NAVISP-EL1-046

GLOWS

Combining ELF with GNSS for improved PNT

Final Presentation

13/11/2023

Agenda

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Foreseen way forward

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Introduction

Project objective

- The need for a robust Position, Navigation and Timing (PNT) system to complement or back up GNSS in critical infrastructure/critical application is widely acknowledged.
  - Renewed interest has appeared for ELF, VLF and LF systems, such as eLORAN or PTB.

> "[…] As the role PNT solutions in safety-critical operations increases, the users' demands in terms of performance and trust grow past the point in which a single-system approach can meet all requirements."
>
> GLOWS Proposal

Objective of the contract

- To study and develop and innovative, robust and reliable PNT concept based on ELF, VLF and/or LF techniques, able to complement GNSS-based services and to provide an alternative in case of outage.
  - Review relevant ELF/VLF/EF state-of-the-art.
  - Trade-off potential implementation.
  - Develop and assess a proof-of-concept.

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Accomplished work

- **Key requirements, uses cases and traded-off techniques**
- **OMICRON 2.0 design**
- **Obtained results**

Foreseen way forward

Questions and Answers

Accomplished work

Key requirements, use cases and traded-off techniques (1/2)

- A set of relevant PNT use cases were defined for the developed technology

Enhanced PNT service (coverage, resilience) for handheld devices	Low-energy positioning	Local enhanced-low-energy positioning for below ground transport and emergency services	Resilient PNT for airborne users
Alternative Timing Service	Enhanced PNT service for maritime users	Global positioning service	

- Then, set of derived requirements were derived in order to trade-off techniques and system concepts

Requirement	Acceptable	Target	Exceed	Domain (Environment)
Coverage	Local	Regional	Global	All (use case dependent)
Position/location accuracy	100m	10m	1m	All
Timing accuracy	2.5e-7	4e-8	1e-11	All
Time to first fix (TTFF)	10 sec	2 sec	2 sec	Land, Sea
Time to first fix (TTFF)	180 sec	10 sec	2 sec	Below ground, Air
Integrity, Availability, Continuity	<10e-3	<10e-5	<10e-6	All

Accomplished work

Key requirements, use cases and traded-off techniques (2/2)

- Lastly, a set of relevant state-of-the-art techniques were analysed and trade-off, considering:
  1. Benefits of each technique
  2. Drawbacks and limitations
  3. Achievable performance based
  4. Areas where the method or techniques could be improved
  5. Already-existent infrastructure for its implementation

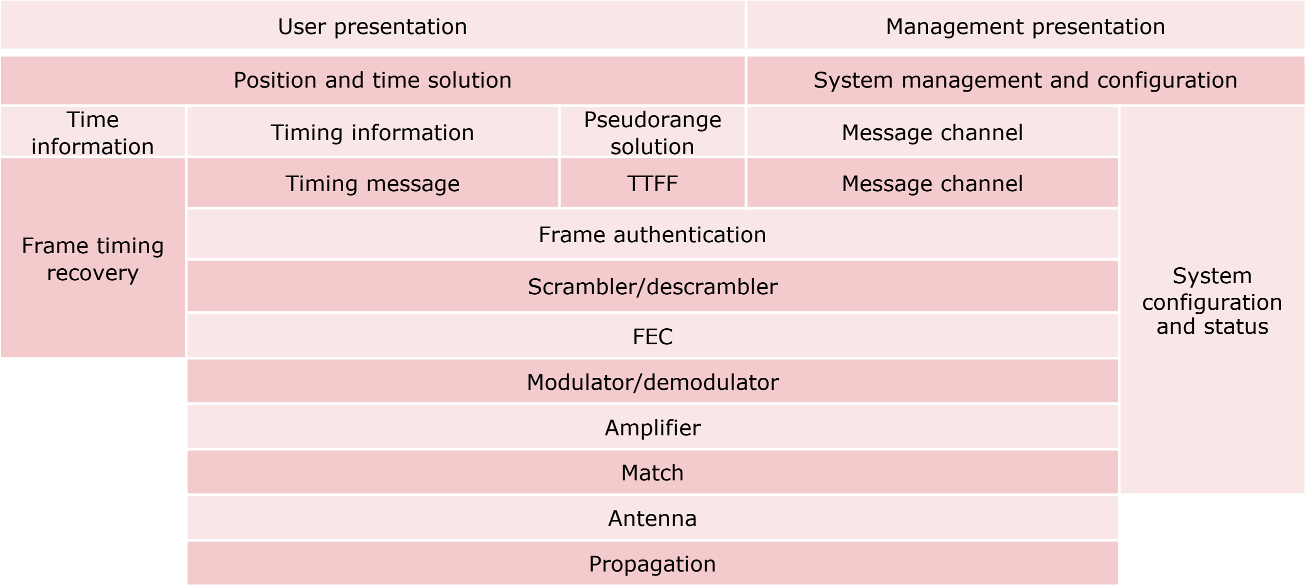
Equi-signal homing	Multiple, directionally transmitted signals from a single location	Timing service
TOA/AOA/Triangulation	Pulse type Hyperbolic navigation	Multi-frequency, multi-transmission, multiple location

