Road Sounder

Development of a smart network for an enhanced road maintenance service

NAVISP-EL2-115

ESA AO/1-10516/20/NL/MP/MK

Final Presentation – FP

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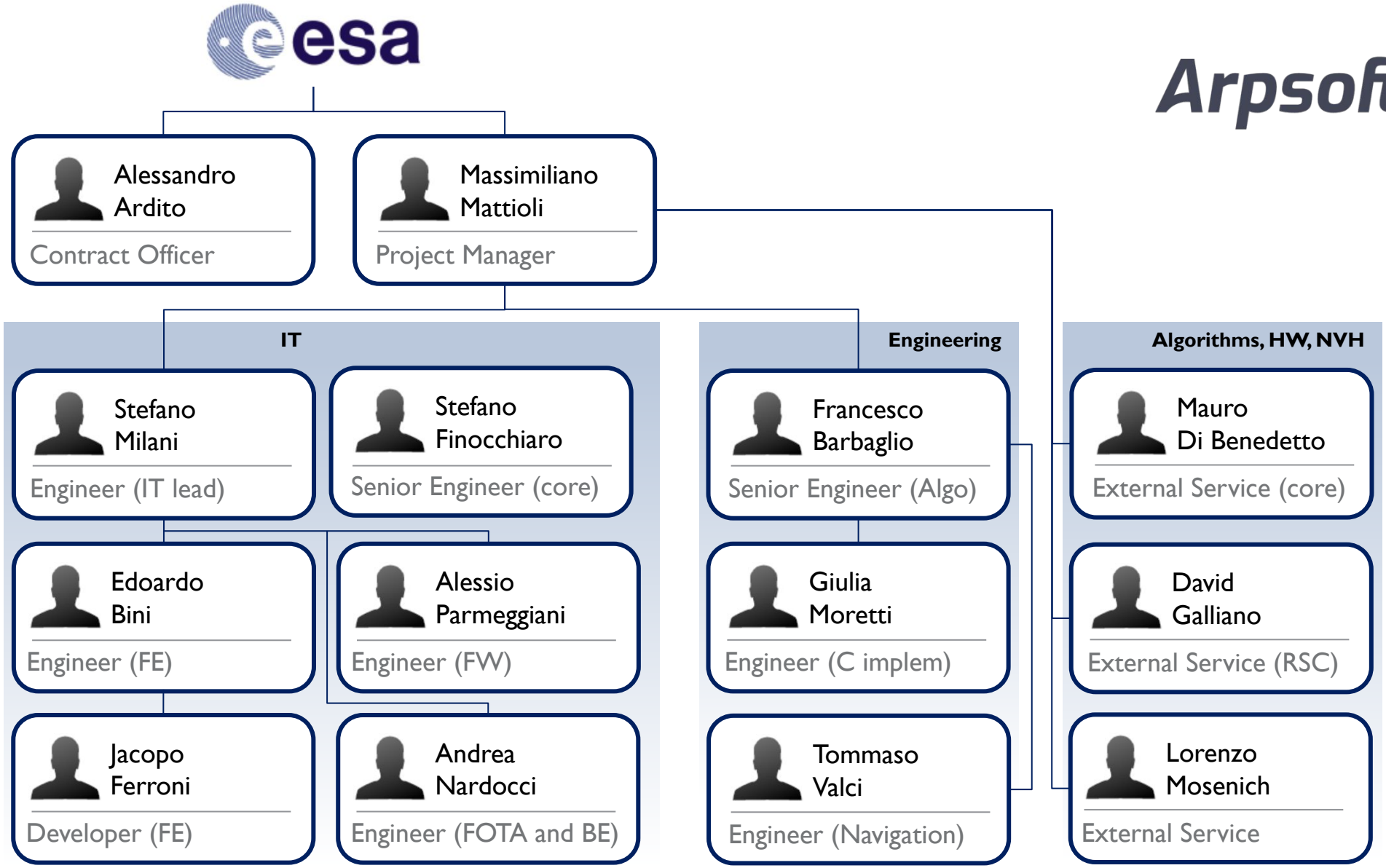
Team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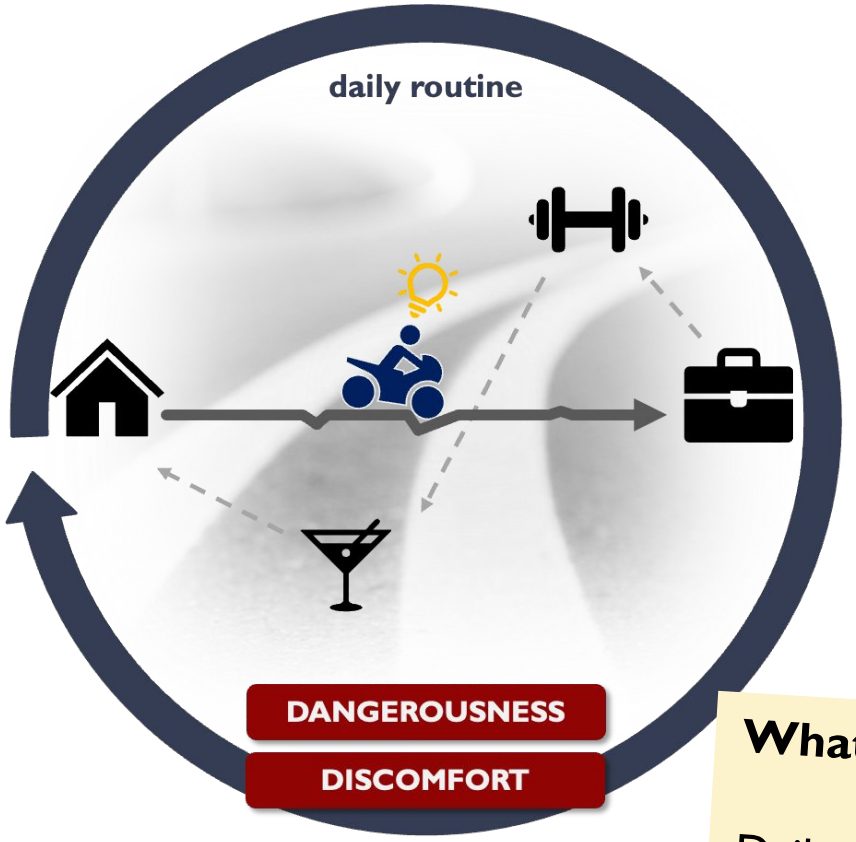
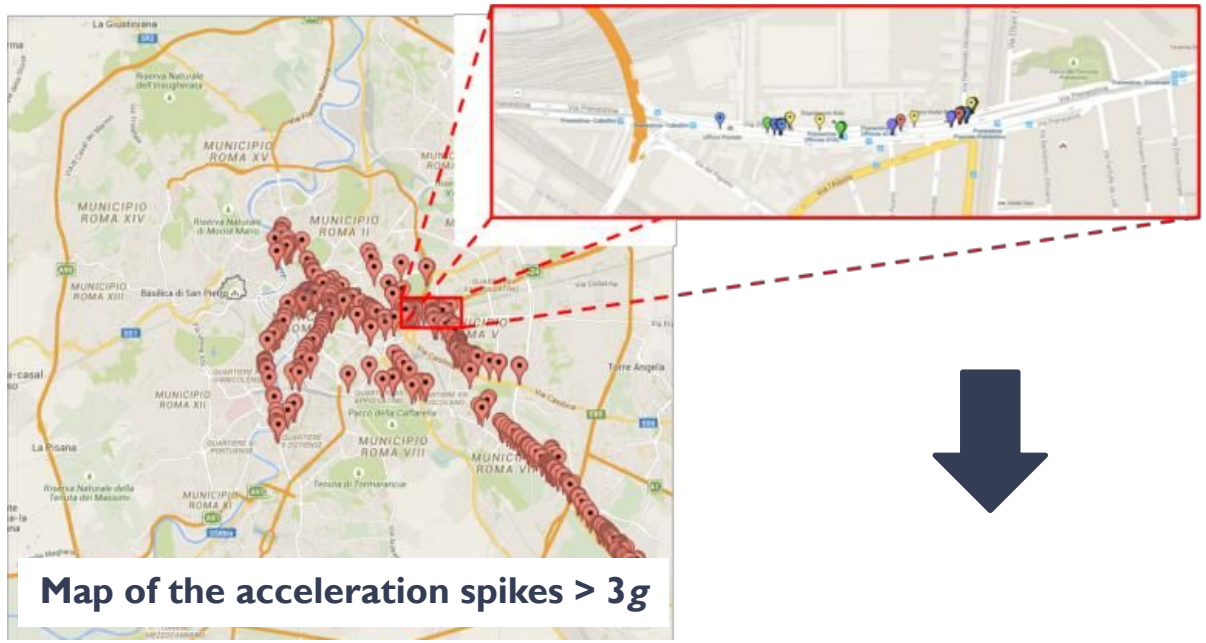
The Idea



Safety

Cost



What if?

Daily routine

+ Automated Autonomous device
  for 365 days/year
  for N vehicles on the roads

Road Sounder
Automatic Surface Monitoring

Road Condition Monitoring Service → **Road Maintenance Service**

- Road Maintenance is a specific responsibility of all local public administrations
  (art. 14 of "Decreto Legislativo n.285 del 30 aprile 1992")
- Road Maintenance is typically not structured nor systematic
- Road Maintenance budgets are typically limited, especially for large districts (e.g. cities)
- Poor maintenance and late interventions cause costs to greatly increase

→ ~ 100k€/km on reconstruction case

→ Rome's municipality recently allocated 10M€ for the cataloguing and the repair activity of the pot holes located on city's roads (~800km)

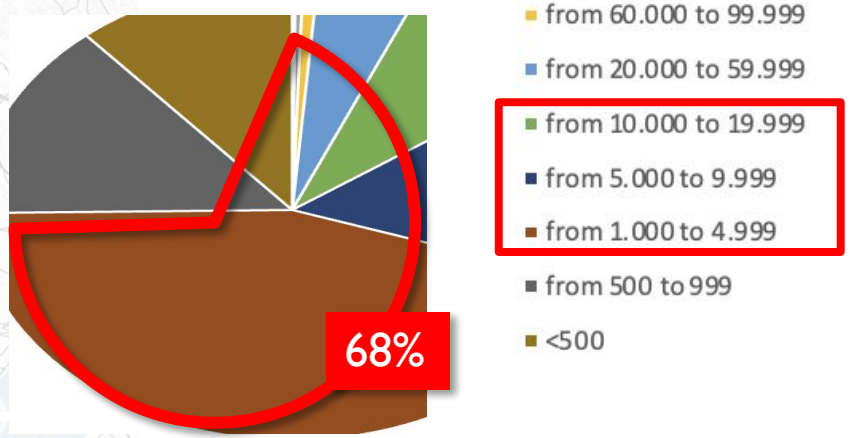
RS Offer

- Road condition monitoring in highly populated, wide area environments.
- Optimization of road maintenance intervention and cost reduction
- Service continuity
- System modularity and scalability

