TOPASE

TrustwOrthy Pnt for unmanned SystEms

13/05/2026

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Project Presentation (1/4): Objectives

"To leverage innovation to design and develop highly reliable, and integrity compatible UAS PNT navigation solutions."

TOPASE KEY OUTPUTS

1. A user centric approach, including the definition of use cases mapped to real commercial activities, ensuring viable business plan and go to market.

2. A Top-Down and Bottom-Up analytical framework (with a focus on the Bottom-up approach) to define PNT architectures and integrity concept covering the different uses cases.

3. An analytical framework sustained by a prototype mapped to one of the use cases, to be chosen building on inputs from ABZero and DRONE Volt and in agreement with ESA team.

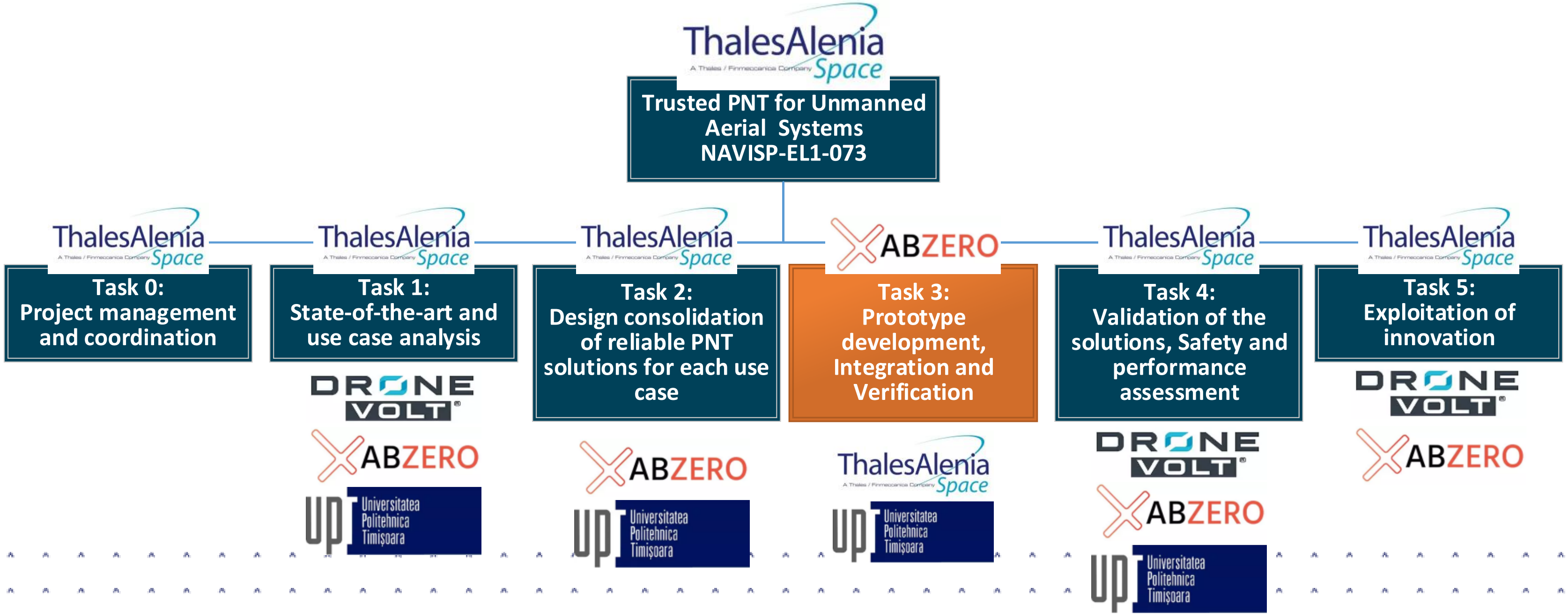
Project Presentation (2/4): Team Organisation

- **Thales Alenia Space France** leads the consortium ensuring the full project management activities, and being in charge of the design of the UAS PNT solutions for the three considered use cases including safety analysis, end-to-end integrity concept, end-to-end simulations, and prototype data analysis.

- **UPT:** is responsible for the fish eye and vision image processing, and leads the payload design and development for integration on board the UAV (referred as navigation block prototype).

- **ABzero:** contributes to the use cases definition and to the design phase as drone commercial player and is the provider of the drone platform and the responsible for the integration and experimentation phase

- **DroneVolt** provides its support and expertise for the technical and safety aspects relying on their deep involvement in the UAS ecosystem, and standardisation groups.



Project Presentation (3/4): Work Logic

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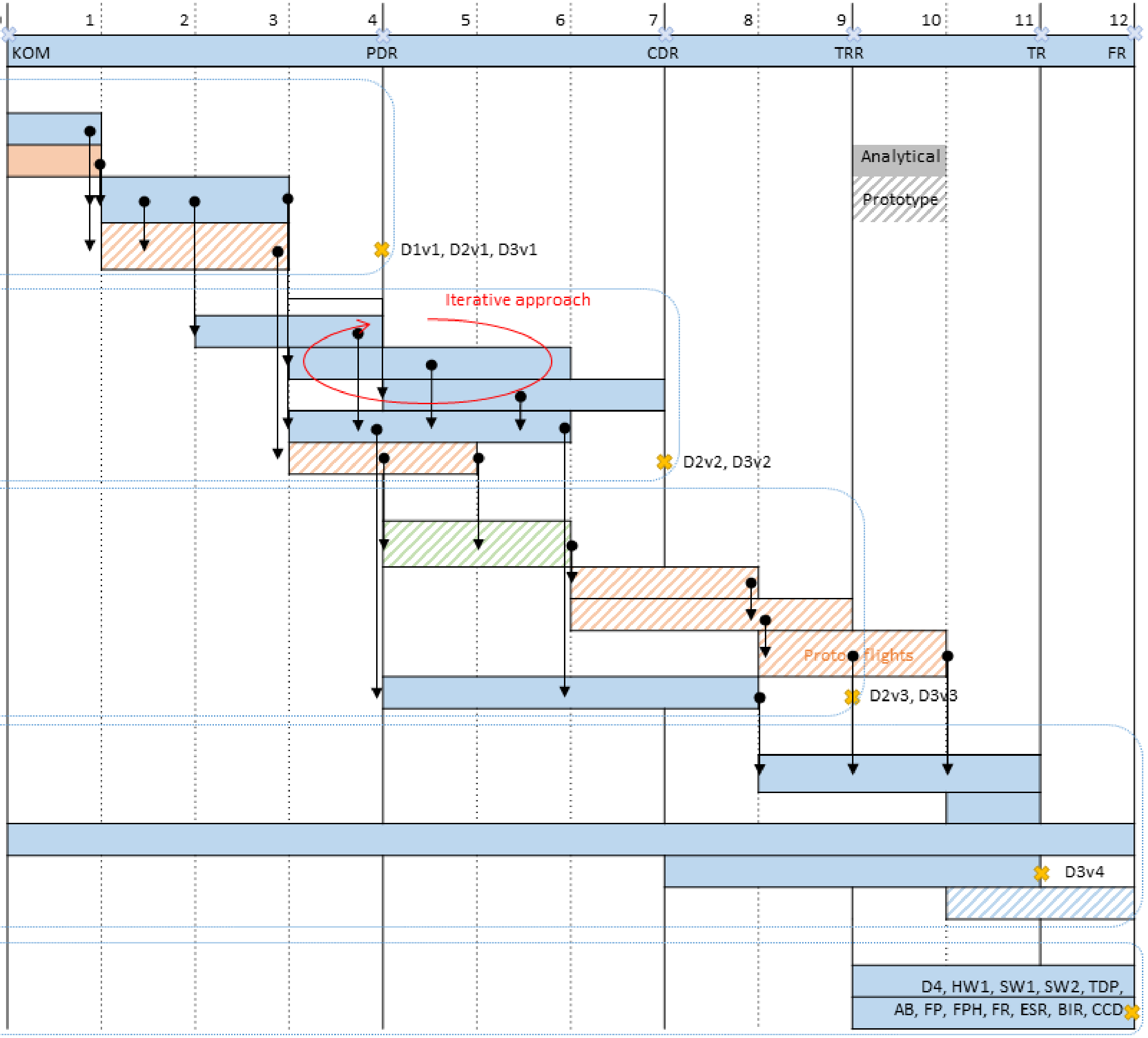
Task 0	**Project management and coordination** (1 progress meeting/2-3 months)	
Task 1	**State-of-the-art and use case analysis**	
Task 1.1	State-of-the-art review (sensors, architectures, integrity, regulation)	
Task 1.2	Use case definition and system requirements	
Task 1.3	Preliminary design for each use case (methodology, preliminary design of the PNT solutions, FTA, DAL, testing strategy, simulation tool)	
Task 1.4	Preliminary design of the UAS navigation block prototype (including FTA, DAL and testing strategy)	
Task 2	**Design consolidation of reliable PNT solutions for each use case**	
Task 2.1	Use case 1: Design consolidation and performance assessment	
Task 2.2	Use case 2: Design consolidation and performance assessment	
Task 2.3	Use case 3: Design consolidation and performance assessment	
Task 2.4	System tools consolidation and design	
Task 2.5	Prototype Design Consolidation	
Task 3	**Prototype development, integration, and verification**	
Task 3.1	Payload development (consolidated design including experience, implementation details)	
Task 3.2	Platform development and prototype integration	
Task 3.3	Test strategy, plan and procedures	
Task 3.4	Verification and execution tests for the prototype (including testing flights)	
Task 3.5	Post-processing and system tools development	
Task 4	**Validation of the solutions, safety and performance assessment**	
Task 4.1	Validation of the solutions	
Task 4.2	Evaluation of the benefits of the proposed solutions	
Task 4.3	Safety analysis	
Task 4.4	Test analysis, test report and user manual	
Task 4.5	Prototype delivery, integration and training and dry run	
Task 5	**Exploitation of innovation**	
Task 5.1	Roadmap and recommendations	
Task 5.2	Final Report	



Project presentation (4/4): technical drivers & challenges

TrustwOrthy Pnt for unmAnned SystEms

- **Technical drivers:**
  - To address features of the different use cases considering the **technical and regulatory framework**
  - To **develop a methodology** for designing different integrity concepts and evaluate the associated reliable sensor fusion based PNT architectures
  - To bind the proposed solutions to the target SWaP and cost assumptions that apply to each use case

- **Technical challenges:**
  - How to validate integrity algorithms targeting low integrity risks
  - Define target performance KPIs for the integrity concept
  - How to derive learning from the project, recommendations and way-forward for future operational UAS systems

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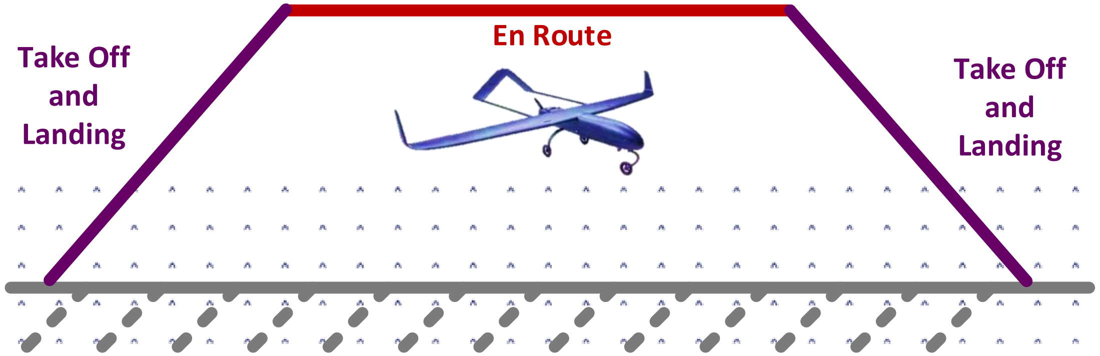
2 – Use cases design and methodology (1/7)

> Selection criteria:

- Three **representative** use cases for UAV operating in **fully autonomous or safety-critical operations**, in ‘**specific**’ and ‘**certified**’ categories.

> Use case 1: Critical infrastructure surveillance (specific category)

- Critical infrastructures surveillance such as site survey or long-range surveillance.
  - Local surveillance such as wind turbines or buildings. It is usually multi-rotors UAS with a dedicated payload.
  - Long distance surveillance such as rail, road or energy networks. It is mainly fixe wing UAS that are used for the long term surveillance.