Selected technique for implementation

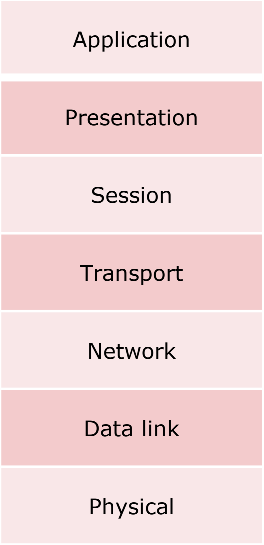
Accomplished work

OMICRON 2.0 design

- The OMICRON 2.0 waveform protocol stack follows the broadly known OSI model



OMICRON 2.0 reference architecture



OSI model

26/09/2023

Accomplished work

OMICRON 2.0 design – physical layer

- The physical layer of OMICRON 2.0 describes:
  - The propagation and path loss models.
  - Antenna specification; (implementation dependent).
  - Antenna matching requirement; (implementation dependent).
  - Amplifier (and filter) requirements for transmit and receive; (implementation dependent).
  - Modulation and demodulation.
  - Forward Error Correction (FEC).

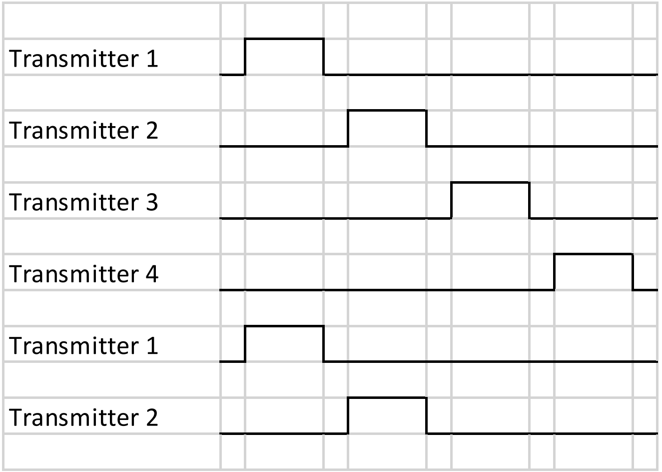
- Key aspects of the physical layer are presented in the table below

Operates in ducted mode between Earth and ionosphere (allows for phase-stable transmissions at large distances, ~ 4000 km)	Four frequencies are used (7.5 kHz, 8 kHz, 8.5 kHz, 9 kHz)	Modulation selected corresponds to 4-4MFSK
The usage of four frequencies improves J/S margin at receiver via processing gain	The selected frequencies allow for ground penetration of PNT signals	FEC selected is a Reed-Solomon code

Accomplished work

OMICRON 2.0 design – data link layer

- The physical layer of OMICRON 2.0 describes:
  - Slotted transmission
  - Omicron 2.0 Waveform (O2W) physical layer frame
  - Scrambler/descrambler
  - Source authentication
  - Timing message/TTFF/message channel transmit and receive



Example of a generic slotted transmission sequence

- Key aspects of the physical layer are presented in the table below

Multiple transmitters are needed in order to allow for position computation	Each slot transmission has three fields: timing channel, TTFF data and message channel	Timing channel carries an Open Time Signal-type information
Slotted approach is used for transmission	Message contains node primary authentication, message integrity, ionosphere parameters, (optionally) secondary authentication	Scrambling and descrambling are implemented via AES-128 Cipher Feedback (CFB) encryption or Galois Counter Mode (GCM)-128 bits

Accomplished work

OMICRON 2.0 design – network, transport and session layers

- The O2W network layer makes use of the transport layer bidirectional message passing between transmission sites.

- Each node is allocated a unique node ID, used to generate the AES scrambling key.

