-precision solutions.


Microsemi
CSAC
SA.45s

Assessing the quality of products and latest performance of Galileo HAS using real-time data

Savchuk S[1], Cwiklak J[1], Kerker V[2], Miduch P[1]
[1]Polish Air Force University, [2]Lviv Polytechnic National University

Biography:
M.Eng. Piotr Miduch – Lecturer in the Department of Navigation and Air Traffic Management at the Polish Air Force University. Currently, I teach classes on satellite systems in navigation, satellite technology and space flight. My interests include aviation, navigation, astronomy and heliophysics.

The Galileo High Accuracy Service (HAS) provides free of charge access, through the Galileo signal (E6-B) and by terrestrial means (Internet), to the information required to estimate an accurate positioning solution using a PPP (Precise Point Positioning) algorithm in real-time. HAS supports both Galileo and GPS constellations across multiple frequencies, including Galileo's E1, E5a, E5b, and E6, as well as GPS's L1 and L5 signals. As of early 2025, HAS provides SSR orbit and clock corrections, as well as clock biases. These corrections allow users to reach decimeter-level positioning (20cm horizontal; 40cm vertical) with convergence time of less than 300 seconds, according to Galileo HAS ICD (Internal Control Document). The main aim of this paper is to compare products, provided by HAS with other analysis centers verify the declared accuracy. Experiment consisted of several steps. Firstly, the real-time HAS data was collected over 3 weeks using Septentrio Mosaic X5 GNSS receiver with high-precision antenna, mounted on the roof of the building. The second step consisted of verifying the integrity of dataset and comparing it with CODE (Center for Orbit Determination in Europe) ultra-rapid products. During the third step, the performance of HAS-aided PPP solution was assessed under different circumstances and using different data processing strategies. By systematically collecting and analyzing real-time data, verifying integrity, and assessing PPP solutions under various scenarios, this work aims to evaluate the reliability and potential of HAS for high-accuracy positioning applications, particularly in the context of aviation.

DIANA-S: A Synthetic UAV Dataset for Maritime Object Detection in Nordic Waters

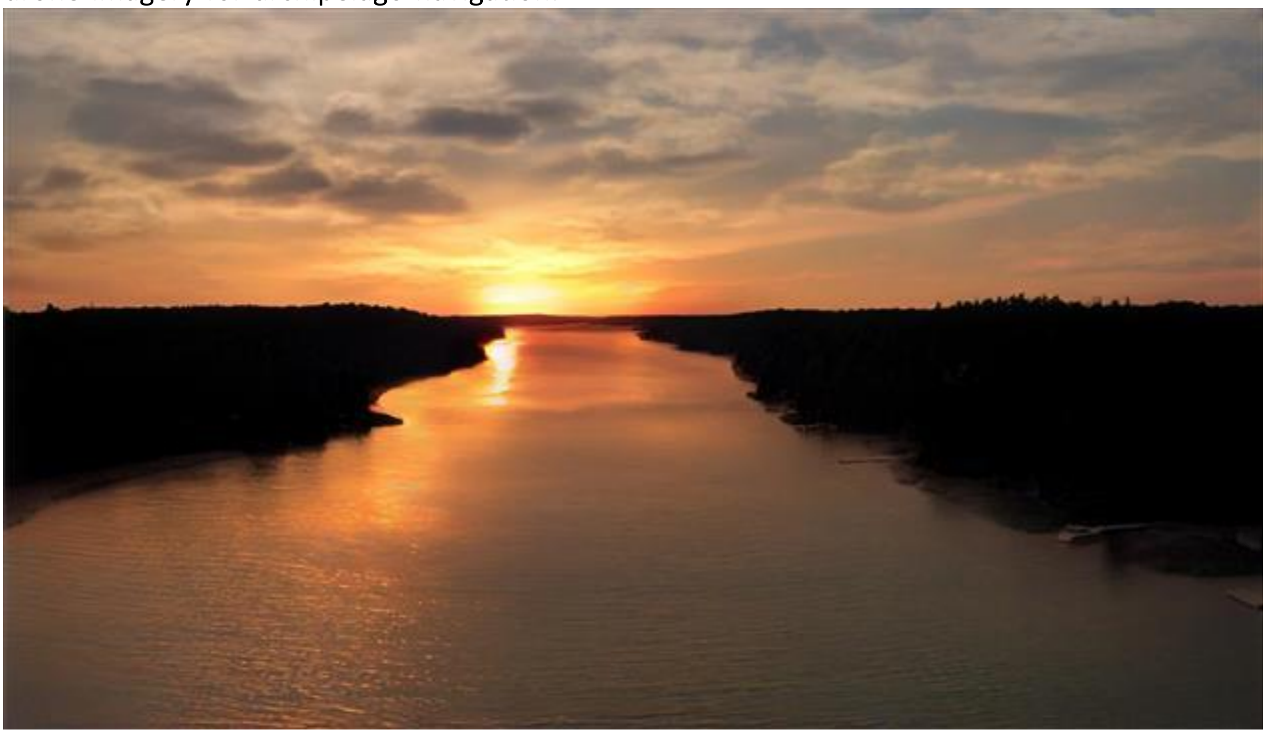
Majd A[1], Asadi M, Kalliovaara J, Jokela T
[1]Turku University Of Applied Sciences

Biography:
Amin Majd is currently a Head of AI and Autonomous Systems at Turku University of Applied Sciences on autonomous vehicles (Ships) with a broad background in computer science. He joined the University of Turku as a PhD student in 2015, and he got his first PhD in 2019. The second PhD has gotten in 2021 from Åbo Akademi University. He is professional in solving high-dimensional complex problems by applying meta-heuristic optimization methods, machine learning, deep learning, and parallel computing on the problems.

The integration of unmanned aerial vehicles (UAVs) into maritime operations, such as debris detection, vessel monitoring, and marine life tracking, is crucial for advancing autonomous navigation. However, the effectiveness of UAV-based object detection is hindered by the limited scale, diversity, and relevance of existing maritime datasets. To address this challenge, we introduce DIANA-S (Synthetic Drone Imagery for Archipelago Navigation and Analysis), the first synthetic UAV dataset collected in the Nordic region. S-DIANA comprises 3,551 high-resolution images with 72,534 annotated objects, spanning diverse maritime environments and object sizes, from small buoys to large vessels.

Our study investigates three key aspects: (i) the impact of data augmentation techniques and a sliding window function on small object detection, leading to an increase in AP from 34.4% to 37.8% in DiffusionDet with GAN-based augmentation; (ii) a benchmark of state-of-the-art object detection models, including CNN-based and transformer-based architectures, evaluating their performance across different object scales; and (iii) key findings demonstrating that transformer-based models, such as DINO and DiffusionDet, excel in detecting small objects.

The dataset and code are publicly available at: https://www.kaggle.com/datasets/aminmajd/diana-drone-imagery-for-archipelago-navigation.



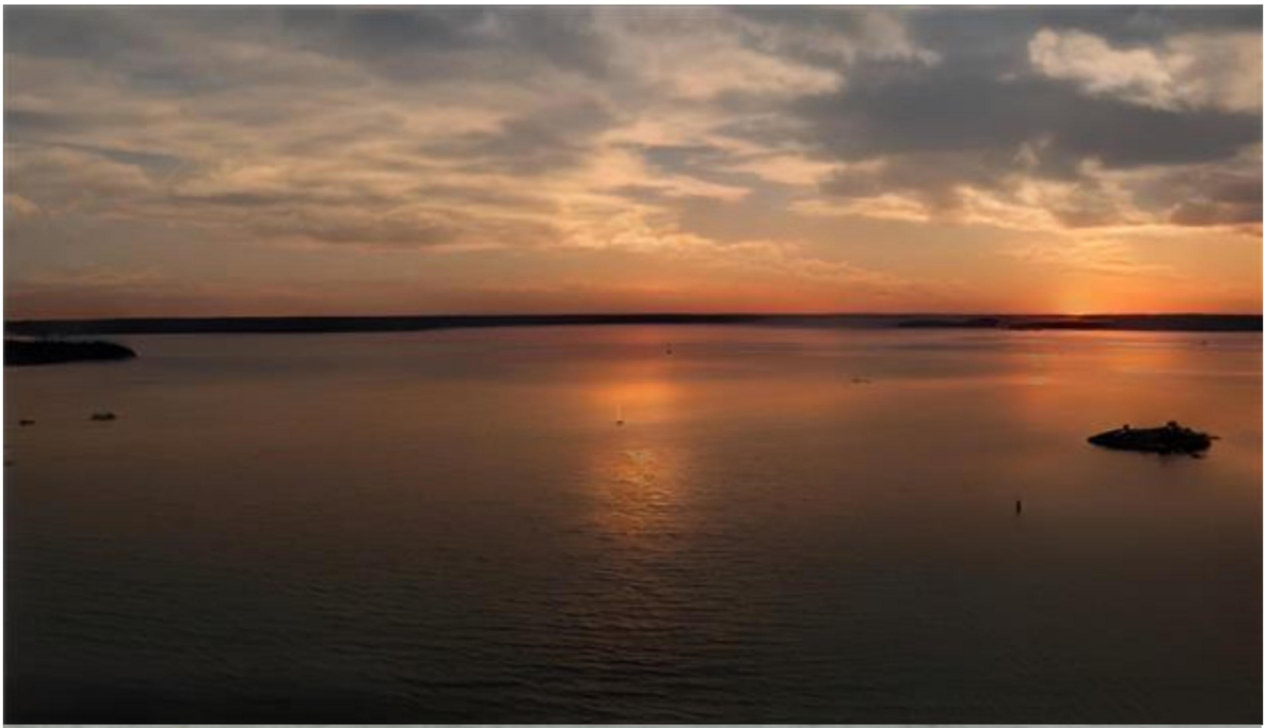


TABLE V: Summary of training hyperparameters for different object detection models.

Model	lr	lr Scheduler	Momentum	# Epochs	Optimizer	Batch Size
Yolov8n [22]	0.01	MultiStepLR	0.937	200	SGD	16
Cascade Rcnn [23]	0.02	LinearLR	0.9	200	SGD	4
DiffusionDet [25]	0.0002	MultiStepLR	-	200	AdamW	3
Deformable Detr [26]	0.000025	MultiStepLR	-	200	AdamW	3
DINO [24]	0.0001	MultiStepLR	-	200	AdamW	2

TABLE VI: Benchmark on different object detection models without using augmented data (IoU=0.50).

