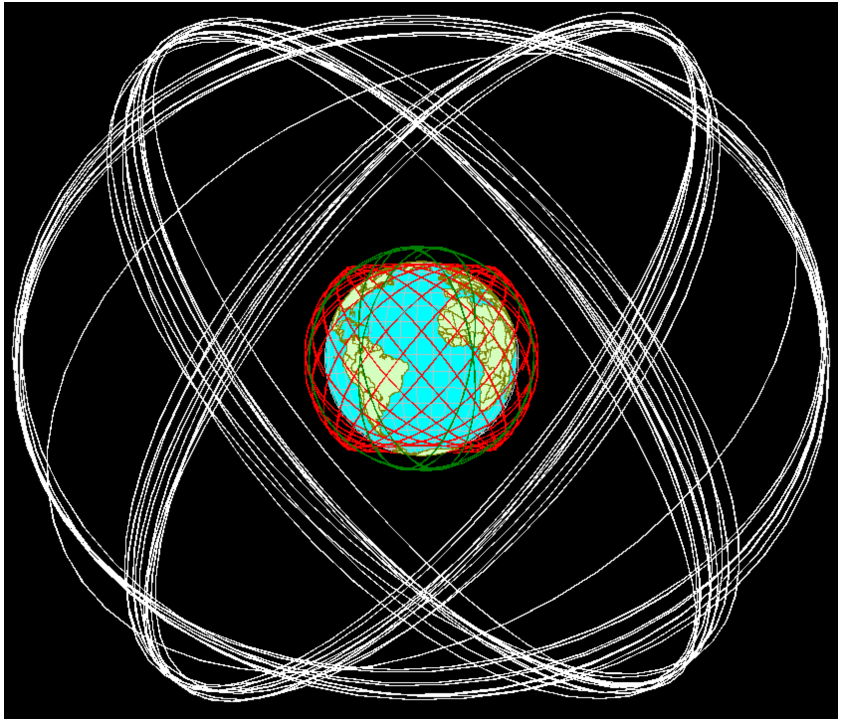
NAVISP-EL1-019: Ultra-Low Power Device Positioning Concepts

# LEOPARD

## Low Energy Optimised Positioning And Receiver Devices

Final Presentation
10/07/2023





gmv INNOVATING SOLUTIONS

# Agenda

**Introduction**

Activity plan

Work summary

Main conclusions and way forward

Questions & Answers

# Introduction

## Project objective

- Nowadays there is an increasing number of low power IoT-type applications. Most of them use GNSS due to their coverage, performance and availability, but GNSS chipsets are power hungry devices and the performance of the GNSS receivers can degrade in challenging environments.

> "[…] it appears necessary to develop a proper understanding of the emerging trends and to investigate solutions that would maintain the adoption of space-based PNT as competitive/preferred positioning enabler for ultra-low energy (and low-cost) positioning devices in the future."
>
> LEOPARD Proposal

### Objective of the contract

- To study and assess performance of **innovative concepts for ultra-low energy positioning devices based on space PNT systems**.
    - Assess against selected use cases.
    - Benchmarking of innovative concepts against reference scenarios.
    - Focused on 5 – 10 years timeframe.

# Agenda

# Activity plan

## Project overview

# Agenda

Introduction

Activity plan

**Accomplished work**

**Use cases and selected KPIs**

**Innovative concepts analysis**

**Obtained results**

Main conclusions and way forward

Questions and Answers

# Accomplished work

## Use cases and selected KPIs

- An initial set of use cases were evaluated during the first stage of this study.

| | | | |
|---|---|---|---|
| Asset/freight tracking | Equipment deployment: farm assets | Electronic Offender Monitoring (EOM) - passive | Man overboard |
| Geolocated seals and Locks | Animal Husbandry/ health | Covert surveillance tags | End of life goods disposal |
| Equipment deployment: Emergency response assets | Farmland Husbandry | Driver detection | Optimised refusal collection |
| Equipment deployment: road assets | Electronic Offender Monitoring (EOM) - active | Tasers/firearms/ stingers | Bike share schemes |

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- Several KPIs were selected in order to evaluate and the selected use cases

| | | | | |
|---|---|---|---|---|
| Position solution accuracy | Battery Life/Power Consumption/Energy per fix | Latency | Scalability | Interoperability and coexistence with other systems |
| Position solution availability | TTFF (Time To First Fix) | Reliability | Coverage | Cost |

# Accomplished work

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Focus of the activity

# Accomplished work

## Use cases and selected KPIs

- Use cases and selected KPIs were mapped to see the importance of each KPI per use case

| Use case | Aval. | Accuracy | Positioning | Cost | Battery Life | Lifetime #fixes | Time to alarm | Information consumption location | Position fix frequency and triggers |
|---|---|---|---|---|---|---|---|---|---|
| **Asset/ freight tracking** | M | H (static)<br>L(moving) | 2D | M | VH | L | H | Remote | P |
| **Geolocated seals and Locks** | H | M | 2D | M | L | M | MH | On device | S |
| **Animal Husbandry/ health** | L | L | 2D | L | M | M | H | Remote | P |
| **Farmland Husbandry** | L | VL | 2D | L | M | M | H | Remote | P |

- Then, realistic targets for these KPIs were set in order to use them as reference for evaluation

| Use case | | | Potential requirements per use case | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Availability (%) | Accuracy (m) | Per device cost (€) | Battery life | Lifetime #fixes | TTFF (s) | Latency (s) | Device size (mm) |
| **Asset/ freight tracking** | 95 | 1 - 5 static<br>10 - 30 moving | 100 | 15 years | 5,500 | < 30 | - | 400x150x25 |
| **Geolocated seals and Locks** | 99.9 | < 10 | 100+ | months | 13,000 | 30 | 30 | 140x50x30 |
| **Animal Husbandry/ health** | 90 | 10 - 20 | 20 | months | 25,000 | < 30 | - | 55x25x25 |
| **Farmland Husbandry** | 90 | 20-30 | 20 | months | 13,000 | < 30 | - | 55x25x25 |

