NAVISP-El1-066
Vector Tracking Loop For Autonomous Vehicles (VTL4AV)

Final Presentation

Virtual

16 July 2025

Vector Tracking Loops for Autonomous Vehicles (VTL4AV)

Final Presentation

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Project Context and Programme of Work

Louise Mercy (Telespazio UK)

Vector Tracking Loops for Autonomous Vehicles (VTL4AV)

The big picture…

Led by **Telespazio UK**, working with **Cranfield University** and supported by **Spirent** Communications to..

Design and develop a receiver implementing VTL techniques, including fusion with external sensors such as LiDAR, visual and inertial

…to tackle the challenges of VTL architectures

The VTL4AV team also worked to create a **fault detection and isolation strategy** to…

Ensure integrity in urban environments, capable of supporting multiple GNSS constellations

Definition and Downselection
(*5 Months*)
* SoA of Rx architectures, coupling, and fault detection and isolation
* Trade-offs
* Architectural Design

Detailed Design
(*4 Months*)
* Sensors deep coupling system
* VTL-Detectors
* VTL-RAIM module

Implementation
(*7 Months*)
* Implementation of deep coupled VTL PoC
* Integration on SDR PoC

Experimentation
(*11 Months*)
* In simulated and real environments
* Characterisation of achieved performances

Conclusions
(*4 Months*)
* Capturing benefits of proposed arch
* Describing areas of interest

Specification of the **functional and performance REQs and mission statement for the AV use case** serving as a baseline

Detailed design and justification of the **architecture, functions, dataflows and interfaces** of the VTL4AV concept

Development, assembly and integration of all **SW and HW** for the PoC VTL4AV system

Comprehensive reporting and analysis of a series of **simulated and real environment experimentations**

Conclusions on the **achievements of the VTL4AV** project and recommendations for **future studies**

Introduction to VTL

Martin Bransby (Telespazio UK)

Introduction to VTL

- GNSS have become the primary means of navigation and source of PNT information for almost all modes of transport and general navigation
- They are vulnerable to interference, natural or deliberate
- Limited view of satellites in “urban canyons” and under vegetation
- MP is a problem in these situations, especially for use cases involving autonomous vehicles
- Other external (to GNSS) sensors such as inertial, wheel odometers, LiDAR & camera can help in a System-of-Systems approach
- VTLs within GNSS receivers have demonstrated improvement in an academic context
- In conventional GNSS receivers, tracking is performed in several independent (scalar) tracking loops providing measurements (pseudo ranges, pseudo range-rates, carrier Doppler) to a navigation algorithm (Kalman filter), controlling the PVT solution.
- In VTL, the two tasks of signal tracking *and* PVT estimations are combined. But…
- VTL architectures are sensitive to data & channel contamination
- Need to combine VTL with some of these other sensors for full benefit
- Importantly, integrity measures supporting MC GNSS are of huge benefit to users
- Through its NavISP programme, ESA asked us to design and develop an SDR proof-of-concept, implementing a Deeply Coupled VTL robust architecture including:
  - Deep Coupling with external sensors (inertial, odometer, etc.)
  - A Fault detection and isolation strategy ensuring integrity in urban environments
  - Support of Multi-GNSS constellations

Project Outcomes

Smita Tiwari (Telespazio UK)
Pekka Peltola (Telespazio UK)
Ivan Petrunin (Cranfield University)
Teng Li (Cranfield University)

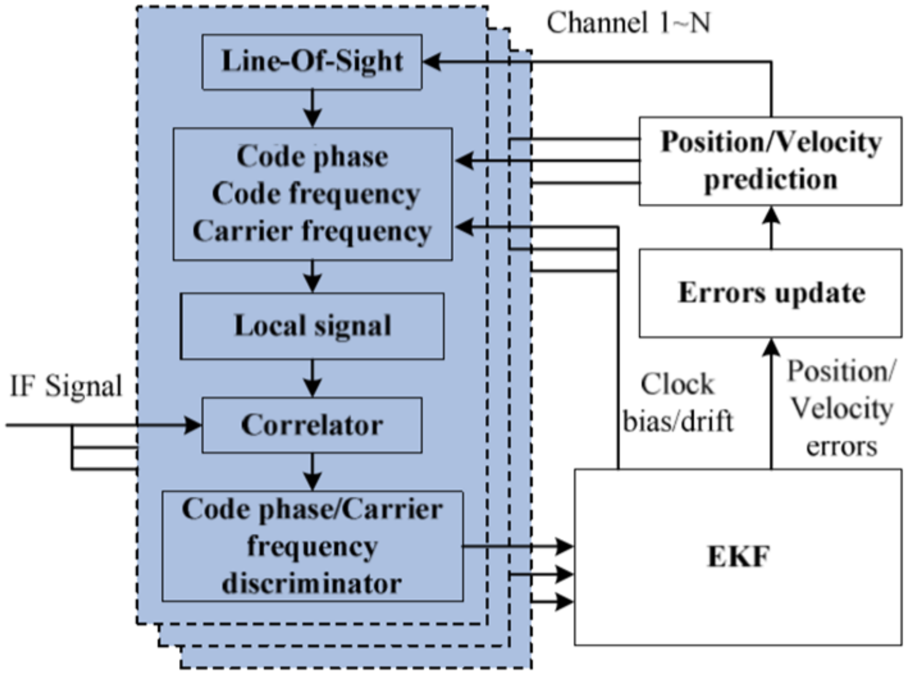
State-of-the-Art and Technology Survey/ Architectural Selection and Justification

Architectural Selection Criteria

Design and develop a SDR proof of concept implementing a Vector tracking loop for Autonomous Vehicle

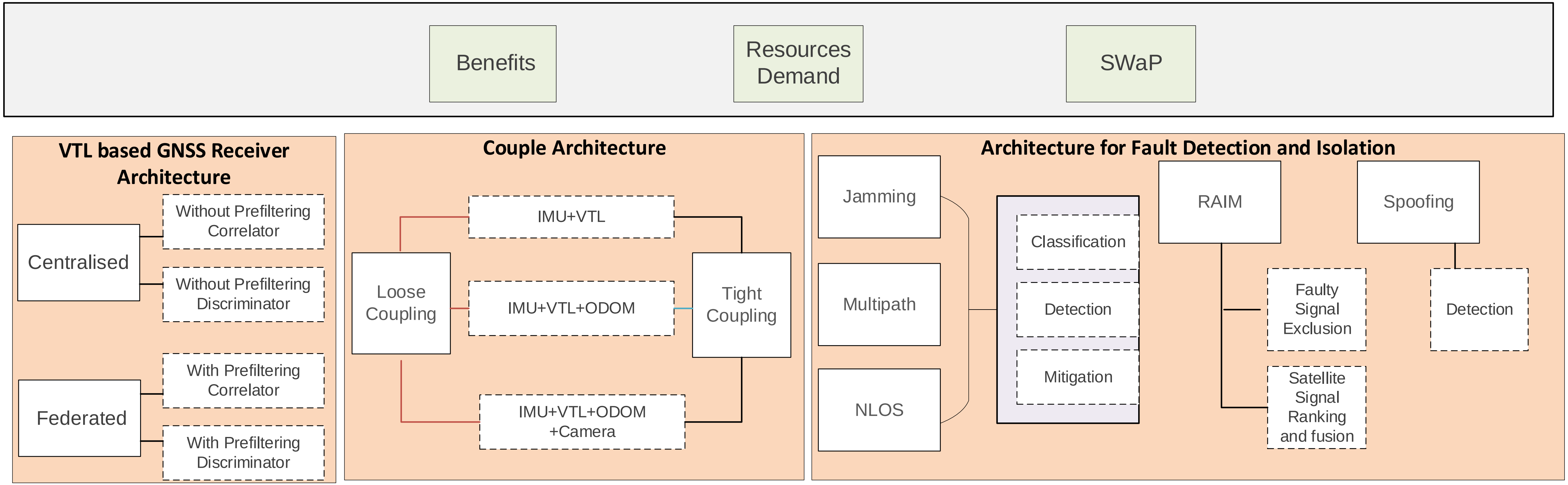
- Limitation
  - VTL architectures are sensitive to channel contamination, and it will affect the overall solution. Therefore,
    - in the VTL a capability of detecting and excluding unhealthy channel is required: for this purpose, **RAIM** module is required to exclude the faulty channel from the solution or compensate its effects
  - Positioning in stringent Urban Environment : It is required to combine the benefits of VTL with **other sensors (IMU)**
  - Environment is full of Interference, multipath and NLOS: necessitates a **detector**
  - **Get benefit from multi GNSS constellation** : remove ionospheric error, more robustness against single system failure, better geometry, give advantage in RAIM (if needed to exclude satellites), resilience to interference and jamming, Better multipath rejection : **MCMF Antenna**