Paper	Without SAHI				SAHI [27]			
	Small	Medium	Large	mAP	Small	Medium	Large	mAP
Yolov8 [22]	0.020	0.506	0.265	0.303	0.023	0.440	0.232	0.272
Cascade Rcnn [23]	0.015	0.117	0.373	0.169	0.056	0.106	0.279	0.140
DiffusionDet [25]	0.310	0.316	0.329	0.271	0.326	0.189	0.281	0.158
Deformable Detr [26]	0.324	0.377	0.302	0.328	0.290	0.358	0.270	0.240
DINO [24]	0.347	0.161	0.315	0.160	0.374	0.158	0.285	0.161

TABLE IV: Reporting the number of parameters and training time for different object detection models.

Model*	# Parameters	Training Time$^{\xi}$
Yolov8 [22]	3.2M	0.56
Cascade-RCNN [23]	69.164M	11.0
DiffusionDet [25]	110M	12.5 for 1000 iter.
Deformable-Detr [26]	40.1M	41.50
DINO [24]	47.548M	26.2

* Data type is torch.float32.

$^{\xi}$ Times are reported in GPU hours on NVIDIA® RTX 4090.

Analysis of the Galileo SAR Return Link Service using the GalileoSARlib open-source library

Galan-Figueras A[1], Fernandez-Hernandez I[1,2], Seco-Granados G[3], Pollin S[1]
[1]KU Leuven, [2]European Commission, [3]Universitat Autonoma de Barcelona

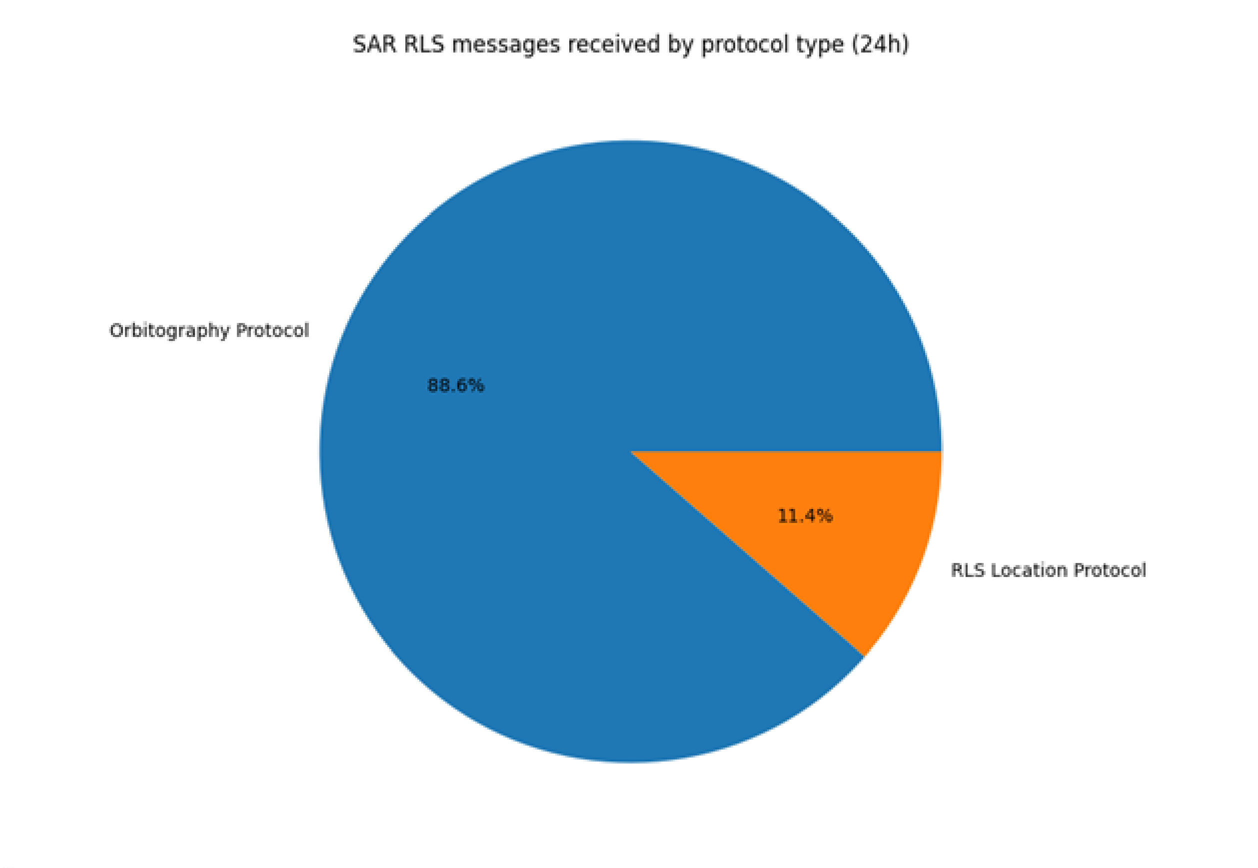
Biography:

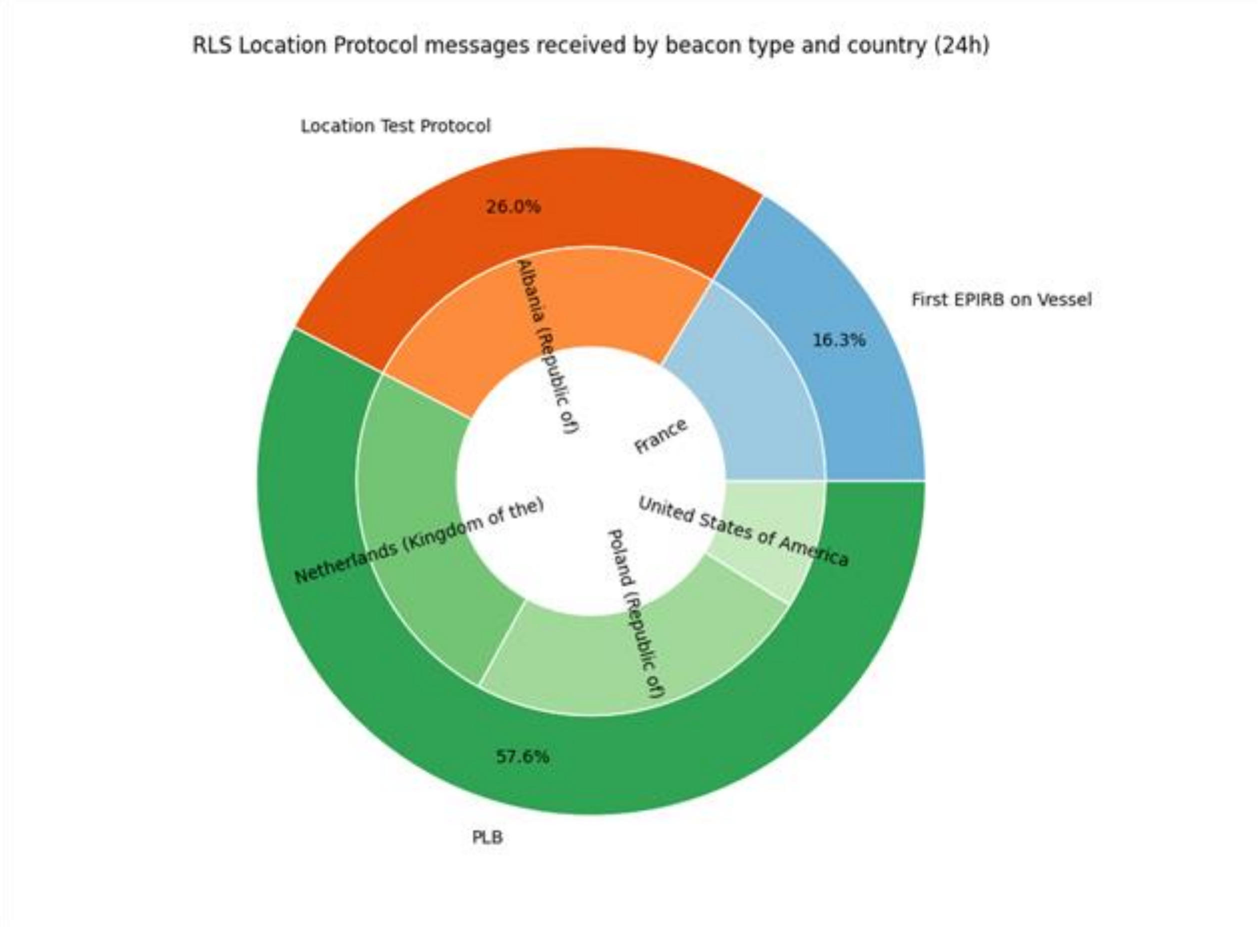
Aleix Galan-Figueras graduated with a BSc in Computer Engineering and a BSc in Telecommunication Systems Engineering from the Universitat Autonoma de Barcelona (Spain) in 2020. He graduated with a MSc in Cybersecurity from the Universitat Politècnica de Catalunya (Spain) in 2022. In 2023, he was awarded a PhD fellowship and has since been pursuing a PhD on GNSS security and resilience at KU Leuven, Belgium. In this presentation, he will analyze the Galileo search and rescue return link service using more than 3 months of real data and a newly developed open-source library.