# Accomplished work

## Innovative concepts analysis

- Analysis on the usage of LEO constellations (LEO-PNT)
- Innovative PNT techniques
- Options on LEO signalling for positioning
- Innovative processing techniques and associated energy consumption
- Creation of assessment tools

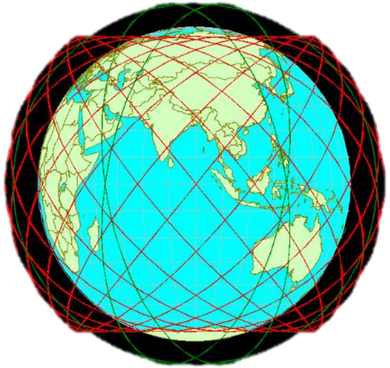
# Accomplished work

## Innovative concepts analysis: LEO constellations

- Emerging LEO systems may help maintain the adoption of space-based PNT as a competitive / preferred positioning technology for ultra-low energy positioning devices.

  - ⇧ Higher Power on Ground (PoG) offers potential for obtaining fixes with less energy consumption.
  - ⇧ Large variation in satellite Doppler supports Doppler-based positioning for potential processing gains.
  - ⇧ High PoG could potentially enable indoor positioning.
  - ⇩ C/No gains from PoG limited by MAI
  - ⇩ Increased almanac size
  - ⇩ Higher Doppler search ranges

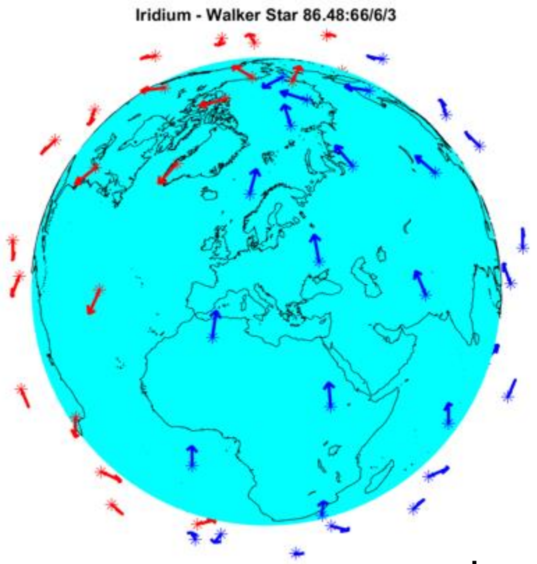
**OneWeb constellation**

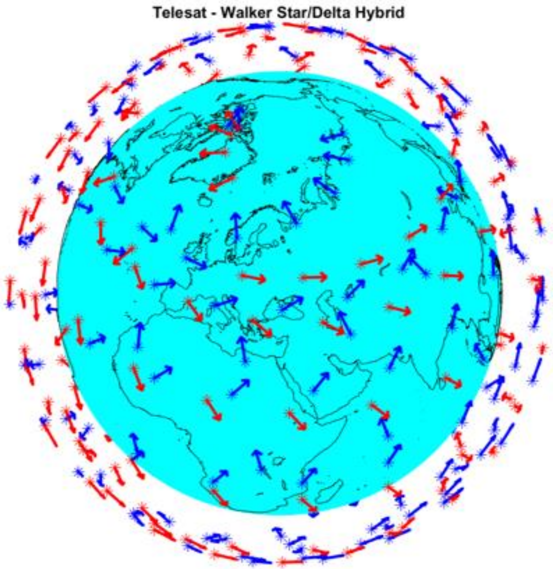


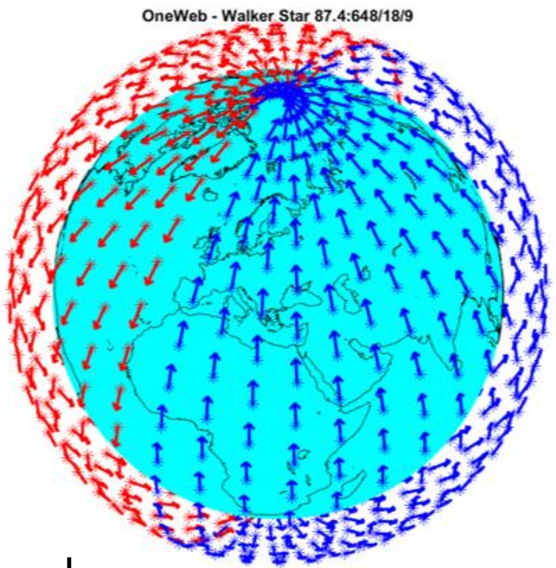
**Telesat constellation**

# Accomplished work

## Innovative concepts analysis: usage of LEO constellations




Iridium-like - Walker Star **66**/6/3, 86.48° inclination and **780 km height**

Telesat-like - Walker Star **78**/6/3, 98.98° inclination and **1015 km height** combined with a Walker Delta **220**/20/1, 50.88° inclination and **1325 km height**

OneWeb-like - Walker Star **648**/18/9, 87.4° inclination and **1200 km height**

# Accomplished work

## Innovative concepts analysis: innovative PNT techniques

- Several PNT techniques were assessed making use of Doppler (Frequency of Arrival or FoA) observables:
  1. FoA-only positioning (multi-epoch), considering a small LEO constellation (Iridium-like).
  2. ToA + FoA positioning, considering a medium LEO constellation (Telesat-like).
  3. ToA + FoA positioning, considering a large LEO constellation (OneWeb-like).
  4. FoA-only positioning (single epoch), considering a large LEO constellation (OneWeb-like).
  5. Hybridise LEO Telesat-like (ToA + FoA) and MEO GPS-like (ToA) constellations.