A basic GNSS receiver architecture with vector tracking loop



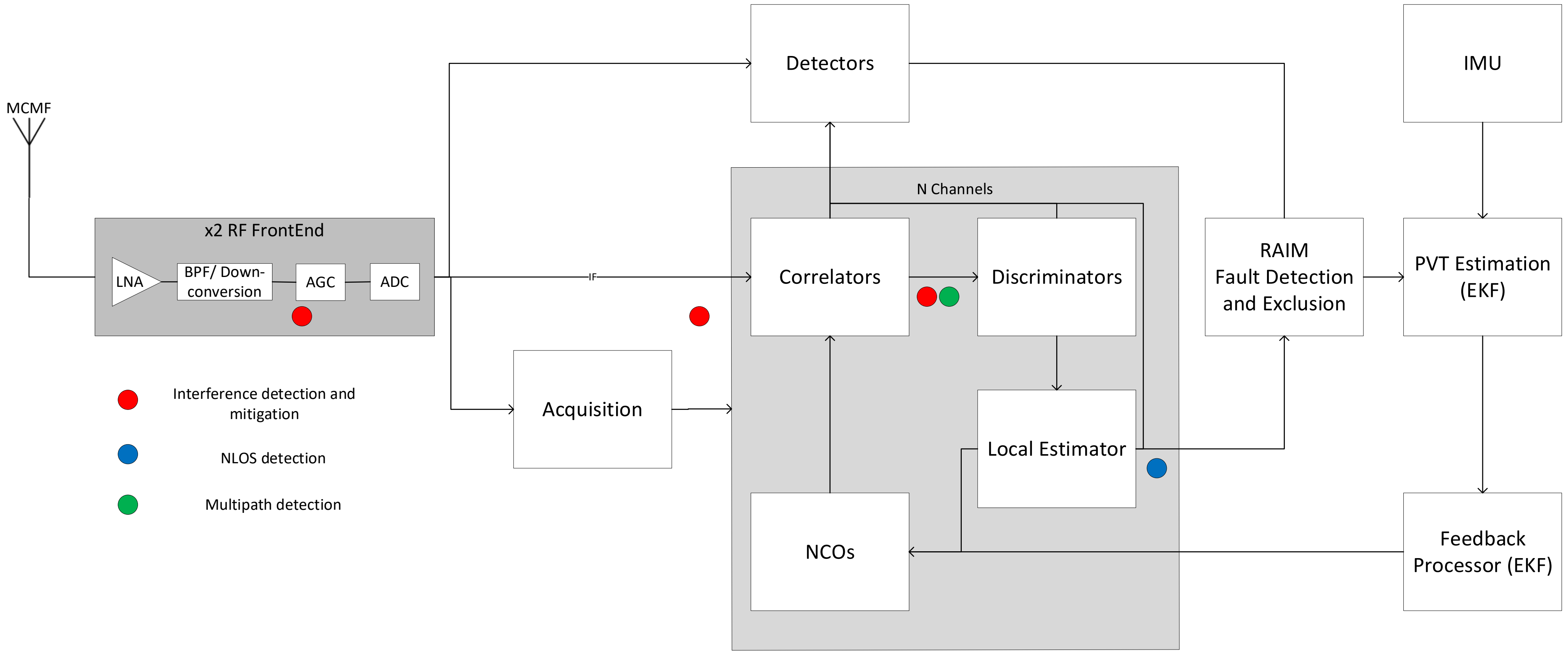
State-of-the-Art and Technology Survey/ Architectural Selection and Justification

Technology Survey



System Design

High Level Architecture



System Design

High Level

Hardware

- Antenna: The antenna is a Dual Band (L1 / L5) active GNSS antenna that filters and amplifies GNSS signals received from the GPS (L1 / L5) and Galileo (E1 / E5) satellite constellations.
- Front-end: The SDR platform feature a Dual channel (two front ends), to down convert to I&Q baseband and digitise two different GNSS signals, at different frequencies, from the satellite constellations. The first channel will be dedicated to processing L1 & E1 signals and the second will process the L5 & E5a signals.
- IMU: The GNSS will be aided by an IMU for robustness, specifically, in GNSS denied harsh environments such as urban areas to increase the integrity level

Software

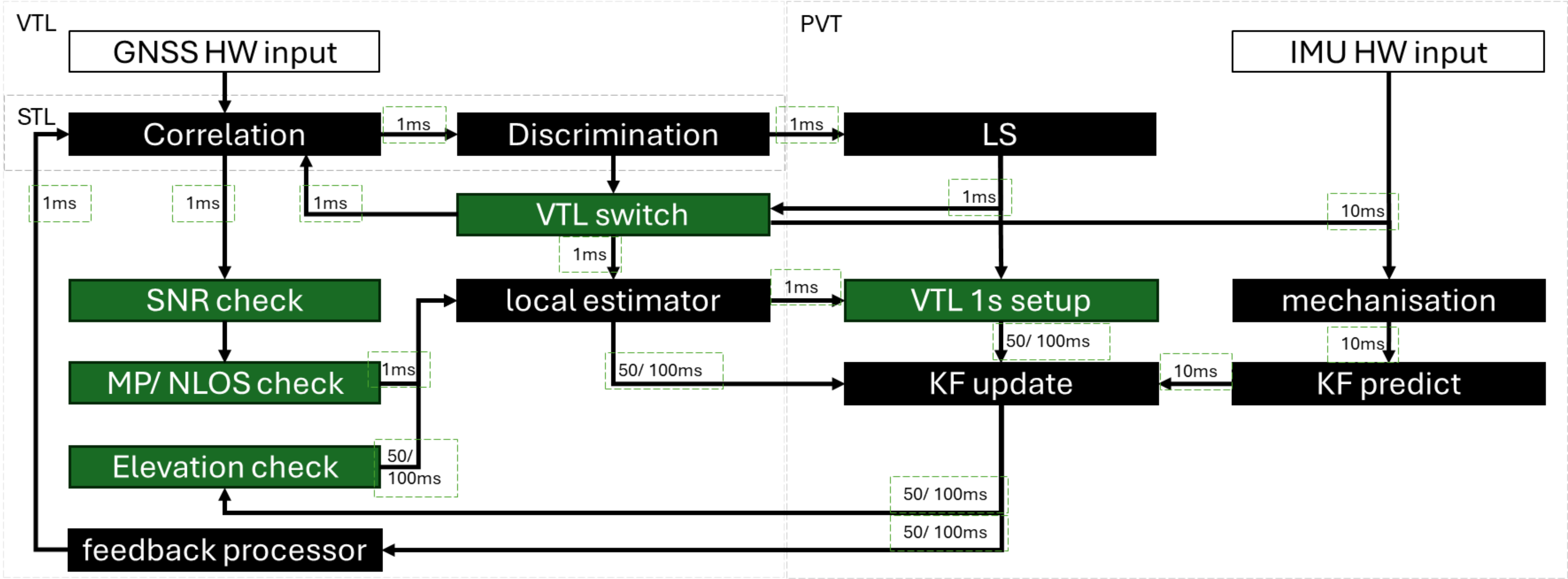
- Acquisition: The acquisition block provides code and carrier estimates. Initial acquisition is conducted using the scalar tracking loop.
- Tracking Channel
- Detectors
- RAIN
- PVT Estimation
- Fusion
- Feedback Processor

Estimated importance to the use case requirements	Computation/ update rate	Accuracy	Availability
Antenna	(High) HW	(High) HW	(High) HW
Front-End	(High) HW	(High) HW	(High) HW
Correlators	High	High	High
Discriminators and local estimators	Low	Medium	Medium
PVT feedback	Low	High	High
Detectors	Medium	High	High
RAIM	Low	Medium	High
IMU	Medium	High	High

System Design

VTL + Fusion Architecture

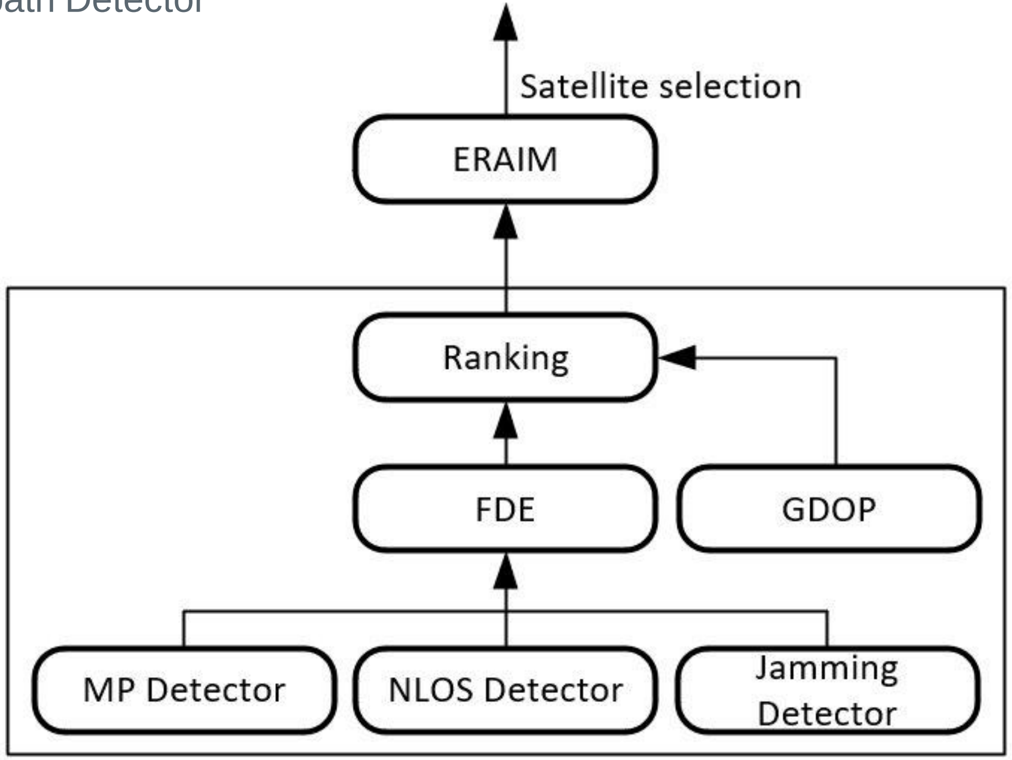
- FGI STL least squares, starting point
- VTL KF
- VTL switch simple
  - STL position available, switch to VTL
- RAIM selection
- Signal power check
- Multipath check
- Non-line-of-sight check
- Elevation check
- Least squares sanity check
- Optimised from 4 day to 4h on 15 min binary (~15Gb)
- Speedometer updates