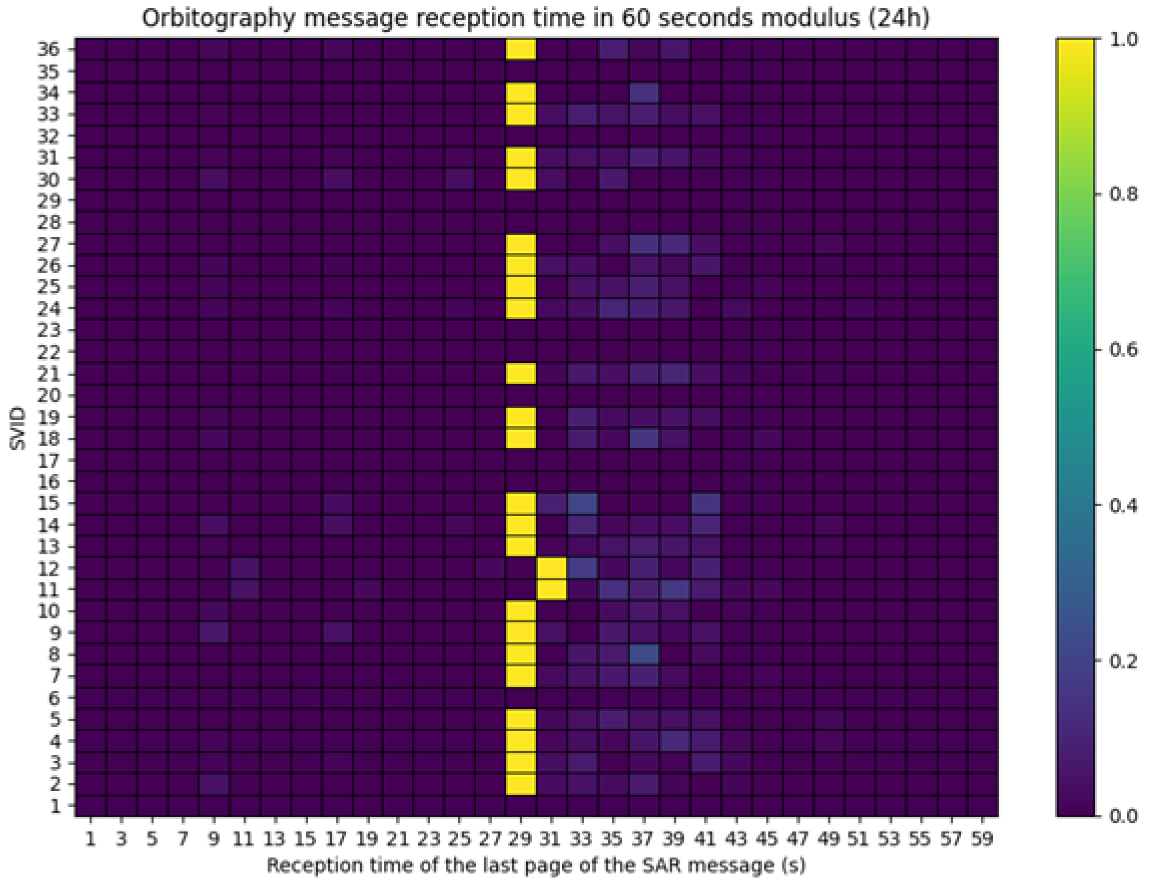
The Galileo Search and Rescue (SAR) service is the contribution from the European constellation to the international Cospas-Sarsat system. This system uses a variety of space and ground infrastructure to detect and localize distress signals from beacons on the 406MHz frequency. Satellites in different orbits detect the signals coming from the Earth and transmit them back to Earth stations that route them to the appropriate government authorities.

On top of the standard detection and rely service, the Galileo constellation is the first to offer a Return Link Service (RLS) that acknowledges the processing of the distress signal with a return link message (RLM) back to the originating beacon. This RLM is transmitted in the SAR field of the E1 signal I/NAV message, which allocates 20 bits every 2-second page. Therefore, transmitting a short RLM (80 bits) takes four consecutive pages or eight seconds. Moreover, each RLM is transmitted in parallel from two Galileo satellites. The RLS has been active since 2020, avoiding the spotlight of the GNSS community.

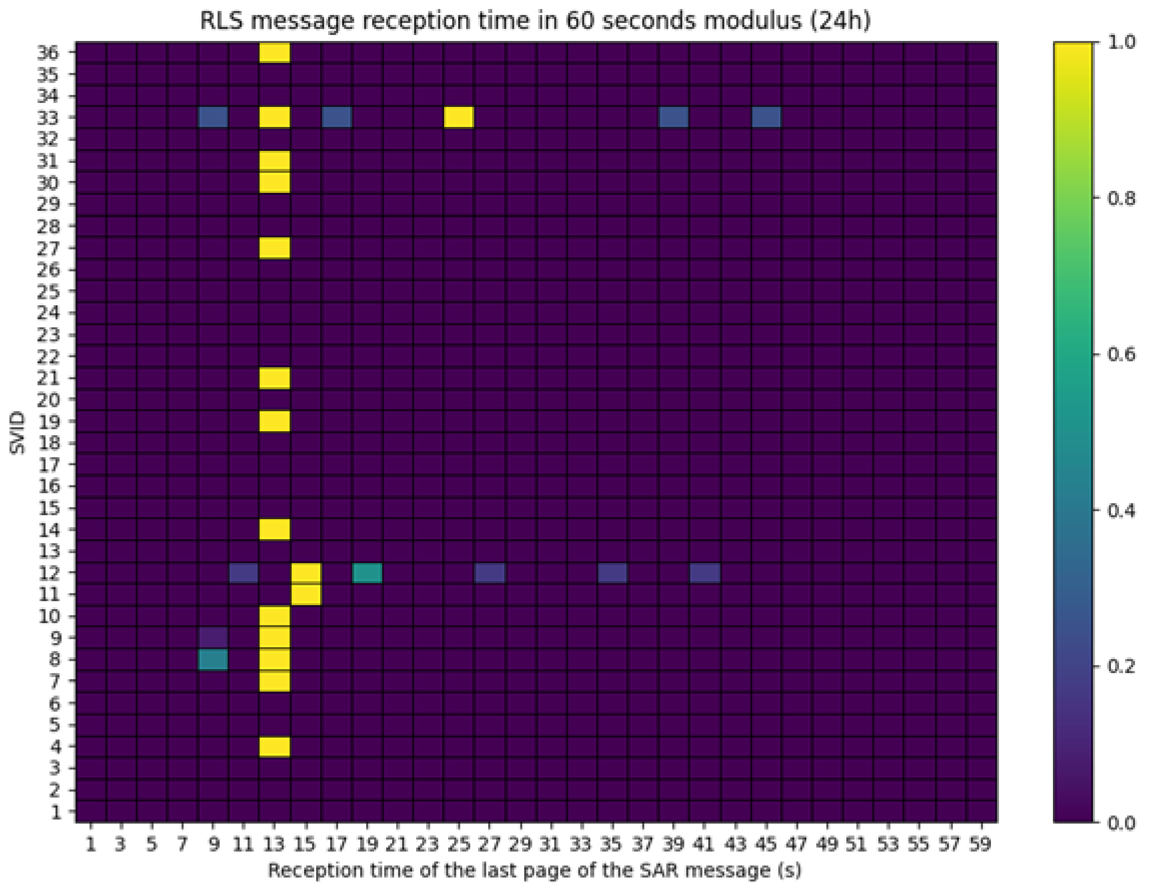
This paper presents an analysis of the SAR return link messages extracted from more than 3 months of signal-in-space data to investigate the current bandwidth use, detect anomalies in the service, and briefly propose authentication ideas for the messages. To extract and parse the return link messages, we have developed and published an open-source Python library called GalileoSARlib on GitHub, which is also detailed in the paper. Initial sample results are shown in the attached figures.


SAR RLS messages received by protocol type (24h)
Orbitography Protocol
88.6%
11.4%
RLS Location Protocol

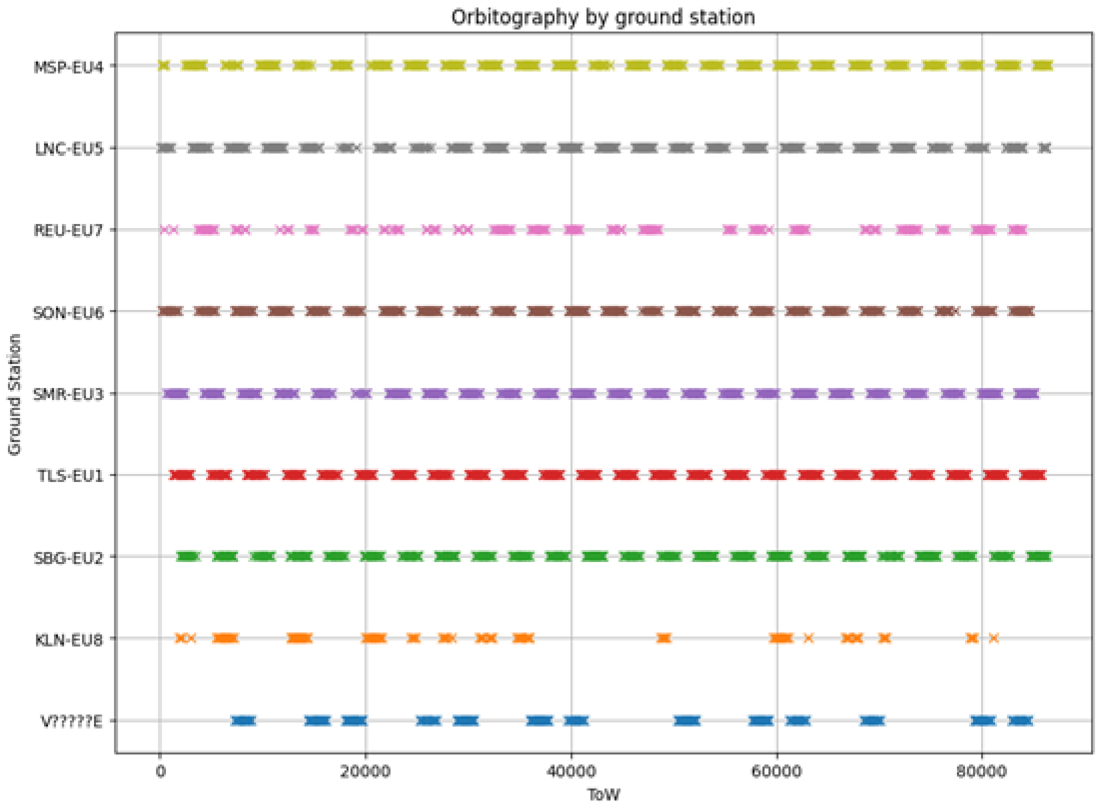

RLS Location Protocol messages received by beacon type and country (24h)
Location Test Protocol
26.0%
First EPIRB on Vessel
16.3%
Albania (Republic of)
France
Netherlands (Kingdom of the)
United States of America
Poland (Republic of)
57.6%
PLB



Caption: All satellites send the messages for the Orbitography protocol on the second 29 but SVID 11 and 12, which are also the oldest satellites



Caption: All satellites send the messages for the RLS protocol on the second 13 but SVID 11 and 12, which are also the oldest satellites


Orbitography by ground station
MSP-EU4
LNC-EU5
REU-EU7
SON-EU6
SMR-EU3
TLS-EU1
SBG-EU2
KLN-EU8
V?????E
Ground Station
0
20000
40000
60000
80000
ToW

Inter-Satellite Links in Galileo Second Generation: Strategies and Challenges

Kur T[1], Sośnica K[1], Kalarus M[2]
[1]Wrocław University of Environmental and Life Sciences (UPWr), [2]Astronomical Institute, University of Bern

Biography:
Tomasz Kur received his Ph.D. in Earth and Environmental Sciences in 2022. His primary research focus is on simulating advanced technologies aimed at enhancing orbit and clock determination. This includes inter-satellite links and future missions such as Genesis.

