NAVISP-EL1-057bis

ADVENT

Development of advanced VDES-R user technologies for alternative PNT

Final Presentation Review

30th May 2024

AGENDA

Introduction

ADVENT Project Introduction

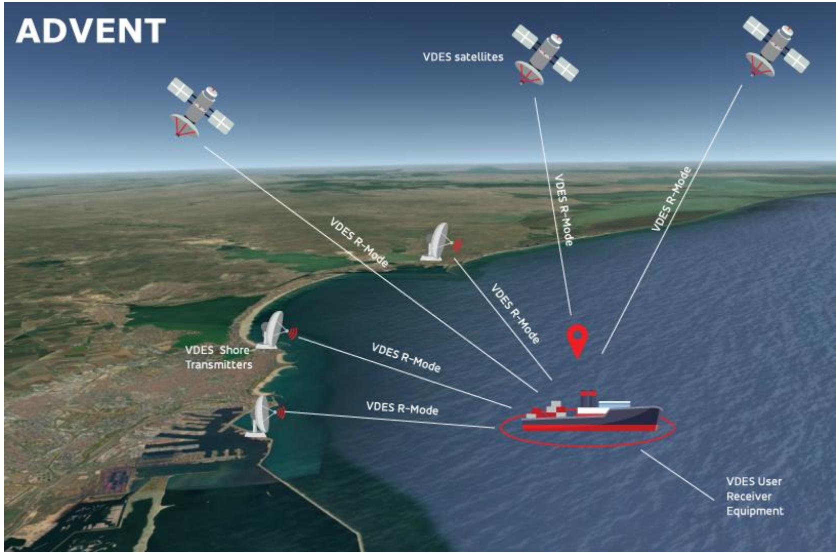
Background and Objective

Background

- The maritime VHF Data Exchange System (VDES) is being considered as a source of alternative PNT for maritime by using its ranging capability, known as VDES-R.
- Further research and demonstrations are required to progress the existing knowledge of the potential of VDES technologies within the maritime navigation domain.

ADVENT Objectives

- Investigate and prove the concepts of **novel user segment VDES technologies** to enhance key performance figures of positioning (such as **accuracy**, **integrity** and **security**).
- Complement ongoing VDES investigations to improve APNT capabilities for relevant maritime use cases.
- Investigate and analyse the impact of the **key system aspects** such as synchronisation/timing issues of VDES-R.
- Assess the alternative PNT solutions based on **VDE-SAT** in combination with **VDE-TER** services.



ADVENT Project Introduction

ADVENT Delivery Team

Prime Contractor

gmv NSL

Expertise in GNSS and complementary PNT systems and sensors

Subcontractors

RHEA GROUP

Consolidation of system & technology requirements for the PoC, preliminary design for the PoCs with the most innovative techniques.

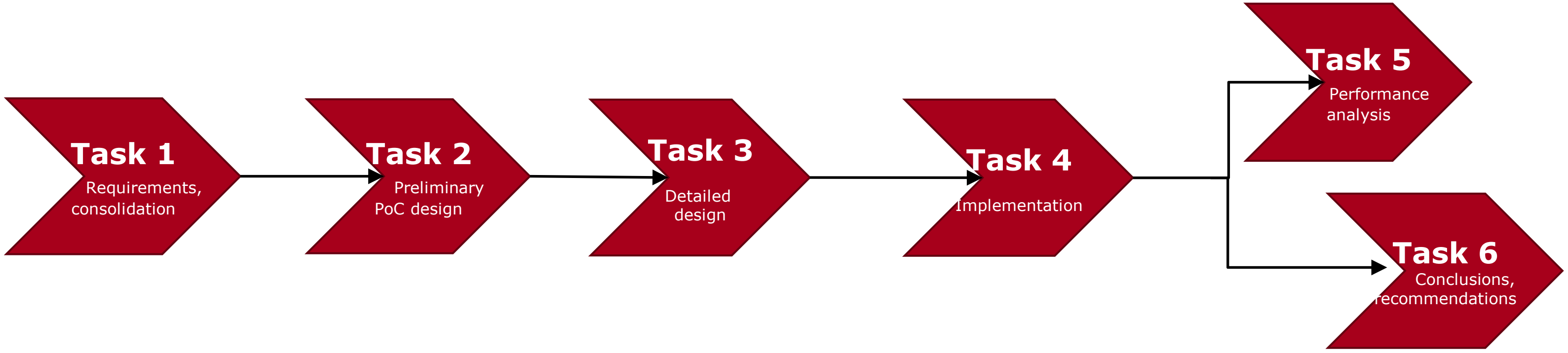
gmv INNOVATING SOLUTIONS

Support on defining use cases and on field trials, managing access to test facilities in Romania.