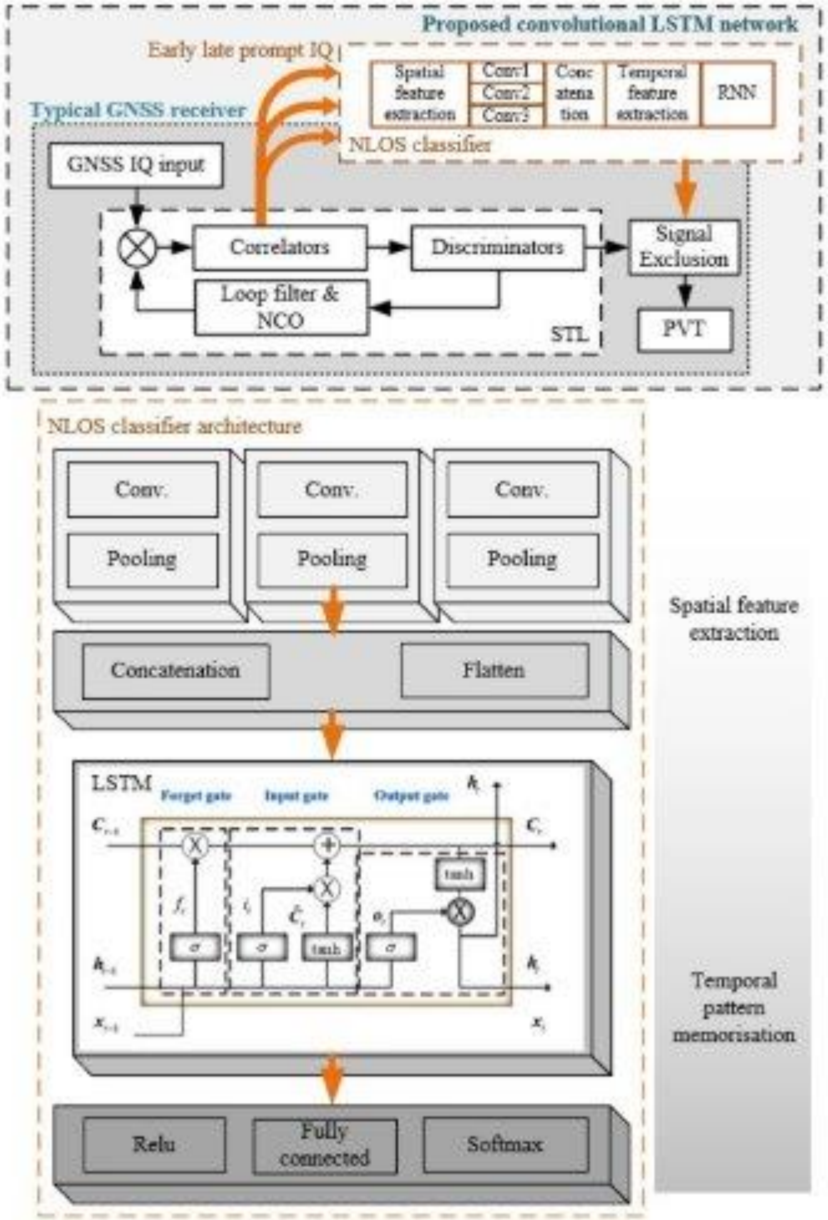


System Design

Detector Architecture

- Jamming Detector
  - Combines energy detector and entropy detector to reduce false alarms, with 3 sigma threshold.
- NLOS/Multipath Detector
- RAIM

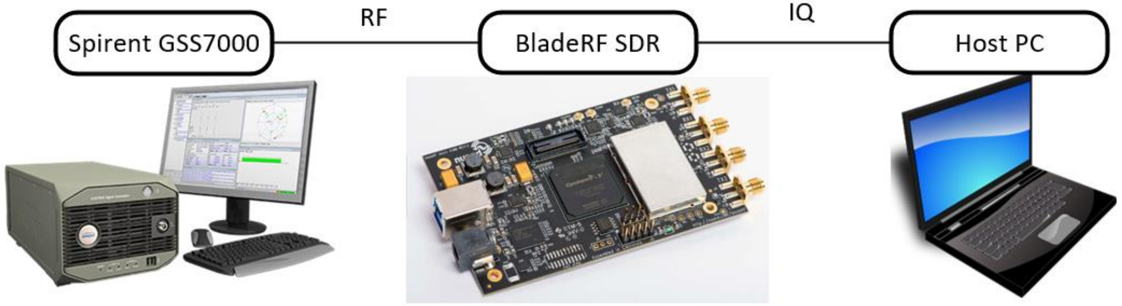


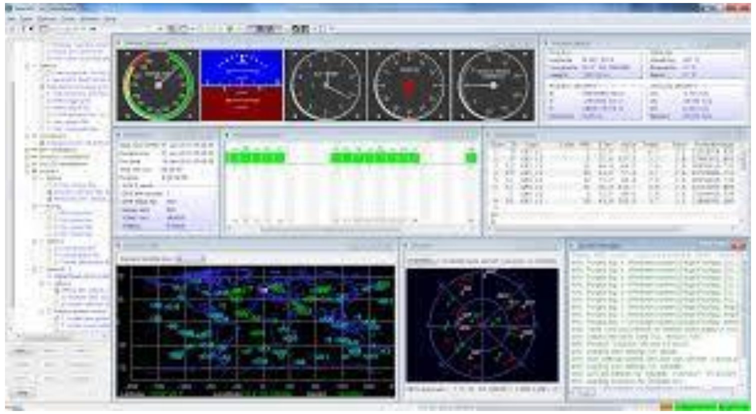


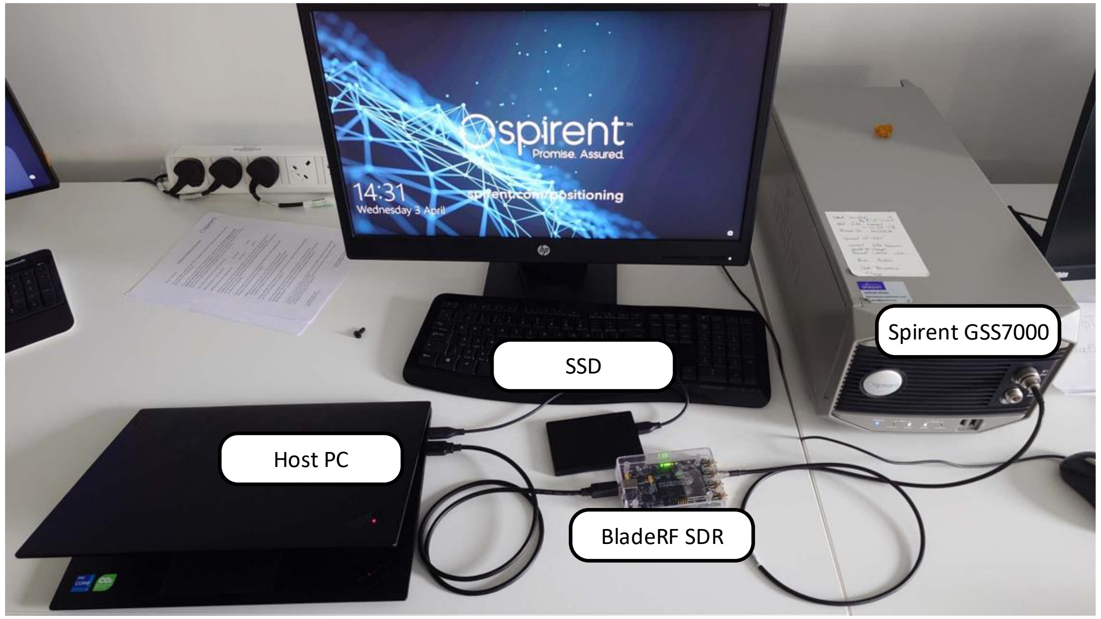
Simulated Environment Evaluation

Simulation Test Analysis

- Simulation implements HIL setup, where constellation effects, signal generation and propagation, environment and vehicle dynamics are represented using Spirent's simulation test rig based on hardware simulator, GSS7000, able to provide up to 256 channels in a simulated RF signal at the output and a software bundle.
- Main simulation capabilities are supported by the SimGen software with additional modules, which include simulation of propagation effects, failures, environmental effects (NLOS/MP), INS aiding and the ability to simulate jamming and spoofing scenarios
- Simulated signals are captured by BladeRF SDR and saved in an external SSD through the host PC.