The upcoming generation of European Galileo satellites will feature inter-satellite links (ISL) to improve orbit determination, communication, and data exchange capabilities. Nonetheless, several challenges persist, especially in data acquisition, scheduling, and processing. These include strategies for parameter estimation and approaches for relative weighting of GNSS and ISL data for orbit determination purposes.

This study offers an in-depth evaluation of the role of ISL in determining the orbits of Galileo satellites. Through a simulation environment, we investigate estimation properties. Furthermore, we assess the potential impact of ISL range biases on the orbit results and compare their estimation with the on-ground calibration of ISL hardware. The analysis considers weighting strategies for GNSS and ISL measurements to enhance performance across both globally and regionally distributed ground station networks. Different ISL connectivity schemes are tested, and the number of GNSS observations is adjusted to identify the most effective setup.

A simulation study indicates that selecting an optimal ISL connectivity scheme can minimize orbit errors. The precision of ISL in orbit determination might be critically influenced by the accuracy of ISL range biases determination that varies according to the chosen ISL connectivity scheme. The on-ground calibration can be replaced with ISL range bias estimation. This study underscores the impact of ISL on orbit accuracy, demonstrating an enhancement of up to 50% in three-dimensional orbit error. Additionally, it reveals an improvement of up to 30% in clock determination for satellite clocks with ISL contribution. These findings offer valuable insights for developing the next generation of GNSS.

Performance Evaluation of GNSS Message Structures: Insights for Future Design

Noh J[1], Choi J[1], Ahn J[2]
[1]Korea Aerospace Research Institute, [2]Chungnam National University

Biography:

JaeHee Noh recently works a senior researcher at KARI(Korea Aerospace Research Institute). Her research interests include designing the satellite navigation signal and message, anti-spoofing techniques, GNSS receiver, and navigation message authentication.

As a fundamental component of GNSS signals, messages act as a critical medium for transmitting information required for PNT, serving the needs of both service providers and users. Over the years, message structures for GNSS signals have evolved from fixed formats to pseudo-packetized and mixed formats. This evolution has facilitated the integration of supplementary data and has driven further research to incorporate new types of information. These developments have highlighted the necessity of flexible and transmission-efficient message structures. In this paper, we propose a set of performance metrics designed for the comprehensive evaluation of GNSS message structures. Using these metrics, we analyze the performance of existing message formats. From the results, it is observed that optimizing message formats based on the purpose and characteristics of the transmitted information could achieve flexibility and transmission-efficient. Based on these findings, we propose a novel approach to designing message structures that address future requirements.

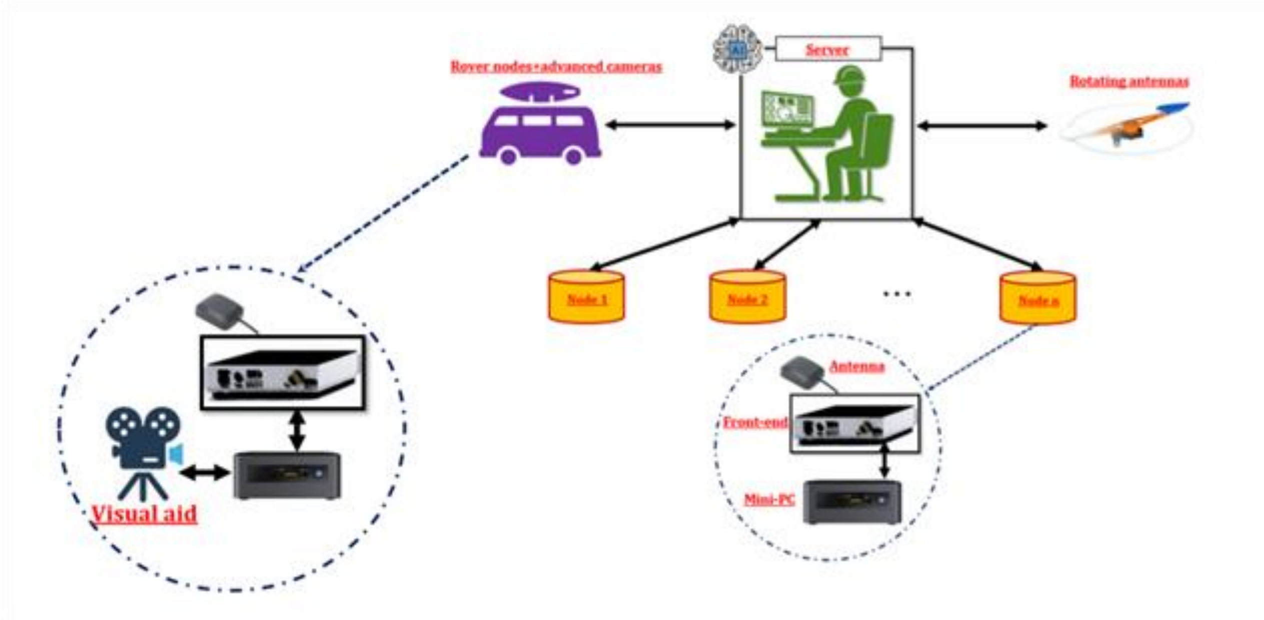
Message Design Parameter	Performance Indicators							
	Accuracy	Timeliness		Flexibility		Robustness	Capacity	
	RET	TTFFD	T_{GST}	$Latency_{new\_message}$	$Margin_{Sbit}$	Data Demodulation Threshold	EBR	Efficiency Factor
Length of minimum information unit	✔	✔			✔		✔	✔
Length of minimum transmission unit	✔	✔	✔	✔	✔	✔		✔
Length of Len_{SX}	✔	✔			✔		✔	✔
Data Rate		✔	✔	✔	✔	✔	✔	✔
Length of Master(Super) Frame					✔			
Length of CED	✔	✔	✔					
Minimum broadcast interval of CED	✔	✔	✔	✔	✔			
Error Detection		✔				✔		
Forward Error Correction		✔				✔		

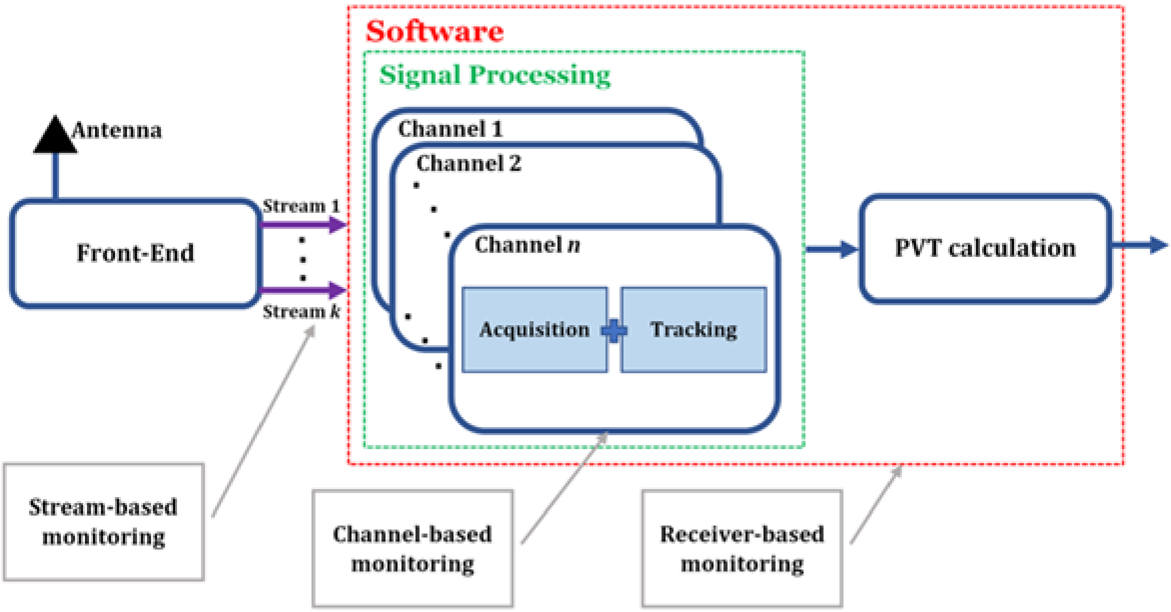
AI-Driven Detection and Localization of GNSS Interference: A Comprehensive Approach Using Portable Sensors

Keshmiri Esfandabadi Y[1], Tabatabaei A[1], Hein R[1], Hein G[1]
[1]Igaspin Gmbh

Biography:
Yasamin Keshmiri Esfandabadi earned her B.S. in Electronics Engineering and M.S. in Mechatronics Engineering from the University of Qazvin, Iran. She completed her Ph.D. and postdoctoral research in Electronic Engineering at the University of Bologna, Italy. Her expertise spans signal processing for guided wave-based nondestructive testing, structural health monitoring, compressive sensing, and wavefield imaging. Currently, she is a Electronic Engineer at IGASPIN in Graz, Austria, working on advanced satellite navigation and positioning systems, leveraging her extensive knowledge in signal processing and engineering innovations.