Activity Plan

Activity Plan

Activity Timeline Overview



Summary of Work & Achievements

Summary of Work & Achievements

ADVENT Main Achievements

- Development of a VDES-R system simulator that can generate VDES signals including timing aspects, timeslot allocation, clock offsets, signal time of flight, and Ionospheric delays.
- Development of a PoC testbed for terrestrial VDES-R based on Software Defined Radios (SDRs).
- Field trial on the Black Sea near the port of Constanta in Romania to deploy VDE-TER stations, transmit a VDES signal, and collect meaningful VDES data in a land and sea set-up (valid pseudoranges, suitable for positioning).
    - The collected data has then been used for assessing the performance of the developed ADVENT PoC.
- The trial results showed a dependence on good geometry and CN0.
    - For the terrestrial only and the augmented case, the 2D solution provided an overall accuracy of <50m (1sigma).
    - The TER case used real trial data while the TER+SAT included additional SAT error modelling (ionospheric delays, orbit and clock errors, link fading and ITU-R M.2092 link ID 33).
- Recommendations for a further enhancement of the ADVENT VDES-R prototype developed as well as a roadmap for enabling technologies required to allow the VDES system to support a future PVT service.

Summary of Work & Achievements

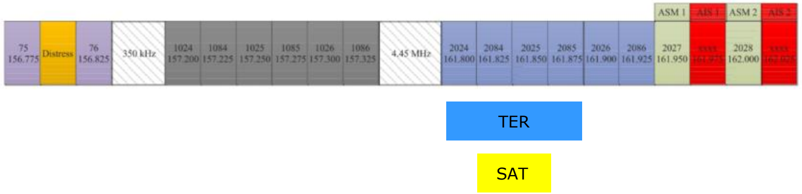
ADVENT System Design Trade-offs in VDES-R mode selection

- Analysis of the IALA G1158 ranging signal and navigation data informs the evaluation of the existing VDES signal specification (ITU-R M.2092-1).
- Key trade-offs in VDES-R system design encompassed modulation techniques, data sequences, channel capacity for R-mode, bandwidth and transmission duration, oscillators for time synchronisation, UE power requirements.
- Trade-offs performed to assess various baseband algorithms and positioning techniques to be implemented.
    - Programmatic trade-off criteria: cost, external constraints, implementation complexity, and hardware availability.
    - Technical trade-off criteria: spectrum usage, multipath handling, signal resilience, scalability, accuracy, coverage, availability, maturity.
- Existing experimentations such as the R-Mode Baltic, Orbcomm VHF satellite test, and the ICING project on NORSAT-TD provided valuable insights for assessing PNT technique trade-off criteria and System Design.
- Time-of-Arrival (TOA) and Hybridisation are identified as suitable PNT techniques.
- Antenna diversity algorithms are identified as suitable techniques for baseband implementation.

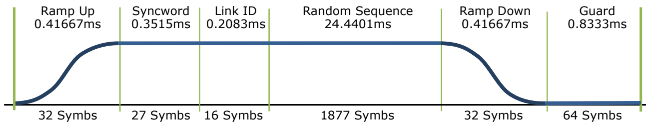
Summary of Work & Achievements

VDES Technical Characteristics

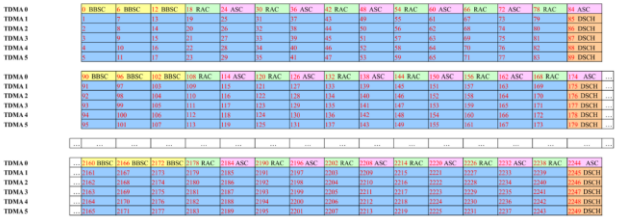
ITU-R M.2092-1 Channels Used



TER Packet Definition

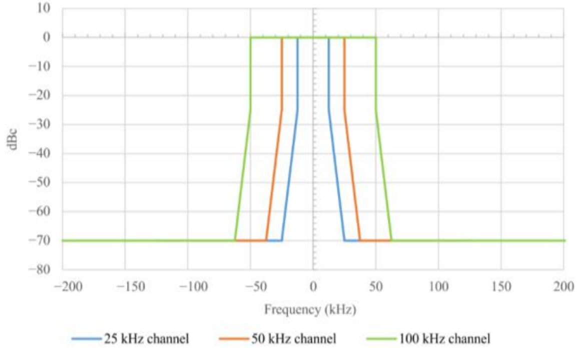


VDES Timeslot Definition



There are 2250 timeslot in every 60s

ITU VDE-TER Transmission Mask



Summary of Work & Achievements

ADVENT System Design

Terrestrial System

- Link ID 37 (as defined in ITU-R M.2092-1) was selected:
  - 100KHz bandwidth
  - Pilot channel using a pilot signal PRN ranging code
  - Pi/4 QPSK modulation
  - One timeslot of 26.6ms
- Ranging packets are transmitted every second for all stations
- Three stations were used so that trilateration of the signal TOA can be used