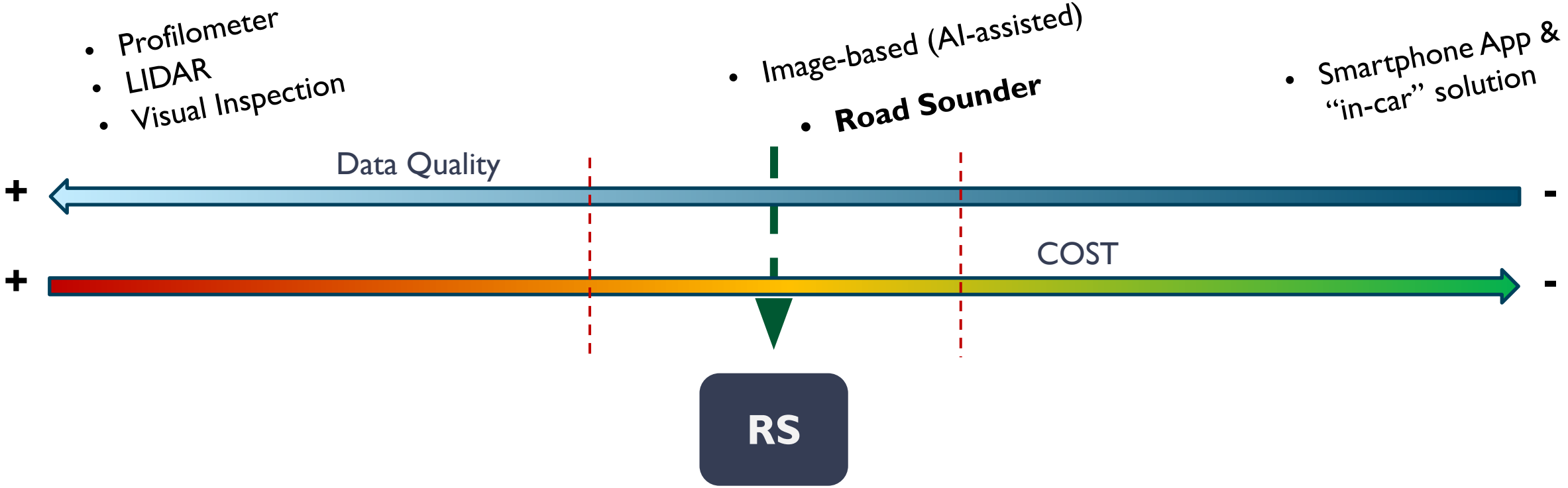
RS Market

- We have an agreement with a partner/potential customer for the implementation of RS on its fleet, that is already used in the maintenance service for the Public Administration of a big city (Rome).
- It targets mid-small cities with population in the range 1k – 20k and roads length 50 – 150 km to gradually enter the market

Cities per population range

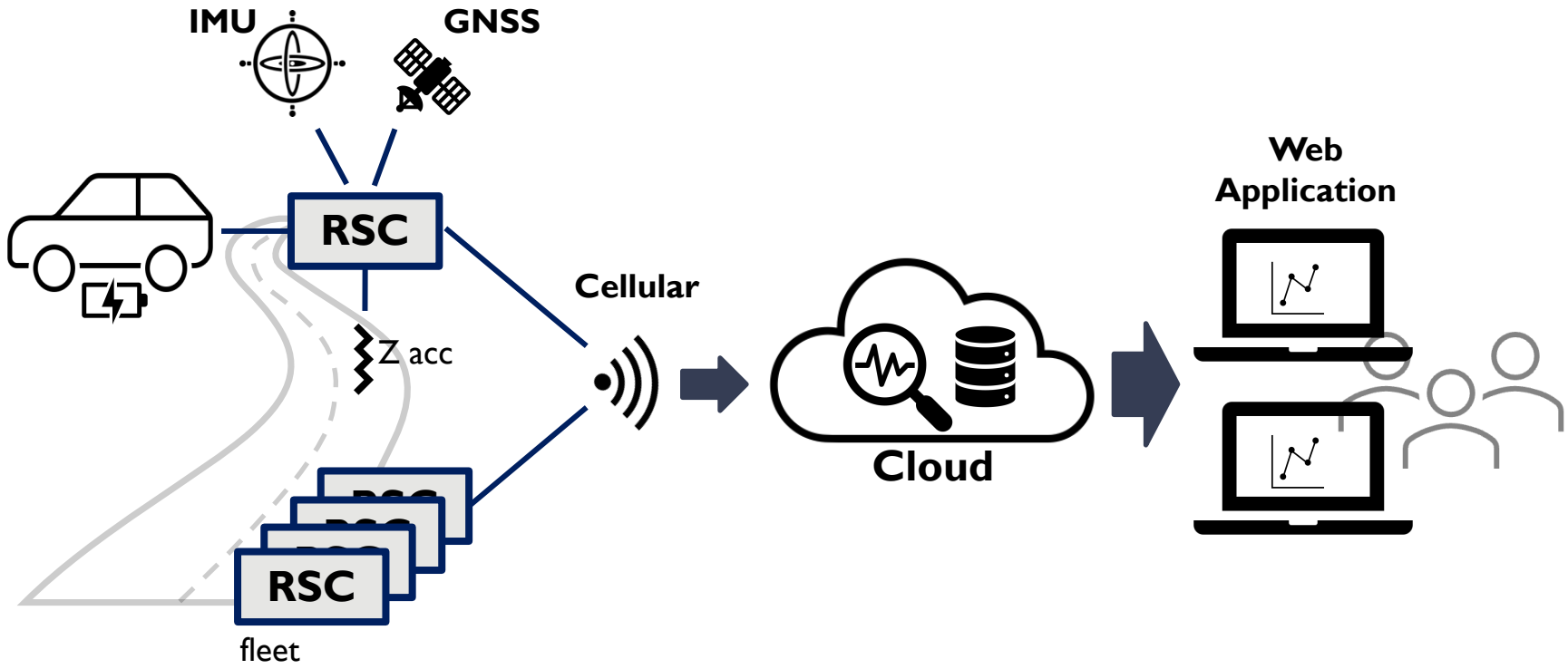


The Competition



PRO:
Service continuity
Totally autonomous
Low impact on host vehicle
Nearly zero maintenance
High Scalability

The Proposed Solution A New Product

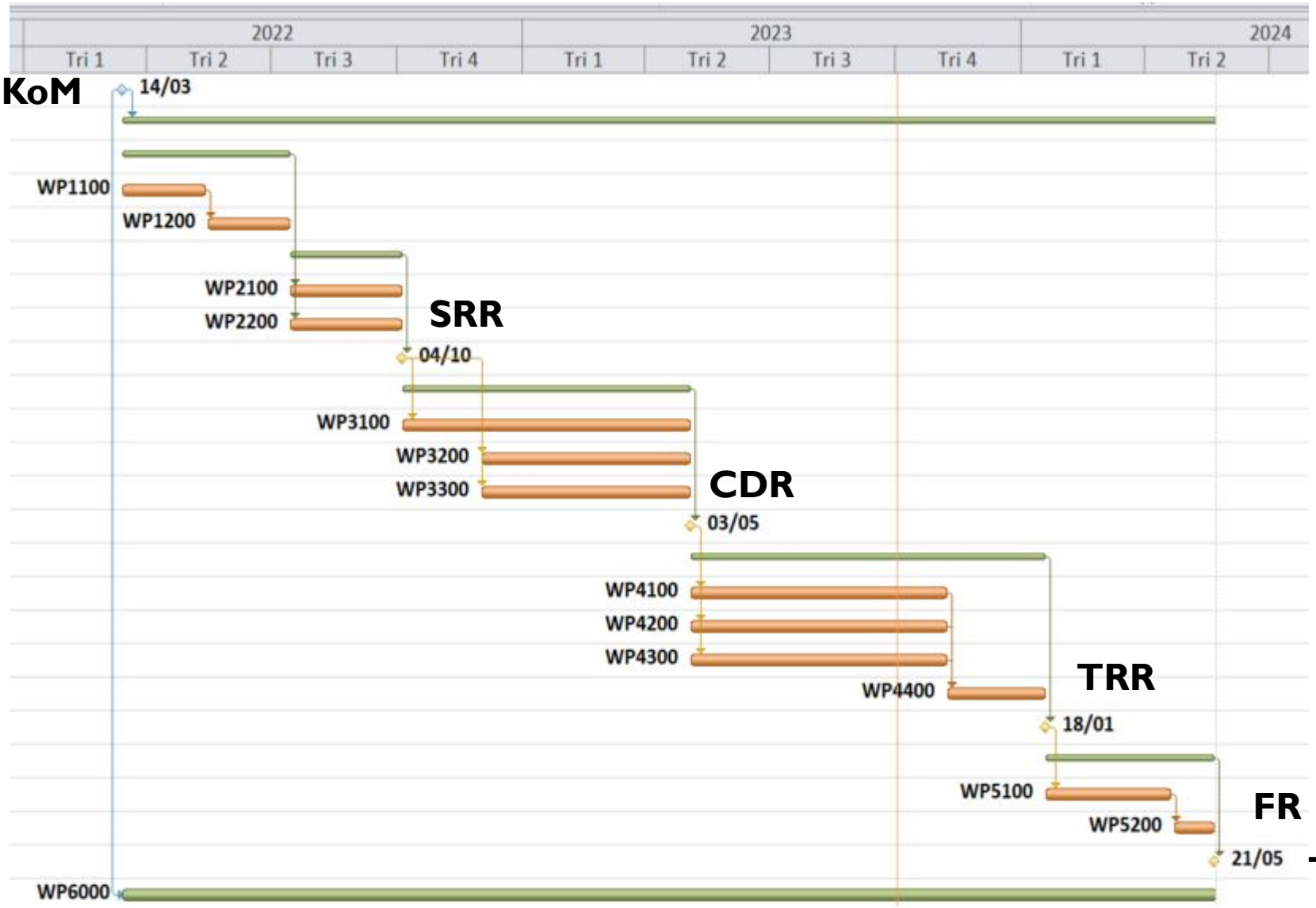


(HW and Firmware) **RSC (+RU) +**

(SW and IT infrastructure) **CLOUD =**

RS

SCHEDULE



+3 months (Aug 24) on the 26 months original schedule (proposal)

Delay on implementation and test phase due to:

- Extra tasks added (for the product improvement)
- Coordination with the potential customer (installation)
- A lot of work and refinement on the firmware to make it work smoothly.

→ **16/09**

FDP – Final Data Package (deliverables)

Documentation (at latest version)

- KO package
- SRD issue3 rev0
- SAD issue1 rev2
- ICD issue1 rev0
- SFVP issue2 rev0
- SUM issue1 rev0 (+IM issue1 rev0)
- SFTR issue2 rev1
- FR issue1 rev1
- ES issue1 rev0