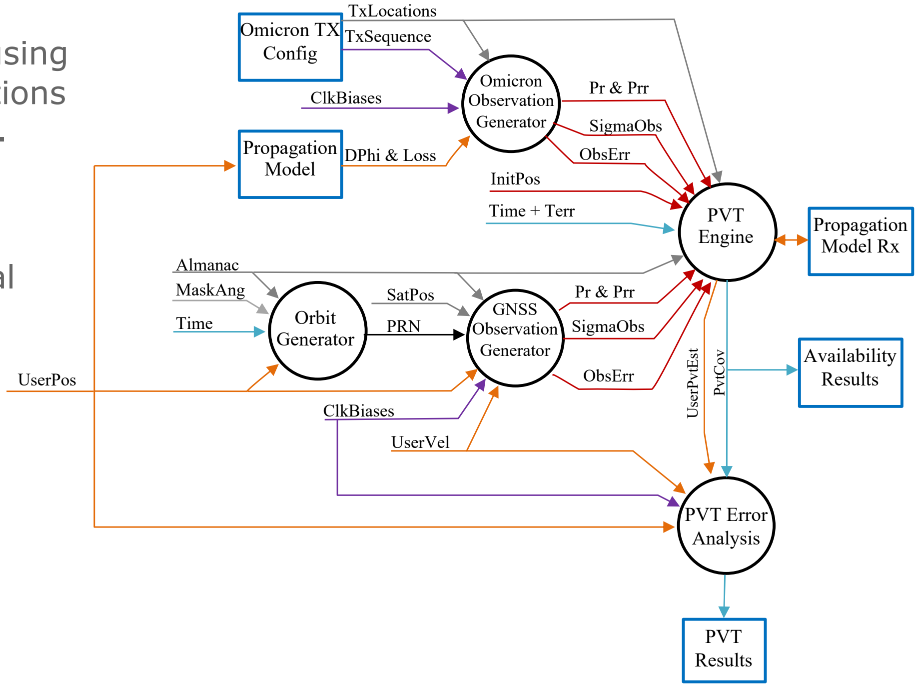
- AES keys are assumed to be pre-placed for this study, but options are proposed:
  - AES-CFB with Message Authentication Code (MAC), which could be carried in the message channel.
  - Use of hashed data, digital signatures or HMAC.
  - Use of public asymmetric key options e.g. ECDSA.

- For enhanced security against spoofing (meaconing) attacks, transmitters reset the AES key every 24 hours to reset the CFB/GCM.

Accomplished work

OMICRON 2.0 design – presentation and application layer

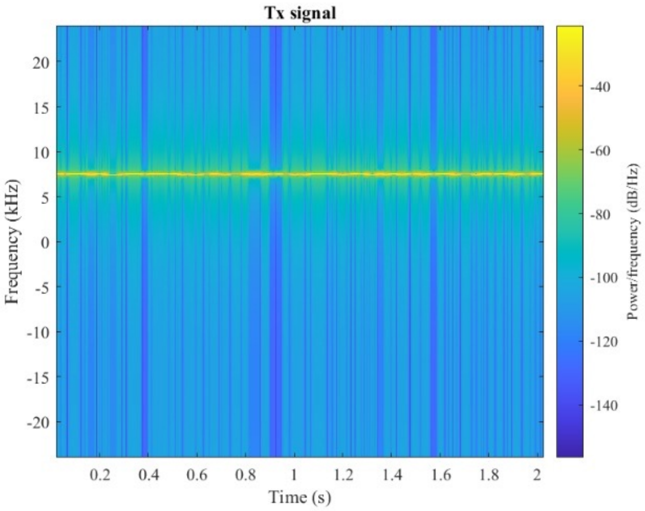
- OMICRON 2.0 waveform is responsible for solving for user position, velocity and clock using pseudorange and pseudorange rate observations as a conventional Least Squares (LS) engine.
- The engine also supports the integration of GNSS observations and estimation of residual phase propagation errors.

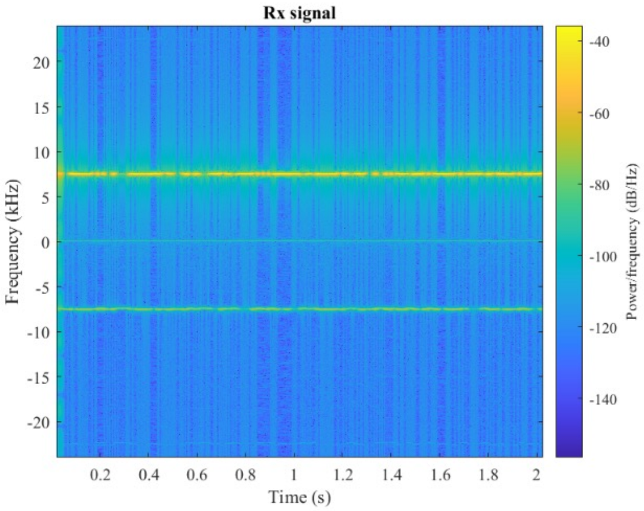


Accomplished work

Obtained results – overview

- In order to verify the OMICRON system, a lab setup was used.
- A single frequency channel (7.5 kHz) was used to validate the concept.