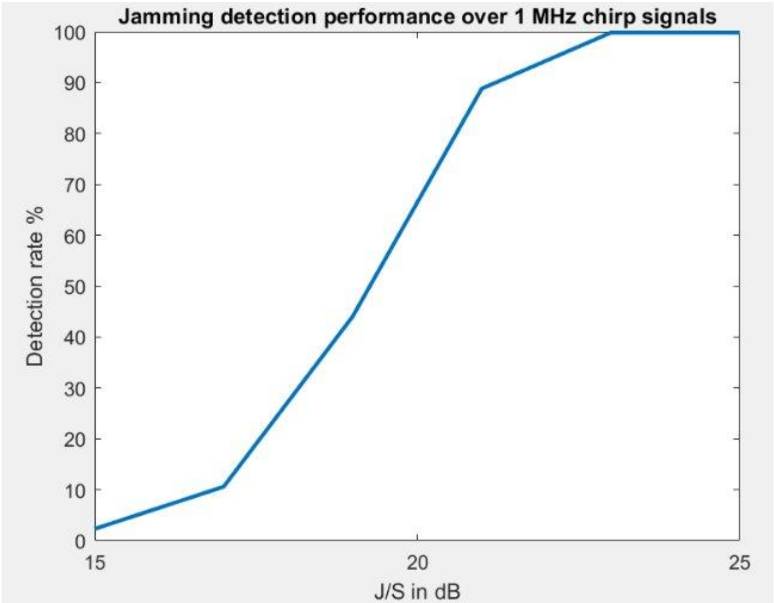


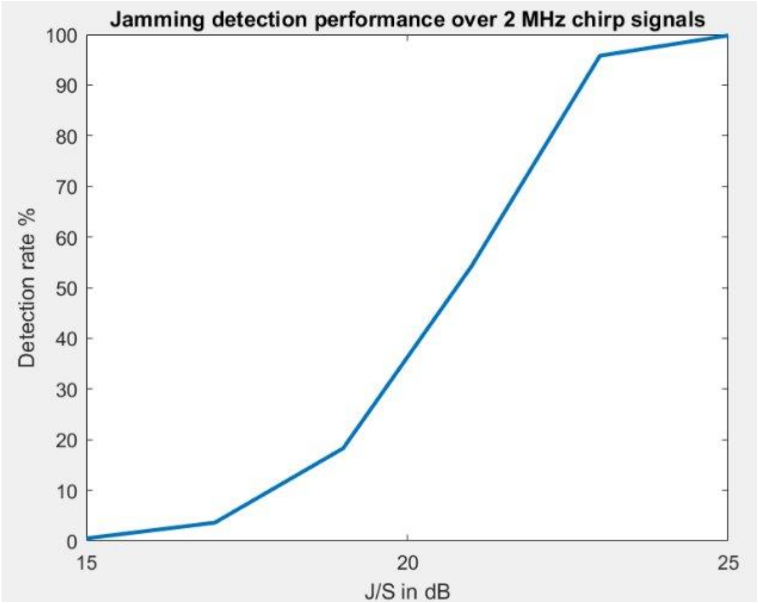
Simulated Environment Evaluation

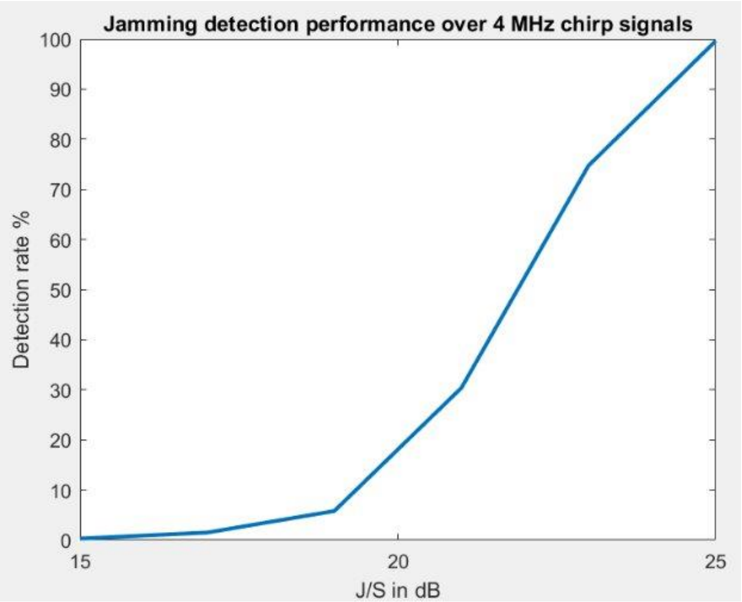
Simulation Test Results – Jamming

- To verify the jamming detector performance, we select 5000 ms signals and inject jamming events for 1000 ms.
- The jamming is detected every 1 ms.
- The detection is based on the analysis of the number of detections within the injected jamming event period.

Tests with chirp signals







Simulated Environment Evaluation

Simulation Test Results – Jamming

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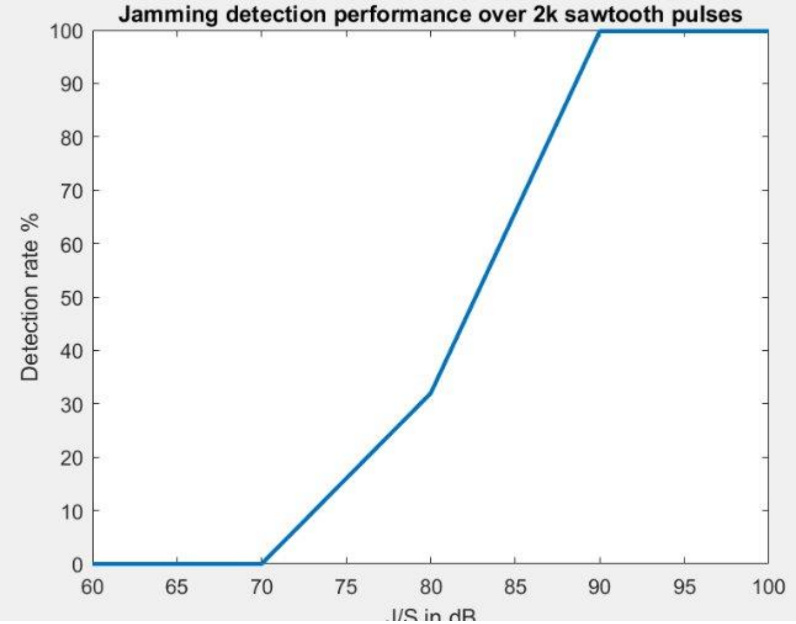
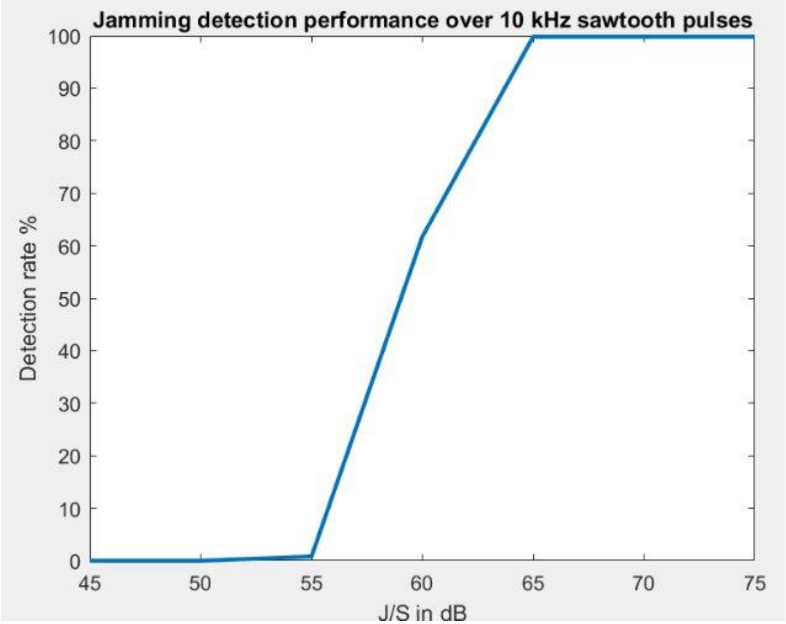
Tests with sawtooth signals

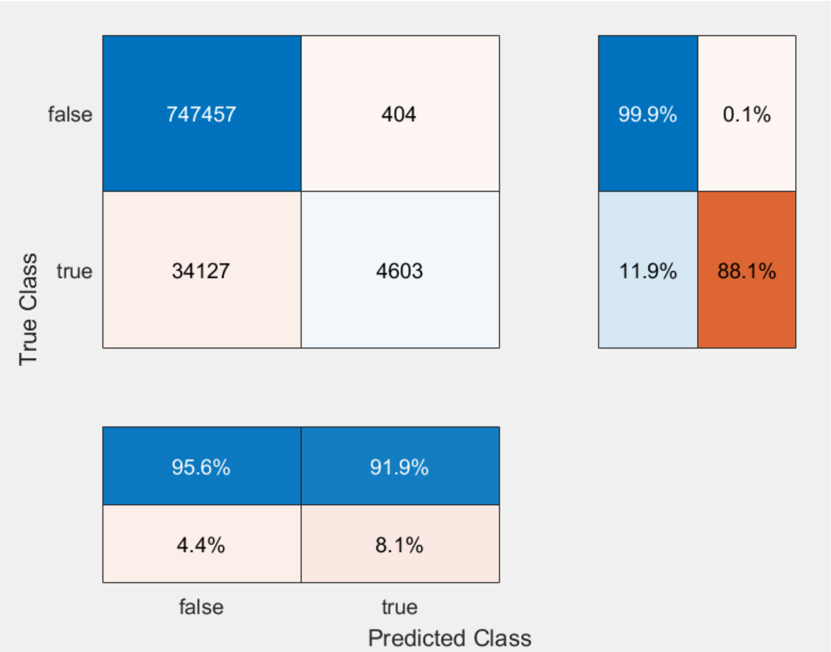




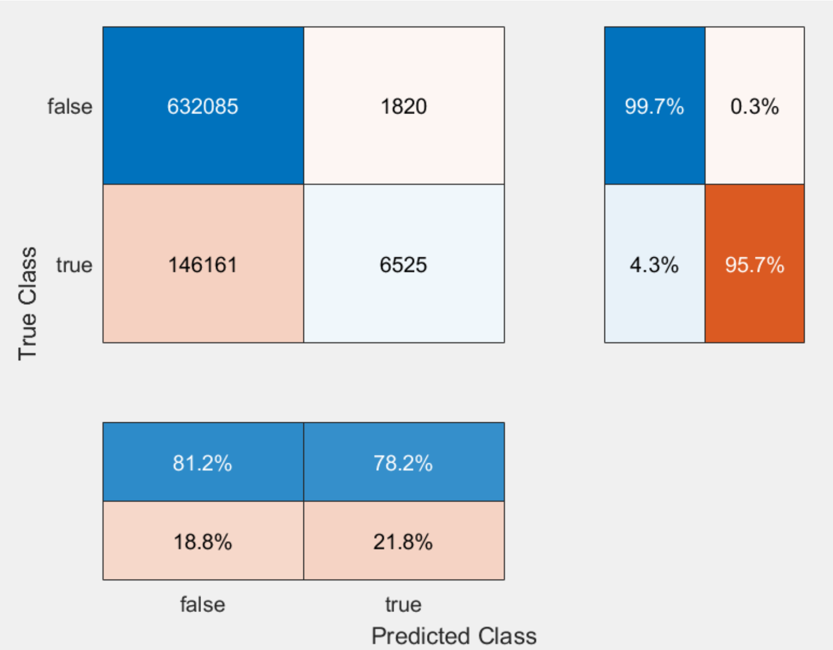
Simulated Environment Evaluation

Simulation Test Analysis – NLOS and MP Detection

- The NLOS/MP detector is using ELP correlator outputs.
- The NLOS confusion matrix (true refers to NLOS, and false refers to non-NLOS) suggests a high precision (over 95%) of detecting NLOS signals, and the precision of 91.9% of detecting non-NLOS signals. This gives us good confidence when labelling NLOS signals.
- The MP confusion matrix (true refers to multipath, and false refers to non-multipath) suggests an 81% precision of detecting multipath signals, and a 78% precision of detecting non-multipath signals. Similar to the NLOS detection case, the detector provides a good detection confidence with a possibility to optimize performance via the training dataset update.