Requirements		Take off and Landing	Cruise
Accuracy (@95%)	Position	8 meters in horizontal 13 meters in vertical	10 meters in horizontal 15 meters in vertical
	Velocity	Proportional to the UAS velocity	
Integrity	Position	$1.10^{-3}/h$	
	Velocity	$1.10^{-2}/h - 1.10^{-3}/h$	
TTA	Position	$< 6s$	
	Velocity	$< 6s$ TBC	
Alert Limits	Position	27 meters in horizontal 22 meters in vertical	32 meters in horizontal 28 meters in vertical
	Velocity	Proportional to the velocity accuracy	
Continuity	Position	$1.10^{-4}/h$	
	Velocity		
Availability	Position	0.9999	
	Velocity		

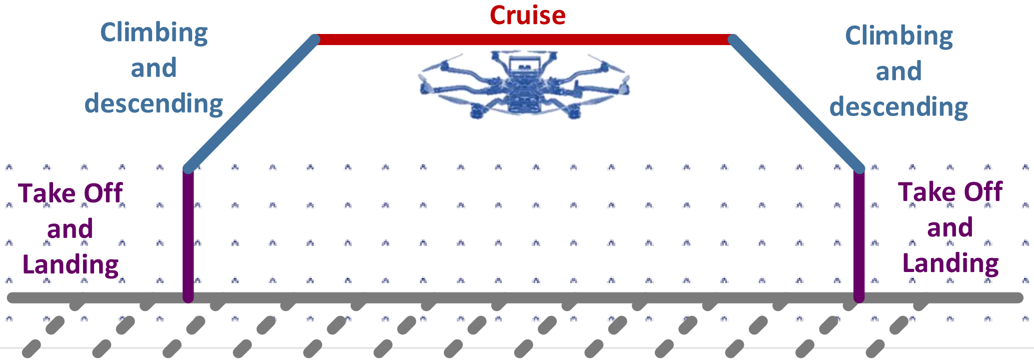
2 – Use cases design and methodology (2/7)

> Selection criteria:

- Three **representative** use cases for UAV operating in **fully autonomous or safety-critical operations**, in '**specific**' and '**certified**' categories.

> Use case 2: Delivery of specific goods between two identified points (specific category)

- A specific use case, mainly multi-rotors UAV. Several cases of delivery:
  - Private package delivery: e.g. "last mile delivery" (Amazon)
  - Delivery of specific goods between two identified points. In this case, the UAS is used to deliver as fast as possible its loading. E.g. transport of critical medical goods between two hospitals such as blood bag or organ transplants. **For this application field, ABzero has developed an innovative UAV solution for the autonomous delivery of medical goods (blood bag).**



Requirements		Take off and Landing	Climbing and descending	Cruise
Accuracy (@95%)	Position	1 meters in horizontal	2 meters in horizontal and vertical	3 meters in horizontal 4 meters in vertical
	Velocity	Proportional to the UAS velocity		
Integrity	Position	$1.10^{-7}/h$		
	Velocity	$1.10^{-6}/h - 1.10^{-7}/h$		
TTA	Position	$< 1s$		
	Velocity	$< 1s$		
Alert Limits	Position	5 meters (HAL, VAL)	10 meters (HAL, VAL)	10 meters (HAL, VAL)
	Velocity	Proportional to the velocity accuracy		
Continuity	Position	$1.10^{-4}/h$		
	Velocity			
Availability	Position	0.9999		
	Velocity			

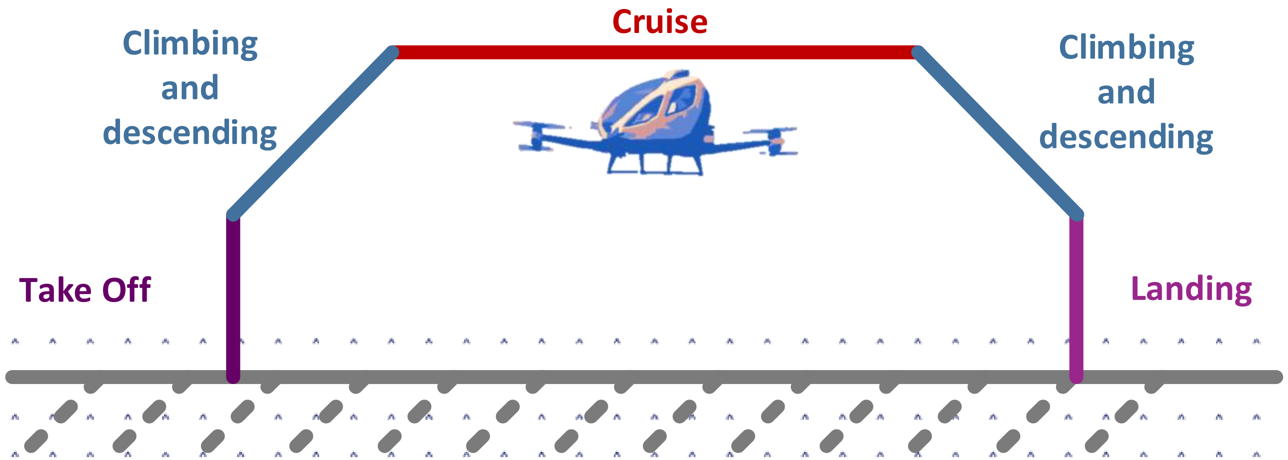
2 – Use cases design and methodology (3/7)

> Selection criteria:

- Three **representative** use cases for UAV operating in **fully autonomous or safety-critical operations**, in '**specific**' and '**certified**' categories.

> Use case 3: Taxi drone (certified category)

- Life embedded applications such as taxi drones or transport of medical staff for emergency situations. It is the certified use case.
- It is also called VTOL-capable aircraft (VCA).

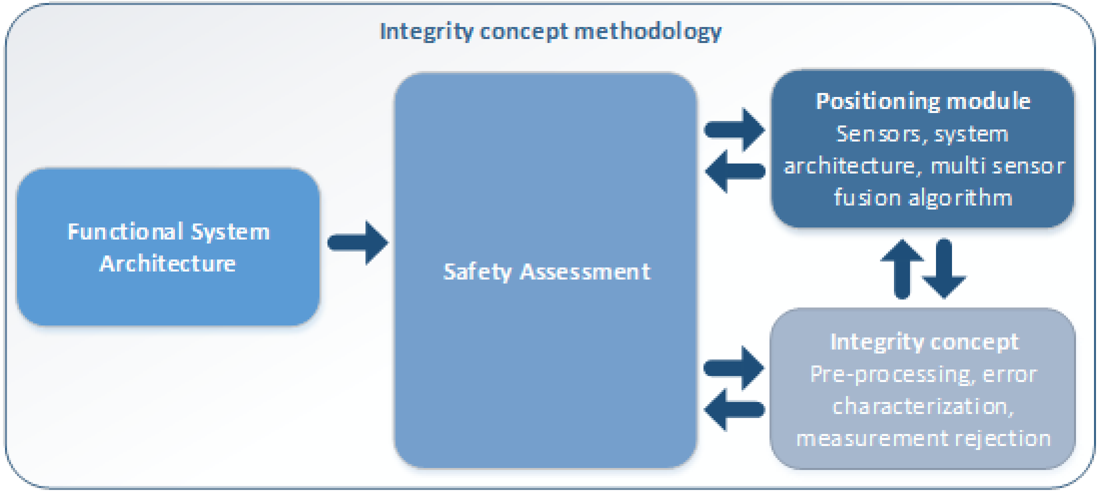


Requirements		Take off	Climbing and descending	Cruise	Landing
Accuracy (@95%)	Position	50 cm in horizontal and vertical	1 meters in horizontal and vertical	3 meters in horizontal 4 meters in vertical	20 cm in horizontal 10 cm in vertical
	Velocity	Proportional to the UAS velocity			
Integrity	Position	$1.10^{-9}/h$			
	Velocity	$1.10^{-6}/h - 1.10^{-7}/h$			
TTA	Position	$< 100ms$	$< 1s$		$< 100ms$
	Velocity	$< 100ms$	$< 1s$		$< 100ms$
Alert Limits	Position	2 meters (HAL, VAL)	5 meters (HAL, VAL)	10 meters (HAL, VAL)	1 meters (HAL, VAL)
	Velocity	Proportional to the velocity accuracy			
Continuity	Position	$1.10^{-4}/h$			
	Velocity				
Availability	Position	0.9999			
	Velocity				

2 – Use cases design and methodology (4/7)

> Definition of the integrity concept methodology at the user level of the UAS

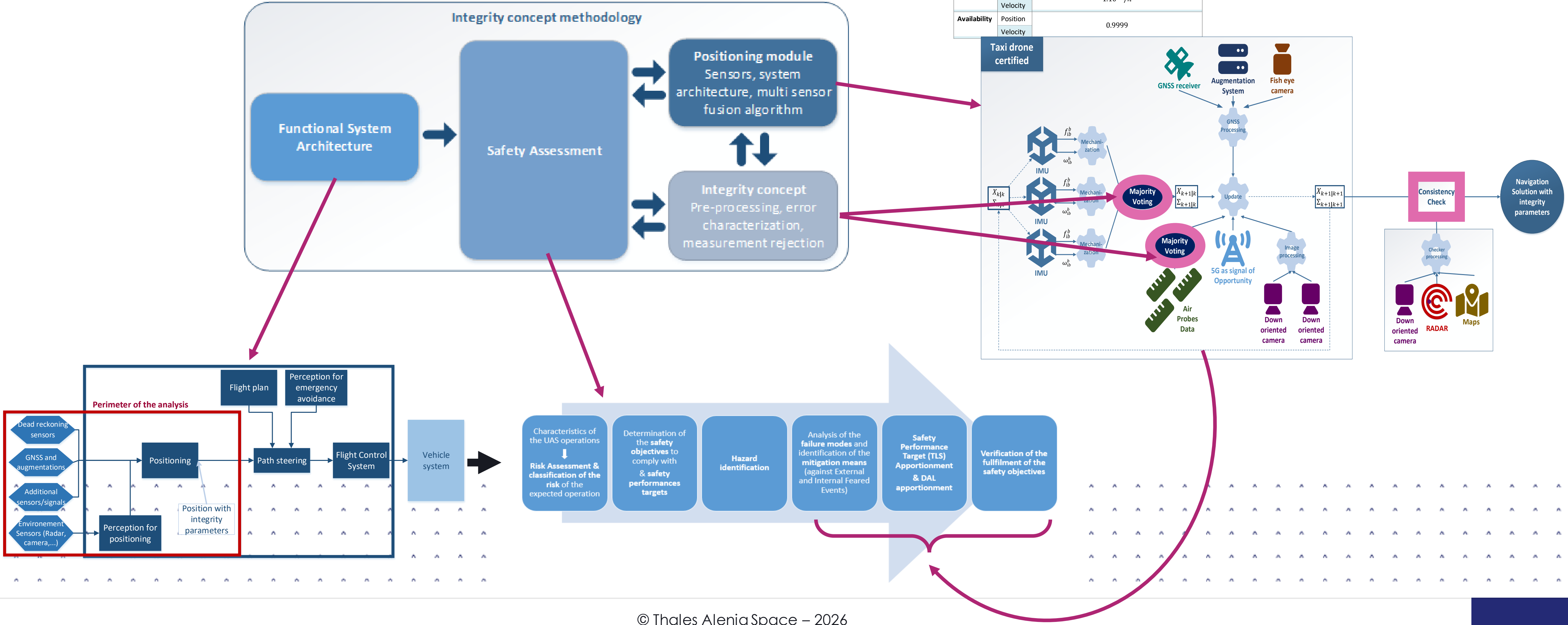
- This methodology is organized in four main steps:
  - Definition of the Functional System Architecture:
    - Definition of the system architecture at the UAS level where several modules as perception, positioning, planning and control interact to ensure the functions of the automated driver
  - Safety assessment:
    - The definition of the Functional System Architecture allows to perform the safety analysis.
  - Design of the positioning module:
    - the requirements defined for the positioning module are used as input for the design of this module.
  - Definition of the integrity concept for the positioning module:
    - the proposed sensors and the architecture of the positioning module as well as the requirements form the safety analysis are used for the final step which is the definition of the integrity concept.