- **Reference**: GPS ToA positioning

$$\begin{bmatrix} \Delta\dot{\rho}_1 \\ \Delta\dot{\rho}_2 \\ \vdots \\ \Delta\dot{\rho}_N \\ \Delta\rho_1 \\ \Delta\rho_2 \\ \vdots \\ \Delta\rho_M \end{bmatrix} = \begin{bmatrix} \frac{\partial\dot{\rho}_1}{\partial u_x} & \frac{\partial\dot{\rho}_1}{\partial u_y} & \frac{\partial\dot{\rho}_1}{\partial u_z} & \frac{\partial\dot{\rho}_1}{\partial \dot{b}} & \frac{\partial\dot{\rho}_1}{\partial t} & \frac{\partial\dot{\rho}_1}{\partial \dot{u}_x} & \frac{\partial\dot{\rho}_1}{\partial \dot{u}_y} & \frac{\partial\dot{\rho}_1}{\partial \dot{u}_z} & 0 \\ \frac{\partial\dot{\rho}_2}{\partial u_x} & \frac{\partial\dot{\rho}_2}{\partial u_y} & \frac{\partial\dot{\rho}_2}{\partial u_z} & \frac{\partial\dot{\rho}_2}{\partial \dot{b}} & \frac{\partial\dot{\rho}_2}{\partial t} & \frac{\partial\dot{\rho}_2}{\partial \dot{u}_x} & \frac{\partial\dot{\rho}_2}{\partial \dot{u}_y} & \frac{\partial\dot{\rho}_2}{\partial \dot{u}_z} & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial\dot{\rho}_N}{\partial u_x} & \frac{\partial\dot{\rho}_N}{\partial u_y} & \frac{\partial\dot{\rho}_N}{\partial u_z} & \frac{\partial\dot{\rho}_N}{\partial \dot{b}} & \frac{\partial\dot{\rho}_N}{\partial t} & \frac{\partial\dot{\rho}_2}{\partial \dot{u}_x} & \frac{\partial\dot{\rho}_2}{\partial \dot{u}_y} & \frac{\partial\dot{\rho}_2}{\partial \dot{u}_z} & 0 \\ \frac{\partial\rho_1}{\partial u_x} & \frac{\partial\rho_1}{\partial u_y} & \frac{\partial\rho_1}{\partial u_z} & 0 & \frac{\partial\rho_1}{\partial t} & 0 & 0 & 0 & \frac{\partial\rho_1}{\partial b} \\ \frac{\partial\rho_2}{\partial u_x} & \frac{\partial\rho_2}{\partial u_y} & \frac{\partial\rho_2}{\partial u_z} & 0 & \frac{\partial\rho_2}{\partial t} & 0 & 0 & 0 & \frac{\partial\rho_2}{\partial b} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial\rho_M}{\partial u_x} & \frac{\partial\rho_M}{\partial u_y} & \frac{\partial\rho_M}{\partial u_z} & 0 & \frac{\partial\rho_M}{\partial t} & 0 & 0 & 0 & \frac{\partial\rho_M}{\partial b} \end{bmatrix} \begin{bmatrix} \Delta u_x \\ \Delta u_y \\ \Delta u_z \\ \Delta\dot{b} \\ \Delta t \\ \Delta\dot{u}_x \\ \Delta\dot{u}_y \\ \Delta\dot{u}_z \\ \Delta b \end{bmatrix}$$

**Jacobian matrix for the considered PNT techniques**

# Accomplished work

## Innovative concepts analysis: innovative PNT techniques

- Several PNT techniques were assessed making use of Doppler (Frequency of Arrival or FoA) observables:

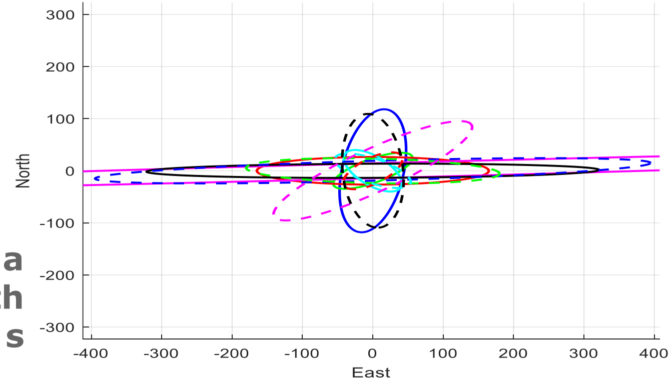
~~1. FoA-only positioning (multi-epoch), considering a small LEO constellation (Iridium-like).~~

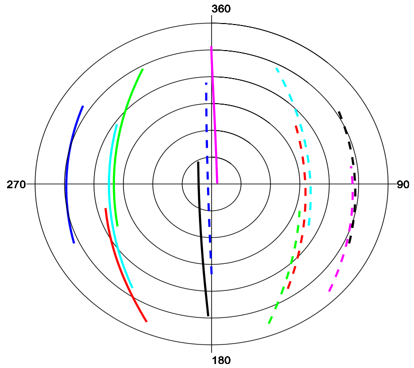
Multi-epoch FoA-only was discarded in earlier stages of the analysis.

- The system scenario showed poor geometry and position accuracy.
- Long observation periods (400 s) was thought excessive for ultra-low power applications.
- Shorter observation periods (100 s) reported accuracies far from the target (60 m vs 10 m).

- **Reference**: GPS ToA positioning

**Geometry and accuracy over a period of 400 s, with observations every 20 s**

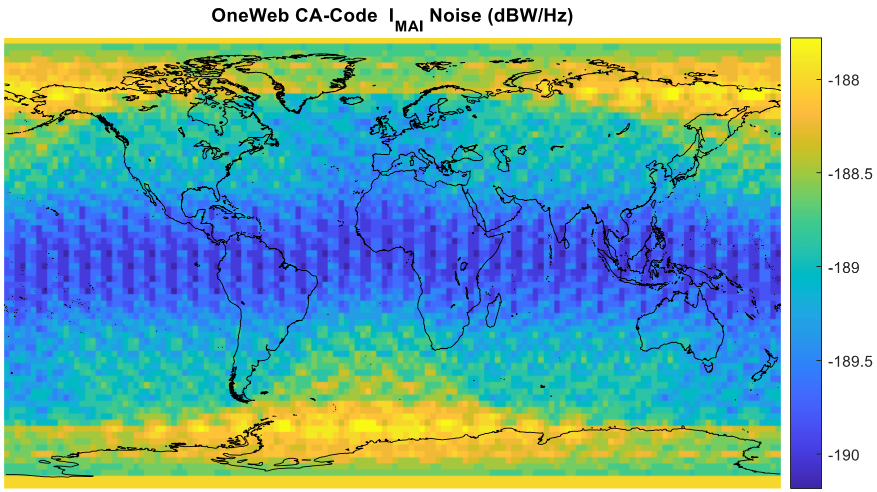


# Accomplished work

## Innovative concepts analysis: LEO signalling

- LEO CDMA scenarios lead to **Excessive Multiple Access Interference (MAI).**
- Assuming 60 dB-Hz nominal PoG, **GPS C/A-Like signals lead to a C/No plateaux ~46 dBHz for OneWeb** (about 14 dB of MAI!)
  - Smooth Spectral Separation Coefficient model