The increasing interest in the development and integration of navigation and positioning services across a wide range of receivers has exposed them to various security threats, including Global Navigation Satellite System (GNSS) jamming and spoofing attacks. Early detection of jamming and spoofing interference is crucial to mitigating these threats and preventing service degradation.
This research introduces an interference detection technique leveraging an artificial intelligence (AI) algorithm applied to GNSS data utilizing various methods to enhance detection accuracy and efficiency. The objective was to develop an effective tool for detecting, characterizing, and localizing interference, thereby reducing associated risks, using modern portable sensors and AI. These sensors and algorithms enable continuous GNSS interference monitoring and support real-time decision-making and interference mitigation.
A server plays a crucial role in managing the entire system. Its primary function is to process data collected from all kinds of sensors called nodes (e.g. static nodes, rover nodes or rotating antennas) or (public) networks. The detection algorithms are grouped into three categories: stream-based, receiver-based, and channel-based methods. Within the interference detection module, various methods were implemented at different points in the receiver S/W architecture. Each method's effectiveness in identifying an interference source depends on its design and capabilities, with outcomes - whether positive or negative - being subject to potential accuracy or errors. To enhance the decision-making process, an AI-based decision-making block has been introduced to determine the presence of interference at a given epoch. The proposed interference monitoring methods were evaluated through experiments using GPS and Galileo signals under clean, jamming, and spoofing scenarios. The results demonstrate the techniques' applicability across diverse scenarios, achieving high performance in interference detection and localization, with an accuracy of 94% based on AI-analyzed data.


Server
Rover nodes+advanced cameras
Rotating antennas
Node 1
Node 2
...
Node n
Antenna
Front-end
Mini-PC
Visual aid


Software
Signal Processing
Antenna
Front-End
Stream 1
Stream k
Channel 1
Channel 2
Channel n
Acquisition
Tracking
PVT calculation
Stream-based monitoring
Channel-based monitoring
Receiver-based monitoring

Towards Safe Localisation for Railways: Results from the EGNSS MATE Project

Wenz A[1], Roth M[2], Silviera Mendes P[3], Ehrler R[1], Bomonti A[1], Dütsch N[3], Parra C[3], Dorins T[3], Martin A[3], Heusel J[2], Kiyanfar K[2]
[1]Swiss Federal Railways (SBB), [2]German Aerospace Center (DLR), Institute of Transportation Systems, [3]Industrieanlagen-Betriebsgesellschaft (IABG)

Biography:
Andreas Wenz heads the Center of Competence for Localization at SBB. He has been working at SBB since 2020. His work focuses on the development of new sensor fusion algorithms for train localisation systems as well as the standardisation of these systems. He currently leads the ESA co-funded EGNSS MATE project and is involved in the EU-Rail R2Dato project. Before his time at SBB, Andreas worked as a researcher at the Norwegian University of Science and Technology, receiving his Ph.D. in Engineering Cybernetics in 2018.

The EGNSS MATE project partners SBB, DLR and IABG have researched map-supported GNSS and multi-sensor localization for rail vehicles within the ERTMS context. The paper summarizes the main achievements of the project.
Within the project the Galileo High-Accuracy-Service (HAS) and the Open Service – Navigation Message Authentication (OS-NMA) were evaluated for their usage in rail applications. It was found out that there is a small improvement in terms of position accuracy performance by applying HAS correction data on GNSS measurements. Additionally, the OS-NMA detection capability under a live-spoofing event was demonstrated, showing that this service could deliver a real benefit for safe and secure rail applications.
Algorithmic advances of the project include the development and implementation of a Kalman filter bank algorithm with several path hypotheses that continuously represent all likely paths that the vehicle is on. For each path hypothesis a Kalman filter is used to incorporate the available sensor data. Furthermore, the Kalman filter performance is monitored over a sliding time interval which facilitates the identification of the driven path or reveals intermediate situations in which the path cannot be resolved based on the sensor data.
The development has been validated using measurement data collected on a rail vehicle over a period of one year. A large test data set was collected, covering most of the Swiss normal gauge network. To validate the results of the algorithm a ground truth process was established which checks several data sources for consistency. We have established an automated simulation and testing pipeline which runs the localization algorithm in a simulated environment. By comparing the results against the ground truth and checking a series of tests criteria the performance of the algorithm was assessed.
Results show that the developed algorithm provides fulfils the requirements on most of the Swiss normal gauge network.

Alternative Navigation Approaches for Railways: Overcoming GNSS Limitations

Steiner J[1], Pech T[2]
[1]Gnss Centre Of Excellence, [2]Chemnitz University of Technology

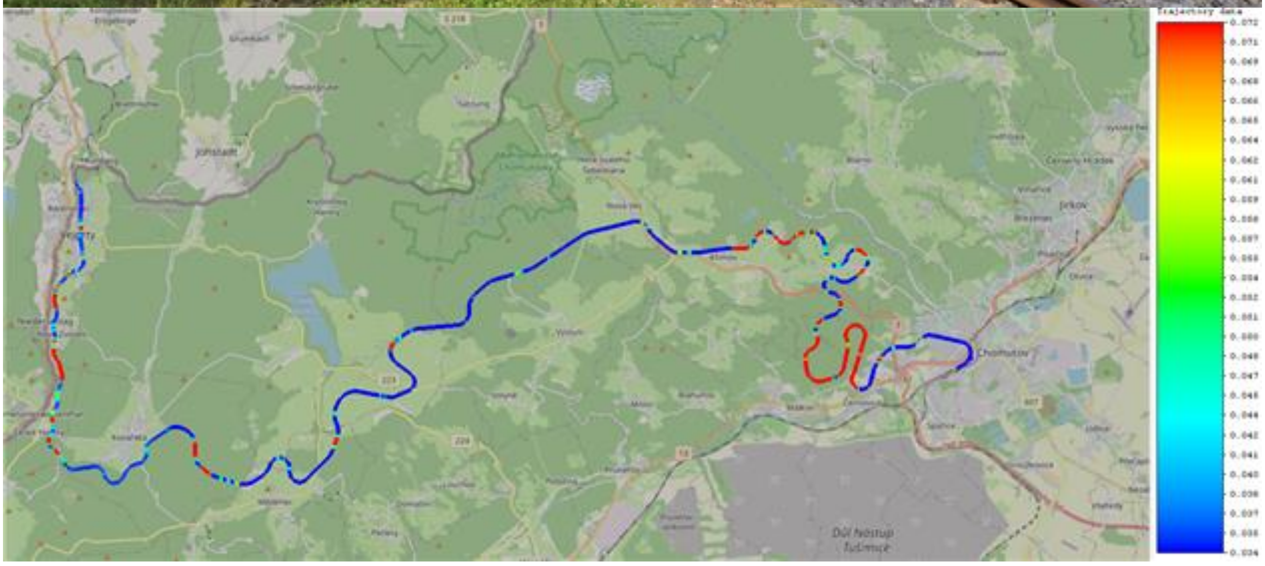
Biography:
Mr Jakub Steiner,
Working as a GNSS Specialist at the GNSS Centre of Excellence, Czech Republic. He is also working on his PhD at the Czech Technical University. His research focuses on GNSS interference, navigation performance testing, and navigation system development. The subject of this research was the feasibility of Alternative PNT solutions for rail transportation.

The field of rail localisation and navigation has traditionally relied on infrastructure-based systems utilising balises, track circuits, and fixed reference points to ensure safety and operational efficiency. While these methods have proven reliable, their implementation and maintenance require substantial financial investment, particularly in rural or remote areas where such upgrades may not be economically feasible. As the demand for cost-effective and scalable solutions grows, there is a need to explore alternative positioning, navigation, and timing (A-PNT) methods that are not infrastructure-based.

The study presents a case study of the rural rail track between Vejprty and Chomutov in the Czech Republic where GNSS-only navigation measurement was performed. The measurement vehicle is showcased in Figure 1. The vehicle included a reference receiver and a mass-market "regular" receiver, apart from other technology. The study includes an analysis of the navigation performance metrics and discusses the limitations of rail navigation using only GNSS in such rural areas. As a preview, Figure 2 displays areas with no GNSS reception in red and high position errors in orange and green. These challenges highlight the necessity of developing robust navigation solutions capable of operating independently of both GNSS and traditional infrastructure.

As a follow-up, this study investigates the potential for existing A-PNT solutions in rail transport. Providing an overview of potential A-PNT methodologies for rail applications, considering emerging technologies such as sensor fusion, onboard inertial navigation systems, and map-matching techniques. Each approach is analysed in terms of feasibility, scalability, and operational reliability under rural conditions.

The findings presented in this paper contribute to the broader understanding of how rail navigation can evolve beyond current limitations, paving the way for more sustainable and versatile transportation networks across Europe and beyond.


Chomutov
Důl Nástup
Tušimice

Estimation of gravity gradients using deep learning for efficient positioning with a quantum sensor

Chadwick D[1], Wright M[1], Mckay K[1], Maclean G[2], Ralph J[1]
[1]University Of Liverpool, [2]Raytheon UK

Biography:
Daniel Chadwick is a PhD student in the Department of Electrical Engineering and Electronics at the University of Liverpool, sponsored by Raytheon UK. His research focuses on parallel processing, machine learning, and data fusion techniques for inertial navigation systems.

Quantum cold atom interferometers can be used to measure inertial quantities. They provide the ability to measure gravitational accelerations and gravity gradients with unparalleled accuracy. With a suitable gravity database, a moving platform can derive its position by matching a sequence of gravity measurements against the map. This has been demonstrated using classical gravimeters [1,2], and methods for gravity gradient map-matching have been developed specifically for cold atom interferometers using particle filters to combine position data with an inertial navigation solution [3]. The main computational barrier encountered with particle filters for this application is the calculation of the gravity gradient values, each of which requires a surface integral calculation over an area surrounding the point of interest [4].