2 – Use cases design and methodology (5/7)

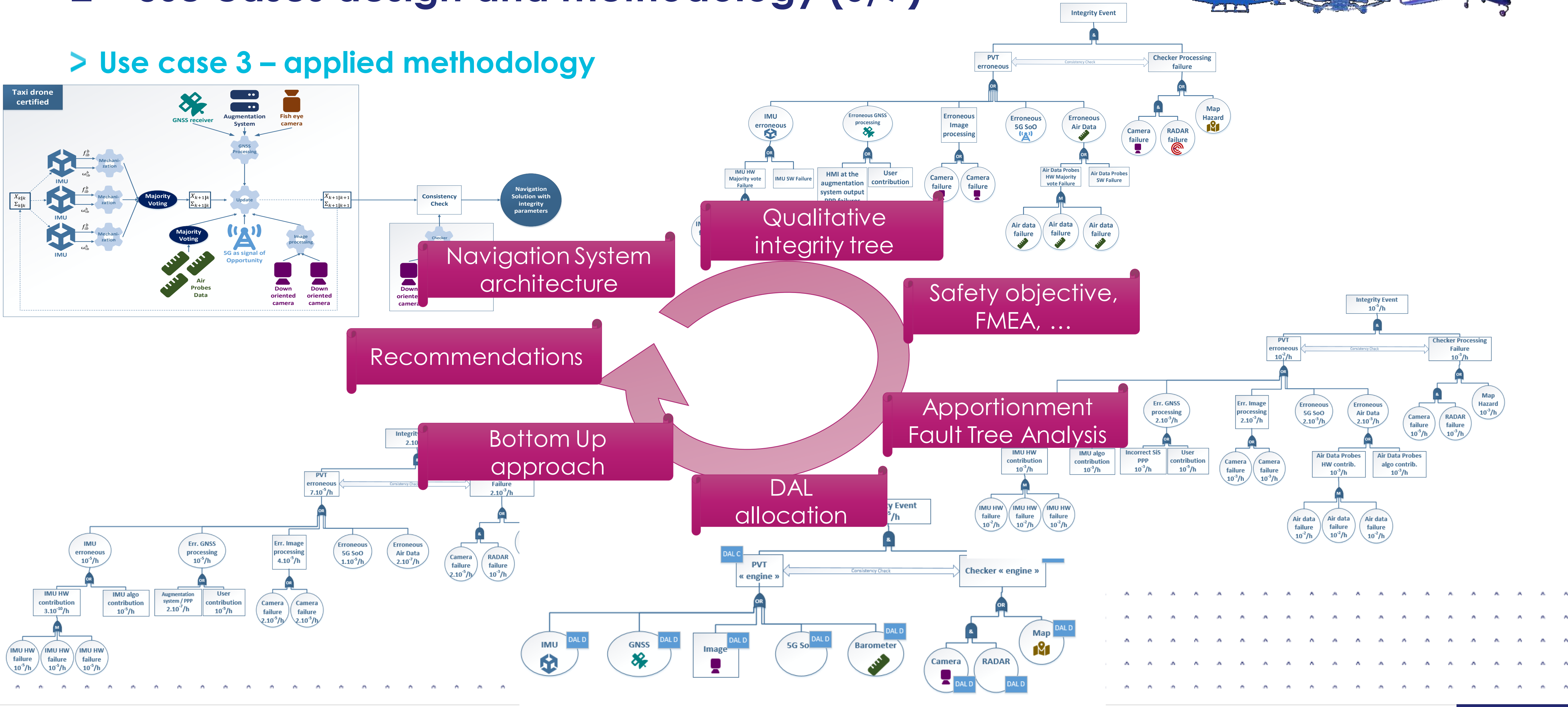
> Applied methodology

Requirements		Take off	Climbing and descending	Cruise	Landing
Accuracy (@95%)	Position	50 cm in horizontal and vertical	1 meters in horizontal and vertical	3 meters in horizontal 4 meters in vertical	20 cm in horizontal 10 cm in vertical
	Velocity	Proportional to the UAS velocity			
Integrity	Position	$1.10^{-9}/h$			
	Velocity	$1.10^{-6}/h - 1.10^{-7}/h$			
TTA	Position	$< 100ms \quad x$	$< 1s$		$< 100ms$
	Velocity	$< 100ms$	$< 1s$		$< 100ms$
Alert Limits	Position	2 meters (HAL, VAL)	5 meters (HAL, VAL)	10 meters (HAL, VAL)	1 meters (HAL, VAL)
	Velocity	Proportional to the velocity accuracy			
Continuity	Position	$1.10^{-4}/h$			
	Velocity				
Availability	Position	0.9999			
	Velocity				



2 – Use cases design and methodology (6/7)

> Use case 3 – applied methodology



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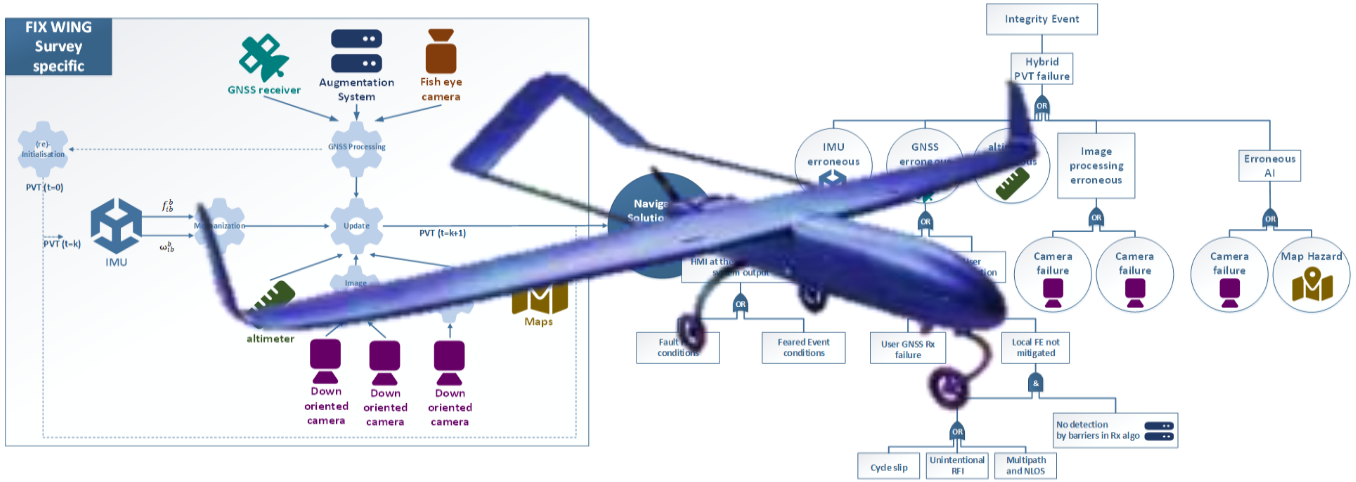
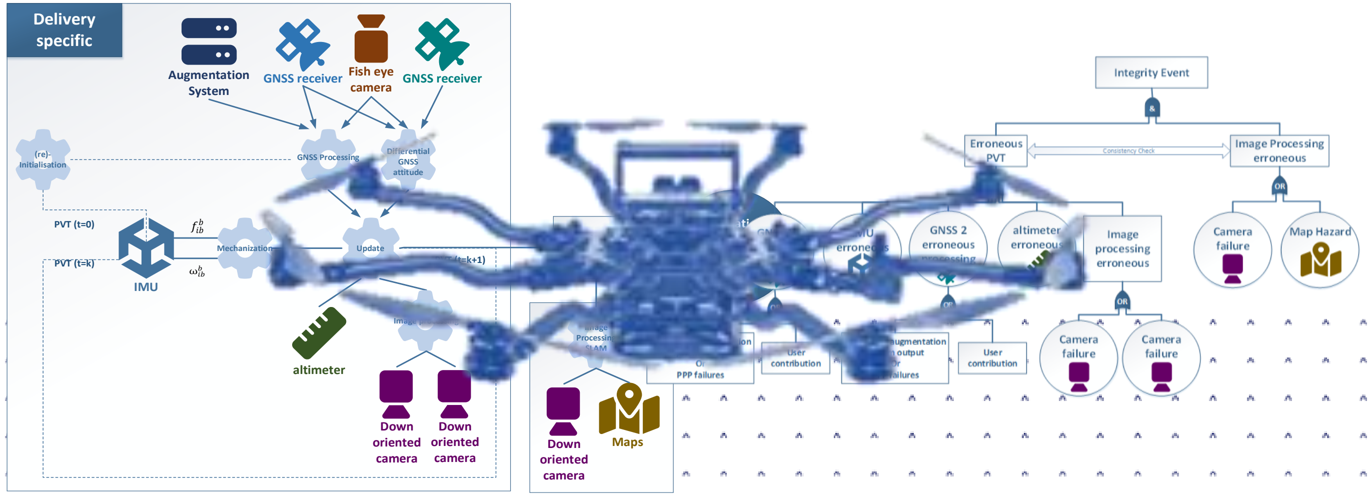
2 – Use cases design and methodology (7/7)

> Methodology extrapolated for the less stringent use cases





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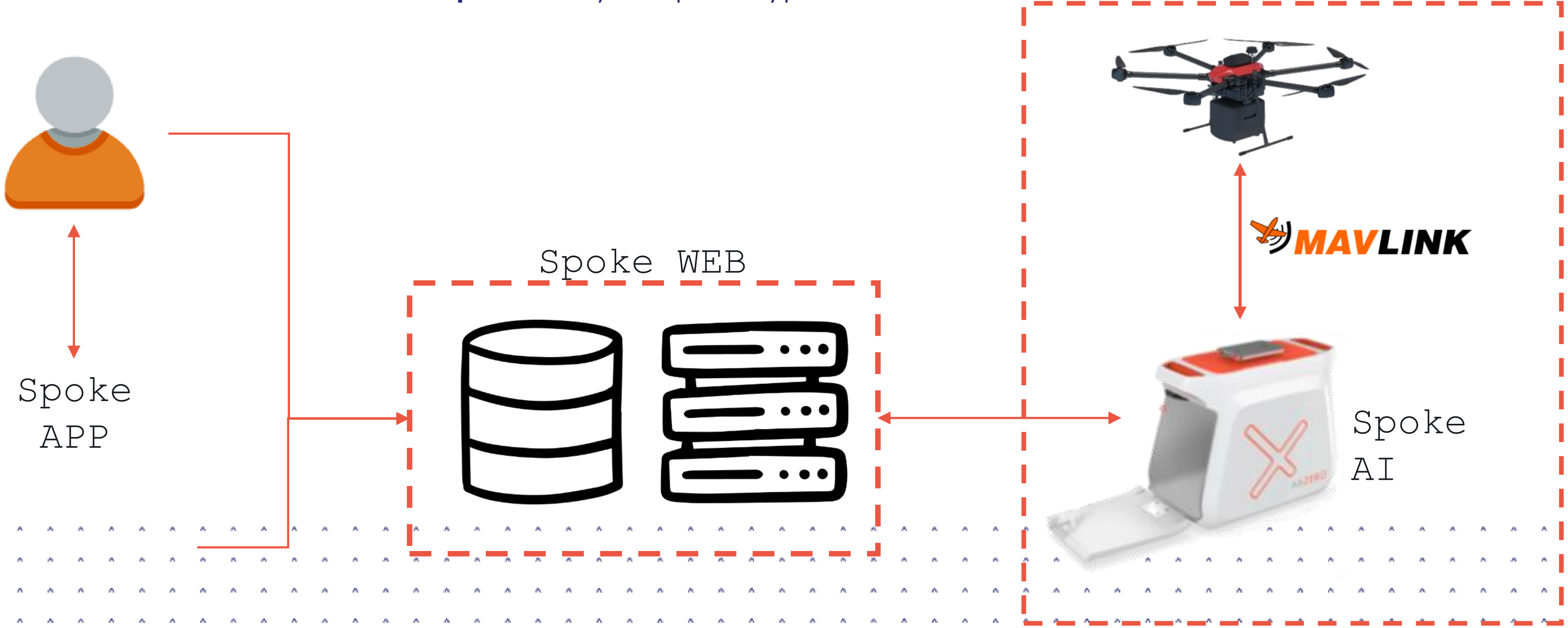
3 – Demonstrator Design Verification and Validation (1/26)

High Level overview of the payload

- The TOPASE project handles use cases considering a **multicopter** provided by **ABzero** for the test flights. The prototype takes into account the **constraints of the UAV** (e.g. total volume and mass, power supply, vibrations, temperatures, etc.). The **navigation function of the UAV is not impacted** by the prototype.