**OneWeb MAI (60 dB-Hz nominal power, -202 dB/Hz thermal noise assumed)**

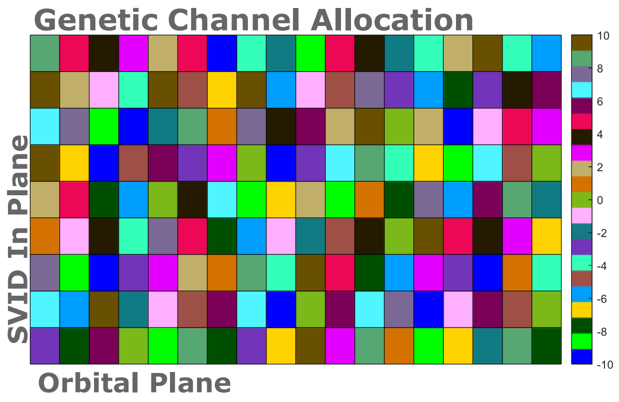
### Solution

- Employ FDMA with CDMA-SS.
- LEO PRN allocations repeated 4 times around orbital plane (visibility property).
- S band transmissions assumed.

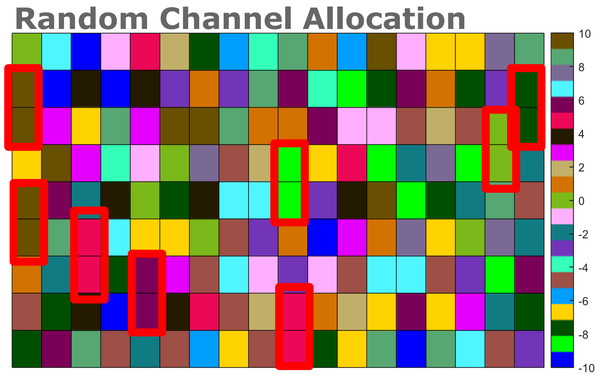
# Accomplished work

## Innovative concepts analysis: LEO signalling

- What about the **FDMA channel allocation**?
  - **Genetic Algorithm search gave ~2 dB MAI power reduction** compared to random in Telesat & OneWeb scenarios.
  - Noise floor increase (caused by MAI) less than 3 dB (-202 dB/Hz thermal noise assumed)




| | Fmod (kHz) | Channels | Spacing (KHz) | MAI Noise (dBW/Hz) | ΔC/No (dB) |
|---|---|---|---|---|---|
| **OneWeb HP1** | 1023 | 21 | 1023 | -202.5 | -2.8 |
| **OneWeb HP2** | 511 | 41 | 511 | -203.8 | -2.2 |
| **OneWeb HP3** | 255 | 51 | 255 | -202.9 | -2.6 |
| **Telesat HP1** | 1023 | 21 | 1023 | -205.4 | -1.6 |
| **Telesat HP2** | 511 | 21 | 511 | -202.3 | -2.9 |
| **OneWeb LP** | 1023 | 1 | N/A | -203.1 | -2.5 |
| **Telesat LP** | 1023 | 1 | N/A | -206.4 | -1.3 |



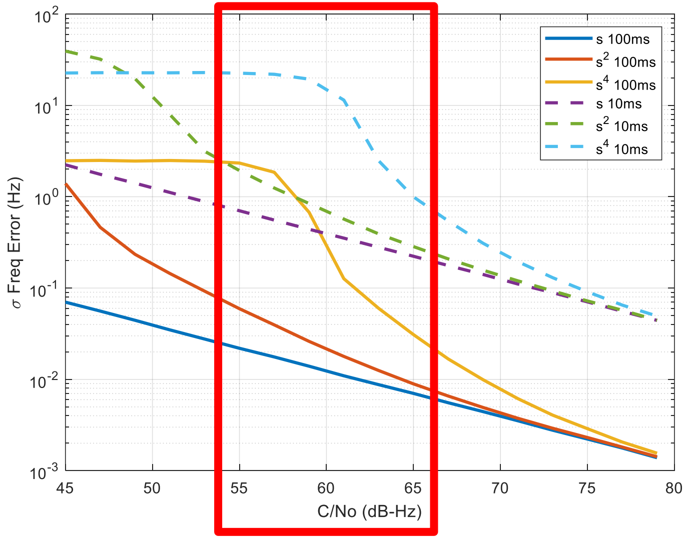

**Same freq. in adjacent channels!**

# Accomplished work

## Innovative concepts analysis: innovative processing techniques

- Squaring (BPSK) / Double Squaring (QPSK) **enables Doppler estimation without correlation** with lower complexity.
    - Coarse Doppler estimation to remove frequency ambiguity (~ 10s Hz).
    - Fine Doppler estimation for FoA-based positioning (< 1 Hz).
- Efficient Direct / Open Loop method, **close to CRLB.**

**Freq. error as a function of C/No working points**




**Working points considered**

### PROs/CONs

- **Number of operations is very small** compared to acquisition, tracking and direct coarse Doppler estimation.
- Reduction in operation count for FoA observation if correlation is not performed.
- Squaring increases the noise.

# Accomplished work

## Innovative concepts analysis: developed tools

### Lifetime calculator

Provides battery lifetime estimations and average power consumptions for software receivers based on a user-defined scenario and configured HW.