NLOS



MP

Simulated Environment Evaluation

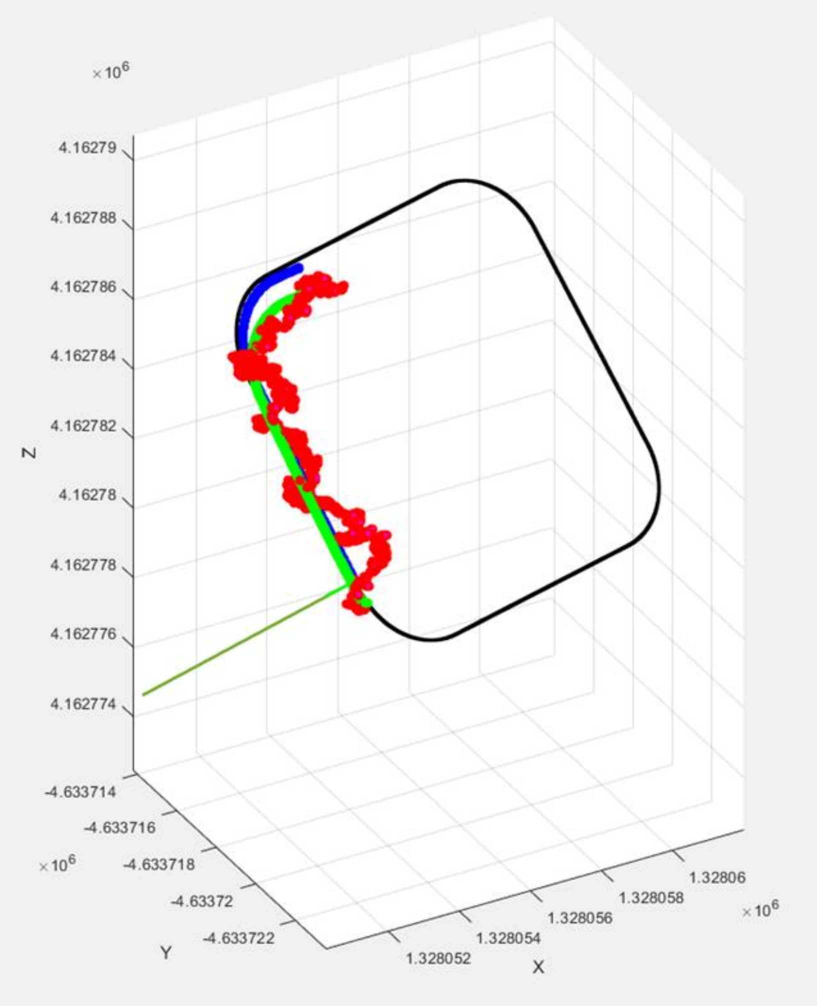
Simulation Test Analysis

STL vs VTL Analysis

- **Data type**: Synthetic data collection of an open sky and urban scenario containing both GPS and Galileo signals along with IMU data.
- **Data Processing**: The VTL and STLs are run using the same dataset as an input. The output position results are analysed and compared with the true position trajectory to determine the position errors throughout the scenario.

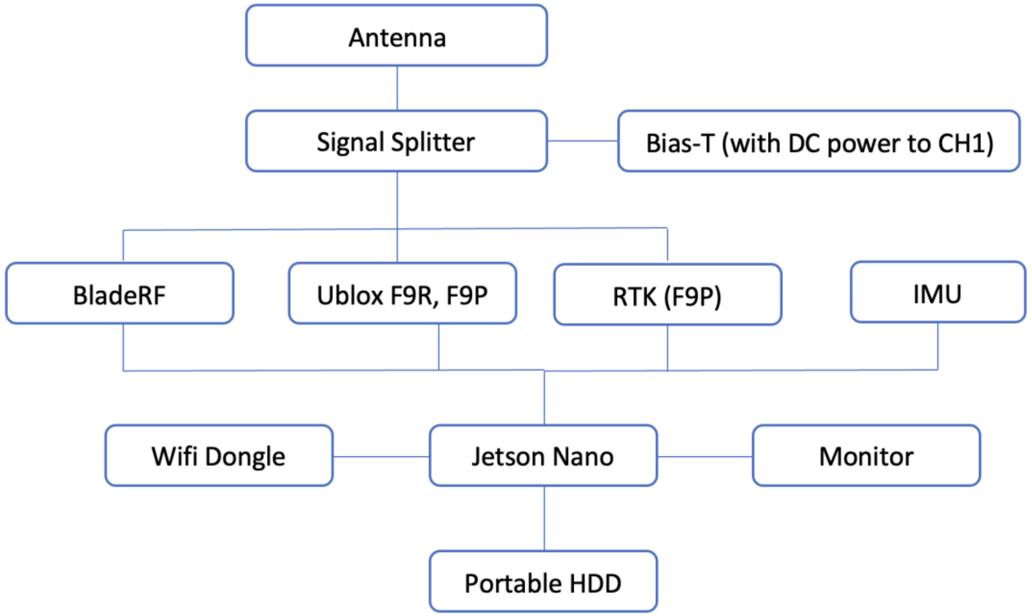
Table: Position Performance of STL vs VTL

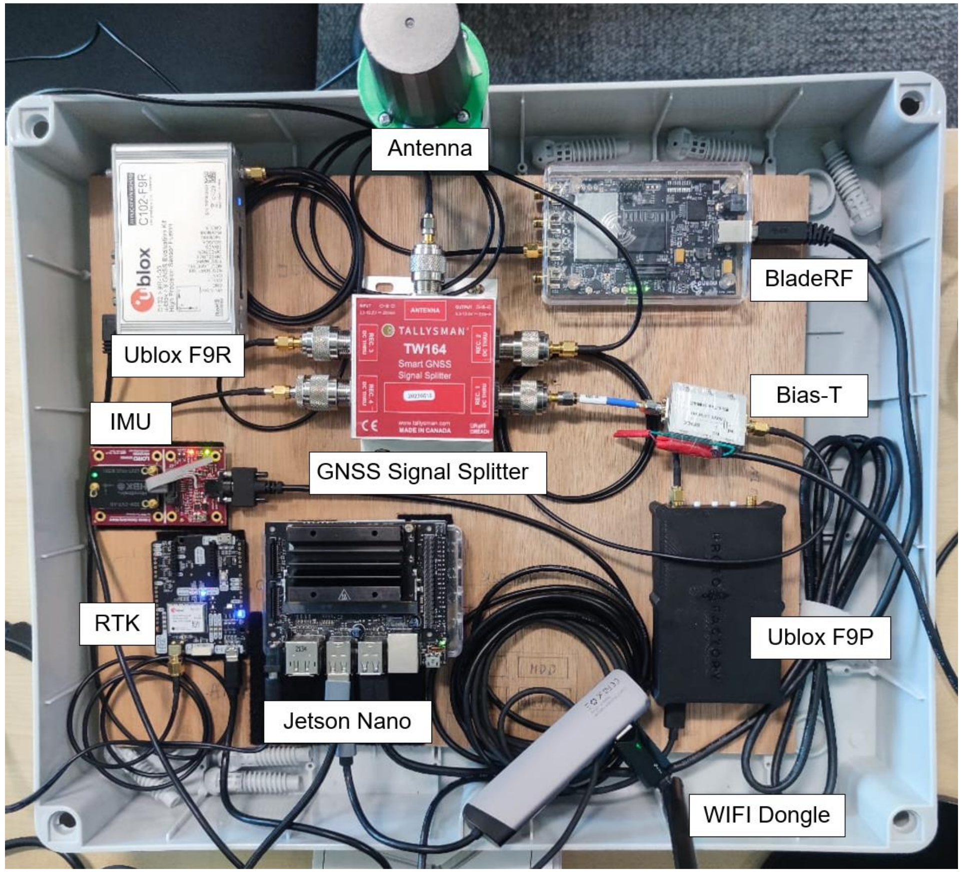
Receiver Type	Positioning accuracy			
	Horizontal (99.5%)		Vertical (99.5%)	
	Open Sky	Urban	Open Sky	Urban
STL	3.9	4.7	4.4	5.2
VTL	2.0	2.7	2.6	3.0