Accomplished work

Obtained results – overview

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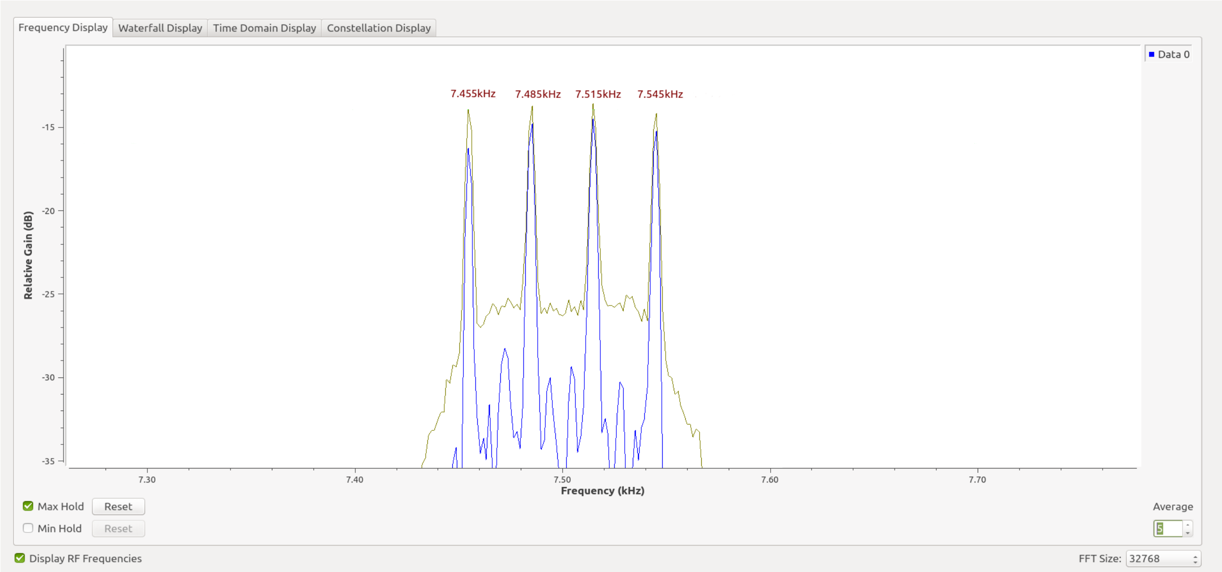
- 4-FSK signal transmitted in the 7.5 kHz channel depicted below. Each channel comprises a 4-FSK signal.



Accomplished work

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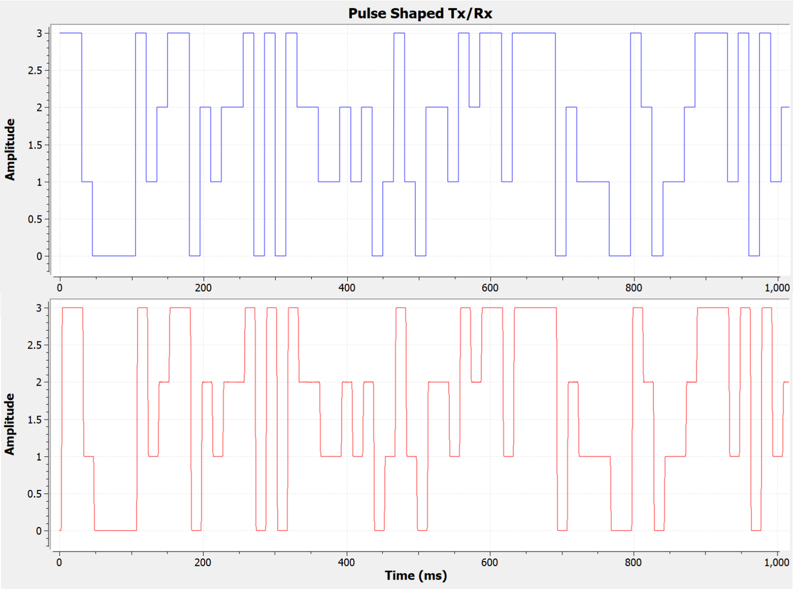
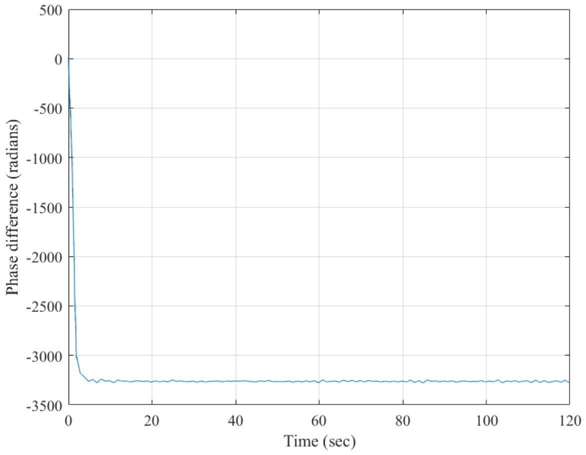


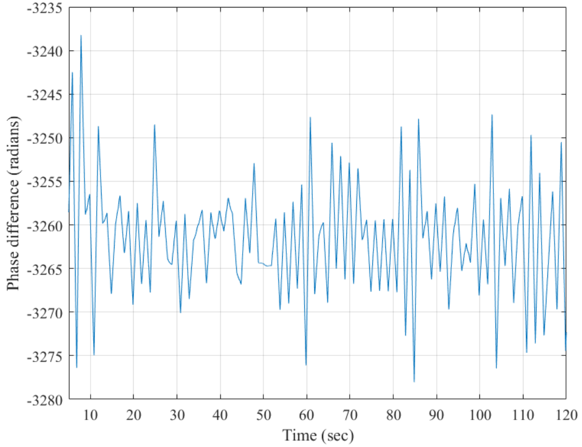
Transmitted and received symbols

Accomplished work

Obtained results – testbed synchronization

- In order to test the testbed synchronization capability, the transmitters were fed with a 10 MHz reference signal, output from a CSAC (SA.45S).
- The impact of clock synchronization was evaluated by computing the instantaneous unwrapped phase difference between the transmitted and received signals.
  - This was done with 10 MHz reference, 1 pps reference and free drift
- Results show that phase differences are large, so in this state pseudorange-based carrier position would not be possible.