- Models device operative cycle in 5 phases
  - Wake-up-> Signal Capture -> Process -> Communicate with remote server -> Sleep
- Allows selection for communication protocol
  - Available: NB-IoT, LoRaWAN
- Outputs mean energy/power consumption, device lifetime.

### NEMO

Computes and provides visualisation of a range of positioning- and geometry-based performance metrics based on constellations and signal configurations.

- Service volume simulator.
- Simulates multiple constellation types: GEO, MEO, LEO, multi-layered constellations...
- Simulates different positioning engines: ToA, FoA, ToA+FoA.
- Produces metrics for geometry, positioning accuracy, availability, continuity, etc.
- Enhanced in the activity to support PNT computation using FoA measurements.

# Accomplished work

## Obtained results: evaluated system scenarios

| Reference System Scenario | | | Freq. Band | Positioning Technique | Signal Type | $C/N_0$ @zenith |
|---|---|---|---|---|---|---|
| **SS0** | GPS C/A | GPS | L-Band | Single epoch ToA | GPS C/A | 52 dB-Hz |
| **Innovative System Scenario** | | | **Freq. Band** | **Positioning Technique** | **Signal Type** | **$C/N_0$ @zenith** |
| **SSX** | **Small LEO constellation** | Iridium-like | S-Band | Multiple epoch FoA (1 SV) | N/A | N/A |
| **SS1** | Medium LEO const. | Telesat-like | S-Band | Single epoch ToA+FoA | SS-FDMA, CDMA<br>Chipping rates studied: 1023, 511.5, 255 kHz | 52 dB-Hz<br>GPS + 15 dB |
| **SS2** | Large LEO constellation | OneWeb-like | S-Band | Single epoch ToA+FoA | SS-FDMA, CDMA<br>Chipping rates studied: 1023, 511.5 kHz | 52 dB-Hz<br>GPS + 15 dB |
| **SS3** | Low-cost large LEO const. | OneWeb-like | S-Band | FoA (8+ SV) | SS-FDMA, CDMA<br>Chipping rates studied: 1023, 511.5, 255 kHz | 52 dB-Hz<br>GPS + 15 dB |
| **SS4** | Medium LEO const. plus GPS C/A | Telesat-like<br>GPS-like | S-band<br>L-band | ToA+FoA single epoch (LEO) + ToA (MEO) | SS-FDMA for LEO<br>GPS C/A for MEO<br>Chipping rates studied: 1023, 511.5 kHz | 52 dB-Hz<br>GPS + 15 dB |

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| SS4 | Medium LEO const. plus GPS C/A | Telesat-like<br>GPS-like | S-band<br>L-band | ToA+FoA single epoch (LEO) + ToA (MEO) | SS-FDMA for LEO<br>GPS C/A for MEO<br>Chipping rates studied: 1023, 511.5 kHz | 52 dB-Hz<br>GPS + 15 dB |

**Constellation, band, PVT technique**

**Signalling, PoG**

# Accomplished work

## Obtained results: power consumption per fix evaluation

### Consumption evaluation

- Performed based on selected use cases, classified by requirements
- Different fix rates, communication protocols and environments analysed.
- Use case 2 and 4 chosen as most relevant cases for evaluation.

| Use Case | UC ID | Fix rate | Communications | Environment |
|---|---|---|---|---|
| **Farm Eqpt. Assets** | UC1 | 24 h | LoRa | Rural |
| **Asset/freight tracking (remote location updates)** | UC2 | 1 h | NB-IoT Mode 2 | Rural |
| **Asset/freight tracking (frequent updates)** | UC3 | 10 min | NB-IoT Mode 2 | Rural, sub-urban, urban |
| **Geolocated seals/locks** | UC4 | 1 h | NB-IoT Mode 2 | Rural, sub-urban, urban |
| **Emergency resp. Eqpt.** | UC5 | 1 h | NB-IoT Mode 1 | Key for urban |
| **Road Eqpt. Assets** | UC6 | 1 h | NB-IoT Mode 1 | Key for urban |
| **Animal care / health** | UC7 | 1 h | LoRa | Rural |
| **EOM (Active)**<br>**Covert surveillance**<br>**Tasers / firearms / stingers**<br>**Driver detection** | UC8 | 10 min | NB-IoT Mode 2 | Key for urban |
| **Man overboard** | UC9 | 10 min | LoRa | Rural |

# Accomplished work

## Obtained results: GPS vs Telesat vs OneWeb (accuracy, 95% @ 24 h, every 1 minute)

- **GPS and Telesat DOP values** are equivalent.
  - Telesat provides poor coverage in medium-high lat.
- **SS2 highly decreases DOP values** due to the increased visibility.
- **Observation time is decreased up to x50 w.r.t. reference.**
- **Accuracy is equivalent to the medium LEO constellation case and ~25% w.r.t reference.**

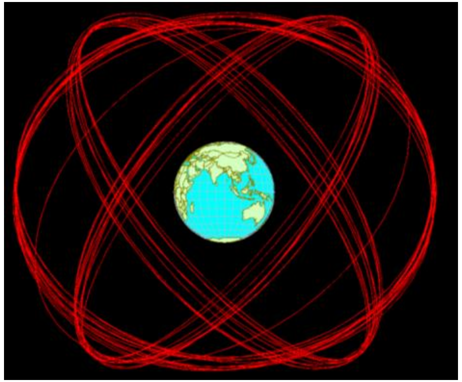
| | GPS C/A (reference), SS0 | Medium LEO ToA+FoA, SS1 | Large LEO ToA+FoA, SS2 |
|---|---|---|---|
| **Const.** | GPS | Telesat | OneWeb |
| **SVs** | 32 MEO | 298 LEO | 648 LEO |
| **C/No @ zenith** | 52 dB-Hz | 52 dB-Hz + 15 dB | 52 dB-Hz + 15 dB |
| **HDOP** | 0.82 | 0.67 | 0.39 |
| **PDOP** | 1.63 | 1.77 | 0.88 |
| **VDOP** | 1.41 | 1.62 | 0.79 |
| **Observation time (ms)** | 100 | 17 | 2 |
| **3D accuracy** | 13.1 | 9.94 | 9.61 |
| **2D accuracy** | 5.77 | 3.86 | 4.26 |
| **Availability** | 100 | 100 | 100 |