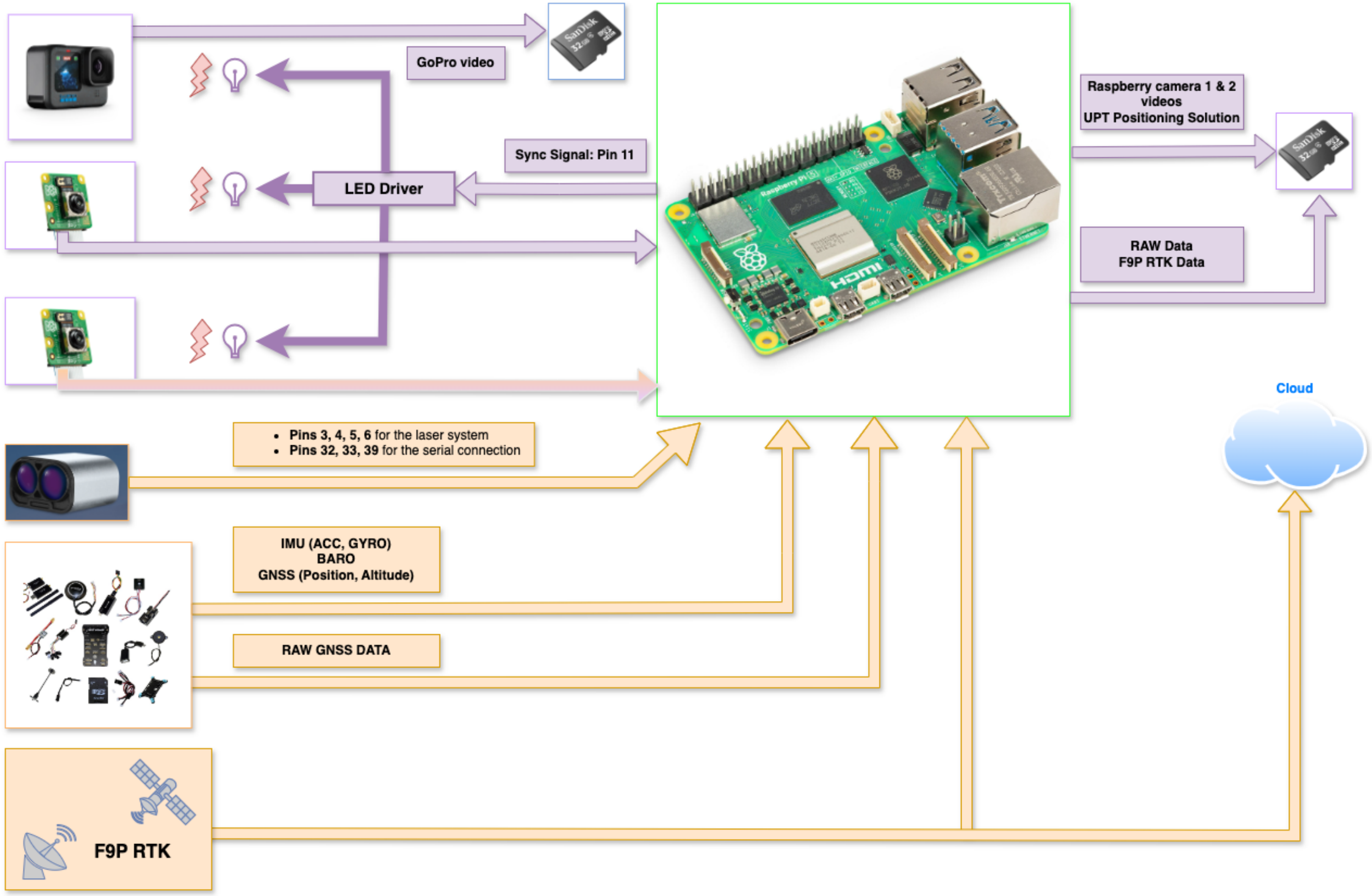


3 – Demonstrator Design Verification and Validation (2/26)

> Payload design

- Parts managed by UPT team are illustrated in purple in the picture
- Parts managed by ABzero team are illustrated in orange in the picture

Components	Proposed Reference	
IMU	ICM-20649	Pixhawk PX4 board (Arm® Cortex®-M4 core running up to 400 MHz, has 2MB SRAM and external XIP Flash with 64MB) – on board of the drone, as part of the drone
Barometer	BMP388	
Gyroscope	MPU-6000/6050	
Altimeter	BMP388	
Magnetometer	BMM150	Part of the drone flight controller
GNSS 1	Mosaic-X5	
GNSS 2	U-Blox F9P	Provided by the ABzero payload
Altimeter	LW20C Laser	Provided by ABZero payload
Camera 1	Raspi Camera Module 2	Provided by UPT Payload
Camera 2	Raspi Camera Module 2	Provided by UPT Payload
Fisheye camera	GoPro camera	Provided by UPT Payload
PC		



3 – Demonstrator Design Verification and Validation (3/26)

> Hardware design

- From the ABzero part the hardware consists of the following components:

Raspberry PI 5

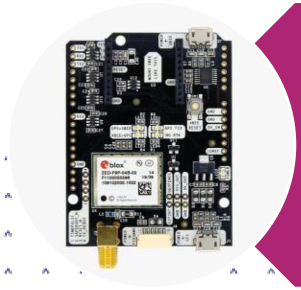
Quad-core Cortex-A76 @ 2.4 GHz, improved I/O bandwidth, dual 4K display support, and PCIe 2.0 for high-performance expansion.

ArduSimple F9P – Base station

Multi-band GNSS board based on the u-blox ZED-F9P, used to generate RTK correction data.

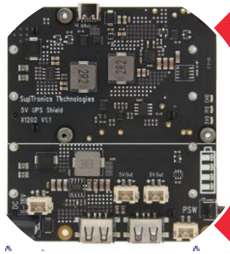
SIMCOM 7600

4G LTE modem with data, SMS, and GNSS support for reliable mobile connectivity.



ArduSimple F9P – Rover

Identical multi-band GNSS board configured to receive RTK corrections and achieve centimeter-level relative positioning.

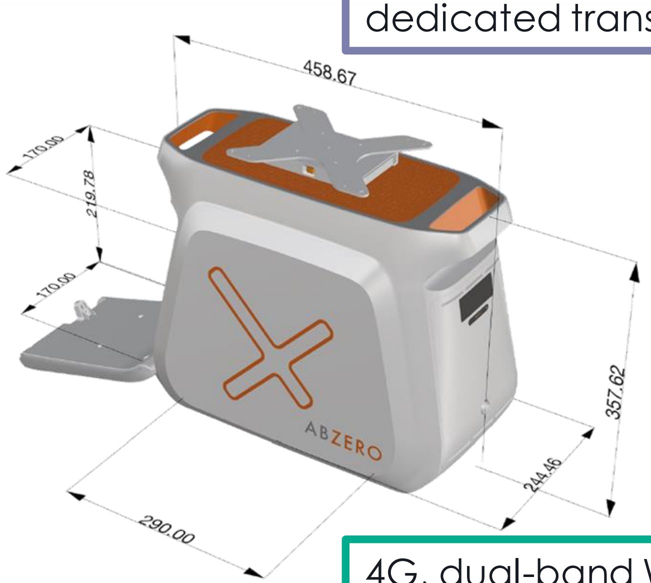


Geekworm UPS module X1202

UPS board with a four-cell battery pack, providing power continuity, automatic charging, and stable regulated output to the Raspberry Pi.

3 – Demonstrator Design Verification and Validation (4/26)

Biomedical-grade insulated polyurethane capsule, sized to hold X/Y-tube blood bags and supplied with a dedicated transport kit.



Structure & Storage

Electronics & Processing

Low-power CPU optimized for AI tasks, real-time camera streaming with GPU-enhanced compression, and a user interface display.

Connectivity & Access Control

4G, dual-band Wi-Fi, Bluetooth, a smart electric lock with event logging, a display interface and a RGB LED indicator.

Power & Environmental Monitoring

Rechargeable battery with 4 hours of autonomy. Internal and external temperature and humidity sensors.

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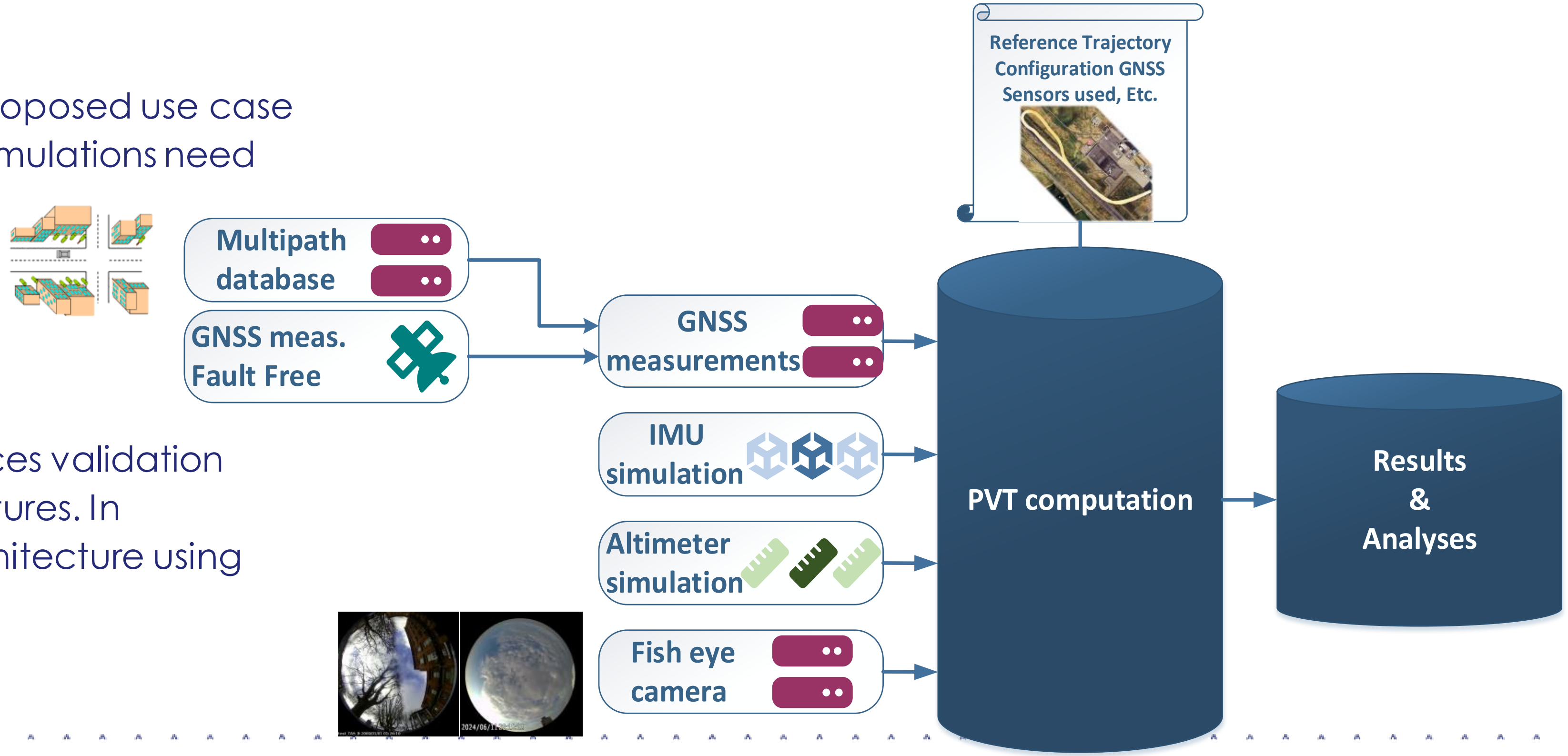
3 – Demonstrator Design Verification and Validation (5/26)

> Real data processing and simulation tool

- To validate the performances of the proposed use case architectures, real data collects and simulations need to be used.