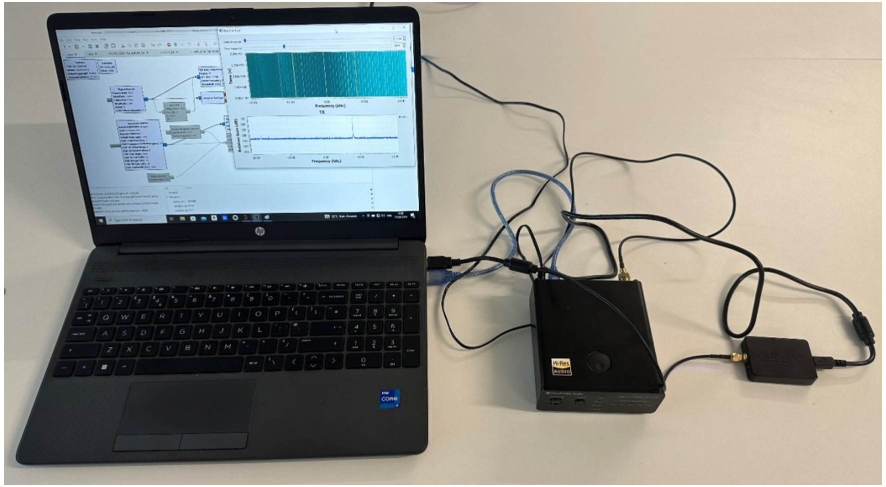




Accomplished work

Obtained results – change of design (1/4)

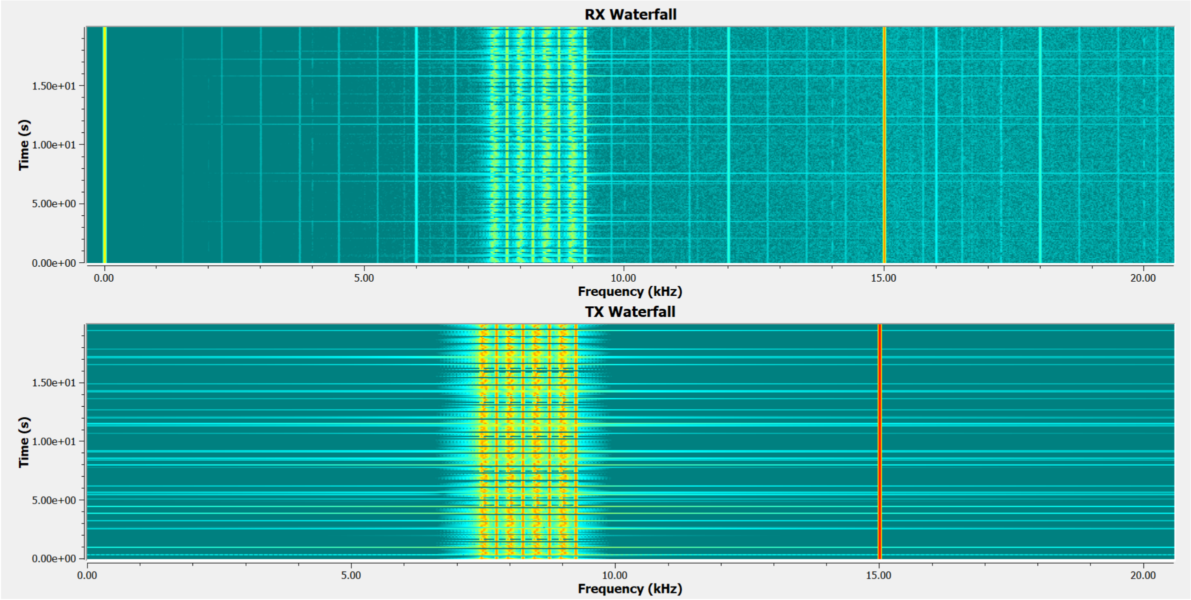
- Due to the mentioned synchronization problematic and others that appeared, which directly affect positioning, it was decided to modify the initially proposed design by using a pilot signal.
- Pilot signals are placed 240 Hz above the 4FSK central frequencies: at 7740, 8240, 8740 and 9240 Hz.
- To compensate for the poor clock stability of the TX/RX, a global pilot signal at 15 kHz was introduced to enable clock instability compensation.
  - This global pilot is a property of the testbench only, as it is assumed that an OMICRON system would employ more stable transmit and receive clocks.