# Accomplished work

## Obtained results: GPS vs Telesat vs OneWeb (consumption)

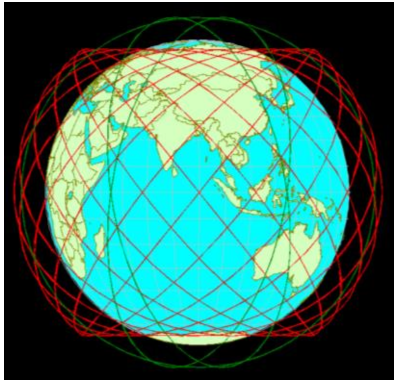
Evaluated with different types of assistance and with/without codeless Doppler estimation

- No assistance
- Almanac
- Tight NB-IoT synchronization + Almanac
- No assistance + codeless Doppler estimation
- Almanac + codeless Doppler estimation



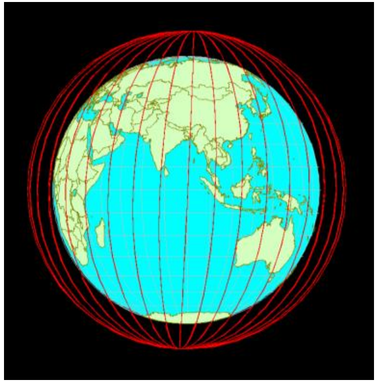
GPS

vs



OneWeb

vs



Telesat

# Accomplished work

## Obtained results: GPS vs OneWeb (consumption)

**Evaluated with different types of assistance and with/without codeless Doppler estimation**

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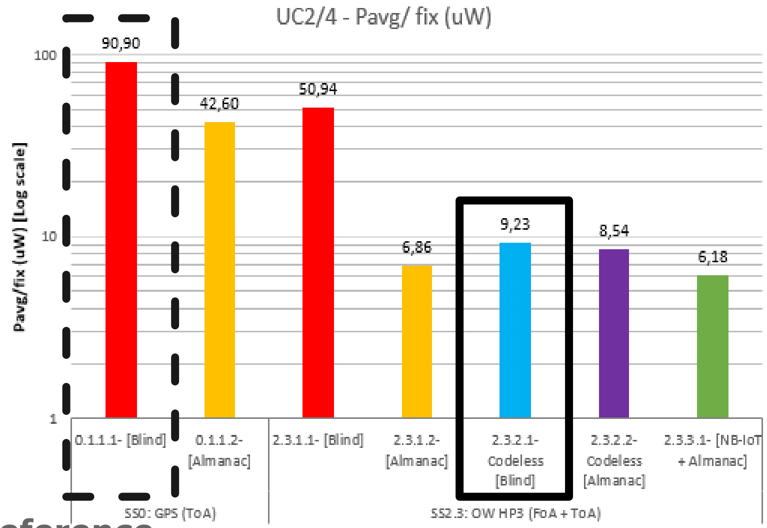


**Reference**

**Conclusions**

- The usage of codeless Doppler estimation reports a **x10 factor in power consumption** savings w.r.t. reference.
- Almanac assistance and tight network synchronization report similar results as blind + codeless.

# Accomplished work

## Obtained results: GPS vs OneWeb (consumption)

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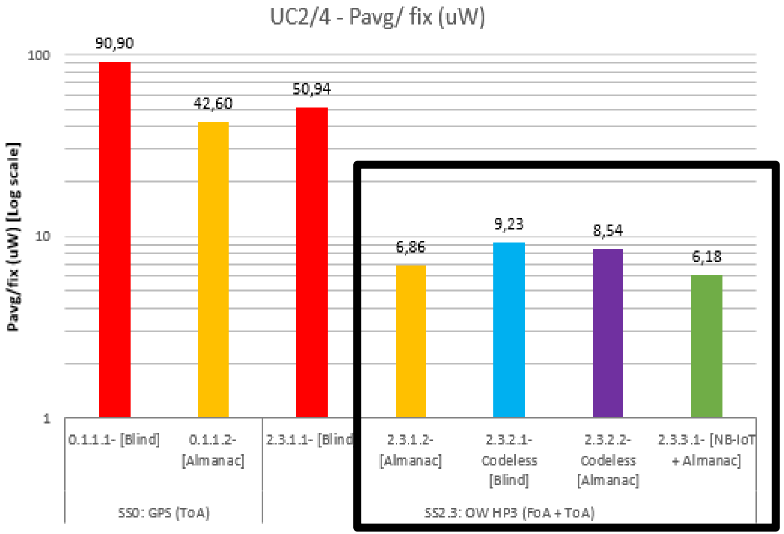
- **Almanac + codeless Doppler estimation**




**Conclusions**

- The usage of codeless Doppler estimation reports a x10 factor in power consumption savings w.r.t. reference.
- **Almanac assistance and tight network synchronization report similar** results as blind + codeless.