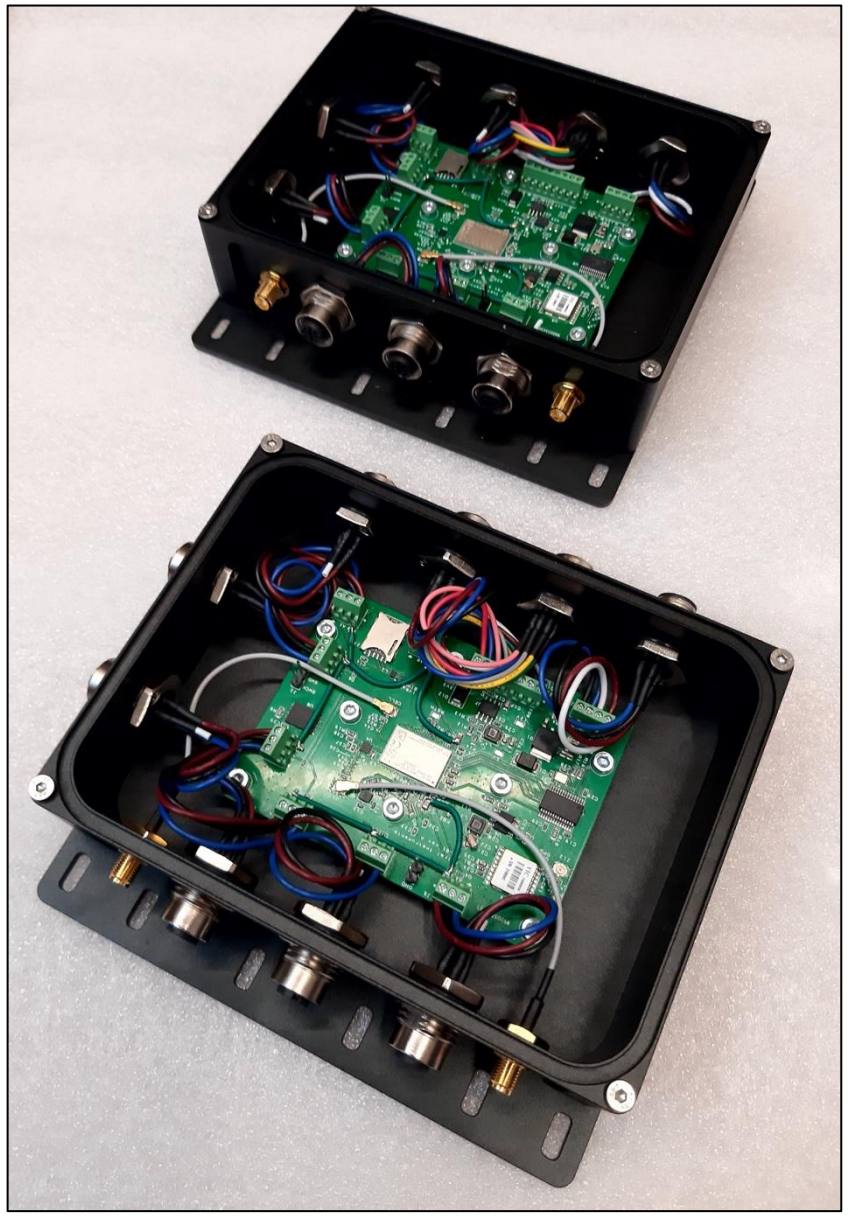
Software

- SWD1 – RSC Firmware (object code)
- SWD2 – RSC Backend
- SWD3 – RSC Dashboard

Hardware

- HWD1 – RSC

Product Overview: RSC + RU

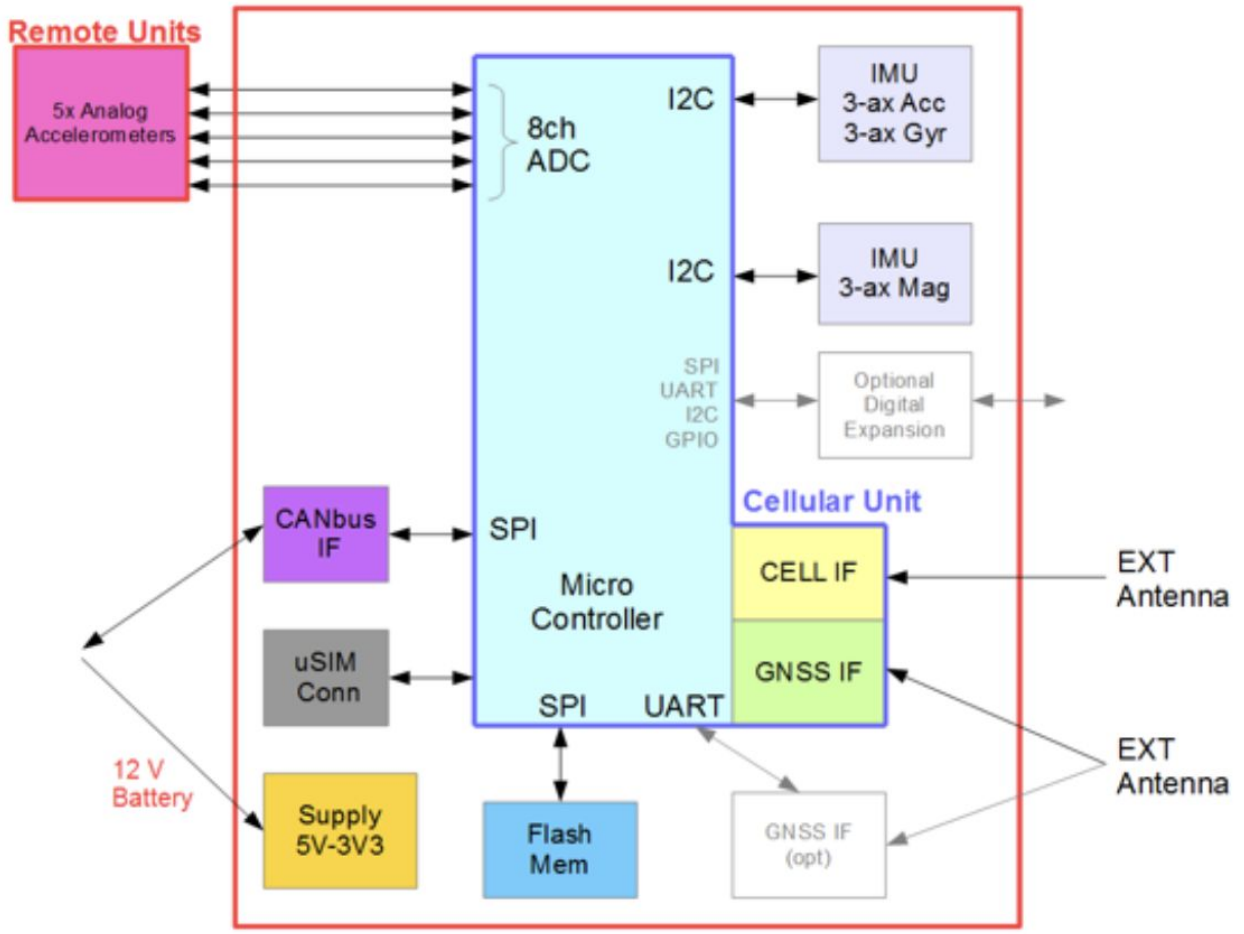


Road Sounder Cell
RSC

Remote Units
RU

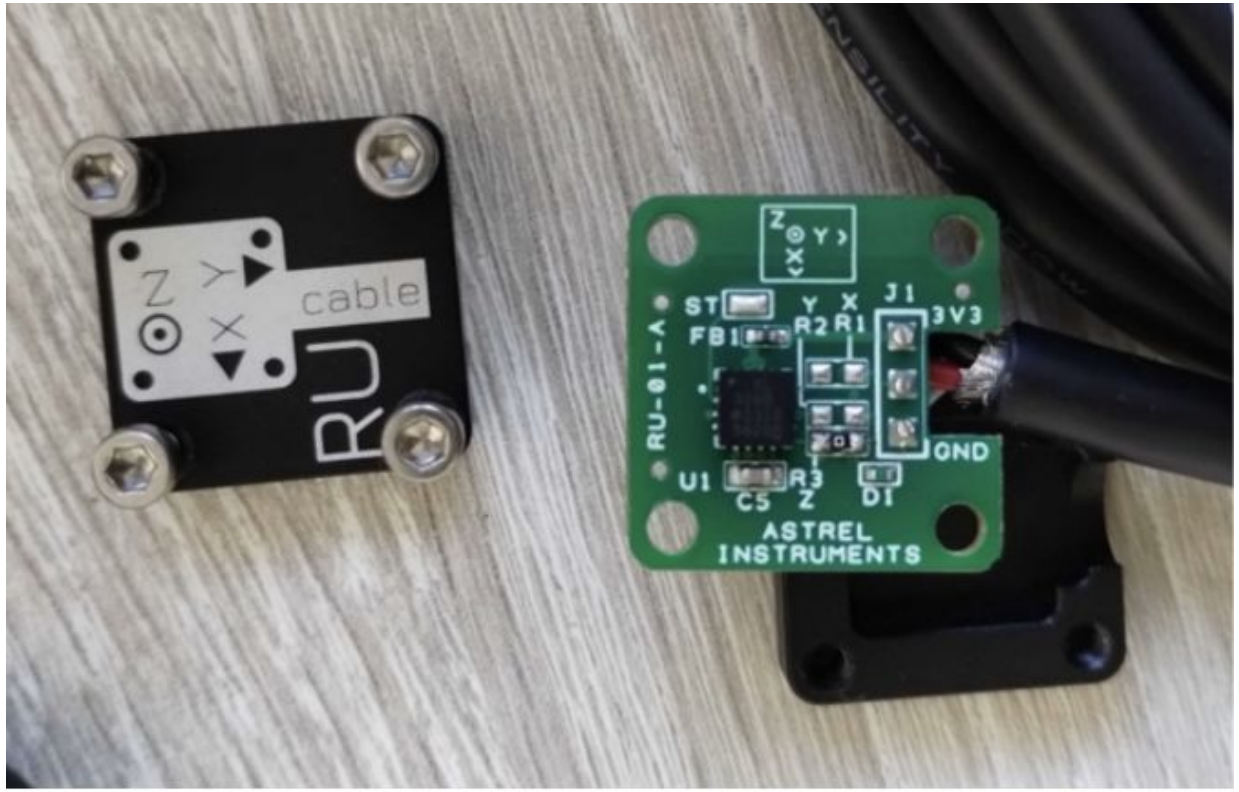
RSC

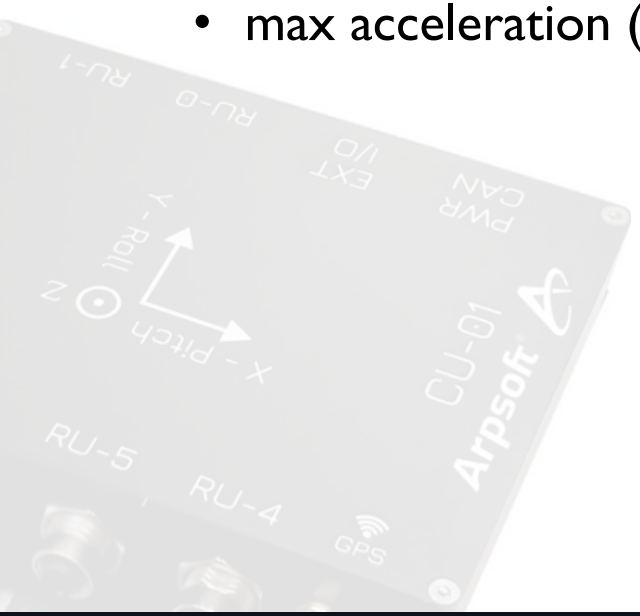
- Micro-Controller,
- Cellular Interface,
- GNSS Interface,
- nano-SIM Card Interface,
- Supply,
- IMU,
- CAN bus Interface,
- Serial Flash Memory,
- Expansion Digital IO (experimental use).



RU

- ±16 g full scale configurable
- 57mV/g sensitivity
- -16g=0.58V/0g=1.5V/+16g= 2.42V
- BW 1600 Hz X and Y-axis / 550 Hz Z-axis
- max acceleration (shock) 10000g.





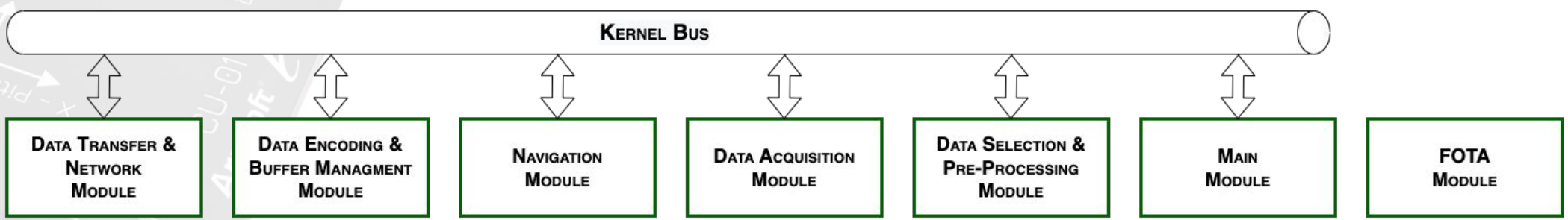
RSC Firmware

Modular Architecture

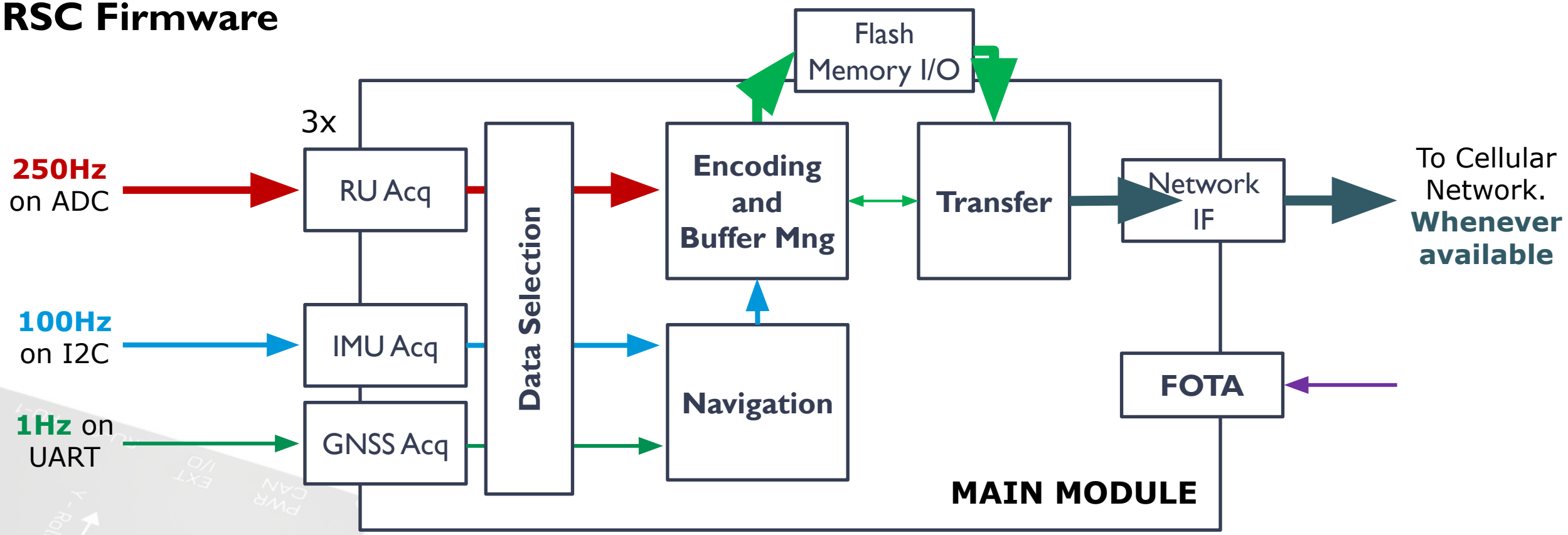
- Navigation Module
- Data Acquisition
- Data Selection
- Data Encoding and Buffer Management
- Data Transfer
- FOTA (Firmware over-the-air) Module

Zephyr RTOS: support to all the major architectures (ARM, Intel, ARCv2, etc.)