Satellite System

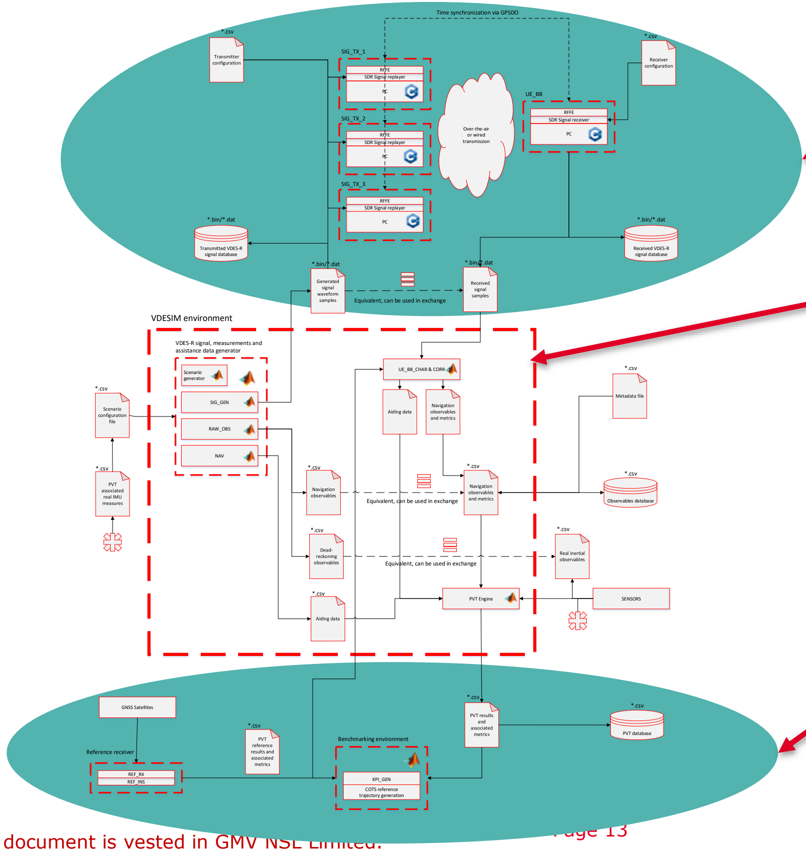
- Link ID 33 (as defined in ITU-R M.2092-1) was selected:
  - 50KHz Bandwidth
  - Pilot channel using a pilot signal PRN ranging code
  - BPSK Modulation
  - 15 Timeslots of 26.6ms (400ms total)
- Ranging packets are sent every 15s from all satellites
- Constellation defined to provide between 3 and 4 visible satellites over the globe
- An orbital height of 600km was used.

PVT Engine

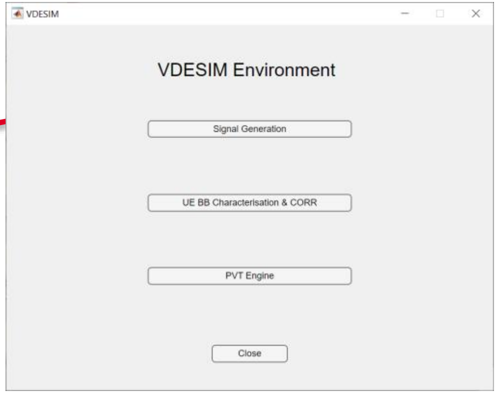
- The PVT Engine used a tightly coupled EKF with IUM and TOA measurements