Testbed used for the validation of the design change

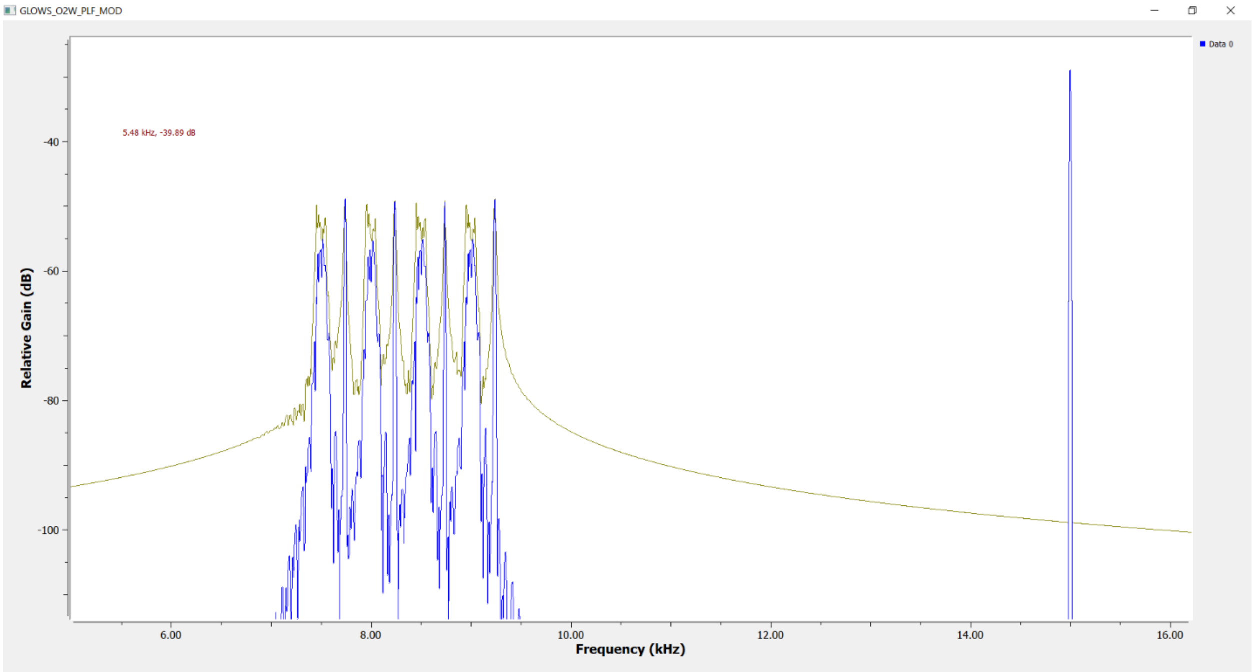
Accomplished work

Obtained results – change of design (2/4)



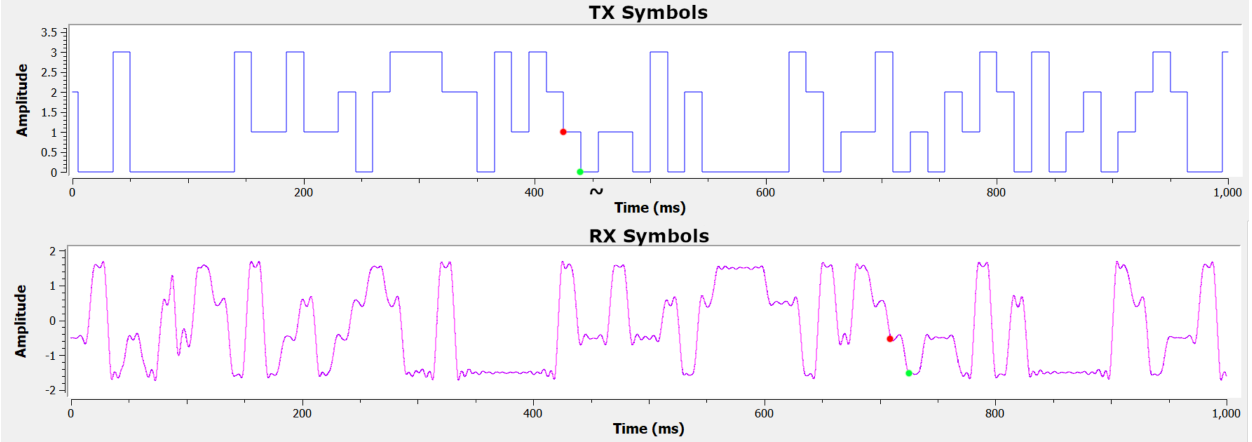
Accomplished work

Obtained results – change of design (3/4)



Accomplished work

Obtained results – change of design (4/4)



Accomplished work

Obtained results – positioning service results

- A Least Squares positioning engine was initially developed and demonstrated to converge to the correct 2D position when fed with synthetic data.