In this paper, we present a deep learning approach to derive the gravity gradient distribution. Related machine learning approaches have been used for modelling gravity directly [5] and to improve estimates of environmental quantities using gravity maps [6]. Here, we integrate deep learning with the map-matching method described in [3] to show its utility for navigation applications. We estimate the accuracy of deep learning by comparing to the full gravity gradient calculation, and we demonstrate the approach for the full positioning system using a simulated inertial navigation system and an example quantum sensor model.

[1] H.Wang, et al, IET Radar Sonar and Navigation 10, 862(2016).
[2] H.Wang, et al, Sensors 17, Paper 1851(2017).
[3] Phillips,Alexander M., et al., AVS Quantum Science 4, no. 2(2022).
[4] Hofmann-Wellenhof,Bernhard, and Moritz,Helmut. Physical geodesy. Springer Science & Business Media,2006.
[5] Liu,Yubin, et al., Remote Sensing 16, no. 22(2024): 4173.
[6] Li,Junhui, et al., Frontiers in Marine Science 11(2024): 1520401.

Orthogonal Moment Based 3D Terrain Matching for Lunar Landing

Zhou J[1], Qu G[2], Wang K[1]
[1]Beihang University, [2]Beijing System Design Institute of Electro-mechanic Engineering

Biography:
My name is Zhou Junjie, a Ph.D. candidate at Beihang University (BUAA), specializing in terrain matching algorithms based on invariant moments. My current research focuses on developing robust and efficient algorithms for terrain matching using orthogonal moments, specifically in the context of lunar landing applications. This work involves comparing different moment-based approaches, such as Zernike moments, Orthogonal Fourier-Mellin Moments, and GPCET, with a focus on improving accuracy and robustness under varying conditions.

An orthogonal moment-based 3D terrain matching method for lunar landing is proposed in this paper. Due to the significant topographic variations of the lunar surface, applying traditional 3D terrain matching algorithms presents substantial challenges. To identify the most effective orthogonal moment for lunar terrain matching, classical moments, including the Zernike moment, orthogonal Fourier-Mellin moment (OFMM), and generic polar complex exponential transform (GPCET), are compared using zero-point and spectrum analysis. Additionally, the 3D spectrum of the lunar surface is evaluated under various conditions. By combining the terrain data responses from different orthogonal moments, it is demonstrated that GPCET, with adjustable parameters, can achieve both robust and accurate matching performance. Numerical results are provided to validate these findings.

Prediction of UT1-UTC Using Least-Squares and Singular Spectrum Analysis Model

Hu Y[1], Zheng W[1], Wang Y[1], Li K[1]
[1]College of Aerospace Science and Engineering, National University of Defense Technology

Biography:
Hu Yu received the B.S. degree in Flight Vehicle Design and Manufacturing Engineering from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2021. He is currently working toward the Ph.D. degree in Aerospace Science and Technology with the School of National University of Defense Technology, Changsha, China. His research interests include high accuracy prediction of Earth rotation parameters and autonomous navigation of spacecraft.

High accuracy predictions of theΔUT1 in Earth orientation parameters, the difference between Universal Time (UT1) and Coordinated Universal Time (UTC), are of great significance in satellite autonomous navigation. This research proposes an innovative ΔUT1 prediction method integrating the least-squares (LS) and singular spectrum analysis (SSA). Initially, the ΔUT1 sequence is processed through leap-second removal and correction of Earth zonal harmonic tidal. Next, the LS method is applied to fit and extrapolate the processed ΔUT1 sequence. Then, SSA extracts principle components like long and short period terms from the LS fitting residuals, which are extrapolated using the SSA iterative interpolation algorithm. By adding the LS and SSA extrapolated values, along with subsequent tidal correction and leap-second restoration, high accuracy prediction ΔUT1 are achieved. Compared with the results of the back propagation neural network, Gaussian process, and autoregressive model results using the same ΔUT1 sequences, the LS+SSA method shows higher accuracy, especially in medium and long period terms forecasts. The comparison with International Earth Rotation and Reference Systems Service(IERS) Bulletin A further validates the effectiveness of the LS+SSA model.

Hybrid Navigation for Vega-E Launcher

Emanuele L[1], Odeven D[1], Cruciani I[1], Roux C[1]
[1]AVIO S.p.A.

This paper presents a comprehensive exploration into the implications arising from the shift in the navigation system of VEGA Launch Vehicle family, from its traditional high-class inertial-based navigation to a contemporary hybrid GNSS-inertial system, called VEGA Navigation Equipment (VNE). The focal point of this work lies in investigating the multifaceted impact of this transformation at system level, highlighting strength, weaknesses and potential criticalities. The main result observed is the enhancement in orbit injection accuracy, a factor that crucially contributes to the success of VEGA missions. In fact, although VEGA and VEGA-C inertial navigation unit (Quasar-3000) is of the highest class, the inherent limitations of a purely inertial system still hold true, i.e. unbounded estimation error. The hybridization of Global Navigation Satellite System (GNSS) technology with inertial measurements, through an Extended Kalman Filter (EKF), allows to bound the estimation error in position, velocity and attitude. Furthermore, the synergy between GNSS and IMU measurements allows the usage of a lower class IMU, without degrading the overall estimation quality, thus significantly reducing the recurrent costs of the system. The paper also analyzes the intricate interactions between the navigation system and the vehicle's guidance and control systems, underlining the dependencies and providing a comprehensive evaluation of the impacts, focalizing the attention to the peculiarities of VEGA-E mission. To summarize, the effects on aspects such as estimation accuracy, orbit injection, aerodynamic loads and upper stage combustion time are discussed in this work. The results indicate that, besides a slight loss in first stage attitude estimation accuracy, no significant negative impacts are observed at system level. Indeed, at payload release, an orbital accuracy improvement of two orders of magnitude is obtained, allowing an important propellant saving for orbital corrections maneuvers. The observed results are really promising, willing to be experienced in flight on VEGA-E future launches.

Celestial Navigation in GNSS Denied Environment for Aircrafts and Space Rovers

Loil M[1], Paul B[1], Gorog F[1], Montel J[2], Eychenne L[1], Ponceau D[1]
[1]Sodern, [2]CNES

Biography:
Maxime Loil is a Systems Engineer specializing in star trackers at Sodern, a subsidiary of ArianeGroup. He graduated from École Polytechnique in France and has an expertise in navigation, optronics, and algorithmics. His professional experience includes contributions to the development and improvement of daytime star trackers, which are essential for autonomous navigation systems. The presentation will focus on how star trackers can be hybridized with inertial navigation systems to achieve accurate and resilient positioning, even in GNSS-denied environments.

In order to enable an autonomous navigation capability in environments where Global Navigation Satellite Systems (GNSS) are either denied (e.g. areas with intentional jamming or spoofing) or not available yet (Moon, Mars), Sodern is currently developing star trackers for Earth-based aircrafts and space rovers. This system is designed to compensate for inertial sensors (IMU) induced drifts by providing an absolute attitude reference. The resulting celestial navigation system (CNS) aims at providing a position evaluation with a 100 meters class precision, independent of the mission duration. In this paper, we present the star tracker design with a specific focus on daytime capabilities and the hybridization strategy to implement the retrieved celestial attitude in the CNS. Additionally, we present two application cases currently under development at Sodern, for space rovers and aircrafts. We evaluate the typical performances that can be reached depending on the IMU and star tracker class in harsh environments (luminance, dynamics, radiations…). We conclude with a brief presentation of future developments in this field.

First Test of a Multi-Constellation, Multi-Frequency GNSS Receiver on board a Sounding Rocket

Braun B[1], Markgraf M[1], Rheinwald L[1], Weiß S[2], Hörschgen-Eggers M[2]
[1]GOSC, DLR, [2]MORABA, DLR

Biography:

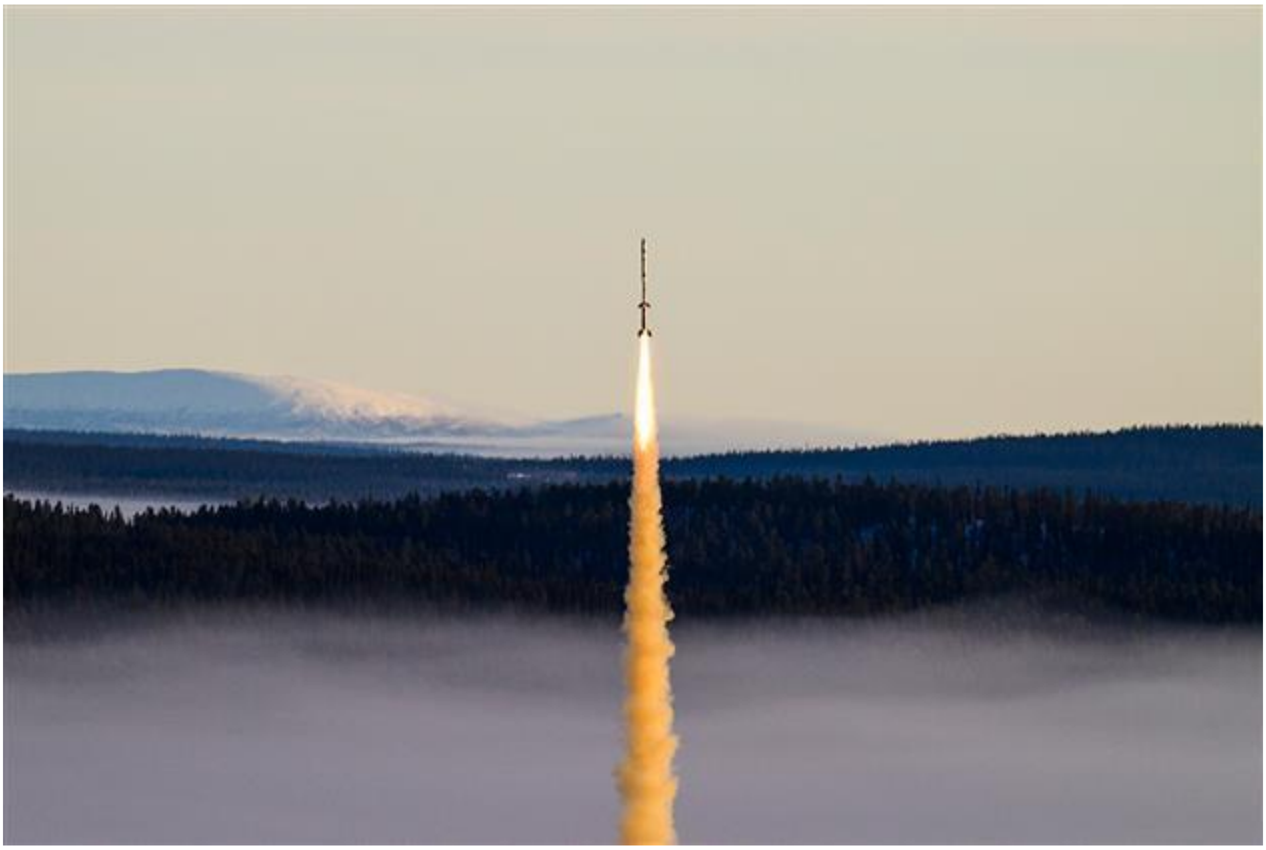
Benjamin Braun has been working at DLR's German Space Operations Center since 2013 and is head of the GNSS Technology and Navigation group. He works on real-time precise orbit determination systems for LEO satellites and hybrid navigation systems for sounding rocket and launch vehicles comprising inertial sensors and GNSS receivers. He received his PhD from the Technische Universität München in 2016 on the topic of "High Performance Kalman Filter Tuning for Integrated Navigation Systems".