Summary of Work & Achievements

ADVENT System Design



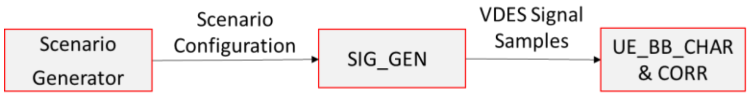
Trial/ Lab Set up



Performance Evaluation

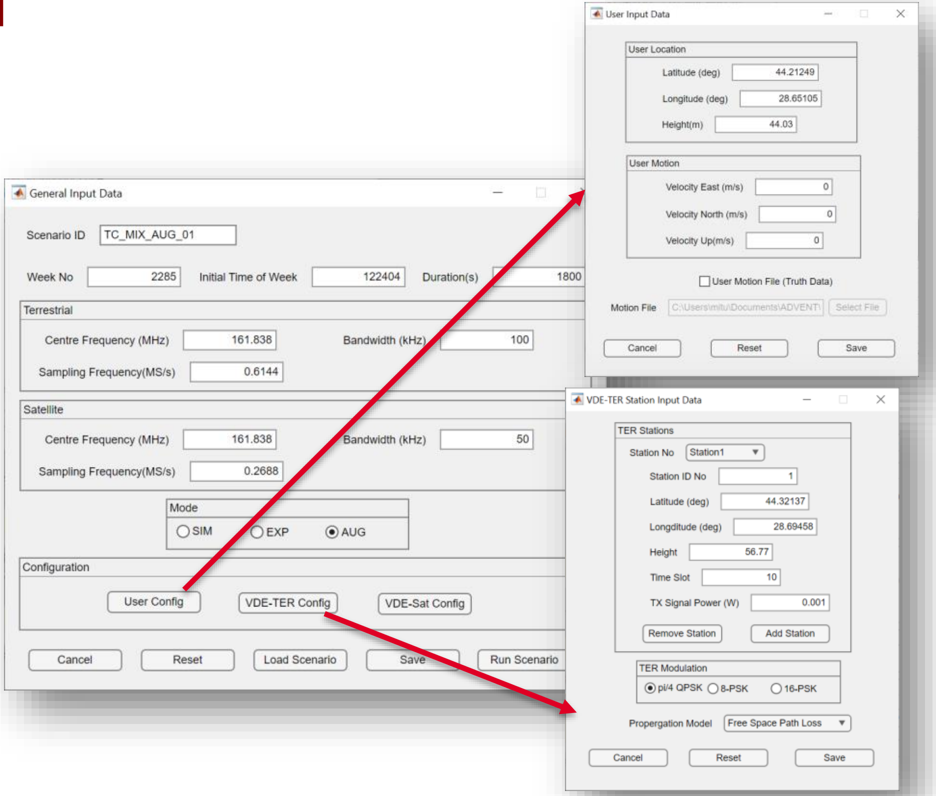
Summary of Work & Achievements

Implementation Overview: Module SIG_GEN



- The SIG_GEN module within the VDESIM environment is responsible for generating VDE signal samples.
- This module can utilize the truth data file from the reference GNSS receiver to define the scenario trajectory and it produces a VDE binary file as output.
- It operates in three modes: Simulated mode (VDE-SAT), Experimentation mode (VDE-TER), and Augmentation Mode (both VDE-SAT and VDE-TER).
- The generated VDE signal samples file contains the signal waveform and is accompanied by a CSV-format metadata file containing VDE signal details.
- The VDE-generated signal samples file follows the specifications as detailed:

Specification	Description
Bit depth	16 bits
I/Q format	Interleaved I/Q
Sampling rate	Dependant on symbol rate and the SDR sampling capability
Centre frequency	161.8375 MHz



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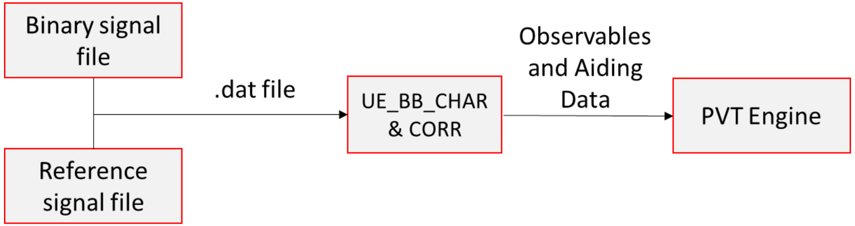
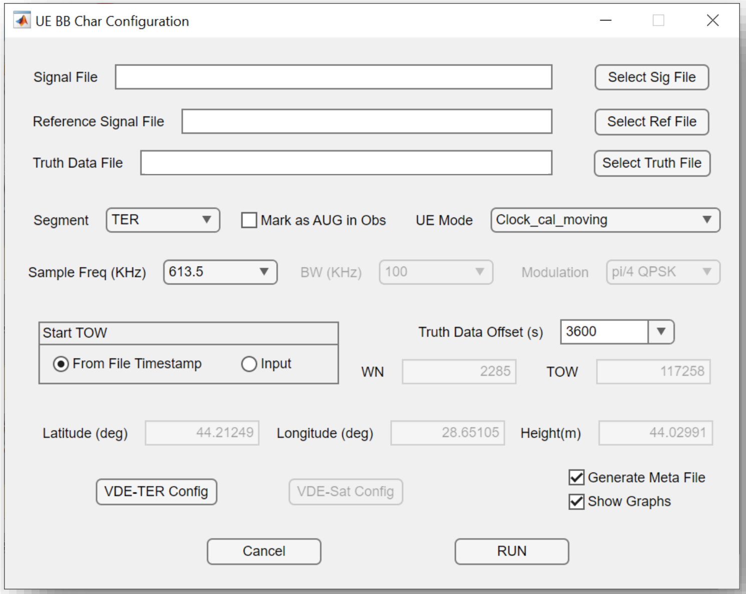
Summary of Work & Achievements