C language

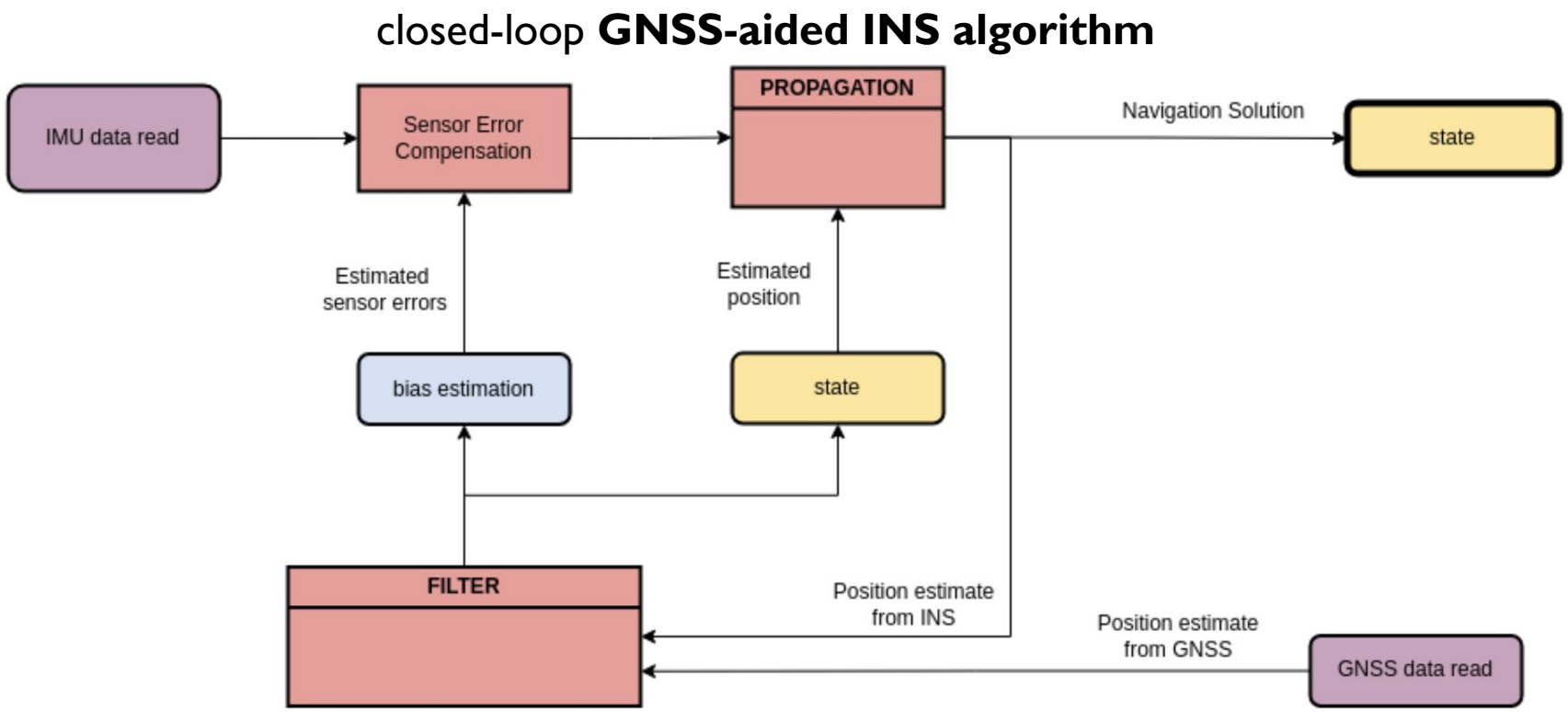


RSC Firmware



- ✔ Every module works independently
- ✔ A lot of work and optimization was needed to make it works at the required rate
- ✔ A big effort has been put for the minimization of the payload size, the efficient management of the Buffer and optimization of the network utilization

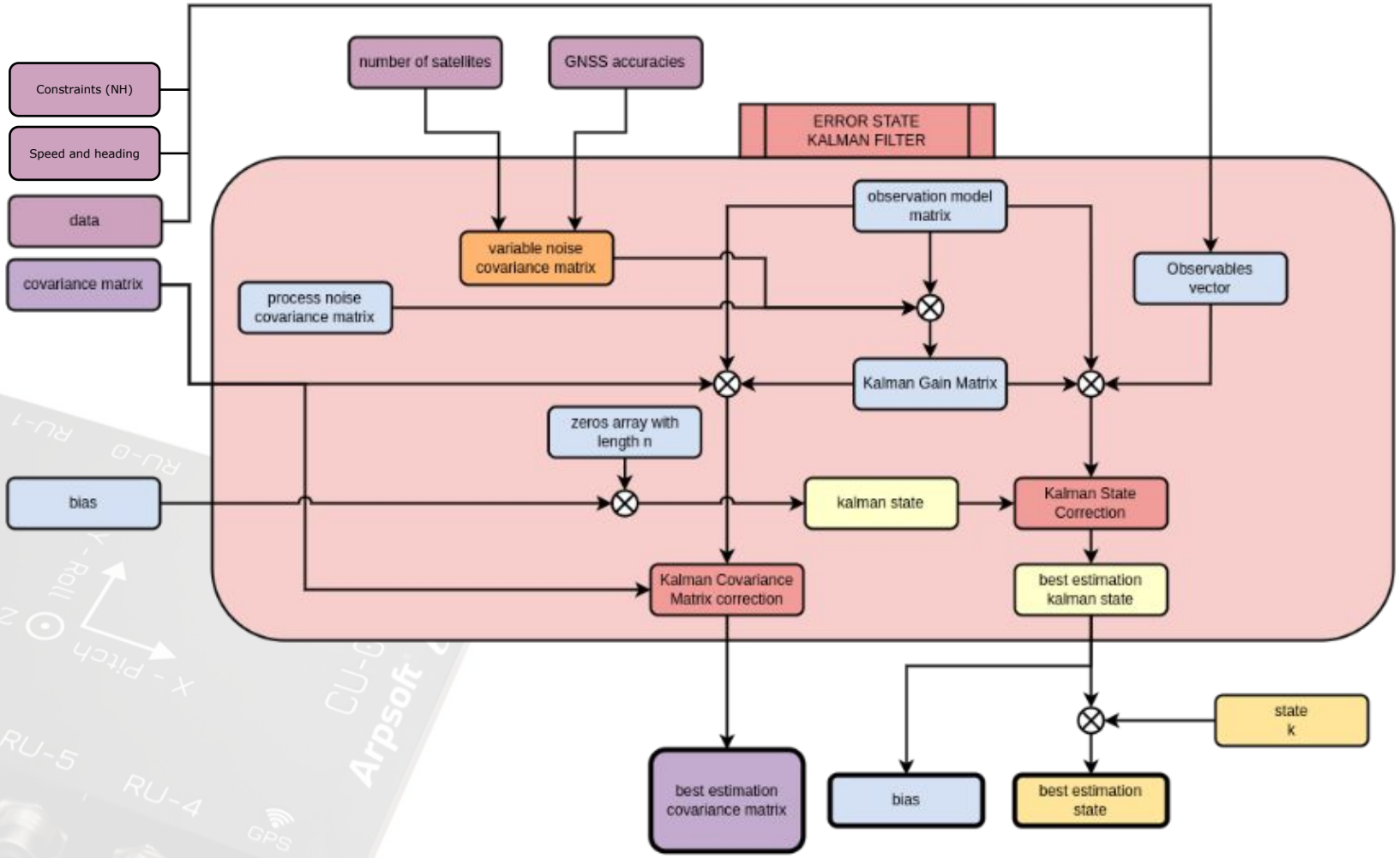
Navigation Module



- The localization performance is mostly related to the GNSS.
- IMU helps providing robustness especially during lack of signal (outage) and very poor GNSS condition.
- The GNSS observables are used in a Kalman Filter to estimate the correction for the position, velocity, attitude and gyro and acc biases.