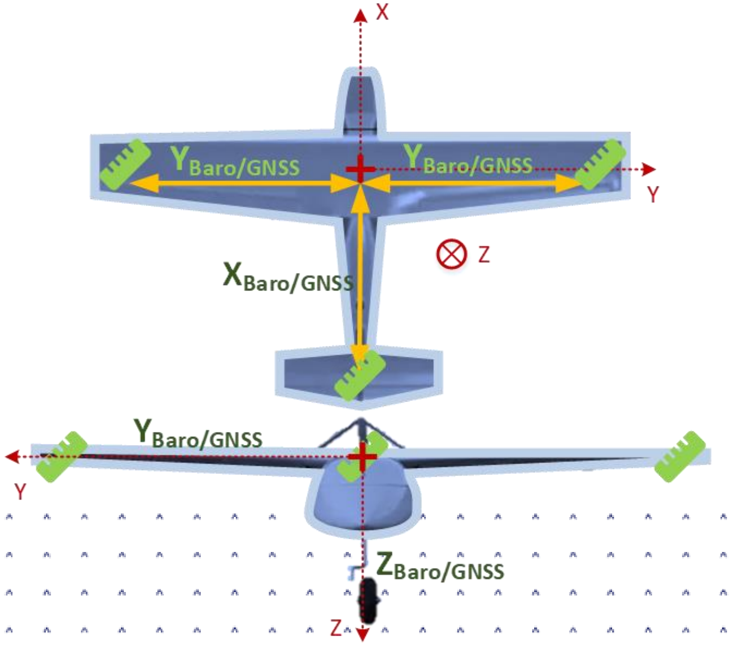
- Simulations, apart from this performances validation aspect, allow to test different architectures. In particular, one can think of testing architecture using different sensor grades.

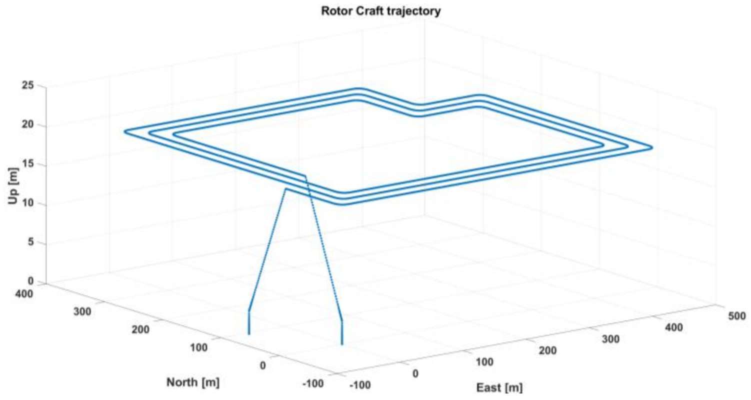


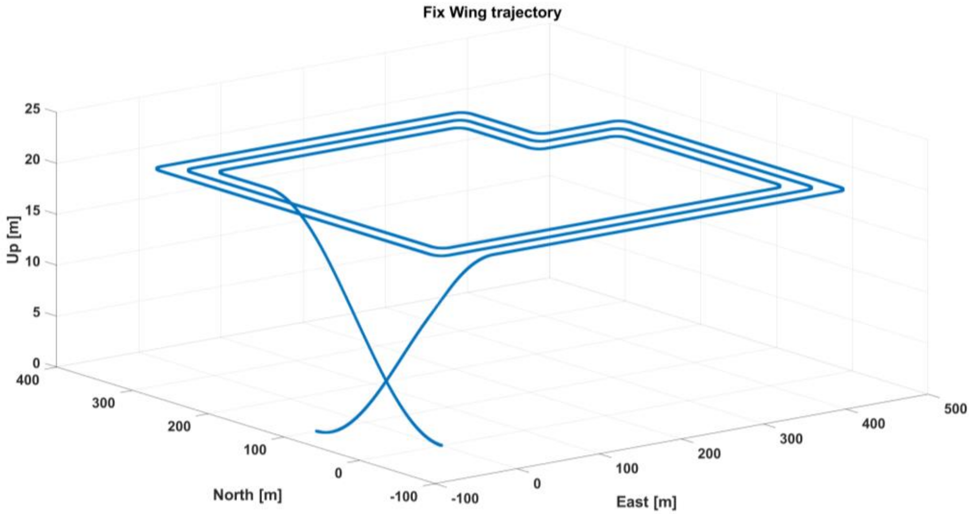
3 – Demonstrator Design Verification and Validation (6/26)

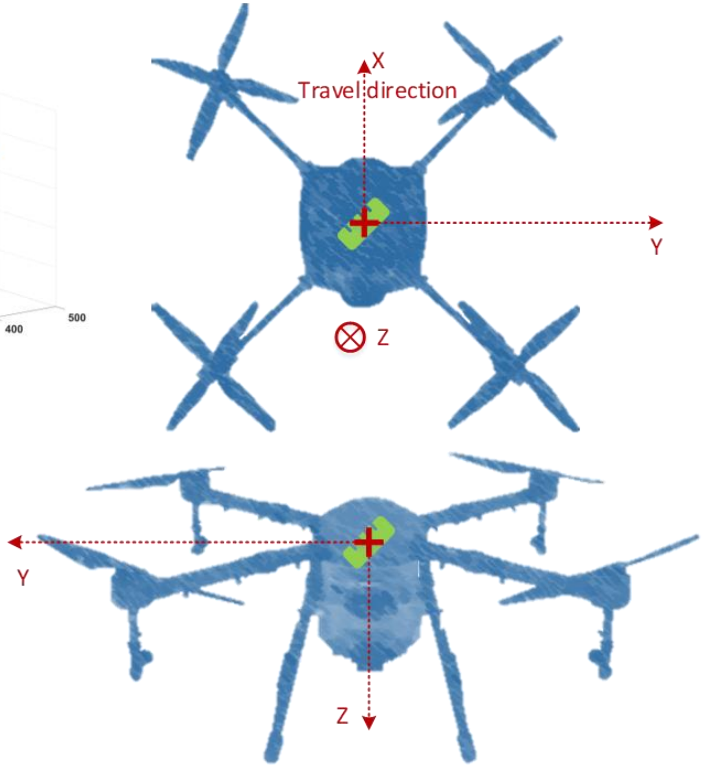
> Real data processing and simulation tool

- Simulation tools is designed to be highly configurable
  - Rotor craft / fixed wing trajectory type
  - IMU / barometer hybridisation
  - 1 or 3 IMUs / barometers





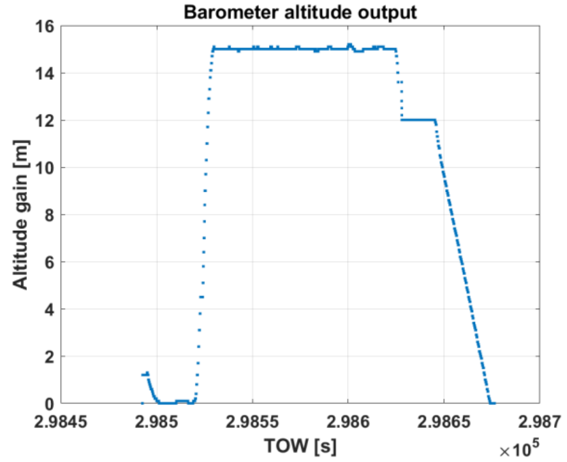


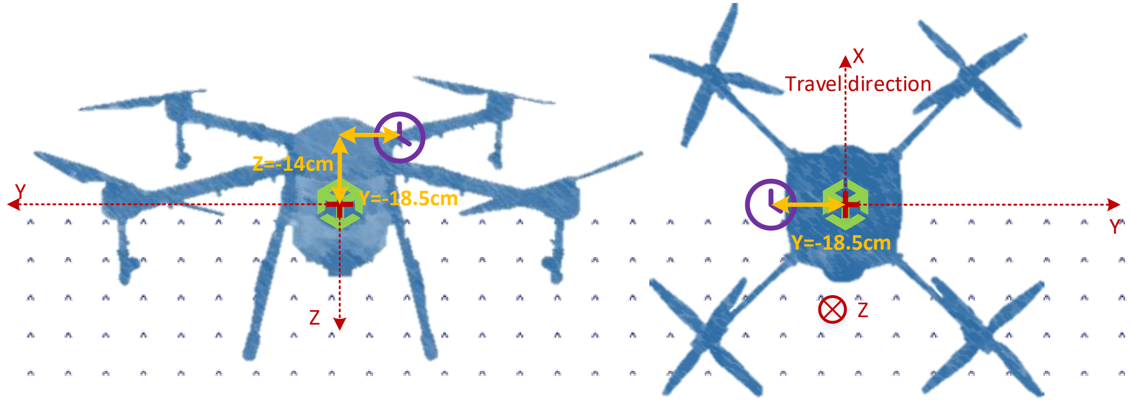


3 – Demonstrator Design Verification and Validation (7/26)

> Real data processing and simulation tool

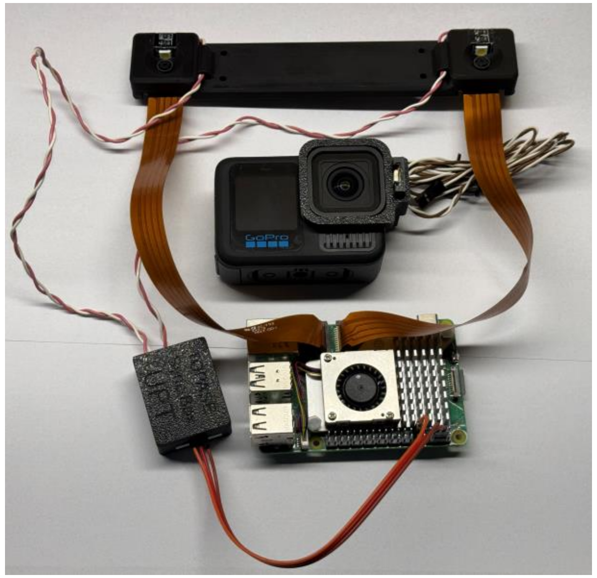
- Real Data processing tools compatible with collected data
  - Data collected by Abzero and post processed by TAS:
    - GNSS data from UBLOX Z9P
      - GPS L1, L2C and Galileo E1/E5BQ
    - IMU data
      - Low grade IMU
      - Lever arm in body frame [0;-0.185;-0.14] in meters
    - Barometer data
      - Altitude gain used in the EKF hybrid

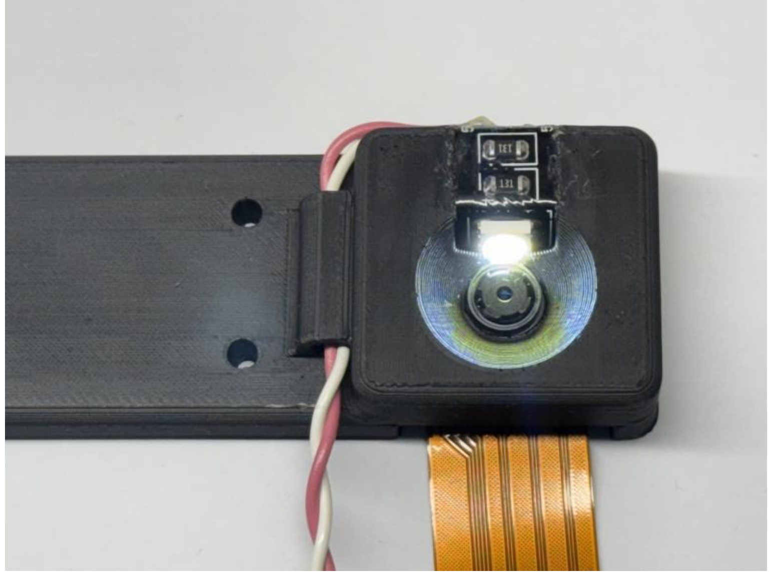




3 – Demonstrator Design Verification and Validation (8/26)

> The camera vision subsystem (Provided by UPT)





UPT payload:
2 x Raspi Camera v2,
1 x GoPro Camera,
1 x Raspberry 5 15GB Board
1 x Synchronization box

RasPI Camera v2 with sync LED ON

GoPro Camera with sync LED ON

3 – Demonstrator Design Verification and Validation (9/26)

> LED modules mounted near the Raspberry Pi camera to provide visual sync signals for the Topase payload.

> GoPro installed in a custom housing with an external sync LED used to align its footage with the Raspberry Pi cameras.