Development and Implementation of the Proof of Concept

Assembled VLT4AV PoC

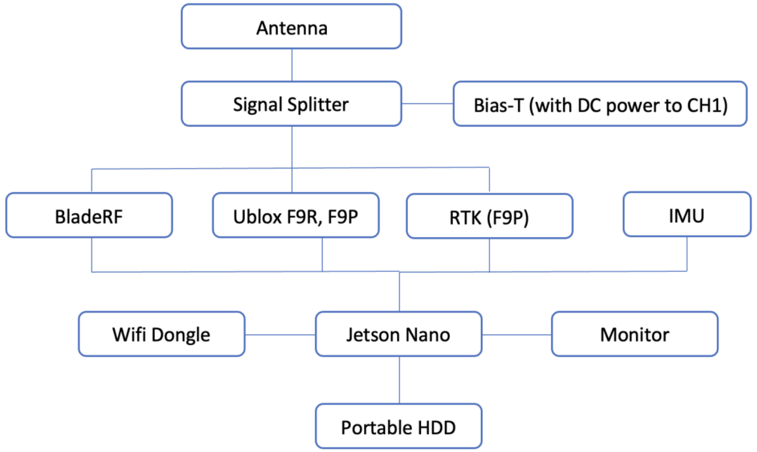


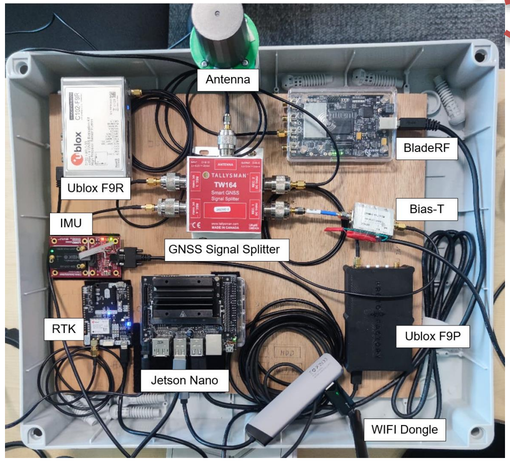


Real-world Experiments

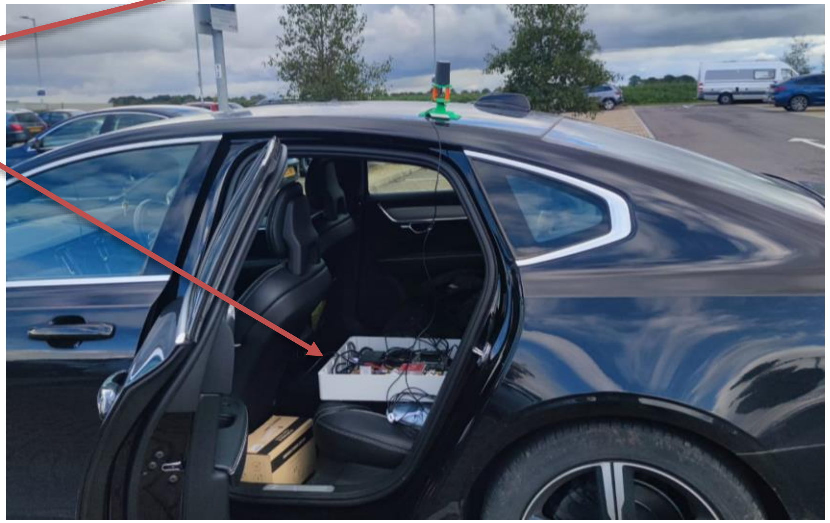
Real Data Collection

- All sensors/receivers need to be configured as desired before integration.
- RF signals are received from the same antenna then split to 4 channels with a GNSS signal splitter.
- BladeRF collects raw RF signal binaries; Ublox F9R and F9P are used for positioning performance comparison; RTK positions are used as the ground truth reference.
- A NVIDIA Jetson Nano board is adopted to run data collection codes
- The data collection platform is fixed in a car with the antenna mounted on the roof of the car.





Static data collection

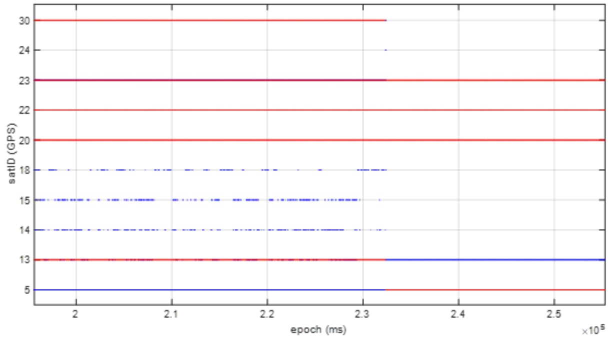


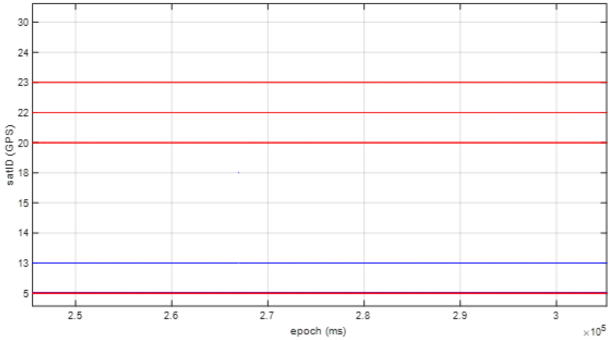
Dynamic data collection

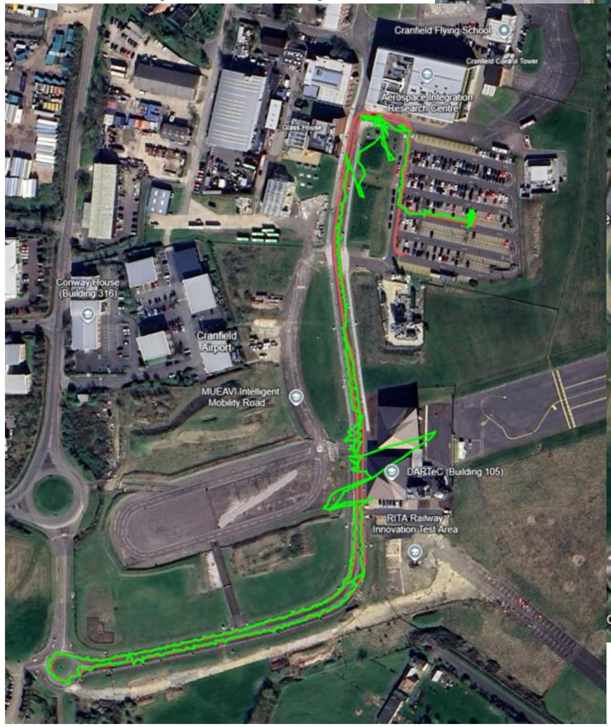
Real-world Experiments

Field Test Results – Cranfield (3 tests)

- Static (inside area with MP), **dynamic 5mph** and 20mph drives
- IMU on backseat, Antenna on the roof for GPS + Galileo
- Captured IMU and GNSS RF fused with NLOS/MP detectors per ms
- Here is shown successful detection and fusion in the campus
- STL LS affected and VTL with RAIM compensation (red ublox)