DLR's Mobile Rocket Base (MORABA) traditionally uses GNSS to determine the trajectories of their sounding rockets. Accurate trajectories are required, for example, for range safety purposes, flight performance analyses or data fusion with inertial measurements to estimate orientation. Until 2024, MORABA's sounding rocket vehicles were equipped with L1-only GNSS receivers, such as the long-serving DLR developed Phoenix GPS receiver or the NovAtel OEM719 receiver.

Since 2022, the GNSS receivers on board the sounding rockets launched from northern Scandinavia have experienced jamming on the L1 frequency in a way that reliable computation of a navigation solution was impossible above altitudes of around 25 km. This fact motivated the test of GNSS receivers that can also receive other signals in the L-band in addition to L1 from all available navigation satellite constellations.

On 11 November 2024, MORABA launched the MAPHEUS-15 sounding rocket from Esrange, which reached an apogee altitude of 309 km. Additionally to the conventional GNSS receivers, two multi-constellation, multi-frequency GNSS receivers, a Septentrio AsteRx-m3 Pro+ and a Septentrio mosaic-X5, were installed on board. The receivers tracked L1-C/A, L2C and L5 signals from GPS, L1-C/A, L2-C/A and L3 signals from GLONASS, E1, E5a, E5b and E5 signals from Galileo and B1I, B2I, B3I, B1C and B2a signals from BeiDou. To receive signals with frequencies in the range between 1164 and 1610 MHz, new multi-frequency GNSS antennas were developed for nose tip and side mounting.

During the flight, the GNSS receivers tracked the signals from up to 40 satellites simultaneously and were thus able to continuously compute a navigation solution from lift-off until atmospheric reentry and during the landing phase on the parachute, even in the presence of jamming. The flight test showed that the robustness of the navigation solution could be noticeably improved by increasing the number of constellations and signals.



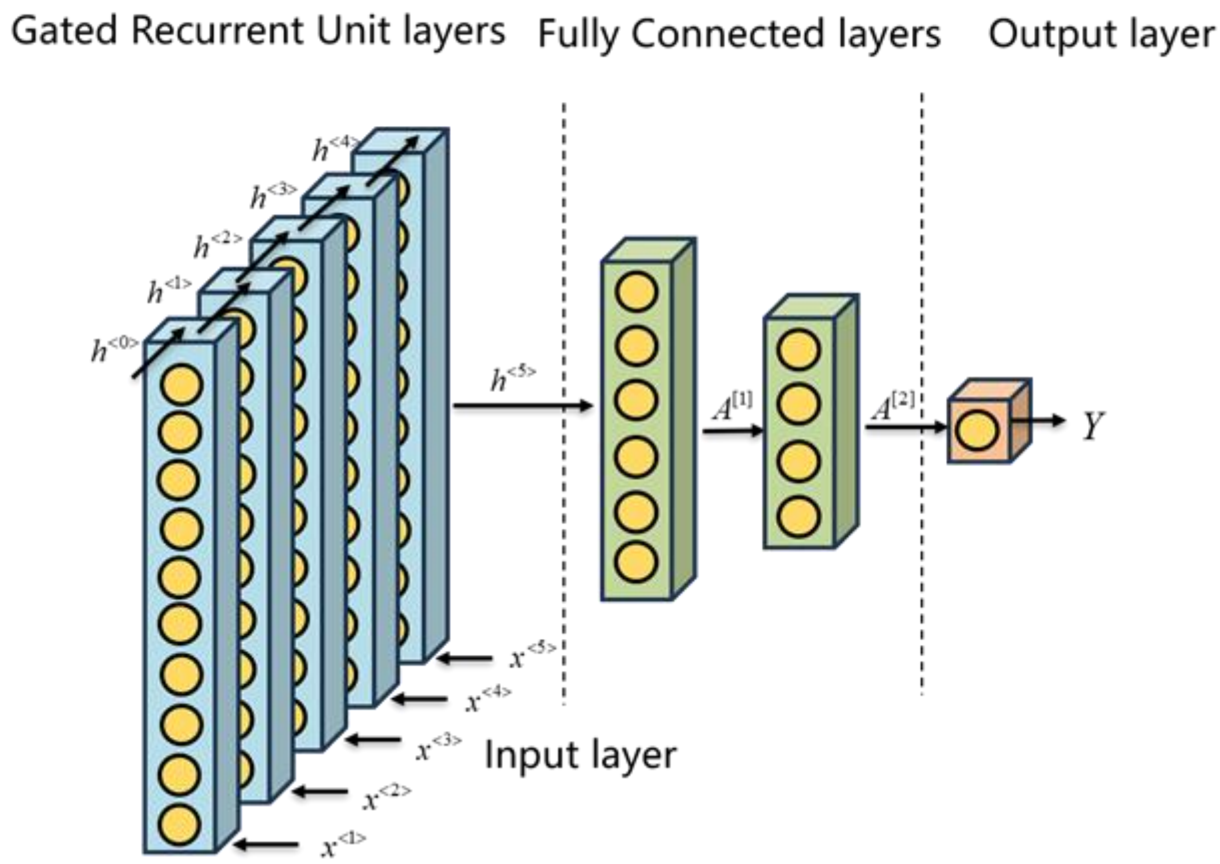

MAPHEUS
15

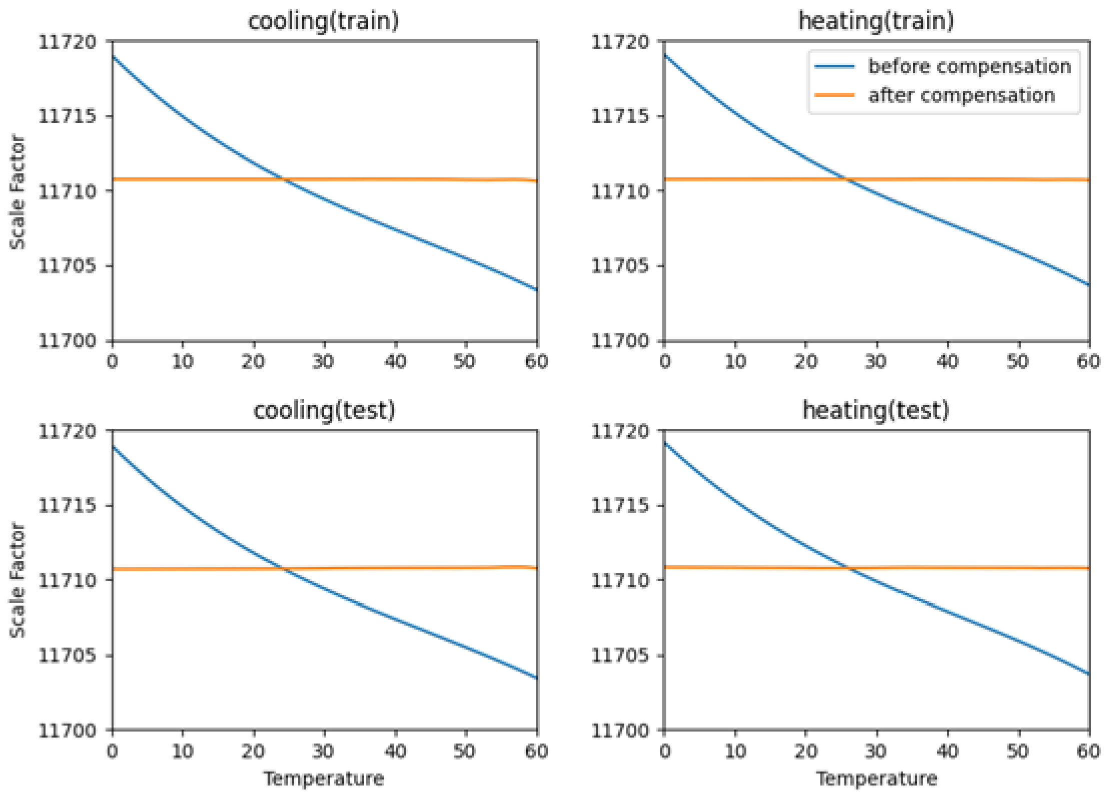
A Temperature Compensation Method of Quartz Flexible Accelerometer based on Gated Recurrent Unit

Zhikun L[1,2], Hongxiang C[3], Lin W[1,2], Yuanhan W[1,2], Zhonghong L[1,2], Honggang G[1,2], Pengcheng M[1,2]
[1]College of Advanced Interdisciplinary Studies, National University of Defense Technology, [2]Nanhu Laser Laboratory, National University of Defense Technology, [3]Huazhong Institute of Electro-Optics-wuhan national laboratory for optoelectronics

Biography:
2018 - Present College of Advanced Interdisciplinary Studies, National University of Defense Technology
2014 - 2018 Ph.D. degree in information and communication engineering from the National University of Defense Technology

Quartz flexible accelerometer (QFA) has been widely applied in the inertial navigation system (INS) due to its high accuracy and reliability. However, the performance of QFA is susceptible to the ambient temperature. Considering the thermal capacity and temperature hysteresis behavior of the magnetic components in QFA, the drift in the output signal of QFA along with the ambient temperature is not only related to the current temperature, but also affected by the spatiotemporal gradient field of temperature.
To address this issue, a temperature compensation model for the output signal of QFA based on the gated recurrent unit (GRU) is proposed in this paper. The model parameters of GRU are trained by the separated scale factor and zero bias of QFA measured by the discrete calibration method in the high-precision temperature box. Leveraging the great nonlinear curve fitting and memory capabilities of GRU, the temperature compensation model could effectively predict and compensate for the temperature drift portions on basis of the spatiotemporal gradient information of temperature. Two sets of temperature cycling experiments are conducted under the same conditions, one for training the model and the other for testing the compensation effect of the model.
Experiment results show that the residual error of QFA scale factor after compensation is better than 10ppm and the root mean square error (RMSE) is better than 3ppm, the residual error of zero bias is better than 7μg and the RMSE is better than 4μg. Compared to uncompensated QFA, the RMSEs of compensated scale factor and zero bias are improved by about 100 times. The proposed temperature compensation model significantly improves the temperature stability of QFA, which would enhance the navigation accuracy of INS effectively.