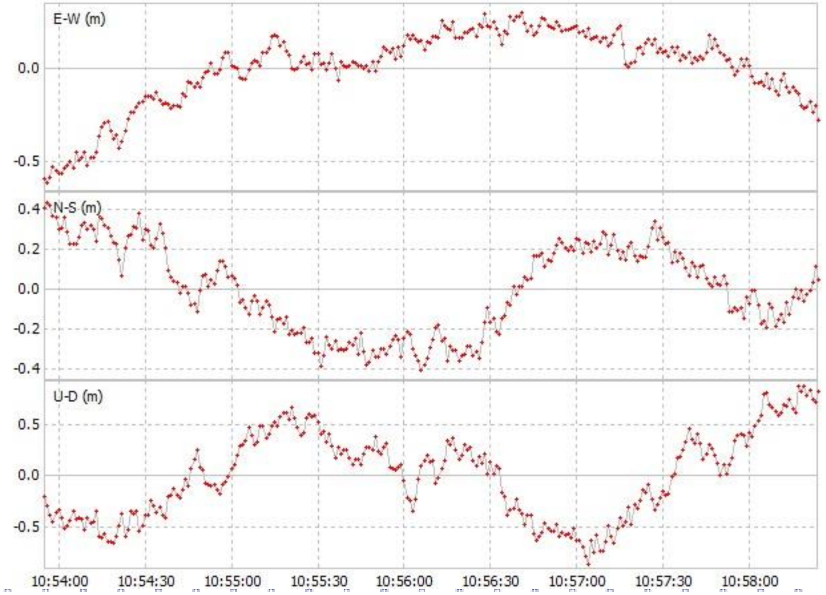
TOPASE payload facing down

TOPASE payload facing up

3 – Demonstrator Design Verification and Validation (10/26)

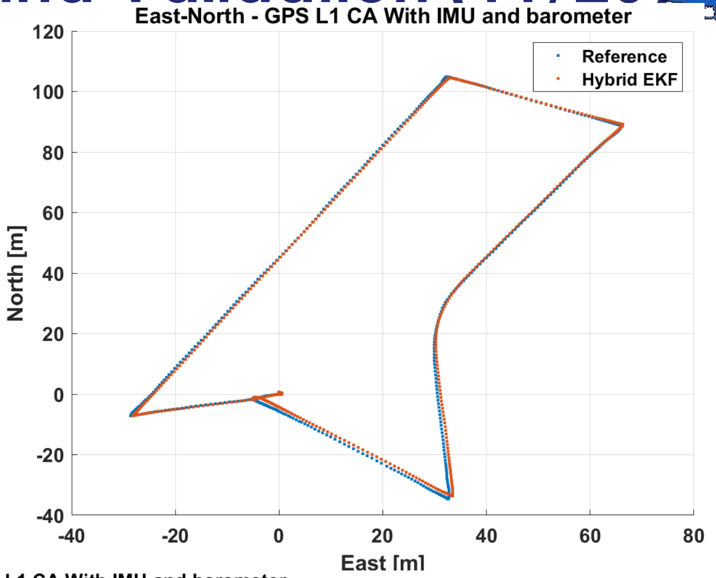
Real data processing

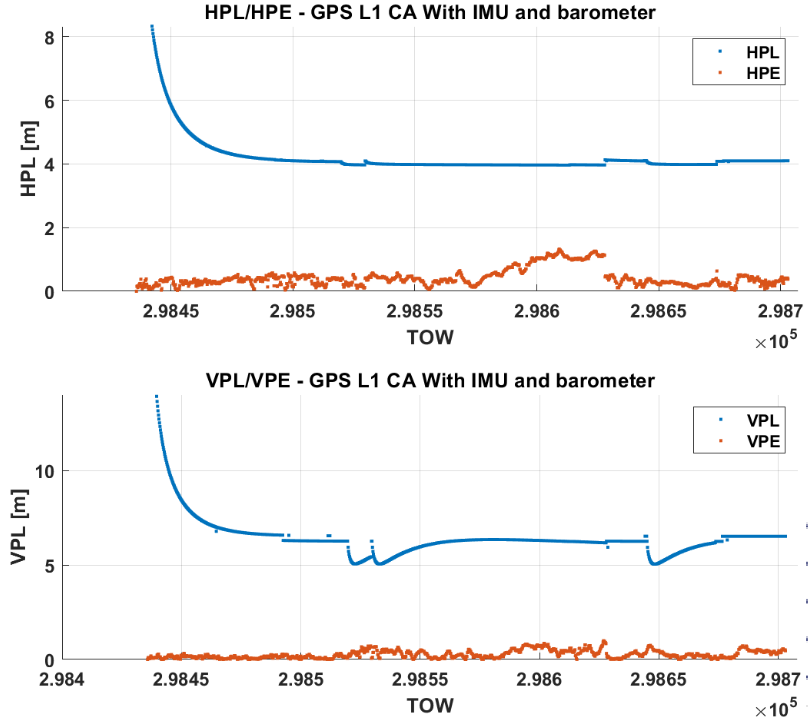
- Post processing step 1: Reference trajectory computation
  - Using both the Rover and the Base station raw measurement
  - Using an OpenSource software (RTKLIB) to ensure independence between softwares
  - Base station localisation obtained by averaging the base station standalone navigation solution

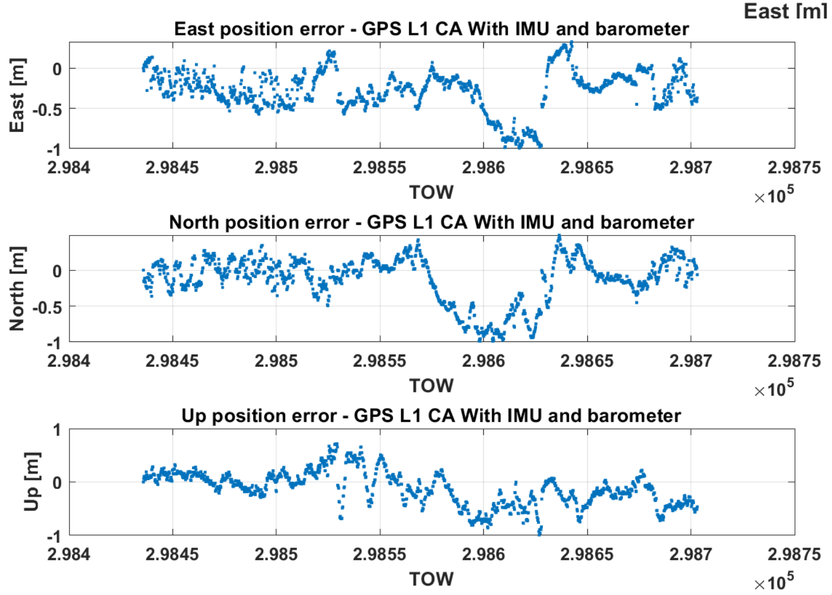


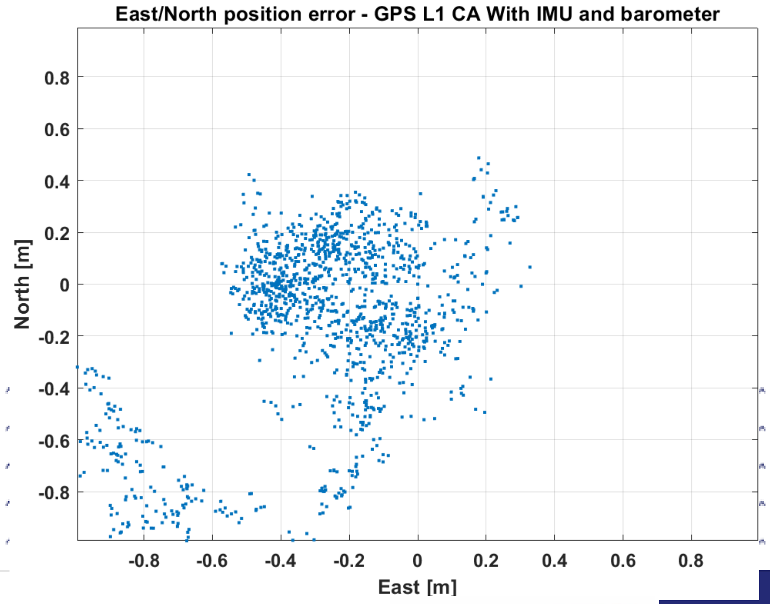
3 – Demonstrator Design Verification and Validation (11/26)

- **Real data processing**
  - Post processing step 2: EKF with hybridization
    - Real GNSS data
    - Real IMU data
    - Real Barometer data





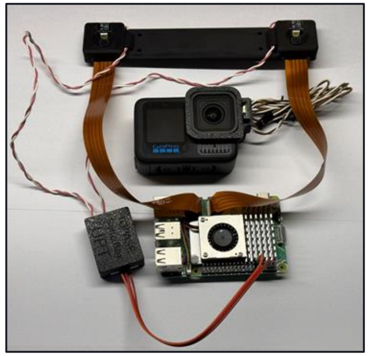


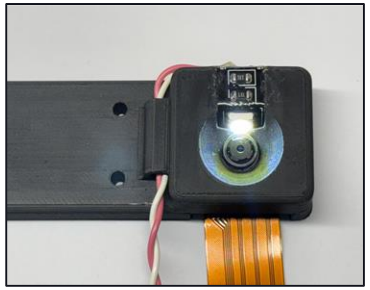


3 – Demonstrator Design Verification and Validation (12/26)

> A fully tested payload …

- Payload component test
- Payload weight test
- Testing the synchronization system
- Payload power test
- Payload reference trajectory test
- Payload connectivity test
- Payload raw measurements test
- Testing the communication between Pixhawk and Raspberry pi
- Vision system tests





3 – Demonstrator Design Verification and Validation (13/26)

> … Before integration inside ABZero capsule

- The tests were conducted using the X6000 Pro drone, a professional-grade UAV designed for precise navigation and reliable performance. This platform ensures accurate positioning and stable flight, making it suitable for both real-time operations and post-processing applications.
- The X6000 Pro integrates advanced dead reckoning sensors, enabling continuous raw data output at high frequency. Its robust design makes it an ideal choice for validation of navigation performance.

Test S1, S2, S3, S4					
#	Description	Mission ID	Altitude [m]	Max Speed (m/s)	Path Length (m)
S.1	Rural scenario tests	1.1	15	6, 8, 10	375
		1.2	20	6, 8, 10	375
		1.3	25	6, 8, 10	375
S.2	Urban scenario tests	2.1	25	6,8	316
		2.2	25	6,8	408
S.3	Langhirano scenario tests	3.1	75	6,8	1324
S.4	Hospital scenario tests	4.1	35	6,8	558

3 – Demonstrator Design Verification and Validation (14/26)

> Base station/rover configuration

- For the tests, an Ardusimple F9P board was configured as the base station, mounted on a tripod with a fixed GNSS antenna to ensure stable and accurate corrections.
- A second F9P board was used as the rover, integrated in the Smart Capsule and connected to a GNSS antenna placed on top of the drone for optimal satellite visibility.
- The two boards communicated via Xbee radio modules, enabling real-time RTK corrections for centimeter-level positioning.

3 – Demonstrator Design Verification and Validation (15/26)

> A high valuable flight campaign

- Diverse environment, altitude, speed, etc.
- Hours of data collected!