Navigation Module

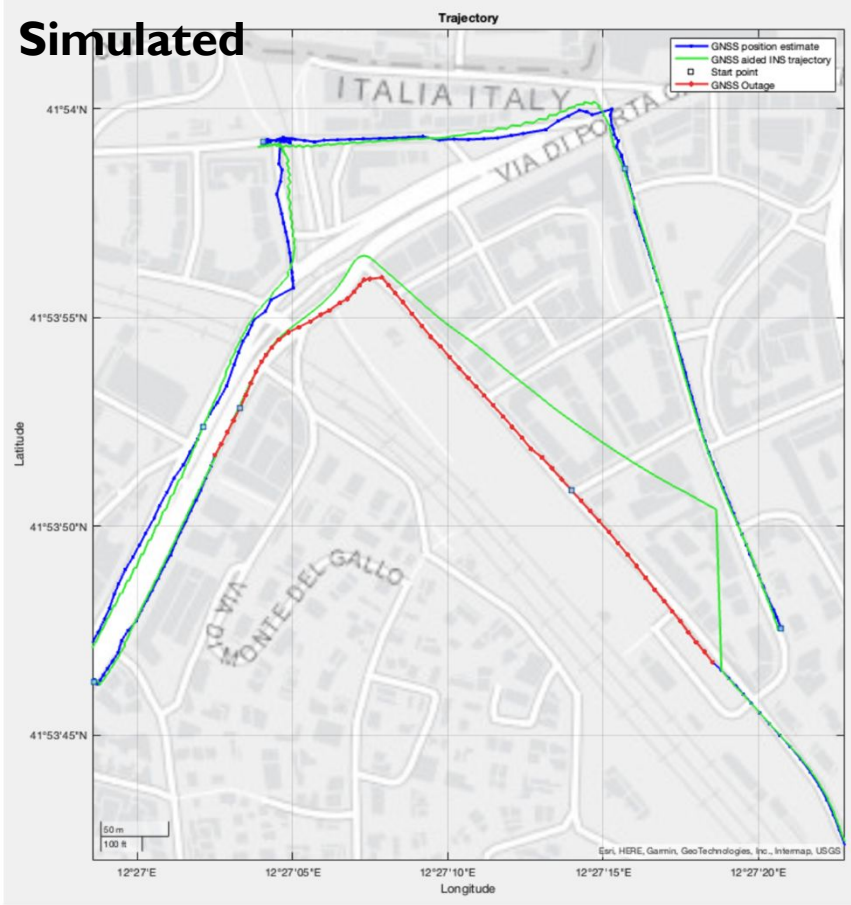
The ESKF

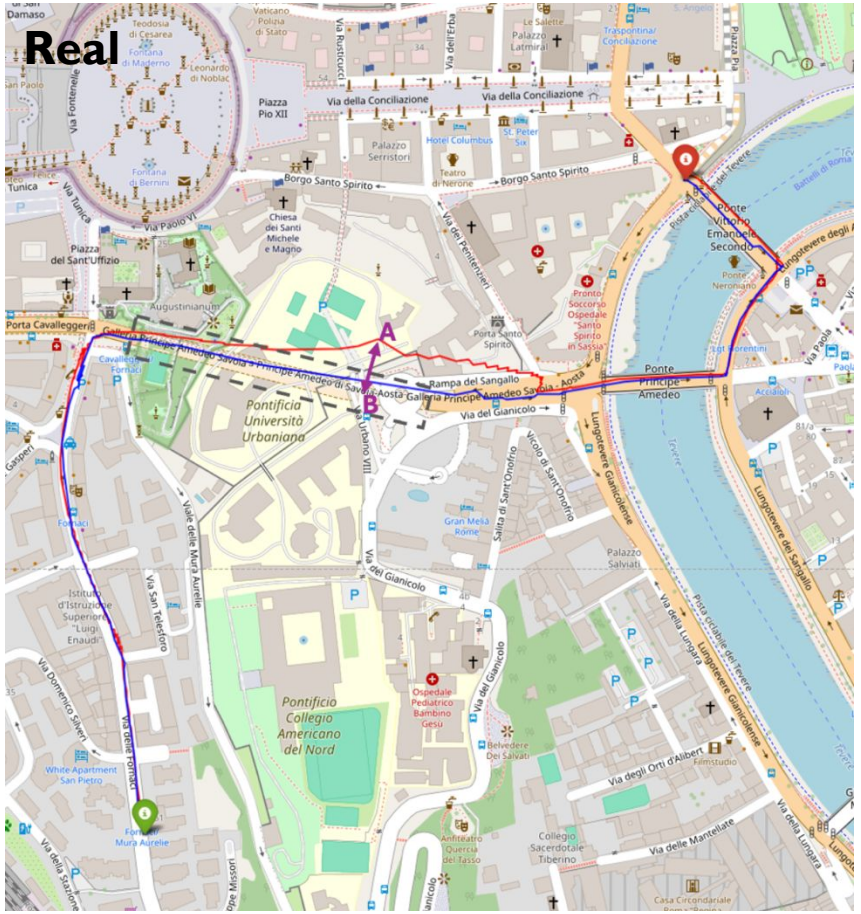


- Kalman state:
  N-length 0 array,
  updated IMU bias
- Measurement noise covariance matrix (***R***) changes according to the GNSS accuracy
- Observation model matrix relates the observables with the state (error in position, speed, heading angle).
- Non-holonomic constraints: side and vertical velocities of the car ~0.

Navigation Module

Navigation results for Simulated and Real Outage.

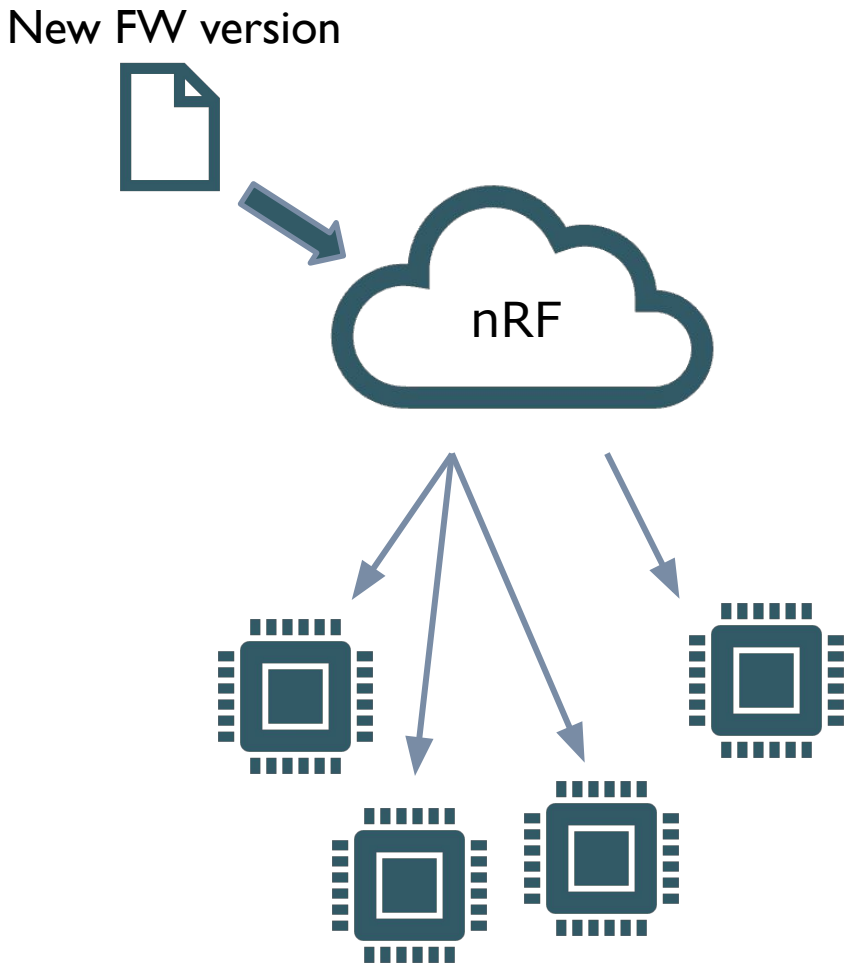




✔ The solution is still acceptable within 20s of outage even if it may depend on particular conditions before the outage (vehicle dynamic, GNSS quality, etc.)

FOTA Update

- RSC supports the Firmware Over-the-air Update: no need for physical connection after the installation.
- 3 firmware types:
  1. Initialization: setup the cell with "base" credential for the remote terminal. It allows the setup of the communication for the specific Cell.
  2. Installation: measure and store in the non-volatile memory the initial attitude of the IMU, store bias for the RU acc.
  3. Operational: the actual firmware for the standard operation.
- FOTA are managed and deployed through the nRF Cloud platform. A special module on-board cell (FOTA) takes care of checking for new updates and for deploying at each reboot.



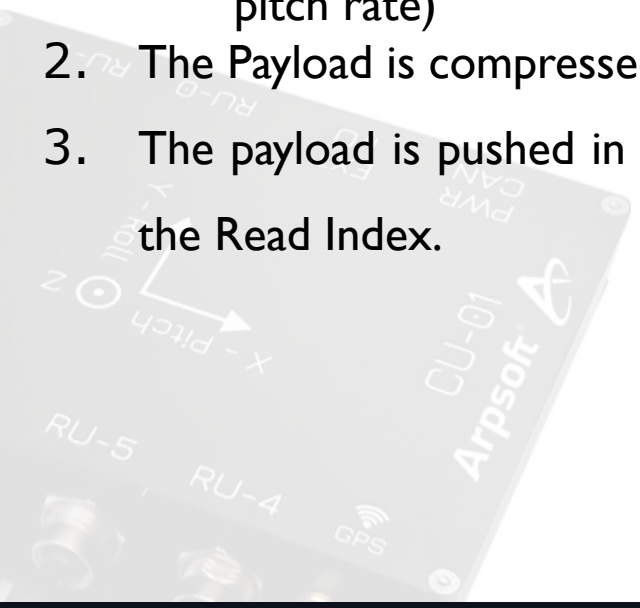
Encoding and Buffer

Encoding

1. Payload of 1 second of data are created (~10.4kB).

   They include:

   - A heading section with cell ID, timestamp, payload coords.
   - 250x3 z-axis acc readings
   - 100x3 navigation output (lat, lon, speed, car pitch rate)
2. The Payload is compressed (~4.5kB).
3. The payload is pushed in the Buffer (FIFO queue) at the Read Index.