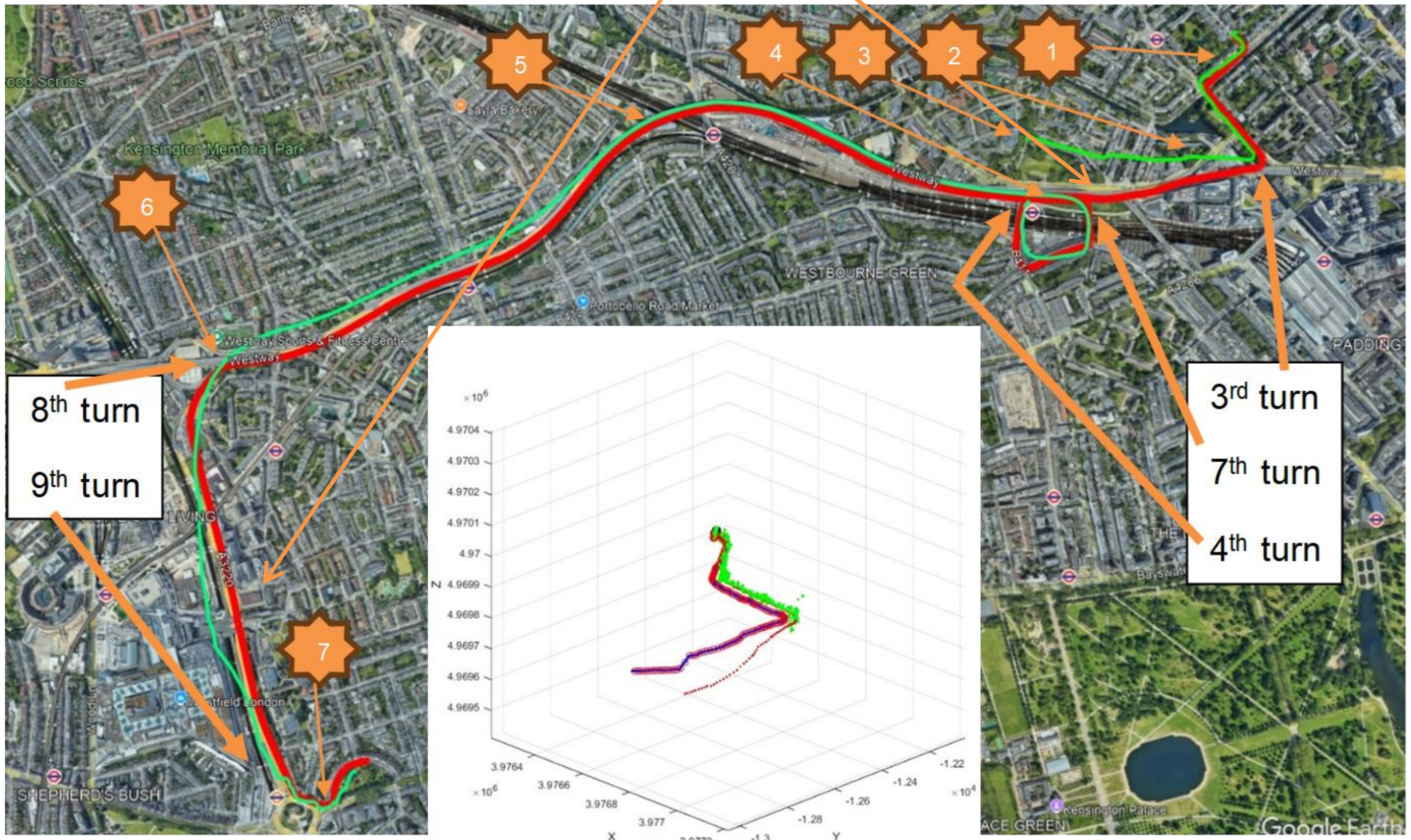


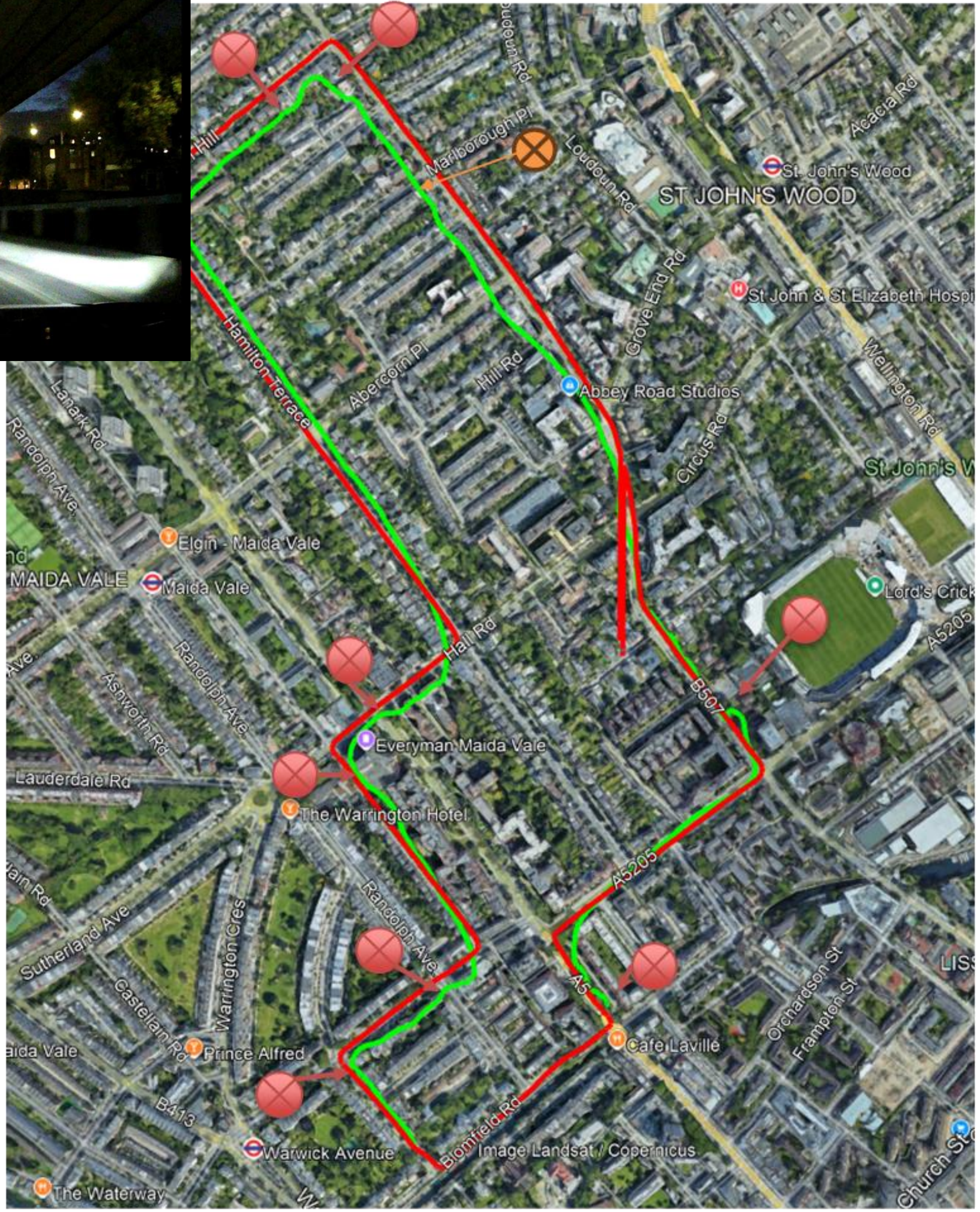


Real-world Experiments

Field Test Results – London (3 tests)

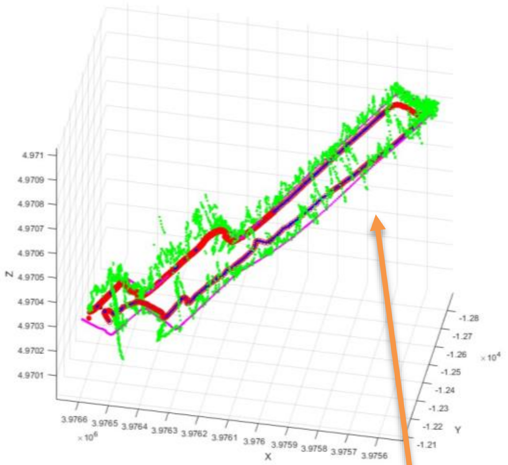
- STL unable to process over 50m per run
- Static, dynamic 20mph and 50mph drives (ublox)
- Fusion accuracy, velocity updates, underpasses





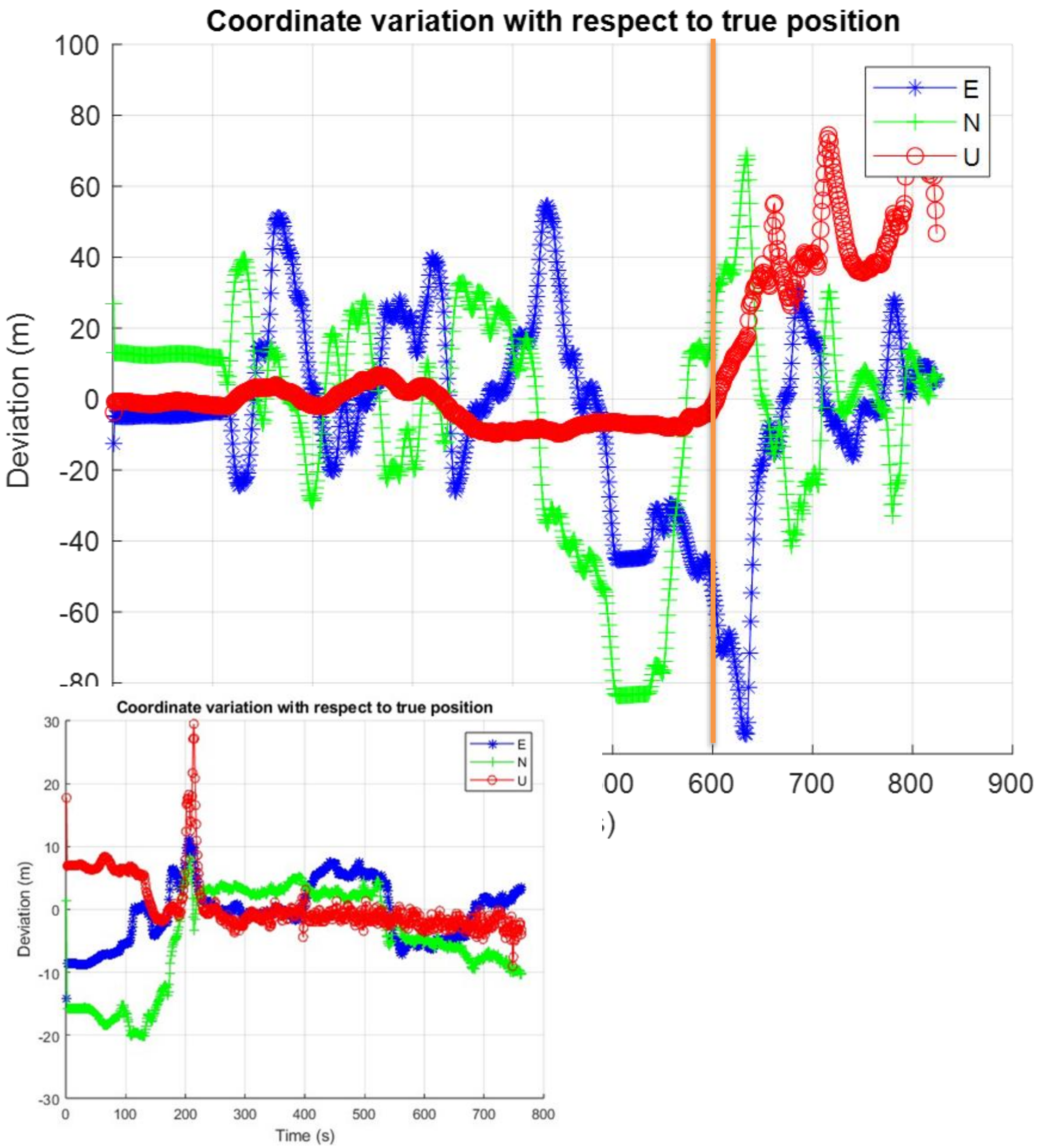
Real-world Experiments

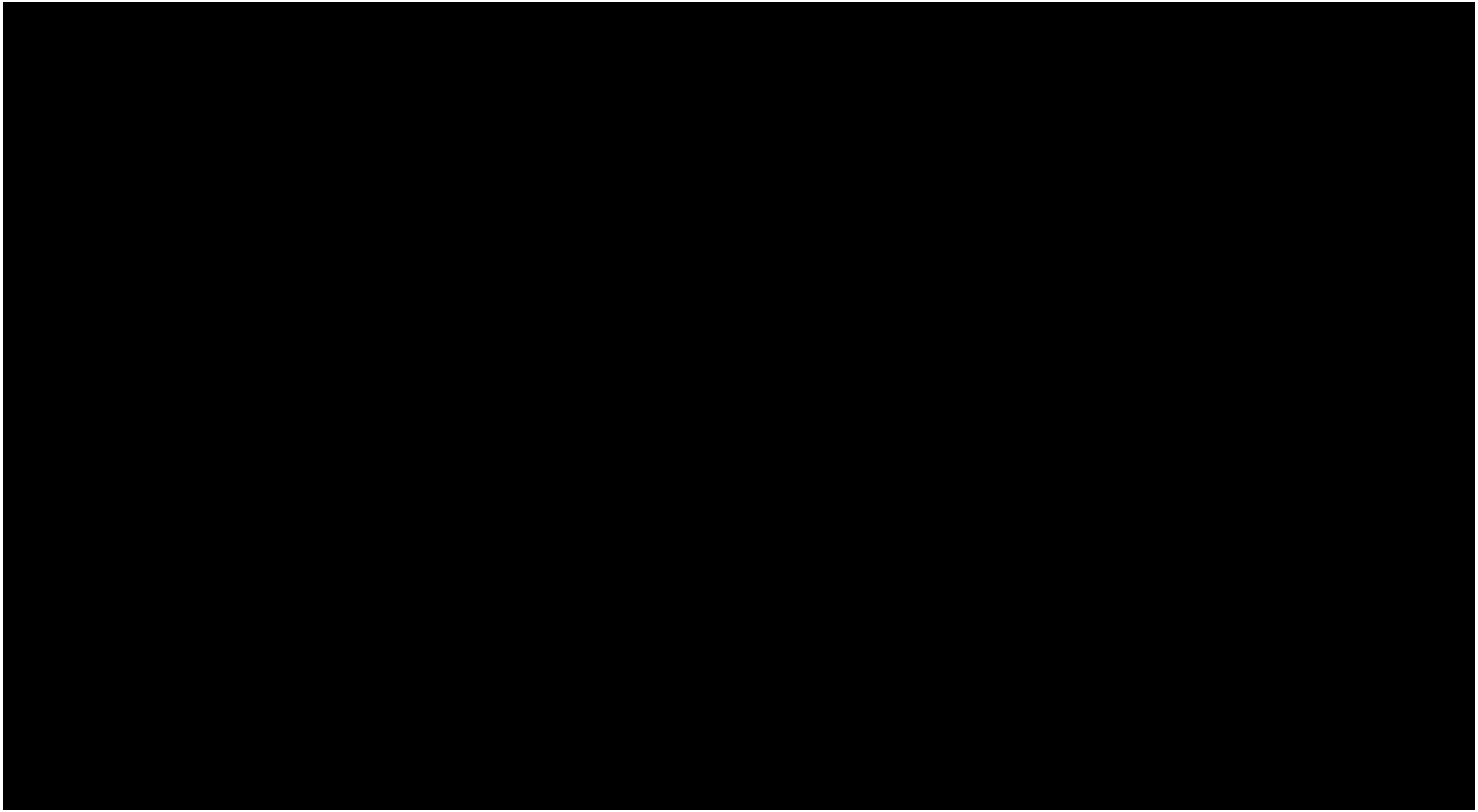
Field Test Results - London



- **5mph University settings for 20mph city scenario**

- Accuracy
- STL fails without reacquisition
- VTL + IMU accuracy depends on the weighting
- Key point is the channel quality estimate
- Secondary comes the fusion method whether
  - Least squares with/without excluding failing channels
  - KF with/without excluding failing channels
- Advantage of VTL is the more robust reacquisition compared to STL
- Up component in least squares is issue, which
  - Leads to KF range fusion to emphasize the horizontal fusion weight over vertical
  - Effect of changing GNSS range fusion weight