Video

3 – Demonstrator Design Verification and Validation (16/26)

> First Scenario

- The first flight scenario was carried out in a rural environment at the GAPL facility in Cascina (Pisa).
- The area is characterized by open fields and limited urban interference, providing stable GNSS reception and minimal multipath effects. The missions were performed by overflying both natural and artificial ground markers to evaluate the capability of the payload in matching satellite images with on-ground features, such as terrain color variations and small built structures.
- This environment was selected to establish a baseline performance assessment under favorable conditions, enabling safe flight operations and reliable acquisition of raw dead reckoning data and navigation solutions.

a) Altitude 15 m, Speed 6 m/s

b) Altitude 20 m, Speed 8 m/s

c) Altitude 25 m, Speed 10 m/s

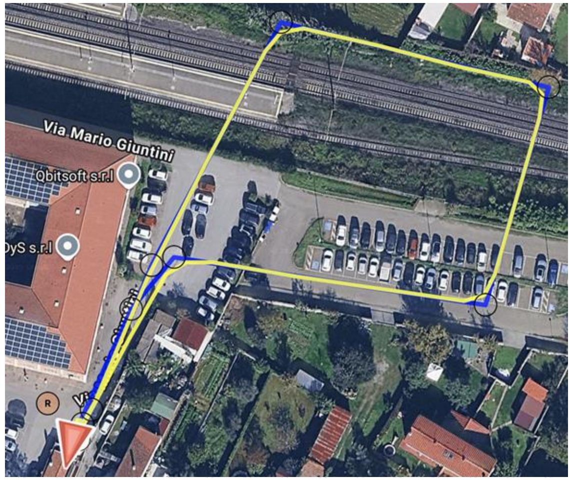
#	Mission ID	Altitude [m]	Max Speed (m/s)	Path Length (m)
S.1	1.1	15	6, 8, 10	375
	1.2	20	6, 8, 10	375
	1.3	25	6, 8, 10	375

3 – Demonstrator Design Verification and Validation (17/26)

> Second Scenario

- The second flight scenario was conducted at the Polo Tecnologico in Navacchio (Pisa), within an urban environment characterized by representative artificial markers, offering a clear contrast to the rural setting previously tested. The presence of buildings, vehicles, roads, and a nearby railway introduced higher variability and complexity, creating a more challenging and realistic operational context. This scenario was designed to assess the robustness of the payload in matching satellite imagery with diverse ground features, ensuring reliable performance even under conditions with potential signal disturbances and increased environmental dynamics.

b) Altitude 25 m, Speed 8 m/s



a) Altitude 25 m, Speed 6 m/s

#	Mission ID	Altitude [m]	Max Speed (m/s)	Path Length (m)
S.2	2.1	25	6,8	316
	2.2	25	6,8	408

3 – Demonstrator Design Verification and Validation (18/26)

> Third scenario

- The third flight scenario was carried out in a semi-urban area near the hospital of Langhirano, along a longer flight path and at a higher altitude compared to the previous scenarios. This setup provided a wider field of view (FOV), allowing the payload to collect data over an extended area. Unlike the rural environment, the presence of buildings, vehicles, road infrastructure, and a nearby bridge introduced additional visual complexity. This semi-urban configuration offered a more realistic operational context to evaluate the capability of the payload in accurately correlating satellite imagery with diverse ground features.

a) Altitude 75 m, Speed 6 m/s

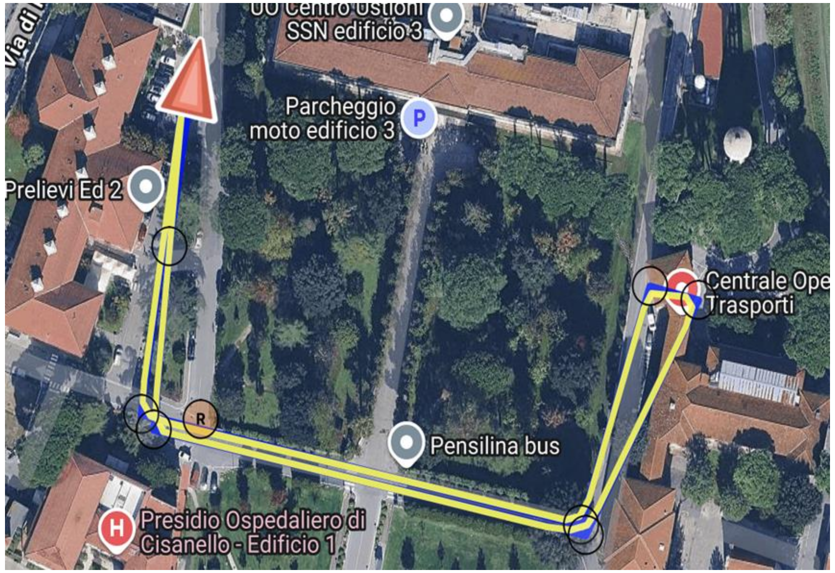
b) Altitude 75 m, Speed 8 m/s

#	Mission ID	Altitude [m]	Max Speed (m/s)	Path Length (m)
S.3	3.1	75	6,8	1324

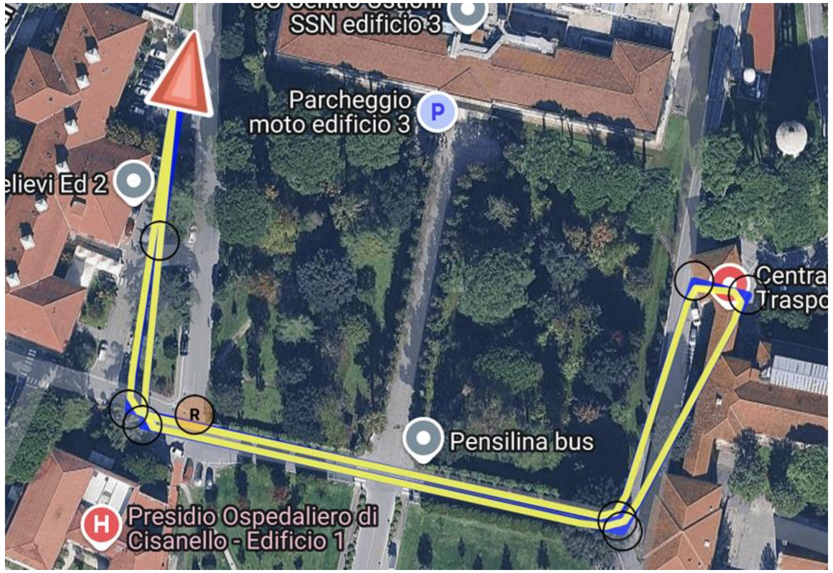
3 – Demonstrator Design Verification and Validation (19/26)

> Fourth scenario

- The fourth flight scenario was conducted in the hospital environment of Cisanello, an area characterized by the presence of large hospital buildings, surrounding road networks, and tree-covered zones. This combination of structural and natural elements provided a diverse set of visual markers, introducing both geometric and textural variability. The scenario offered a complex operational context, suitable for assessing the payload's ability to interpret and accurately correlate satellite imagery with heterogeneous real-world features.



a) Altitude 35 m, Speed 6 m/s



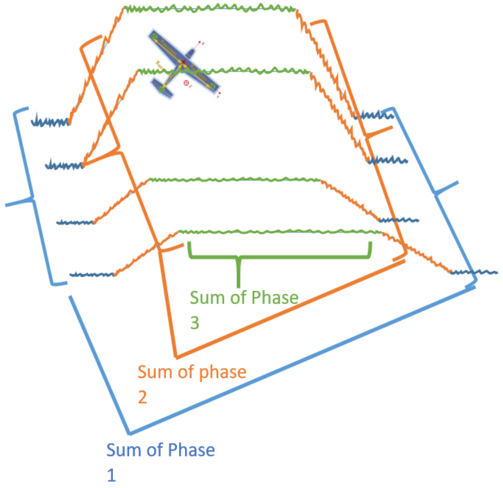
b) Altitude 35 m, Speed 8 m/s

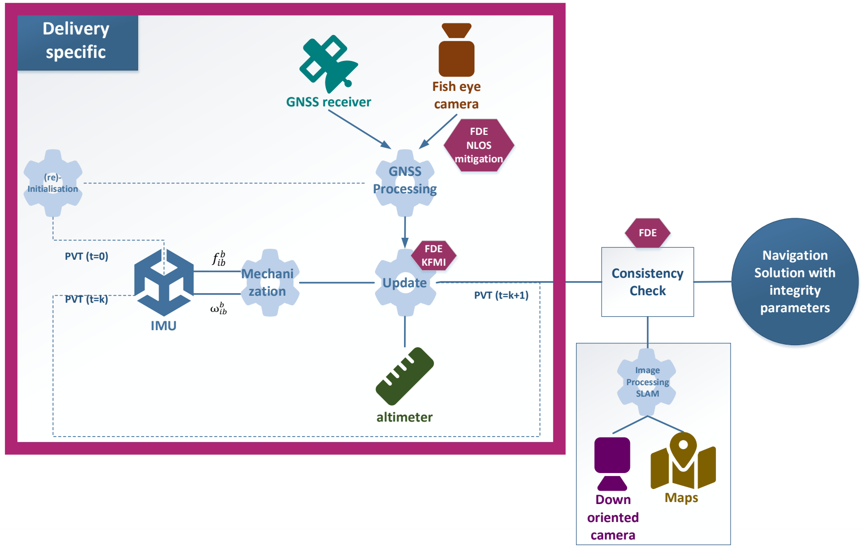
#	Mission ID	Altitude [m]	Max Speed (m/s)	Path Length (m)
S.4	4.1	35	6,8	558

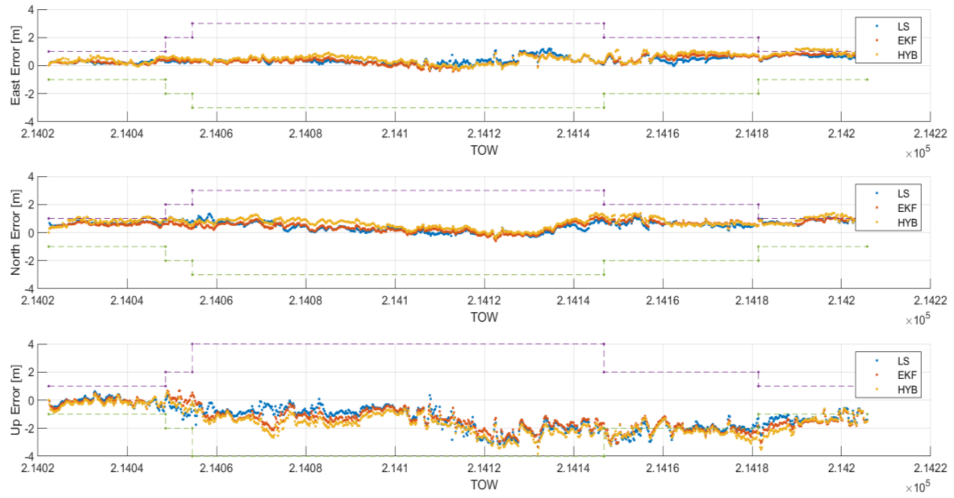
3 – Demonstrator Design Verification and Validation (20/26)

> Post processing of data collected

- Multiple receiver configurations
  - Frequencies available: L1CA, L2C, E1OS, E5a
  - Combination tested: mono/by frequency (Uncombined, Ionofree)
- 3 algorithms implemented
  - WLS,
  - GNSS standalone EKF
  - Hybrid EKF (IMU + GNSS + BARO)
- Integrity configuration
  - Apply CN0 FDE or not : 20 [dBHz]
  - Apply Elevation FDE or not : 10 [deg]
  - Apply KFMI FDE or not
    - Probability of False Alarm: 1e-3
    - Probability of missed detection: 1e-6
- KPI analysed
  - RMS position and velocity error in 3D, 2D and Vertical direction.
  - Horizontal 2D and Vertical (UP): % integrity event with time
  - → KPI per phases: static, take off and landing, cruise



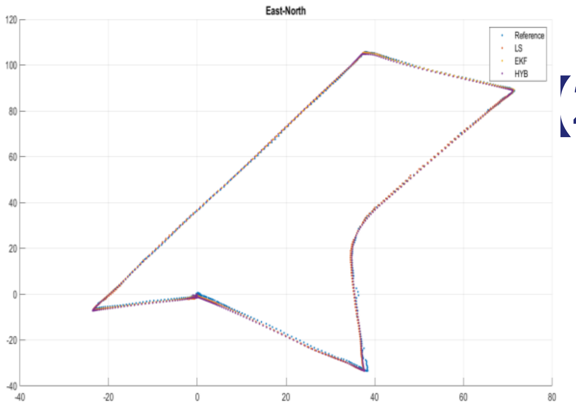




3 – Demonstrator Design Verificatic (21/26)

> Post processing of data collected

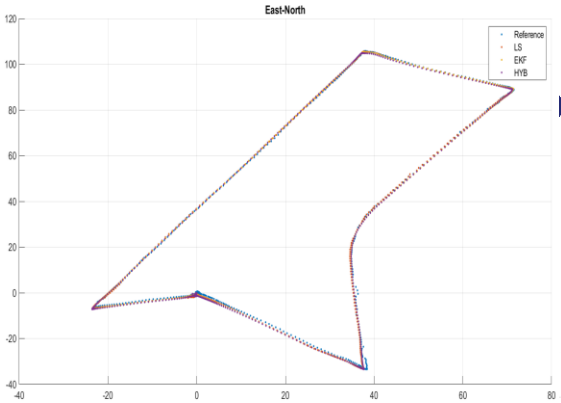
- Extract scenario 1 – Mono frequency L1CA



- Accuracy analysis in position and velocity:
  - Requirements envelop provided for analysis