- When PLL-derived pseudoranges were employed from an end-to-end test and integer ambiguities corrected the position solution converged but with a large positioning error (in the order of km).

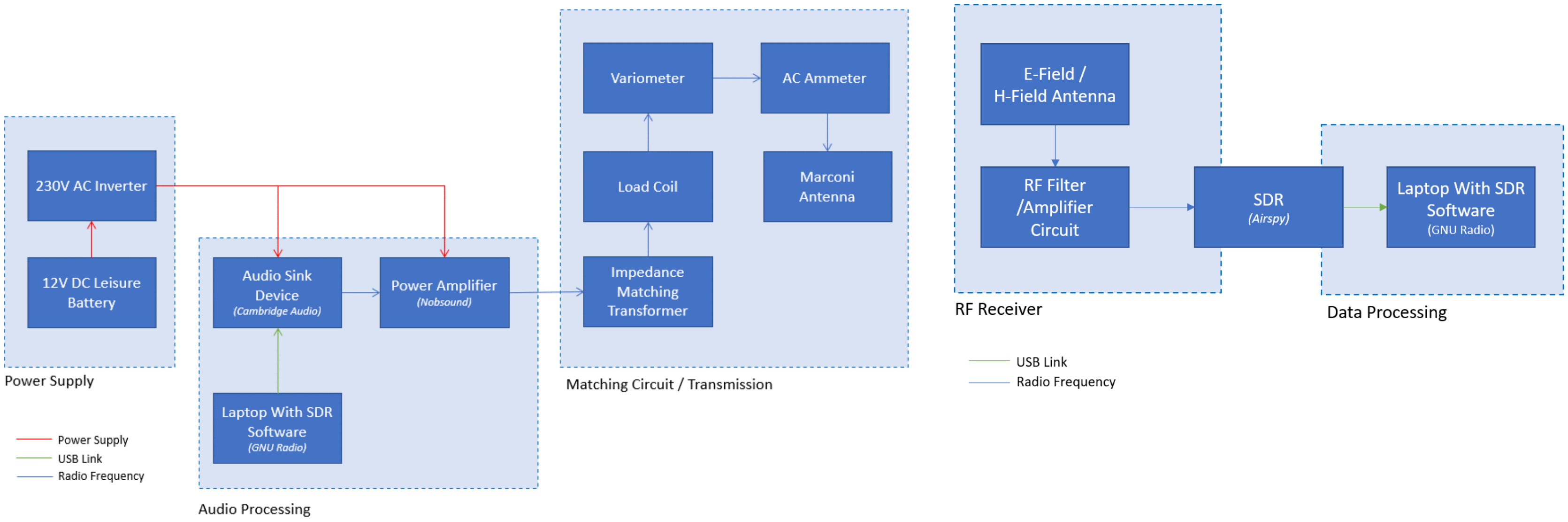
- PLL-derived synchronous pseudoranges were found to produce highly accurate positioning results, but the HW end-to-end seemed to have asynchronous pseudoranges due to the slotted transmit pattern.

- While the PLLs were observed to pull-in and reach steady-state with healthy SNR and low phase noise and compensation for the lack of synchronicity of pseudorange observations was made, it is thought that this issue effected by both transmitting and receiver clock stabilities over several seconds could be the source of the error.

Accomplished work

Obtained results – field trials (1/5)

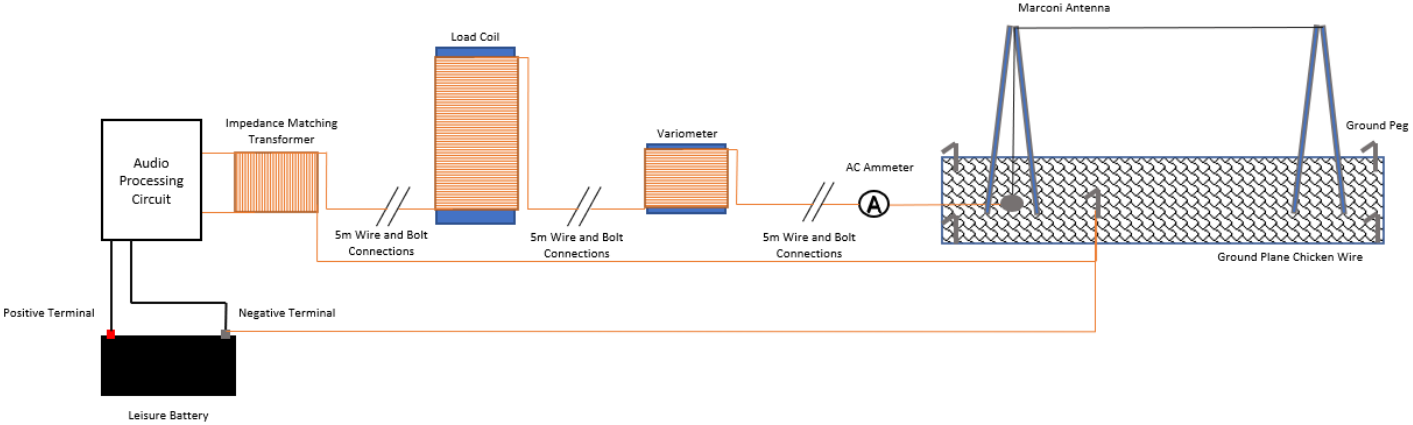
- A field trial transmitter chain was built in order to assess the developed proof-of-concept.