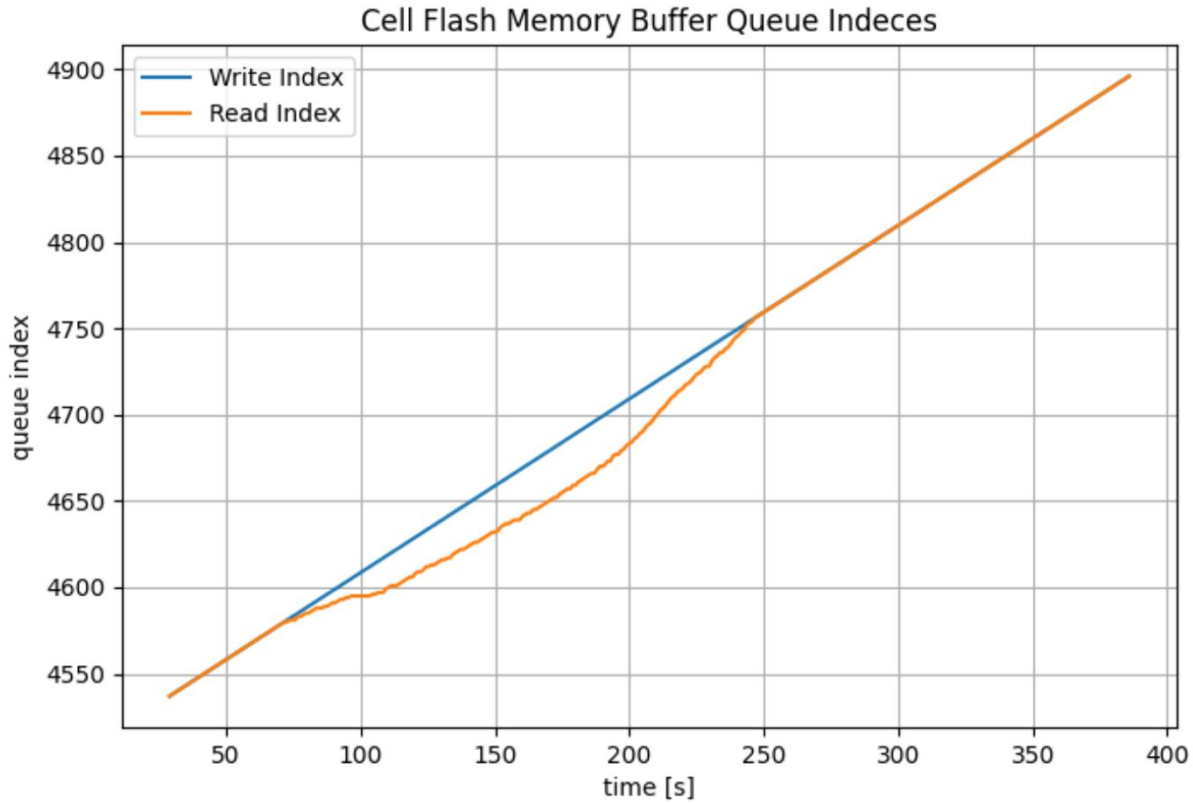


Buffer

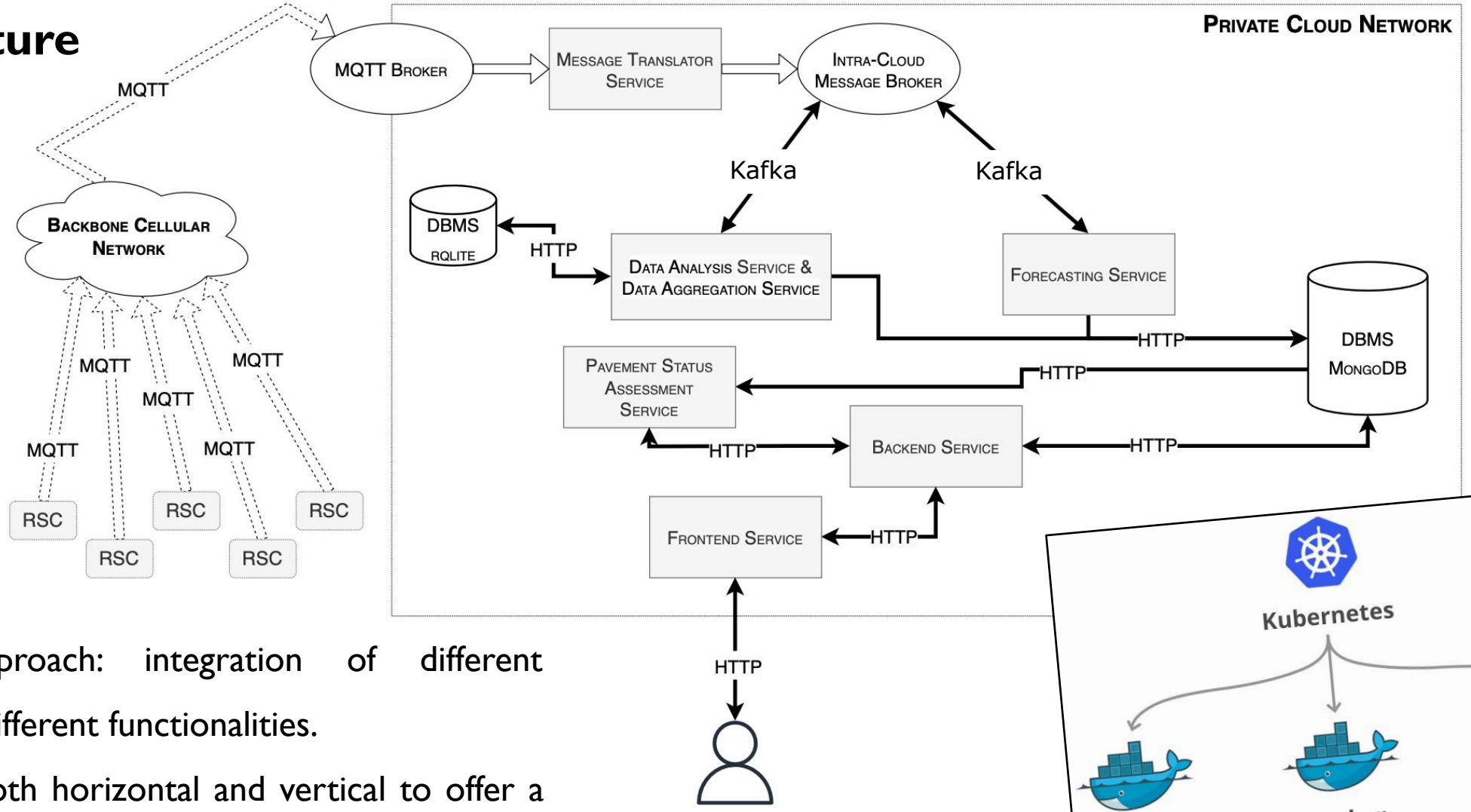
- The buffer is a FIFO queue stored in the Flash Memory (non-volatile).
- It is preserved over cell reboot.
- It is accessed by the encoding module for writing and by the Transfer module for reading.
- It manages a write and a read index as pointers on the memory. Every time a new data is store the write index is incremented; the same on a read execution. The indices are stored on a reserved section as well to be available upon reboot.
- It can store more than 3 hours of continuous operation with no losses.

Transfer

- Data is submitted over the cellular network to the Cloud using MQTT protocol.
- A QoS 2 is used to guarantee zero losses and no duplicates.
- The module autonomously handles loss or poor connection conditions.
- It read data from the buffer at the Read Index.



IT infrastructure



- ✔ Microservice approach: integration of different technologies for different functionalities.
- ✔ High Scalability: both horizontal and vertical to offer a high degree of customization based on customer needs.

MQTT Broker

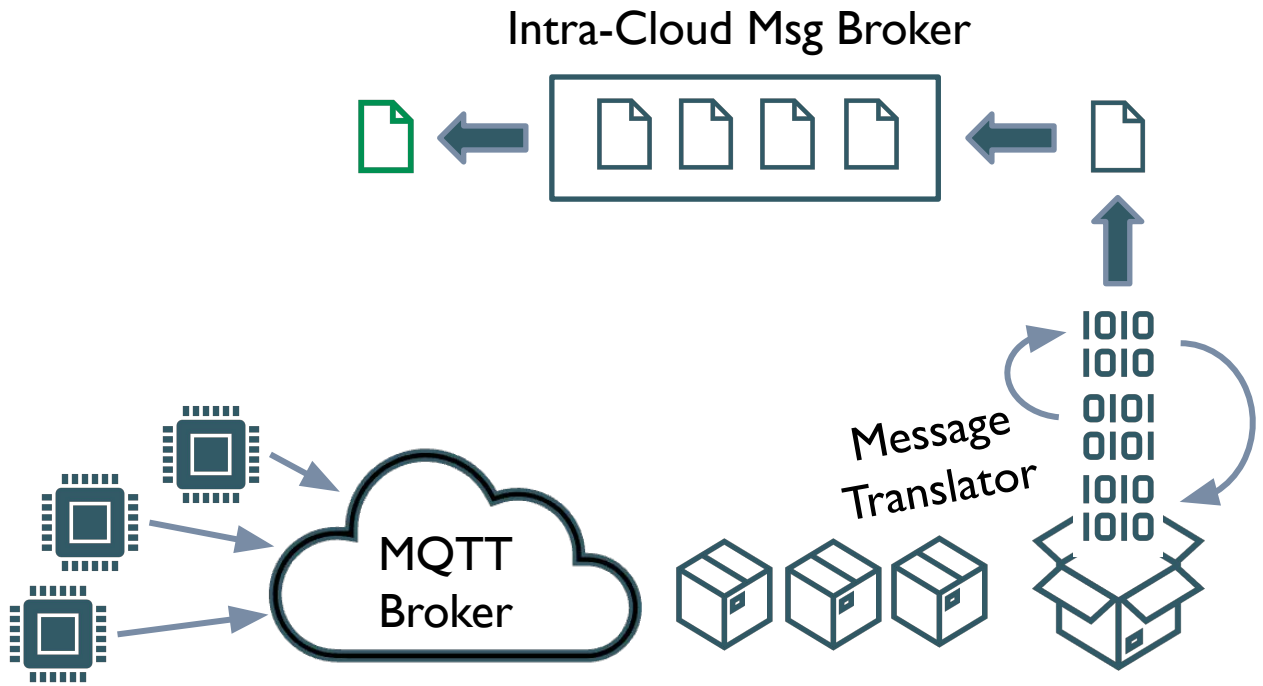
- Receives data from the WSN.
- Pushes data to the Message Translator
- MQTT is a lightweight, open-source protocol (typical in IoT and M2M applications)
- Deployed with a fully-managed service solution (EMQX)

Intra-cloud Message Broker

- Uses Kafka
- Uses a publish/subscribe pattern to operate on the internal queue.
- Manages the information/data exchange across cloud services.

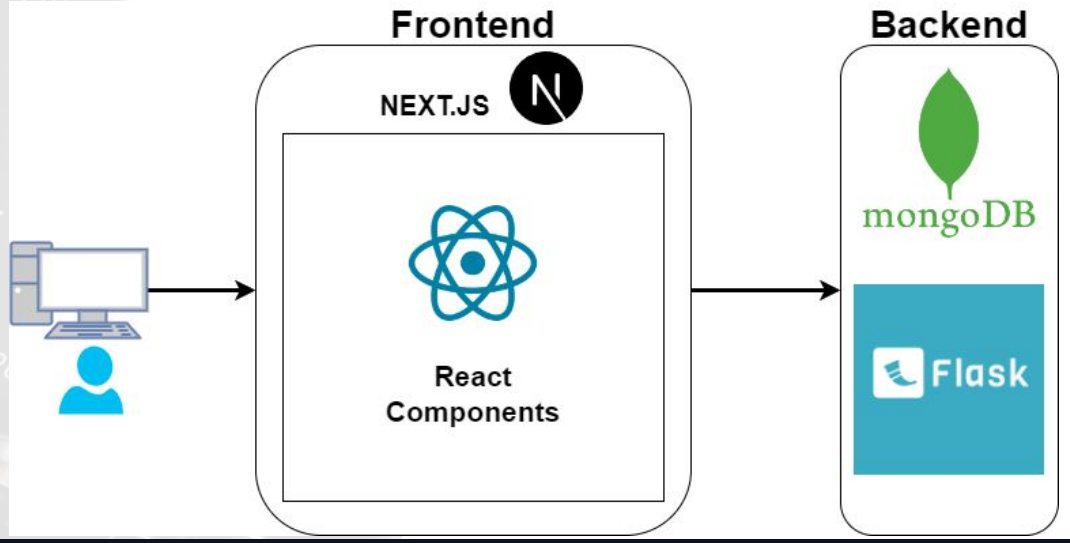
Message Translator

- Consumes data from the MQTT Broker (Cell payloads)
- Decompresses and unpacks payload
- Builds a package of 1 minute of continous data to be submitted for processing.



Backend

- Handles authentication and user requests
- RESTful API:
  - Manage user authentication and authorization.
  - Retrieve the Areas and Users
  - Retrieve the Cells.
  - Retrieve data for visualization



Mongo DB

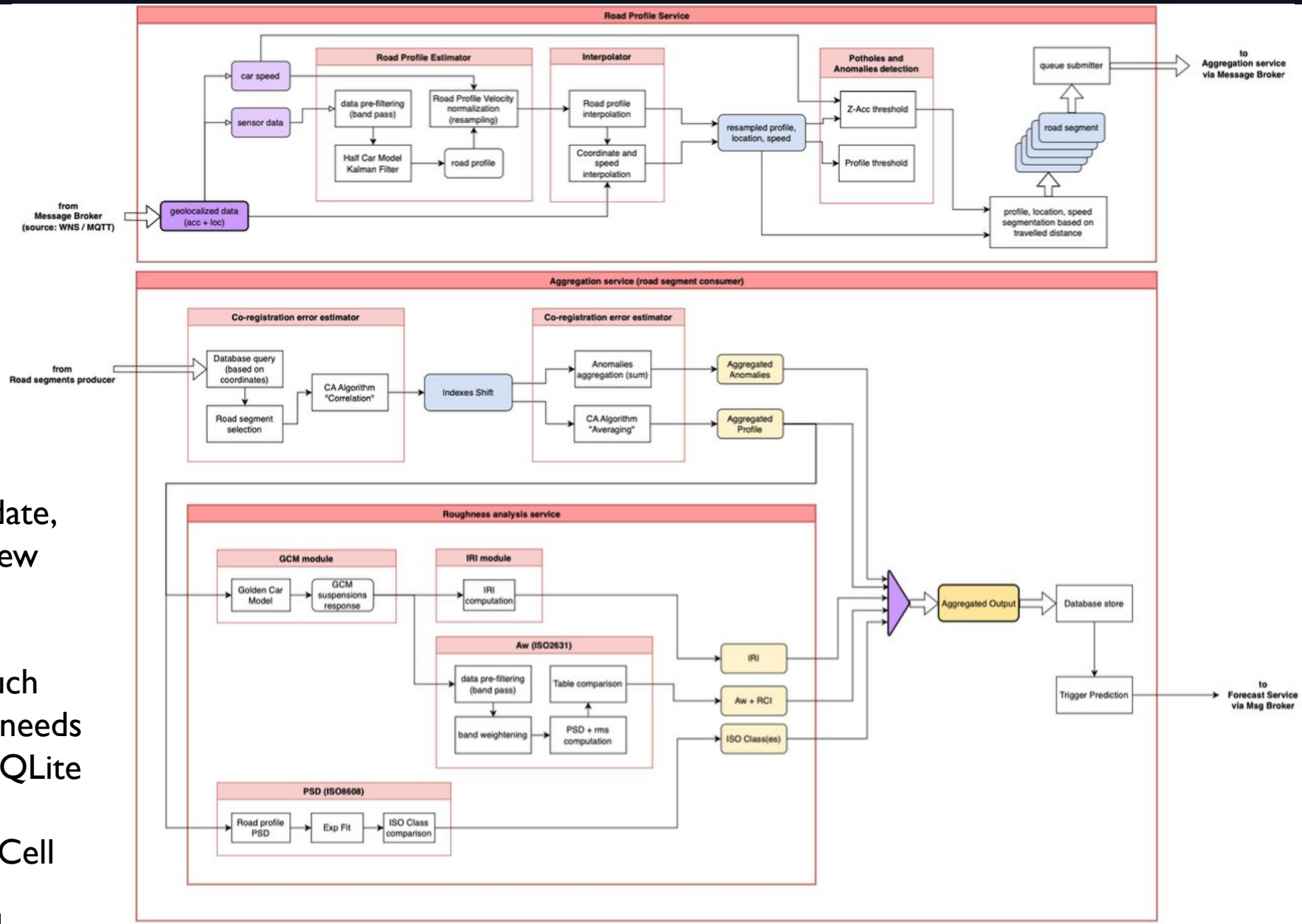
- open-source NoSQL.
- Supports all the major languages and technologies.
- Supports Geospatial queries (GeoJSON) for fast retrieval of data on map.