# Accomplished work

## Obtained results: GPS vs GPS+Telesat (accuracy, 95% @ 24 h, every 1 minute)

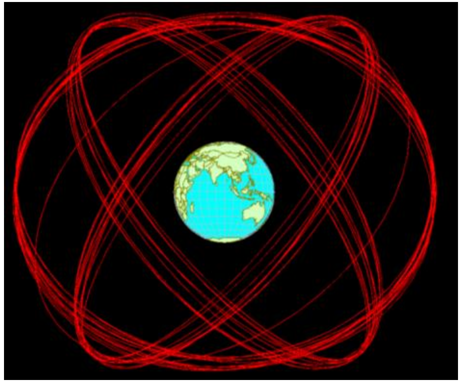
- **DOP values decrease to values equivalent to OneWeb** due to GPS providing mid-high lat. visibility.
- **Observation time of Telesat + GPS is equivalent to Telesat alone (about ~80% improvement).**
- **Accuracy is improved by ~40% w.r.t reference.**

| | GPS C/A (reference), SS0 | Medium LEO ToA-FoA plus GPS C/A, SS4 | Large LEO ToA+FoA, SS2 |
|---|---|---|---|
| **Const.** | GPS | GPS + Telesat | OneWeb |
| **SVs** | 32 MEO | 32 MEO + 298 LEO | 648 LEO |
| **C/No @ zenith** | 52 dB-Hz | 52 dB-Hz + 15 dB | 52 dB-Hz + 15 dB |
| **HDOP** | 0.82 | 0.45 | 0.39 |
| **PDOP** | 1.63 | 0.95 | 0.88 |
| **VDOP** | 1.41 | 0.84 | 0.79 |
| **Observation time (ms)** | 100 | 23 | 2 |
| **3D accuracy** | 13.1 | 7.52 | 9.61 |
| **2D accuracy** | 5.77 | 3.45 | 4.26 |
| **Availability** | 100 | 100 | 100 |

# Accomplished work

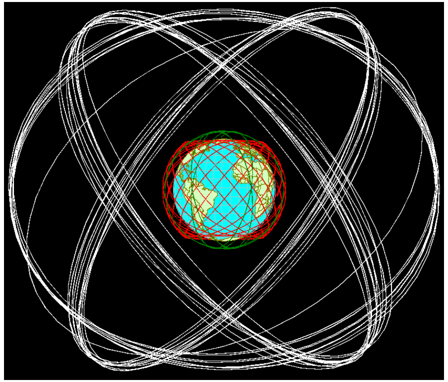
## Obtained results: GPS vs GPS+Telesat (consumption)

- The power consumption of GPS+Telesat is demonstrated to be **comparable (or even higher) than the one by the reference.**
  - This is caused by the necessity of using a double front-end (for Band L and Band S), which causes higher power consumption.

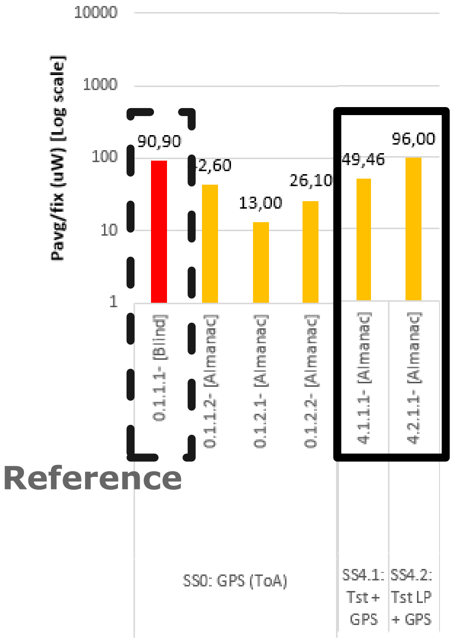


GPS

vs



GPS + Telesat



# Accomplished work

## Obtained results: GPS vs FoA-only OneWeb (accuracy, 95% @ 24 h, every 1 minute)

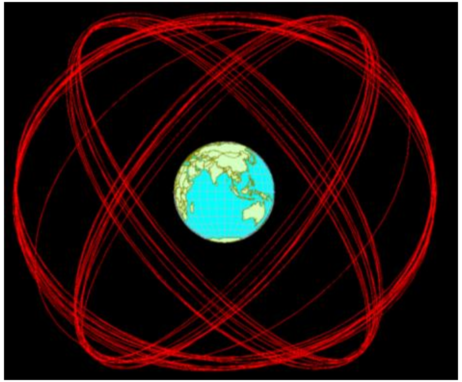
- **Not possible to compare DOP values** due to being computed on different basis.
- **Observation time improved by a factor of 3.**
- While **2D accuracy is worse than reference**, **3D accuracy is better.**
  - Vertical accuracy is better determined by the LEO constellation.

| | GPS C/A (reference), SS0 | Large LEO FoA-only, SS3 |
|---|---|---|
| Const. | GPS | OneWeb |
| SVs | 32 MEO | 640 LEO |
| C/No @ zenith | 52 dB-Hz | 52 dB-Hz + 15 dB |
| HDOP/DHDOP | 0.82 | 227.15 |
| PDOP/DPDDOP | 1.63 | 269.04 |
| VDOP/DVOP | 1.41 | 143.44 |
| Observation time (ms) | 100 | 35 |
| 3D accuracy | 13.1 | 9.37 |
| 2D accuracy | 5.77 | 7.11 |
| Availability | 100 | 100 |

# Accomplished work

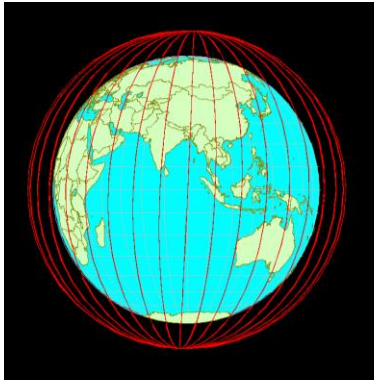
## Obtained results: GPS vs FoA-only OneWeb (consumption)

- Codeless Doppler estimation was found to also offer efficiency gains for FoA-only computation.
- It is possible to observe **~x7 consumption computation savings** comparing the reference blind acquisition vs the FoA-only codeless Doppler + 1D search approach.