Implementation Overview: Module UE_BB_CHAR & CORR

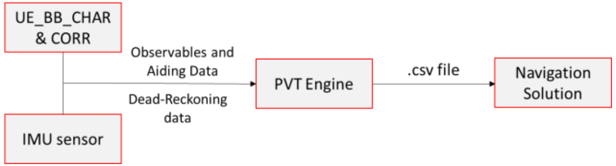




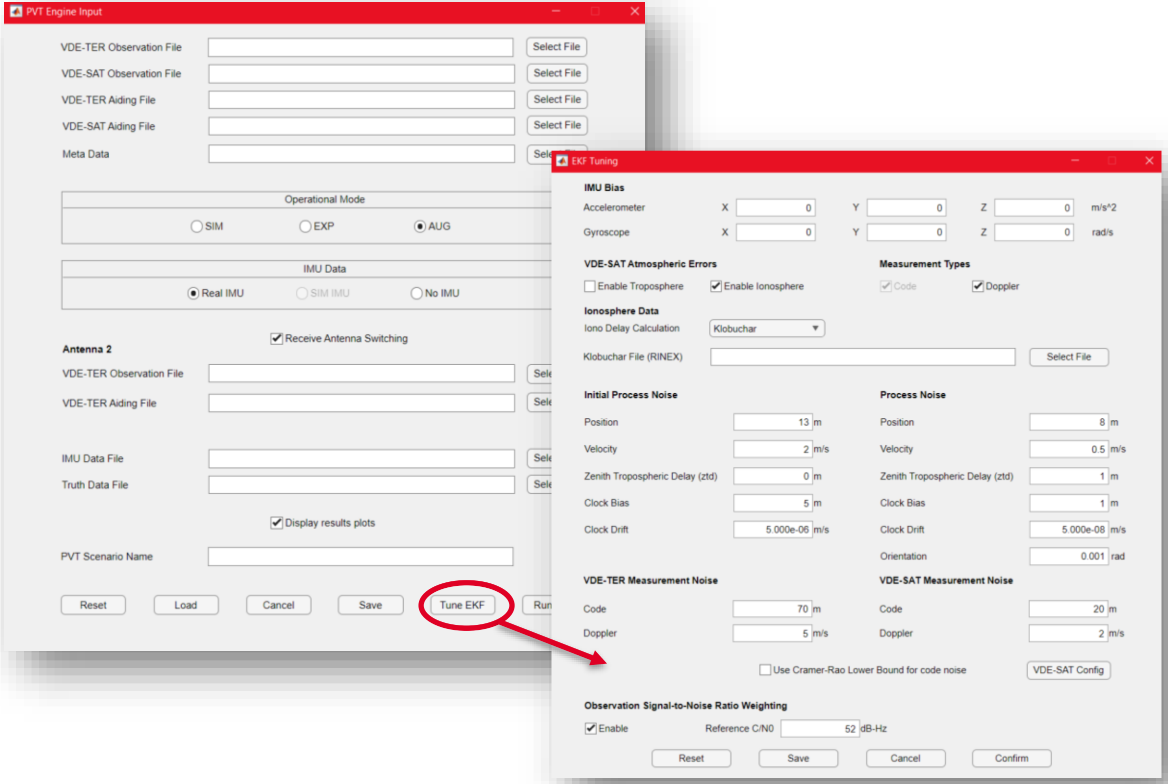
- The "UE_BB_CHAR & CORR" module is responsible for the baseband processing i.e., acquisition and tracking of VDE signals.
- It accepts input signals from either the simulated waveform (VDE-TER or VDE-SAT) generated by the SIG_GEN module or from VDE-TER captures e.g. in the sea-trial scenarios.
- The UE mode can be configured differently for dynamic or static scenarios in this module. This configuration is needed to determine the truth data so a clock correction model can be calculated for the aiding file.
- Observables are generated such as code delay, Doppler, and CNo, for processing in the PVT Engine.
- Aiding data encompasses clock offset, TER/SAT station position and velocity, to facilitate the PVT Engine's computation of the receiver solution.

Summary of Work & Achievements

Implementation Overview: Module PVT Engine



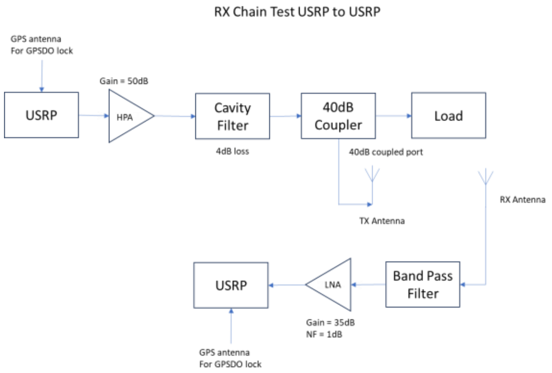
- The PVT Engine module processes the VDES-R observables with Aiding Data and inertial measurements from IMU to generate the navigation solution (position/velocity and standard deviation, HDOP).
- Initial position/velocity states using integrated GPS on the IMU sensor.
- Final solution performance assessed against dual frequency GNSS PPP truth data.
- A final position is obtained through a tightly coupled IMU in an Extended Kalman filter (EKF).
- Can be configured with Antenna Diversity, VDE-SAT ionospheric delay and observation CN0 weighting.

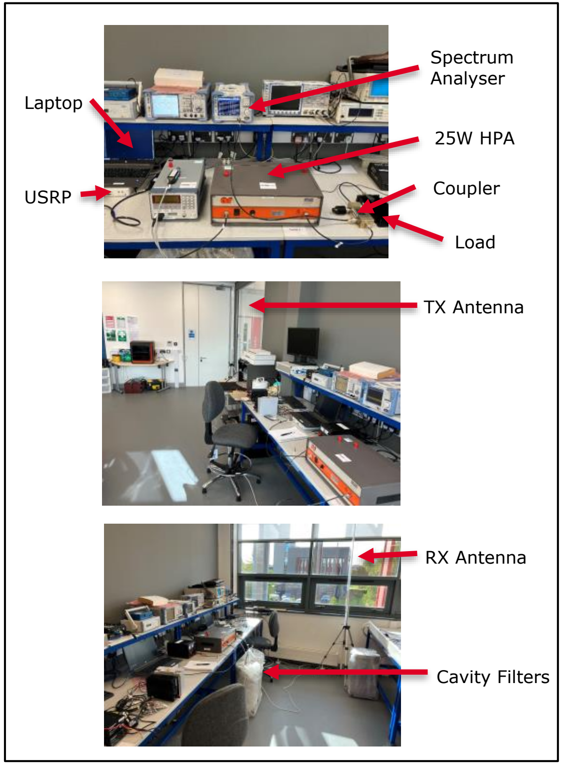


Summary of Work & Achievements

ADVENT ETB Validation: TX Chain, RX Chain, and End-to-End test

- The ETB validation aimed to confirm hardware compliance with the performance criteria and ITU standards.
- Validation and sea-trial utilised:
  - Ettus X300 fitted with UBX40 daughter board and GPSDO oscillator
  - Transmitted & Receive data: 16-bit IQ format
  - HPA: 25W, 50W and 100W amplifiers
  - Maximum licence power was 12.5W but was limited to 1W in the sea trial to ensure margin & linear operation.
  - TX Resonant cavity filter to limit TX spectrum
  - RX filter covered the full VHF band
- Precise synchronisation ensured through both USRPs linked to GPS Disciplined Oscillators (GPSDO)