Gated Recurrent Unit layers
Fully Connected layers
Output layer
$h^{<0>}$
$h^{<1>}$
$h^{<2>}$
$h^{<3>}$
$h^{<4>}$
$h^{<5>}$
$A^{[1]}$
$A^{[2]}$
Y
$x^{<5>}$
$x^{<4>}$
$x^{<3>}$
$x^{<2>}$
$x^{<1>}$
Input layer


cooling(train)
heating(train)
cooling(test)
heating(test)
before compensation
after compensation
Scale Factor
Temperature
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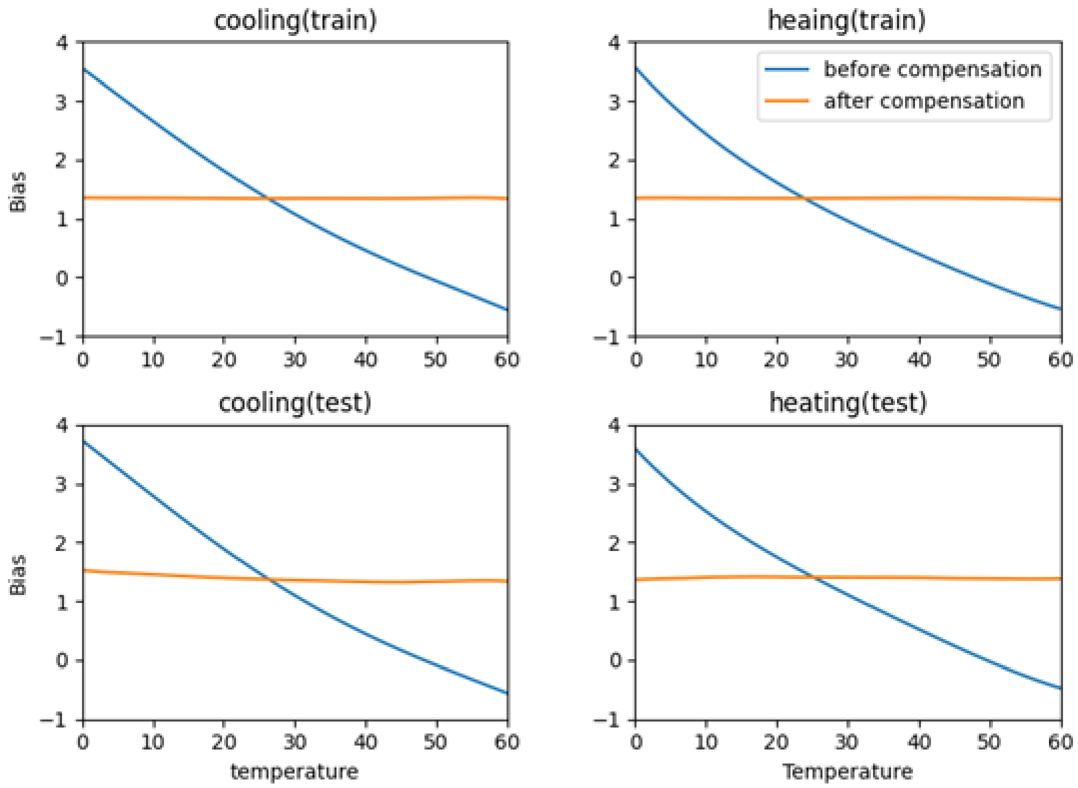
11715
11710
11705
11700
0
10
20
30
40
50
60


cooling(train)
heaing(train)
cooling(test)
heating(test)
before compensation
after compensation
Bias
temperature
Temperature

Integrating Smartphones with Low-Cost GNSS Receivers for RTK Positioning Across Diverse Environments

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Biography:
Milad Bagheri received his master's degree in Environmental Engineering with a focus on Climate Change from Politecnico di Torino (Italy). He is currently a PhD student in Civil and Environmental Engineering at Politecnico di Torino, specializing in high-precision positioning with low-cost devices. His research focuses on GNSS quality control, monitoring techniques using Geomatics instruments, low-cost INS and GNSS systems for mobile mapping, and indoor positioning for navigation applications. He is part of the Geomatics group at DIATI, contributing to advancements in low-cost positioning technologies and their applications in engineering and environmental monitoring.

The rapid advancement of GNSS technologies has created opportunities for achieving high-precision Real-Time Kinematic (RTK) positioning using low-cost hardware. While plenty of research has explored RTK using smartphones, these studies primarily focus on geodetic networks and professional-grade setups. This study introduces a novel approach by comparing geodetic-grade systems, low-cost GNSS receivers, and smartphone-based RTK solutions, evaluating their performance across diverse configurations.
Three setups are analyzed: (1) a smartphone and a low-cost GNSS receiver receiving corrections from an affordable RTK correction service, (2) a low-cost GNSS receiver serving as a base station with the smartphone acting as the rover, and (3) a geodetic-grade base station providing corrections to both the low-cost receiver and the smartphone as rovers. Field tests are conducted in varied environments, including open fields and suburban areas, to evaluate the impact of environmental conditions on positioning accuracy.
The study focuses on key performance metrics such as horizontal and vertical accuracy, initialization time, fix reliability, and responsiveness across the different configurations. Cost-effectiveness and ease of setup are also considered to assess the practical feasibility of these systems for real-world applications.
Preliminary results indicate that the integration of smartphones with low-cost GNSS receivers, supported by affordable RTK correction services, can achieve sub-meter accuracy in favorable conditions. However, environmental factors such as signal obstructions and multipath effects significantly influence performance. Comparisons with geodetic-grade equipment highlight the trade-offs between cost and accuracy, emphasizing the potential of low-cost solutions for applications where ultra-high precision is not critical.
This research provides a comprehensive analysis of low-cost RTK systems and their suitability for applications such as precision agriculture, urban mobility, and environmental monitoring. By exploring the viability of integrating smartphones with low-cost GNSS receivers, this study aims to bridge the gap between affordable technology and high-precision GNSS applications.

VTOL Landing Navigation Based on Radar Altimeter and Ground RF Repeaters

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Biography:
Petr Kejik graduated from PhD studies at Brno University of Technology. He has been working for Honeywell International s.r.o. as research and development scientist since 2011. His research areas include radar signal processing, GNSS and alternative navigation. A novel navigation concept utilizing onboard radar altimeter and active radio frequency repeaters on the ground will be presented.

Navigation is one of the key enablers for autonomous air vehicle operations for urban air mobility vehicles and unmanned aircraft systems (UAS). The most critical phases of vertical take-off and landing (VTOL) vehicle autonomous flight, especially in terms of navigation accuracy and integrity requirements, are the approach and landing phases in complex/urban terrain surrounding highly constrained sites.

The navigation solution for these phases assumes hybridization of various sensors and systems to create solutions that meet stringent navigation accuracy and integrity requirements in GNSS available and denied environments. One potential sensor set for the navigation system includes a radar altimeter with extended capability to provide not only 1-dimensional range measurements to the ground but full 3-dimensional position measurements. This can be achieved with the help of dedicated ground-based beacons at known positions, using the multilateration method and advanced detection algorithms. The beacons can be either passive or active.

This paper introduces a novel concept utilizing onboard radar altimeter(s) and active Radio Frequency (RF) repeaters on the ground. In contrast to passive reflectors that just reflect the radar signal, active repeaters can each modify and retransmit the incoming signal to get unique echoes. Signal modification, with possible amplification, delay, and transmission of multiple copies of the received signal, overcomes the issues with reflector's installation and identification. As a result, the radar altimeter will receive not only the reflected signal from the ground but additional unique signal from each repeater. Thus, the onboard radar altimeter detects the surface and the artificial echoes. Unique sets of artificial echoes can be used to enable detection and unique identification of individual repeaters and landing zones.

This contribution describes the novel navigation concept and UAS flight test experiments with the repeaters. Flight tests included three repeater prototypes with known positions relative to the landing zone.

Poster

Assessment of correlation between Seismologic activity and Ionosphere disturbance using GNSS TEC products: Case of North Algeria

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The search for reliable earthquake precursors remains a crucial task in seismology. This study investigates ionospheric disturbances as potential precursors of seismic events, focusing on seismic activity preceding earthquakes. By using spaceborne measurements to monitor the ionospheric layer, we will be able to perform a comprehensive analysis of the ionospheric behavior before the earthquake through extensive data collection, processing, and analysis.
Notable TEC anomalies, observed in the first days before earthquakes, suggest a plausible correlation between TEC disturbances and impending seismic activity. This study will focus on the relationship between the ionosphere and seismic activity, highlighting the importance of GNSS-based ionospheric monitoring. Integrating TEC observations into seismic hazard assessments holds promise for advancing early warning systems and improving our understanding of earthquake precursor phenomena.