Accomplished work

Obtained results – field trials (2/5)

- A field trial transmitter chain was built in order to assess the developed proof-of-concept.
- The architecture of the built transmitter can be seen next:



Accomplished work

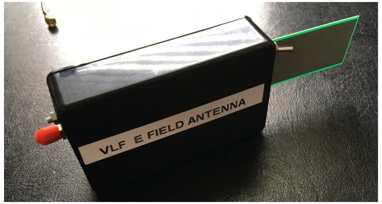
Obtained results – field trials (3/5)

- Transmitter setup for the field trials

Accomplished work

Obtained results – field trials (4/5)

Transmitter load coil



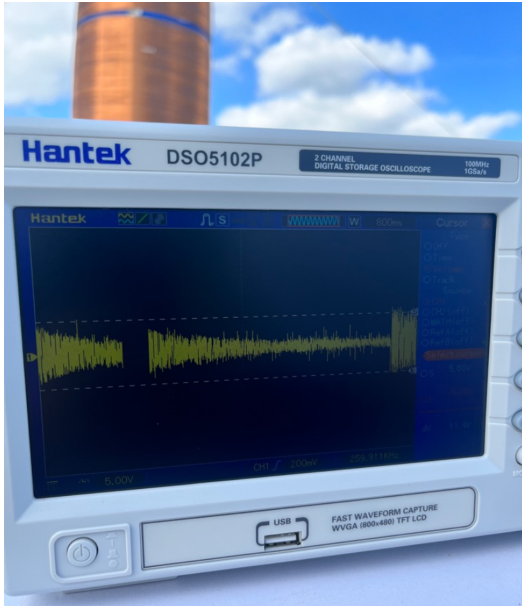
E-field antenna

Variometer – rotating inner barrel for inductance adjustment

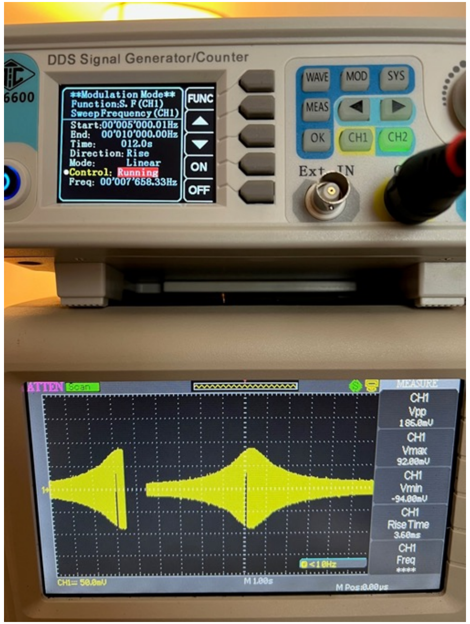
H-field antenna

Accomplished work

Obtained results – field trials (5/5)



Field trial resonance measurement using built transmitter



H-field antenna resonance measurement using signal generator

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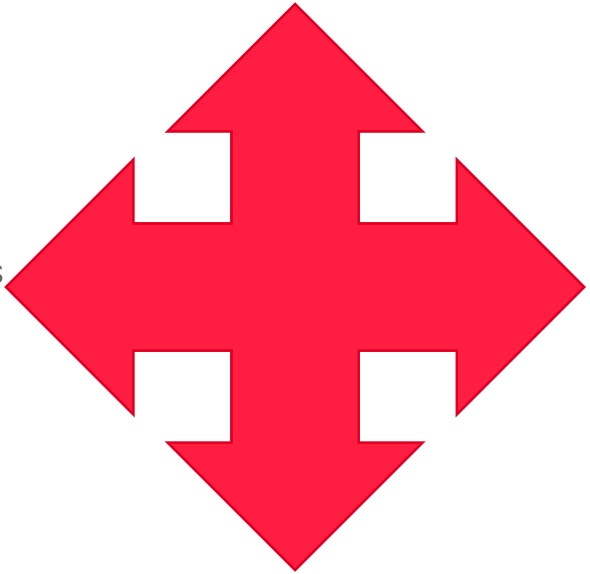
Foreseen way forward

What’s next?

Focus on obtaining dependable Phase-Locked Loop (PLL)-based observables and associated engine (EKF)

Implement technology on breadboards or miniaturized systems



Dedicated effort towards dedicated field trials

AI potentially employed in signal design e.g. signal impairments detection and mitigation

Thank you

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