Lab setup

Summary of Work & Achievements

ADVENT ETB Validation: Truth Data and IMU

Truth Data

- The reference receiver for the experimentation campaign was the NovAtel PwrPak 7D-E2, featuring an embedded Epson G370 MEMS Inertial Measurement Unit for SPAN data generation in GNSS/IMU integration.
- Connected to a NavXperience 3G+C Maritime GNSS antenna
- Post-processed PPP with dual frequency, multi-constellation GNSS
- A static test near the GMV Nottingham office validated the reference receiver’s accuracy with stable position accuracy below 0.5 m standard deviation in East-North-Up body frame coordinates.

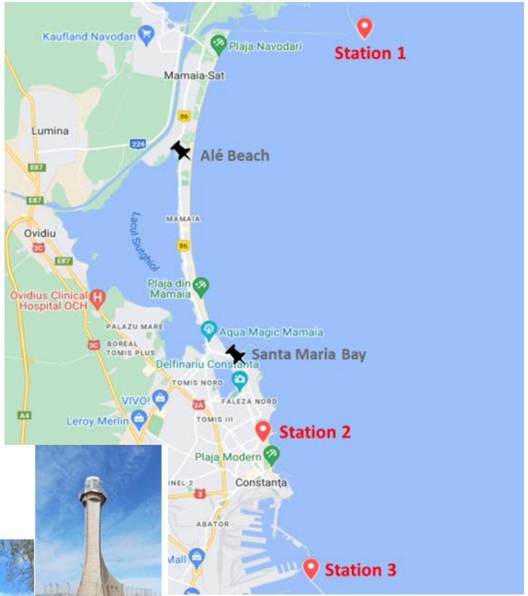
IMU

- XSens MTI-7 IMU sensor used, including an integrated GPS sensor.
- Time synchronisation for PVT solution computation was achieved by using the GNSS 1PPS signal from the integrated U-Blox M8 receiver.
- Stationary data captured in GMV Nottingham lab to validate sensor data.
- The velocity data showed a Root Mean Squared Error (RMSE) of 0.013 m/s for a stationary sensor.
- Despite sporadic peaks, accelerometer measurement remained relatively stable, with an RMSE of 0.04 m/s2, attributed to the industrial-grade quality of the IMU and the specified sensor noise density.

Summary of Work & Achievements

ADVENT Black Sea Trial Overview

- The ADVENT field trials took place in Romania from 12th – 26th October 2023.
- Objectives included the successful installation of the VDE-TER stations in the designated locations, transmissions of VDES signals, and collection of meaningful VDES data for PVT post-processing.
- Trials were conducted in two settings: land and sea. Land tests served to validate stations' setup and ensure proper operation, while sea tests aimed to gather data for dynamic scenarios.
- The map illustrates the relevant land (static) locations used.



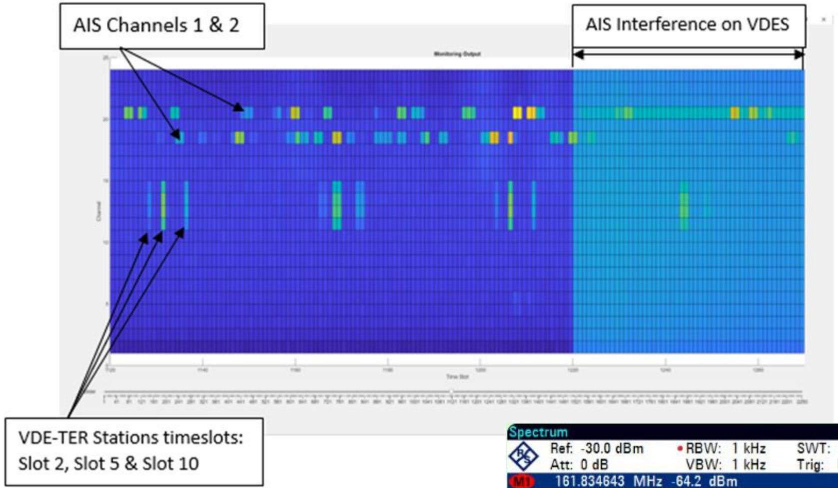
Ale's beach antenna setup

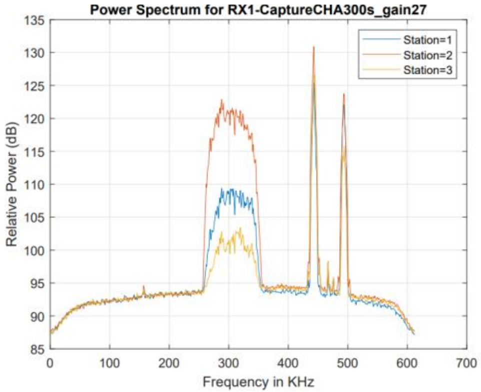
Santa Maria bay antenna setup

Summary of Work & Achievements

ADVENT Black Sea Trial Tx Set-up

- The field trials captured received IQ data, IMU data for input to the PVT Engine, and GNSS reference data for performance analysis.
- Each TX station position was surveyed by capturing approximately 1-minute of GNSS data. The data was processed using PPP in NovAtel Inertial Explorer, resulting in a standard deviation of approximately 0.5 meters.
- Six scenarios were successfully recorded during the sea trial.
- The proximity of AIS frequencies explains the presence of high-magnitude signals alongside VDES signals observed during the field trial. Other wide band VHF interference was also present.
- Station 1 was synchronised with the 10th slot, Station 2 with the 5th, and Station 3 with the 2nd slot relative to the 1s epoch.
- The slot designation was selected for the clear visibility of the stations.