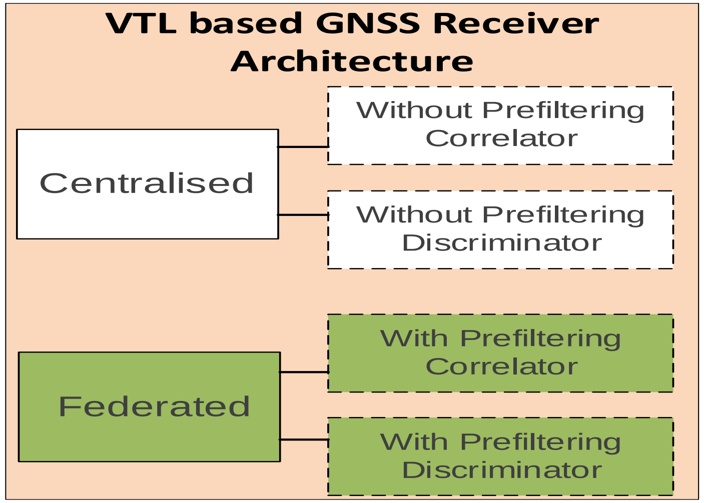


Conclusions and Lessons Learned

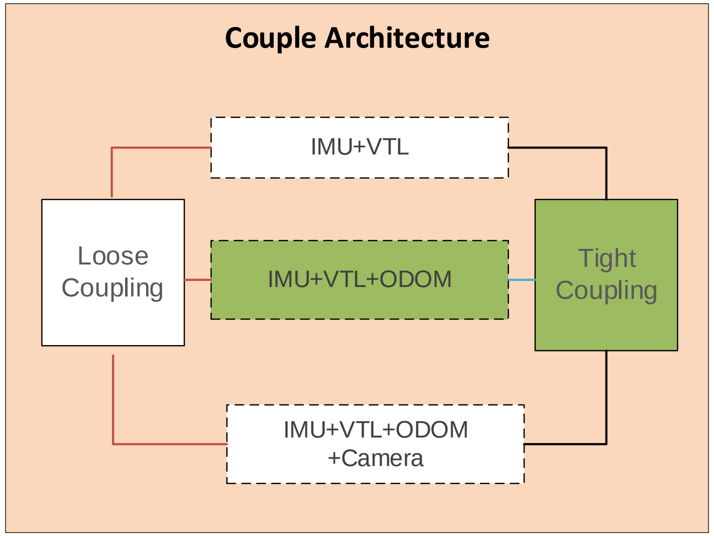
Smita Tiwari (Telespazio UK)

Conclusions and Lessons Learned

Benefit of the Proposed Architecture



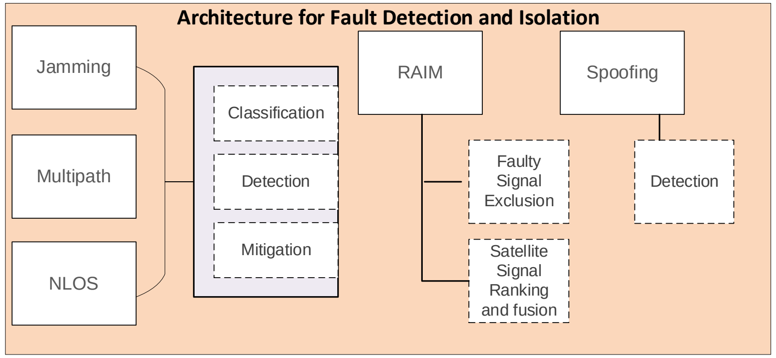
Benefits	Resource demand	SWaP-C	Comments
Good in high dynamics, Positioning and Pseudo-ranging.	Less complex sync with PVT.	Multiple threads processing, channel integrity check prefiltering.	Selected due to simplified sync and resource needs.



Benefits	Resource demand	SWaP-C	Comments
More accurate dead reckoning estimates.	Fast, slight increase to IMU+VTL.	Acquiring reliable odometry data can be difficult.	Tight coupling, VTL combined channels feedback without the seen risk of drift.

Conclusions and Lessons Learned

Benefit of the Proposed Architecture



Selection	Benefits	Resource demand	SWaP-C	Comments
Jamming detection	Beneficial for RF awareness and improvement in availability, robustness, and accuracy.	Fast with SNR and without converting to the frequency domain. Medium with ML and frequency domain processing.	Small computation with known jamming feature without ML.	Implemented as a fundamental feature.
Multipath detection	Good in improving accuracy in urban operations by selecting good quality antenna signals.	High latency with correlators. Relatively faster with observables but still requires more processing if processing in the frequency domain. Medium with ML	Medium hardware resource requirement with assessment on multiple channels without ML. High with ML.	Implemented to improve GNSS performance.
NLOS detection	Good in improving accuracy in urban operations.	Fast with NLOS detection from multiple channels. Slow with crossing matching with 3D maps.	Medium with assessment on multiple channels without ML. High with ML.	Implemented without antenna / new front-end designs and 3D map interfaces.
RAIM	Critical in improving accuracy for VTL by exclusion of faulty channels.	Slow with KF or with ML.	High hardware requirements to provide on-time FDE services.	Implemented as it is fundamental to VTL.
Satellite selection	Critical in enhancing PVT accuracy with VTL.	Slow if fusion with IMU or using other detector output or developing KF or ML	Require high performance hardware to deal with multi-dimensional dataset.	Developed for its performance improvements.
Satellite ranking	Potentially useful for satellite selections.	Slow if using ML regressor	High performance hardware support if demanding ML.	Developed with lower priority given limited benefits.

Conclusions and Lessons Learned

- Performance results based on the real time data collection from both Cranfield University and London, show clear advantages of VTL over STL-based positioning, with VTL able to handle noise better in both the open sky environment, and in an urban environment.
- The interference detection function demonstrated a high probability of detection >=90%,was able to detect interferences with equivalent effect of 3dB of C/N0 reduction.
- The MP/NLOS detection functions were able to successfully remove NLOS/MP satellite data from the results, thereby decreasing the position deviation normally caused by degraded/corrupted inputs.
- Processing time is currently excessive and will need considerable optimisation.
- The developed RAIM component targets a time to alarm within 10 seconds.
- The closed loop GNSS+IMU fusion algorithm produced good results specially where GNSS availability is compromised, but velocity updates will be needed for car applications.

Way Ahead and Recommendations

Martin Bransby (Telespazio UK)
Ivan Petrunin (Cranfield University)

Way Ahead and Recommendations

Possible Further Work

There are several areas, components and features which would benefit from further work:

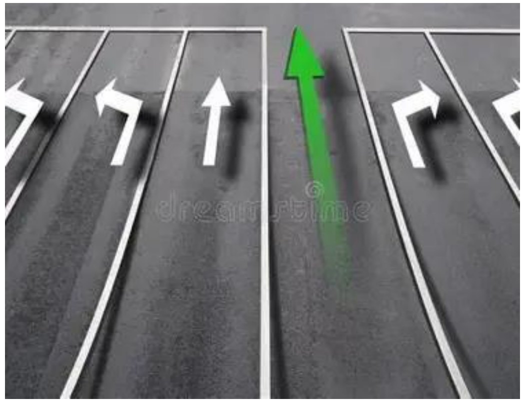
- **VTL** – Support for additional frequencies
- **Dead reckoning** – Managing weightings and errors for IMU
- **GNSS Receiver Range Processing** – Experimentation with a more sensitive receiver
- **Sensor Fusion** – Fusion of IMU, GNSS, map and velocity constraints.
- **Detector** - ML algorithms retraining is needed with real data.
- **MP Detector** – Support for predictive MP detection using 3D urban map data
- **NLOS Detector** – Incorporation of sensor fusion with additional visual data inputs
- **Jamming and Spoofing Detectors** – Exploration of context aware jamming detection
- **RAIM Module** – Development of more realistic protection level calculations as well as more refined TTA for safety critical applications.

Way Ahead and Recommendations

Potential Way Forward

A way forward has been identified, as follows:

- VTL4AV was a very challenging project, designing and developing a receiver to implement VTL techniques, including fusion with external sensors and creating a fault detection and isolation strategy to ensure integrity in urban environments, supporting multiple GNSS constellations.
- The consortium is now considering how the techniques and designs developed in VTL4AV may be used within other domains, such as drones and potentially within the maritime environment.
- There is also much interest, particularly for military applications.
- The consortium's intention is now to develop applications built around VTL4AV, utilising either internal research and development funding and/or funding through ESAs NavISP Element 2, or similar domestic funding routes.
- We also intend to collaborate with automotive companies to develop VTL-based GNSS receivers and collect some real data.
- This has a clear route to market through automotive companies and potentially other vehicle-manufacturers once the system is proven at higher TRLs.



Q&A

VTL4AV Team (Telespazio UK and Cranfield University)

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