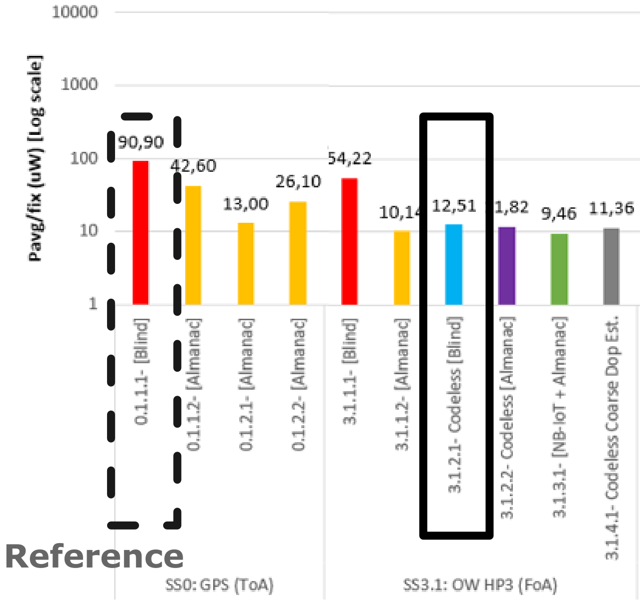


GPS

vs



OneWeb



# Accomplished work

## Obtained results: energy consumption per fix

- Possible to observe up to x3 improvement on position computation energy consumption.
- The communication chain consumption limits the gains up to around a 10%.

| Scenario | Aiding | Position computation chain energy consumption | Communication chain energy consumption | Total energy per fix |
|---|---|---|---|---|
| **Reference** | **No aiding** | **0.356 J** | **3.884 J** | **4.240 J** |
| Medium LEO ToA+FoA | No aiding | 0.854 J | 3.897 J | 4.751 J |
| Large LEO ToA+FoA | No aiding | 0.411 J | 3.903 J | 4.314 J |
| Large LEO FoA-only | No aiding | 0.224 J | 3.903 J | 4.127 J |
| **Reference** | **Almanac** | **0.182 J** | **3.884 J** | **4.066 J** |
| Medium LEO ToA+FoA | Almanac | 0.067 J | 3.897 J | 3.963 J |
| Large LEO ToA+FoA | Almanac | 0.054 J | 3.903 J | 3.958 J |
| Large LEO FoA-only | Almanac | 0.071 J | 3.903 J | 3.975 J |
| MEO + Medium LEO ToA+FoA | Almanac | 0.207 J | 3.923 J | 4.130 J |

# Accomplished work

## Obtained results: compliance with use cases

| Use case family | Fix rate | Accuracy (95%) | Lifetime (max achieved) | Compliance |
| --- | --- | --- | --- | --- |
| **Assets, freight tracking, non-frequent (target)** | Low (24 h) | Low (20 – 30 m 2D) | 13.000 fixes (35 years at fix/24 hours) | N/A |
| **Achieved** | 24 h | 3 – 9 m 2D | 43 – 46 years | Total |
| **Assets, freight tracking, mid-frequent (target)** | Medium (1 h) | High (1 – 5 m 3D) | 15 years | N/A |
| **Achieved** | 1 h | 10 – 15 m 3D | 6 – 7 years | No |
| **Geolocated seals, animal care (target)** | Medium (1 h) | Low (20 – 30 m 3D) | 13.000 fixes (1.5 years at fix/hour) | N/A |
| **Achieved** | 1 h | 10 – 15 m 3D | 6 – 7 years | Total |
| **Assets, freight tracking, frequent (target)** | High (10 min) | Low (20 – 30 m 2D) | 5 years | N/A |
| **Achieved** | 10 min | 3 – 9 m 2D | ~ 1 year | Partial |
| **EOM, cover surveillance (target)** | High (10 min) | Medium (~ 10 m 2D) | 50.000 fixes (1 year at fix/10 min) | N/A |
| **Achieved** | 10 min | 3 – 9 m 2D | ~ 1.5 years | Total |

- Compliance with use cases is total when the accuracy requirements is higher than 10 meters.
- A trade-off between accuracy and energy consumption (i.e. lifetime) is observed.

# Agenda

# Main conclusions and way forward

## Contract conclusions

1. ~ 1 order of magnitude on power savings can be obtained for the GNSS DSP element.
   - The **communications component limits the battery life savings**.

2. Higher PoG in LEO-PNT scenarios **reduces tracking integration time.**
   - ~100 ms GPS @52 dB-Hz vs 50 ms to 2 ms for LEO @57 dB-Hz to achieve the desired 10 m accuracy.

3. As LEO increases Doppler search range, **blind acquisition for LEO-PNT is unattractive for ULEPD**.
   - Codeless Doppler techniques enables coarse Doppler determination for energy savings.

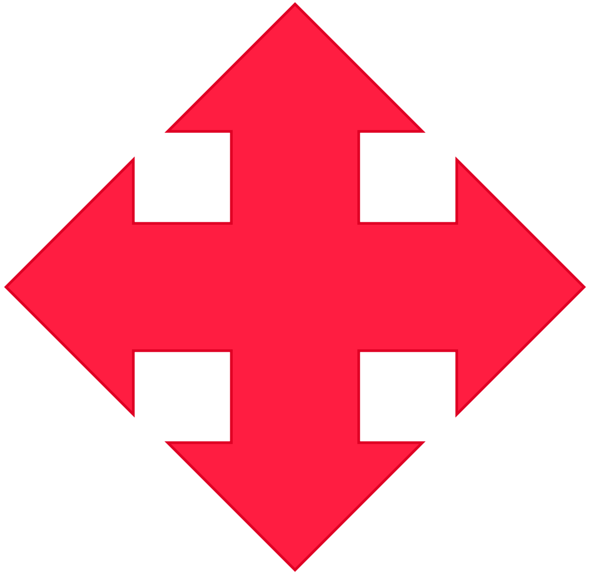
4. The combination of **FoA measurements with ToA demonstrates benefits in terms of accuracy and availability**.
   1. While FoA-only is not as accurate but can enable **low-cost LEO constellations** (no need for tight time synchronization).

5. **Chipping rates reduction delivered a significant reduction** in acquisition power consumption.
   - x2 – x4 times lower, ~proportional to chipping rate reduction (studied: 1023 kHz, 511.5 kHz, 255 kHz).

# Main conclusions and way forward

## What’s next?

Consideration of further use cases (e.g. indoors) and limitations (e.g. resilience to impairments)



Dedicated signal study for ultra-low power navigation purposes

Focus on other relevant KPIs (latency, cost, etc.)

Consideration of regulations e.g. ITU for signals enabling ultra-low power applications

# Thank you

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