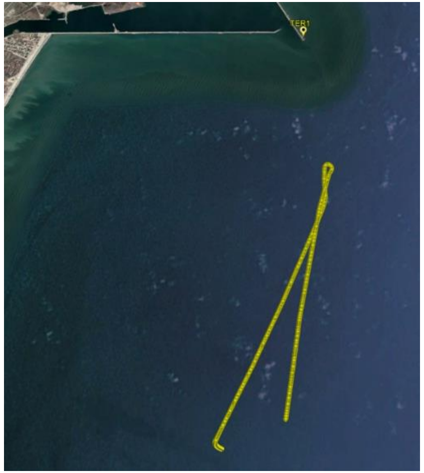




Summary of Work & Achievements

ADVENT Black Sea Trial Scenarios

Test ID	Description	Duration
1	"Static" with drift caused by sea motion.	30 minutes
2	Dynamic motion. Includes linear motion, heading turn and another linear motion.	30 minutes
3	"Static" with drift caused by sea motion. Repeat of Test 1 at similar location.	20 minutes
4	Deleted as receiver lost synchronisation due to interference	NA
5	Dynamic. Circular motion in to linear with return to Port.	30 minutes
6	Dynamic. Approach to Port.	20 minutes
7	Dynamic. Continuation of Port approach and Docking.	20 minutes



Scenario ID #2

Scenario ID #5

Scenario ID #6

Scenario ID #7

Summary of Work & Achievements

Assumptions

The following results are presented to show the main achievements:

VDE-TER, IMU

- VDE-TER using Link ID 37 and 1W of TX power
- VDE-TER measurements from sea-trials (3x Transmitters)
- Processing with and without Antenna Diversity (switched diversity based on RX SNR only)
- Tightly-coupled IMU in EKF
- Time-of-Arrival PNT technique

VDE-SAT, IMU

- VDE-SAT using Link ID 33 at 600km orbital altitude and 0.6W EIRP on a Isoflux antenna
- Observations interpolated to 1 sec epochs (min. 3 sats in view)
- Ionospheric delay modelled with IONEX at signal generation, Klobuchar at user PVT
- Orbit and Clock error modelled (1m and 12.8m mean error, respectively)
- Log Normal Fading (4.2 dB)
- Tightly-coupled IMU in EKF
- Time-of-Arrival PNT technique

VDE-TER, VDE-SAT & IMU

- VDE-TER ID 37 from sea-trials augmented with VDE-SAT using Link ID 33
- Antenna Diversity
- Tightly-coupled IMU in EKF
- Time-of-Arrival PNT technique
- Ionospheric delay, orbit and clock and Log Normal Fading on VDE-SAT
- Non-interpolated VDE-SAT observations (mean of 1 to 2 satellites in view)

Summary of Work & Achievements

Results: VDE-TER only + IMU, Scenario ID 7

- Scenario 7 was challenging for navigation due to large VHF interference.
- Captured data from two antennas mounted on the test vessel during the experiment test campaign.
- Implemented antenna diversity algorithm in the PVT calculation for the terrestrial case, to enhance availability.
- Improved availability (58%→73%) of VDES-R measurements was achieved through the implementation of the antenna diversity.
- Mean error not improved, but decreased standard deviation of positions.
- The IMU sensor led to significant drift, especially under heavy saturation on both antennas caused by Station 3 observations.

Without Antenna Diversity

With Antenna Diversity

No Diversity

Position error statistics for VDE-TER, SCE -7

Overall Positional Errors (m)					
Mean	153.81	**Std Dev**	126.75	**Max**	611.01
East/West Positional Errors (m)					
Mean	-105.81	**Std Dev**	88.51	**Max**	195.76
North/South Positional Errors (m)					
Mean	-80.22	**Std Dev**	119.39	**Max**	589.22
VDES-R Availability: 58.1%					

With Diversity

Position error statistics for VDE-TER, using Antenna Diversity, SCE -7

Overall Positional Errors (m)					
Mean	153.913	**Std Dev**	92.291	**Max**	627.008
East/West Positional Errors (m)					
Mean	-120.471	**Std Dev**	79.150	**Max**	491.73
North/South Positional Errors (m)					
Mean	-85.147	**Std Dev**	64.622	**Max**	389.02
VDES-R Availability (%): 73.11					

Summary of Work & Achievements

Results: VDE-SAT only + IMU, Scenario 2

- The VDE-SAT mode relies only on VDE-SAT R-Mode with aiding from an IMU.
- Satellite CN0 ranged between 50- and 55-dB Hz in this scenario.
- To simulate additional errors, ionospheric delay estimation from IONEX maps was incorporated into signal generation, mitigated at the user PVT level via the Klobuchar model.
- Additionally Log-Normal Fading of 4.2 dB was introduced to the VDE-SAT signal, along with mean orbit and clock errors (1m and 12.8 m) applied to the aiding data.
- The dominant error source in the position results is the effect of the ionosphere.