Front END

- User Authentication (sign in, sign up, retrieve, modify and rest password),
- Road Status visualization on map,
- Management of the Cells (modify information about a specific cell, create a new one),
- Management of Users and Areas to profile users and allowed visualization on the map.

Data Analysis and Aggregation Service

- Road profile estimator
- Map Matching
- Co-registration error estimator
- Co-registration compensation
- Road Roughness analysis

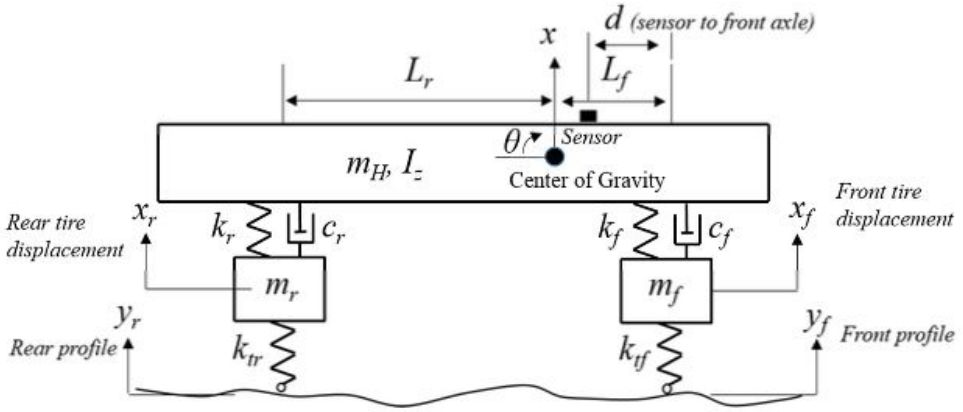


- ✔ A big effort for the architecture update, algorithm study and development, new service implementation during implementation phase.
- ✔ It required also the handling of a much bigger amount of data (road profile needs to be stored), and the usage of an RQLite DB for the OSM data.
- ✔ Improved performance on multiple Cell combination

Road Profile Estimator

A KF uses a Half Car Model (HCM) to propagate the vehicle dynamic and fuses the accelerometric and pitch rate measurements to provide and estimation for the road input profile

HCM



$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \boldsymbol{K}\boldsymbol{x}(t) = \boldsymbol{P}\mathbf{y}(t)$$

$$\mathbf{M} = \begin{bmatrix} m_H & 0 & 0 & 0 \\ 0 & I_z & 0 & 0 \\ 0 & 0 & m_f & 0 \\ 0 & 0 & 0 & m_r \end{bmatrix},$$

$$\mathbf{C} = \begin{bmatrix} c_f + c_r & L_r c_r - L_f c_f & -c_f & -c_r \\ L_r c_r - L_f c_f & L_f^2 c_f + L_r^2 c_r & L_f c_f & -L_r c_r \\ -c_f & L_f c_f & c_f & 0 \\ -c_r & -L_r c_r & 0 & c_r \end{bmatrix},$$

$$\mathbf{K} = \begin{bmatrix} k_f + k_r & L_r k_r - L_f k_f & -k_f & -k_r \\ L_r k_r - L_f k_f & L_f^2 k_f + L_r^2 k_r & L_f k_f & -L_r k_r \\ -k_f & L_f k_f & k_f + k_{tf} & 0 \\ -k_r & -L_r k_r & 0 & k_r + k_{tr} \end{bmatrix},$$

$$\mathbf{x}(t) = [x\ \theta\ x_f\ x_r]^T,$$

$$\mathbf{P} = \begin{bmatrix} 0 & 0 & k_{tf} & 0 \\ 0 & 0 & 0 & k_{tr} \end{bmatrix}^T,$$

$$\boldsymbol{y}(t) = [y_f \quad y_r]^T.$$

Kalman filter

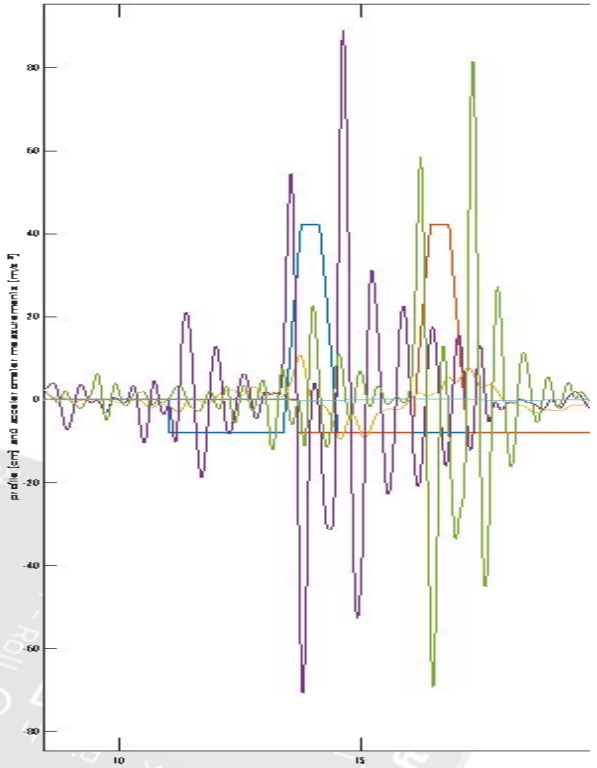
$$\begin{aligned} x_{k+1} &= A_k x_k + b_{m,k} \\ z_k &= H_k x_k + b_{s,k}, \end{aligned}$$

4 observables:

- 3 z-axis accelerometer
- Car pitch rate

Product Overview: CLOUD

HCM tuning w/ Matlab System Identification Toolbox



Measured Input Hump profile

Measured Accelerometric and pitch rate data

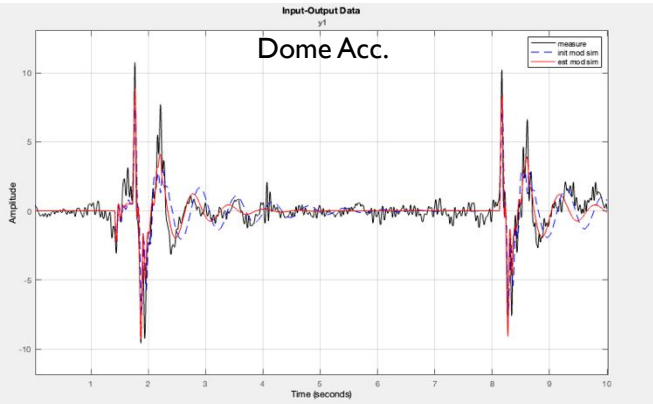
Matlab SID

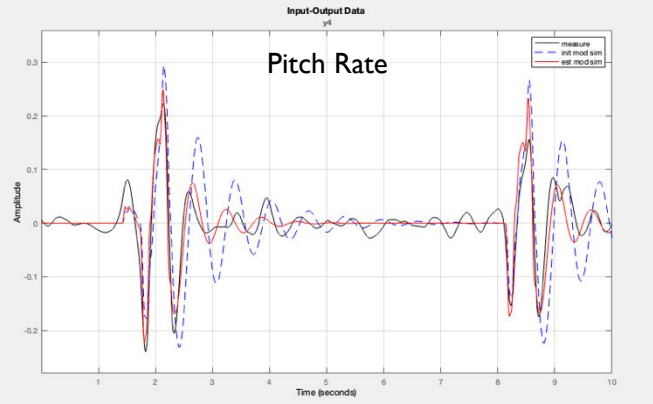
Gray Box HCM

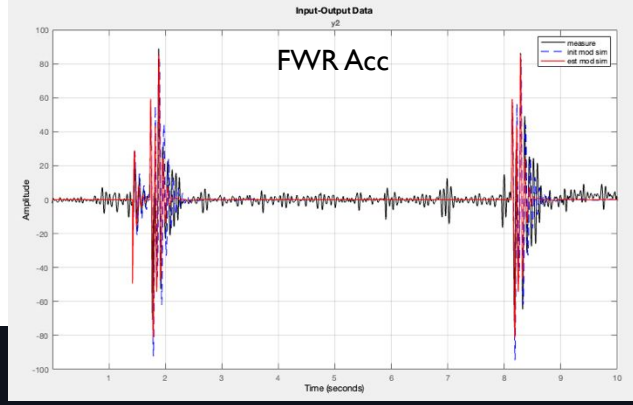
Params: **Model Init**, Identification method, etc

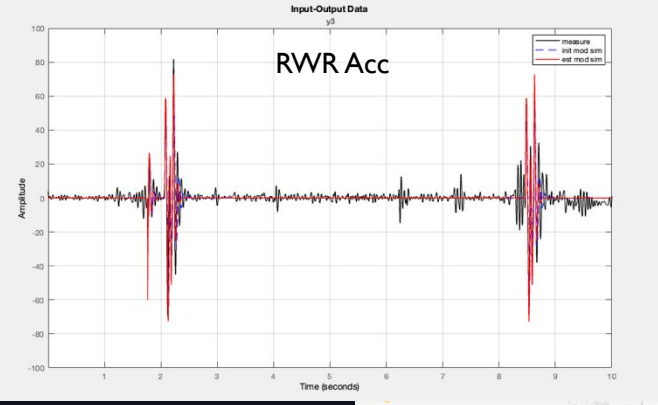
HCM Constants + Output comparison

- Masses,
- Spring const,
- Dump const,
- Inertia,
- Barycenter position

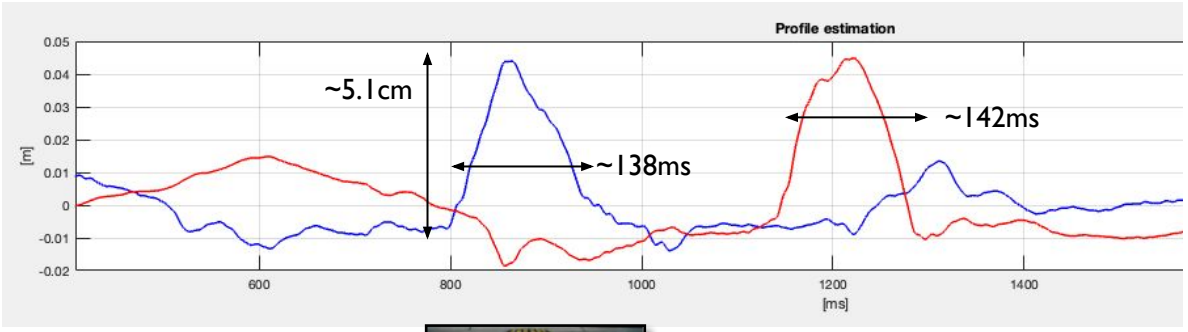








Hump Test – HCM validation



Front

Rear

K, C, M, I Estimated on reference car

Monte Carlo Analysis on model parameters

IRI validation.

Strategy: keep K, C and I parameters as per reference and tune M and geometry properties (car length, masses, distances)

Hump height = **0.05m**

Estimated profile height = **~0.051m**

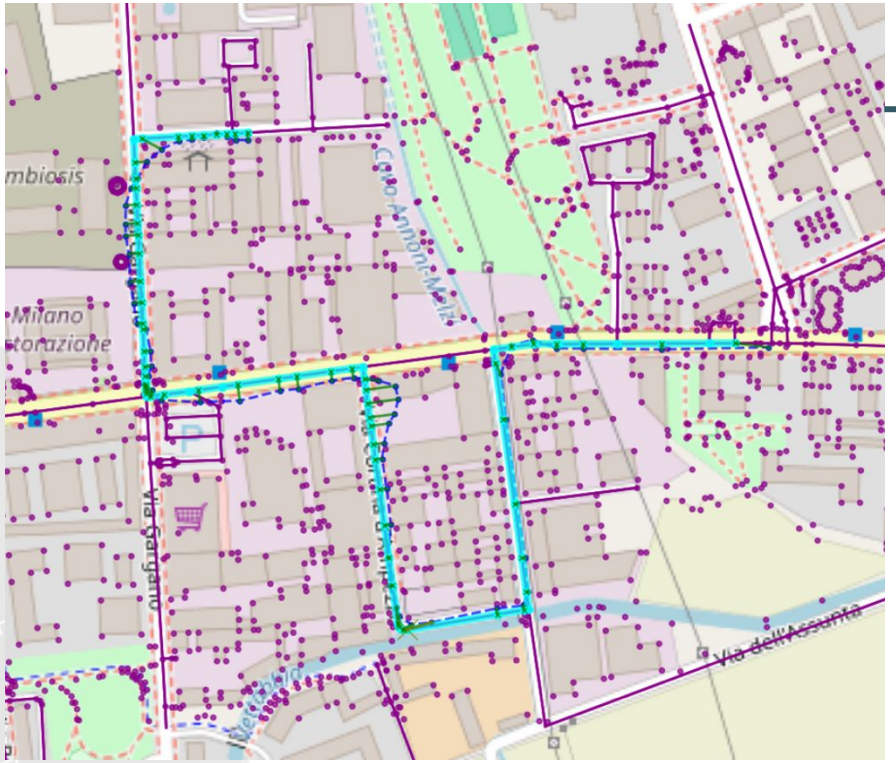
Hump length = **0.9m**

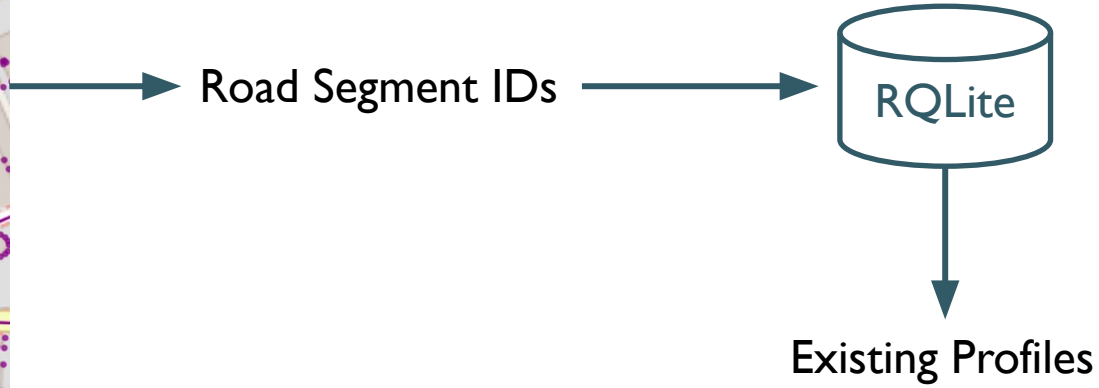
Speed = 7.6m/s

Estimated profile length = Speed*0.14s =**~1.1m**

Map Matching

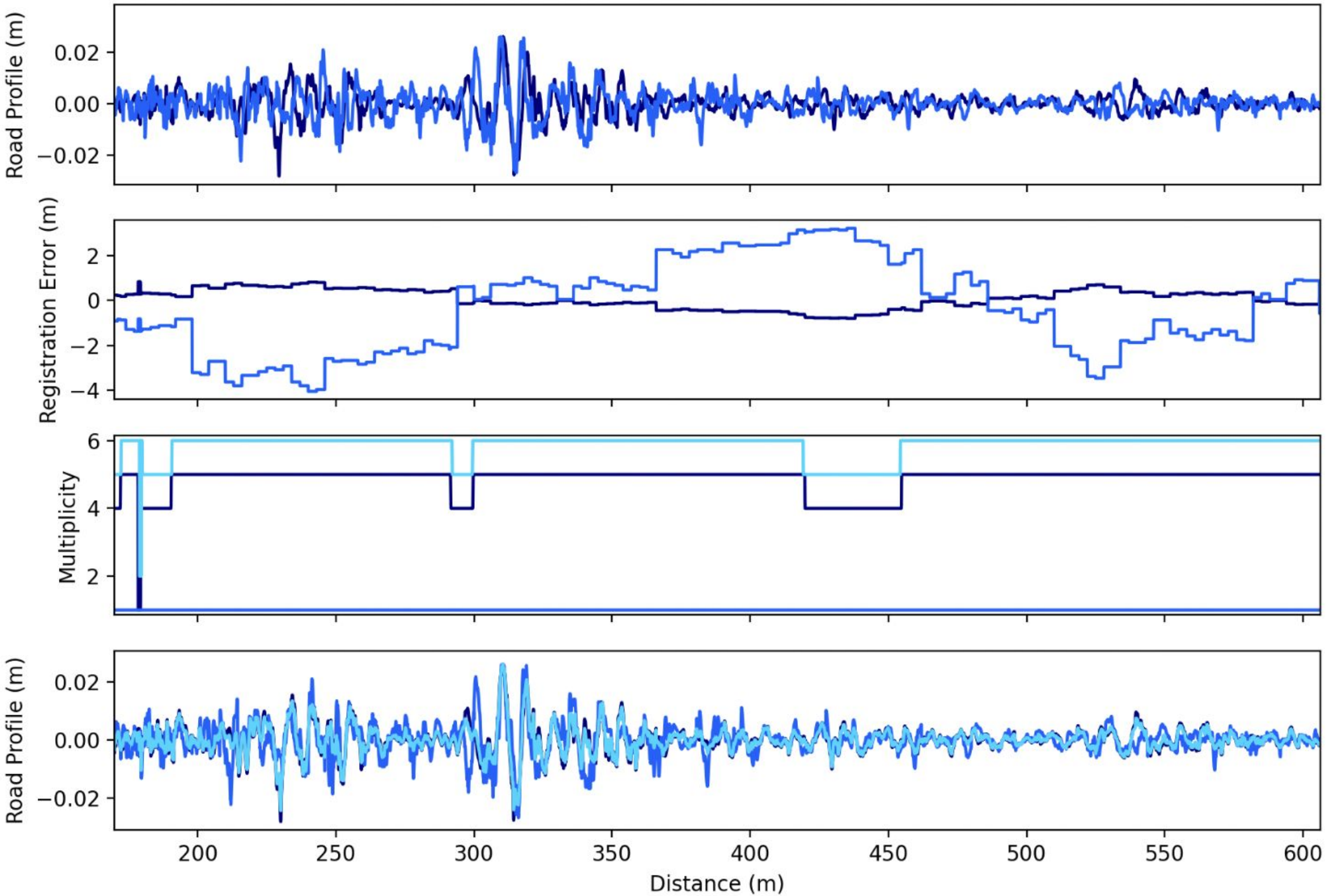
1. Retrieval of OSM from local DB or from OSM repo and update locally
2. Projection of the trajectory on the actual road map.
3. Road segments retrieval





CA Algorithm

1. Co-registratio
   multi-segment
   small shift (reg
   chunks.
2. Co-registratio
   profile positio
   profile history
3. Update profile



Road Roughness Analysis

Road Profile → **IRI**

- IRI 2m base length
- IRI 5m base length
- IRI 10m base length
- ⋮
- IRI 500m base length

ISO2631

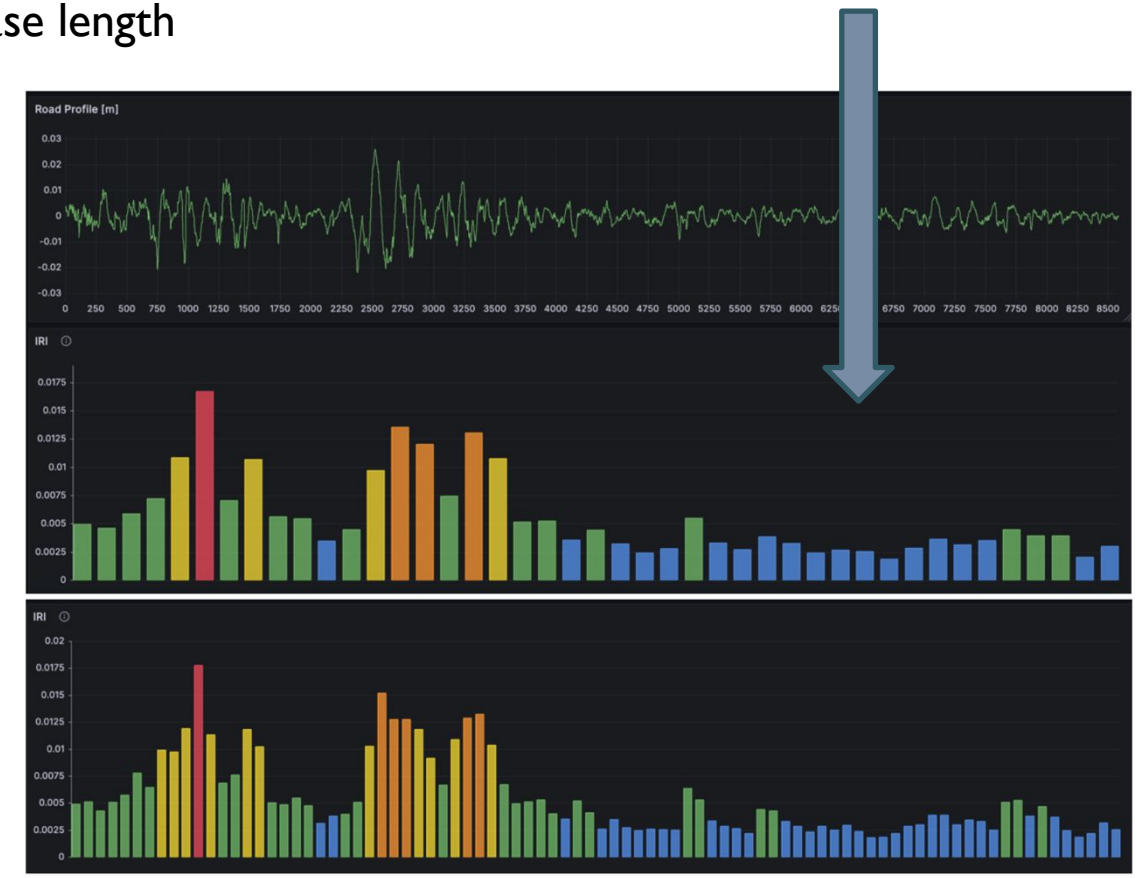
ISO8608

→ **DB** →

Status Assessment
Thresholds on IRI values to define the **Quality Index**, rendered by colour.

To support map visualization

$$IRI = \frac{1}{L}\int_0^{L/V} |\dot{Z}_s - \dot{Z}_u| dt$$



Road Sounder
Automatic Surface Monitoring

FINAL CONSIDERATION

Main Objectives

- ✔ Retrieve the road profile from accelerometric measurement.
- ✔ Provide a qualitative assessment of the road status.
- ✔ Build an autonomous WSN and exploit the high-volume data
- ✔ Reach TRL 6/7
- ✔ Perform a E2E test in operational environment
- ✔ Define a data and processing pipeline
- ✔ Build an effective user interface for exploiting the product

FINAL CONSIDERATION

Lesson learnt

- The smaller the better (RSC installation)
- Cabling and components optimization (cost breakdown)
- Can the Map matching replace the Navigation entirely? (Simpler and cheaper system)

Forthcoming activities

- Using the results achieved so far to promote the product (starting from the video presentation)
- Investing time and resources to reach the smaller administration (free-trial). Marketing activities
- Arpsoft supported GIS for the application in a call for Tender emitted by ATAC, the public transportation administration in Rome. GIS awarded the contract and it's including RS as a part of the services offered to ATAC.
- Attracting funding and application to national funding initiatives to accelerate the market approach.

Comune di Viterbo

atac

GIS GESTIONE INTEGRATA SERVIZI

Brochure available

Website Coming soon

Road Sounder Automatic Surface Monitoring

Ideas for future development

- **AI algorithms** introduction as powerful tool for road distress **identification.**
  - Access to a huge amount of data (RS)
  - Potentially applicable on Cell (edge solution)
  - Can be seamlessly combined with the current solution
- Investigation on **image-based solutions** to eventually complement RS.
  - Opportunity to reach the competitors in the same market area
  - Possibility to identify distresses

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