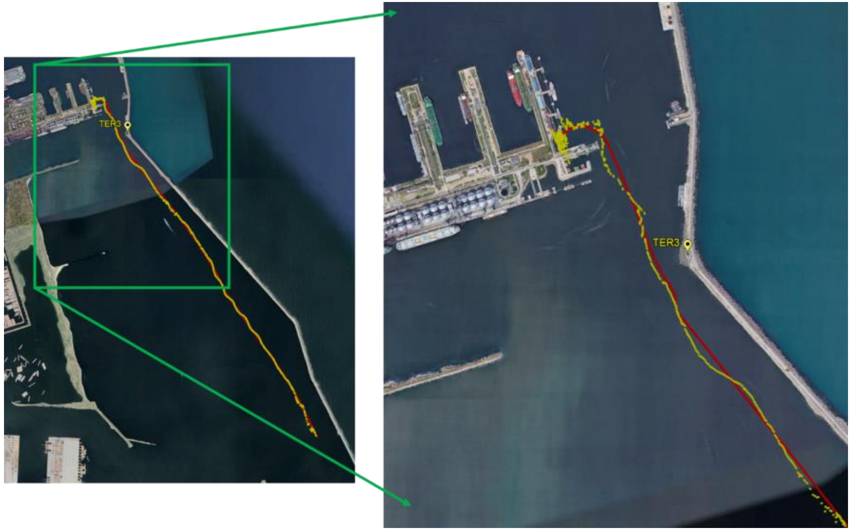
Position error statistics for VDE-SAT, with Ionospheric error, SCE -2

Overall Positional Errors (m)					
Mean	539.941	**Std Dev**	621.374	**Max**	2593.268
East/West Positional Errors (m)					
Mean	-10.331	**Std Dev**	102.190	**Max**	291.556
North/South Positional Errors (m)					
Mean	29.026	**Std Dev**	271.034	**Max**	1121.661

Summary of Work & Achievements

Results: VDE-SAT and VDE-TER, Scenario 7

- The augmentation mode which combines both sources of VDES-R measurements (VDE-TER and VDE-SAT) with aiding from an IMU.
- The received satellite CN0 for the scenario was between 50- and 55-dB Hz for the satellites and between 50- and 65-dB Hz for the Terrestrial stations.
- The availability of 3 or more VDES-R observations is greatly increased due to adding the VDE-SAT measurement to the VDE-TER data (with Antenna Diversity).
- Position error and Standard deviation are significantly improved compared to the VDE-TER only case.



Overall Positional Errors (m)					
Mean	153.81	Std Dev	126.75	Max	611.01
East/West Positional Errors (m)					
Mean	-105.81	Std Dev	88.51	Max	195.76
North/South Positional Errors (m)					
Mean	-80.22	Std Dev	119.39	Max	589.22
VDES-R Availability: 58.1%					

Position error statistics for VDE-TER only, SCE -7

Overall Positional Errors (m)					
Mean	53.434	Std Dev	44.078	Max	279.411
East/West Positional Errors (m)					
Mean	-5.666	Std Dev	12.481	Max	63.02
North/South Positional Errors (m)					
Mean	-0.205	Std Dev	21.622	Max	101.40

VDE-TER, VDE-SAT, and IMU positioning results, SCE -7

Main Conclusions & Way Forward

Main Conclusions & Way Forward

PoC Testbed Enhancements

Future VDESIM Enhancements

NorSat Configuration
Configure VDESIM to model other system configurations, e.g. NorSat-TD.

Combining Diversity Implementation
Implemented inside PVT Engine, at pseudorange level.

Yagi Antenna
Isoflux currently used, Yagi is specified for VDE-SAT in the ITU-R M.2092 specification

Bandwidths/Modulations
Adapt VDESIM to simulate other configurations from the ITU standard.

Single-Node Positioning
Implementation of PNT Techniques such as Multi-Epoch Doppler & Two-Way Ranging.

Standard Timeslot Numbering
Apply slot numbering consistent with VDE TDMA frame structure.

Bulletin Board
Design bulletin board message to include transmitter information to the users.

Main Conclusions & Way Forward

Way Forward

System Tools

Trade-off analysis tools covering satellite constellation, signal design, PVT performance and system capacity

System Testbed

Long-term trial system to allow development, enhancements and system evolutions

Commercial Equipment

Prototype user terminals and TER transmitter stations, prioritising single enclosures, real-time operation, and configurable software.

In-Orbit Test Satellites

VDESim testing with real SAT signals with real-time processing. Characterisation of ionospheric delay and Bulletin Board

Test Equipment

End-to-end simulations with testing tools, equivalent to GNSS RF Constellation Simulation. Used for signal generation and user terminal characterisation.

Questions & Answers

Thank you

ADVENT Team

For further details and the ADVENT activity contact: Maria.Ivanovici@gmv.com