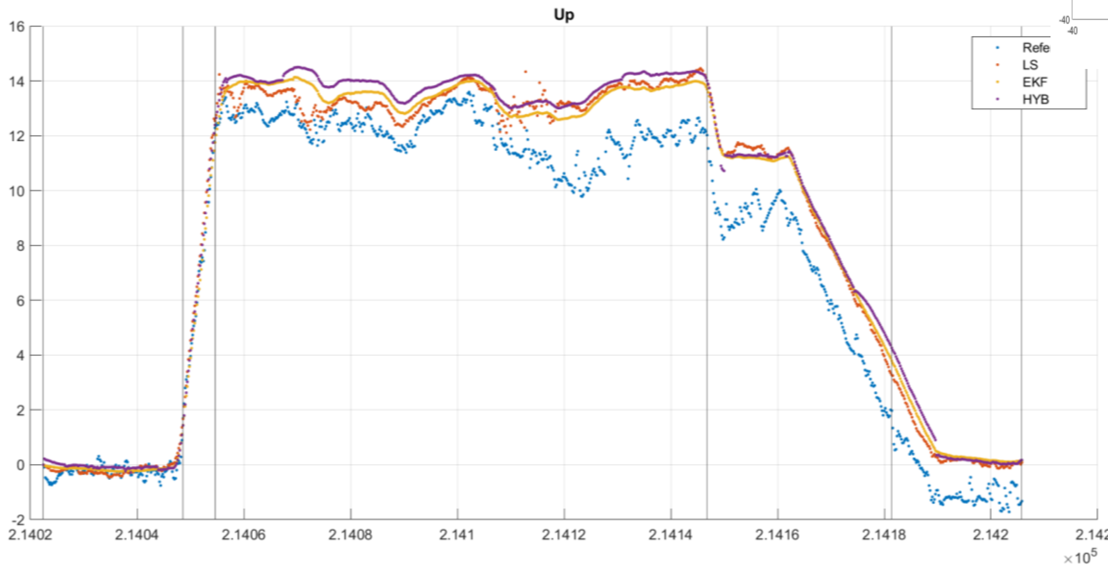
- Observations
  - Generally, cruise requirements are easily fulfilled
  - Take off and landing phases requirements are more challenging

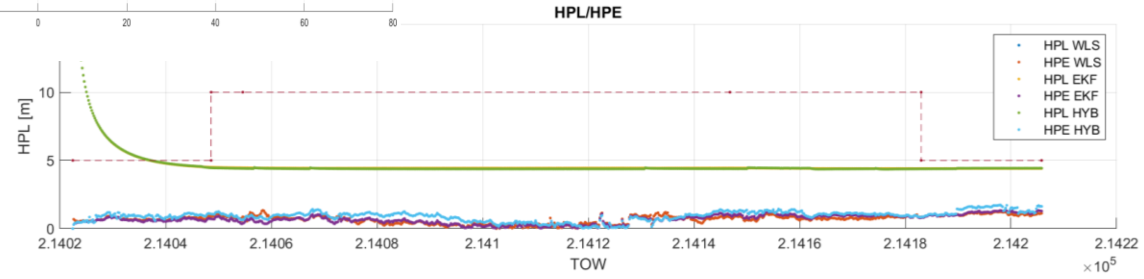
3 – Demonstrator Design Verifica… n (22/26)

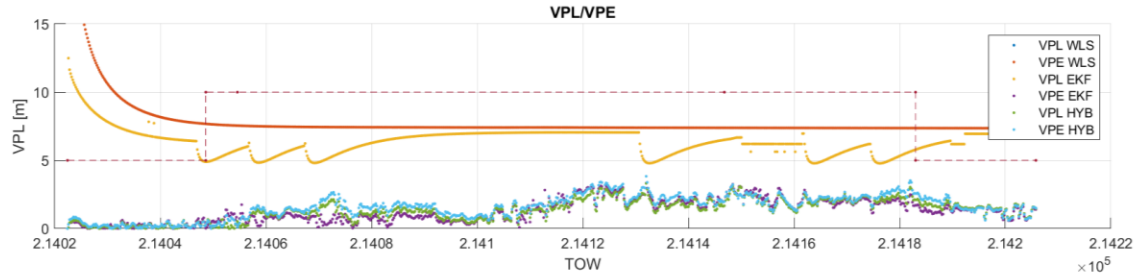


> Post processing of data collected

- Extract scenario 1 – Mono frequency L1CA





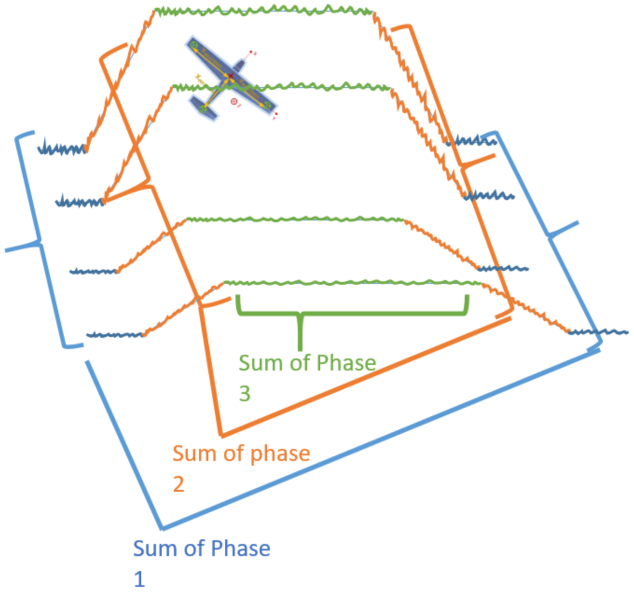


- Observations
  - Limits observed on the reference trajectory
  - Lack of continuity / accuracy with the reference trajectory

- Observations
  - Generally, cruise requirements are easily fulfilled
  - Take off and landing phases requirements are more challenging

3 – Demonstrator Design Verification and Validation (23/26)

> Analysis over all flights of scenario 1



GPS L1 CA	WLS			EKF GNSS standalone			EF TC IMU GNSS and barometer		
Phase	1	2	3	1	2	3	1	2	3
RMS 3D pos [m]	1,7	1,8	2,1	1,5	2,5	2,1	1,6	2,4	1,8
RMS Hor pos [m]	1,3	2,1	1,5	1,3	2,1	1,5	1,3	2,1	1,5
RMS Vert pos [m]	2,2	2,8	2,6	2,1	2,8	2,6	1,8	2,5	2,4
RMS 3D velocity [m/s]	0,2	0,2	0,1	0,2	0,2	0,1	0,2	0,2	0,1
RMS Hor vel [m/s]	0,1	0,2	0,6	0,1	0,2	0,6	0,1	0,2	0,6
RMS Vert vel [m/s]	0,3	0,3	0,6	0,3	0,3	0,6	0,3	0,3	0,6
Hor integrity event [%]	0	0	0	0	0	0	0	0	0
Vert integrity event [%]	0	0	0	0	0	0	0	0	0

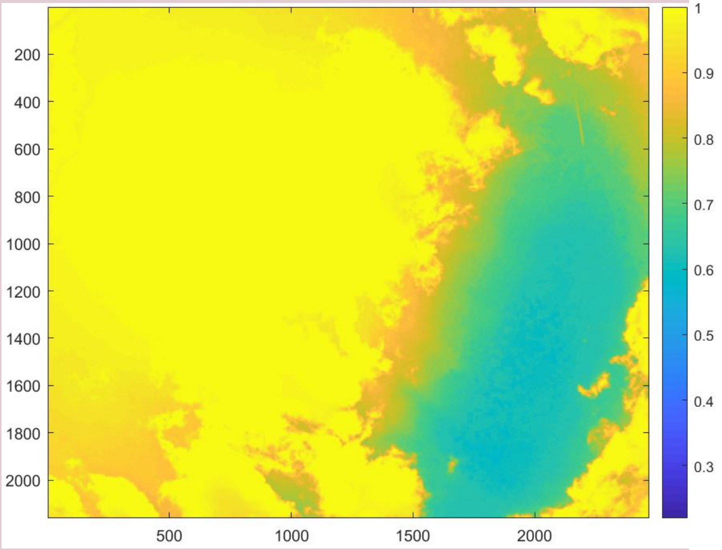
GPS L1+L2C GAL E1OS+E5a Uncombined	WLS			EKF GNSS standalone			EF TC IMU GNSS and barometer		
Phase	1	2	3	1	2	3	1	2	3
RMS 3D pos [m]	1,4	1,6	1,6	1,5	1,7	1,6	1,5	1,7	1,7
RMS Hor pos [m]	0,9	1,0	1,1	0,9	1,0	1,1	1,0	1,1	1,2
RMS Vert pos [m]	1,7	1,9	2,0	1,8	2,0	2,0	1,9	2,1	2,1
RMS 3D velocity [m/s]	0,3	0,4	0,3	0,1	0,2	0,1	0,1	0,3	0,2
RMS Hor vel [m/s]	0,1	0,2	0,6	0,1	0,1	0,6	0,1	0,2	0,6
RMS Vert vel [m/s]	0,3	0,5	0,6	0,2	0,2	0,6	0,2	0,4	0,6
Hor integrity event [%]	NaN	NaN	NaN	0,2	0,2	0,2	1,3	1,3	1,3
Vert integrity event [%]	NaN	NaN	NaN	0,4	0,4	0,4	3,3	3,3	3,3

Observations

- Improved accuracy
- Some integrity events
  - decreased covariance matrix due to increase signals used

3 – Demonstrator Design Verification and Validation (24/26)

> Fish Eye analysis

Fish-Eye shot	Associated probability map
	

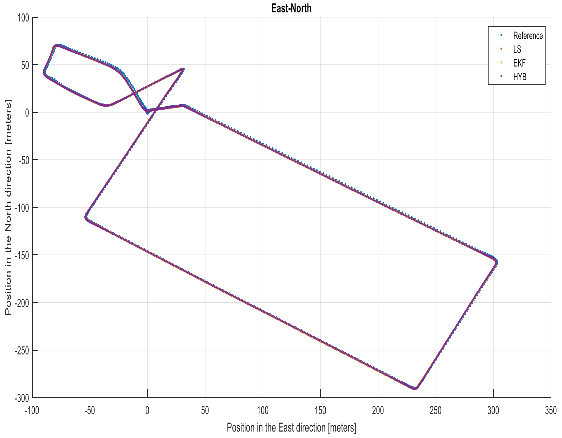
	Without Fish-eye	With Fish-eye
RMS 3D position	1.6577	1.7244
RMS Horizontal position	1.1023	1.1854
RMS Vertical position	1.2353	1.2524
RMS 3D velocity	0.4953	0.5056
RMS Horizontal velocity	0.4318	0.4374
RMS Vertical velocity	0.2425	0.2535
Horizontal integrity event	2.0161	0.1792
Vertical integrity event	1.0304	0

- Observations
  - Slight degradation of PVT solution accuracy,
  - Slight degradation of PVT solution availability (especially in single-constellation single-frequency scenarios)
  - Improvement of PVT solution integrity (explained by higher PLs when less satellites are considered in the PVT solution computation)
  - Interest is expected be higher in take off and landing in urban environment

3 – Demonstrator Design Verification and Validation (25/26)

> Extract scenario 3

- More constrained environment



GPS L1+L2C + GAL E1OS+E5a Uncombined	WLS			EKF GNSS standalone			EF TC IMU GNSS and barometer		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
RMS 3D position [m]	3,10	1,36	1,91	3,10	1,45	1,73	3,02	1,40	1,74
RMS Horizontal position [m]	2,09	0,96	1,82	2,14	0,86	1,63	1,98	0,90	1,65
RMS Vertical position [m]	2,29	0,96	0,58	2,24	1,16	0,56	2,28	1,07	0,55
RMS 3D velocity [m/s]	0,56	0,24	0,56	0,58	0,18	0,57	0,55	0,22	0,59
RMS Horizontal velocity [m/s]	0,30	0,15	0,54	0,31	0,12	0,55	0,30	0,14	0,54
RMS Vertical velocity [m/s]	0,47	0,18	0,13	0,49	0,14	0,12	0,46	0,16	0,22
Horizontal integrity event [%]	0	0	0	2,09	2,09	2,09	2,24	2,24	2,24
Vertical integrity event [%]	0	0	0	0	0	0	0	0	0

Observations

- Generally, cruise requirements are easily fulfilled
- Take off and landing phases requirements are more challenging
- In DFMC, accuracy is improved but integrity is not always ensured

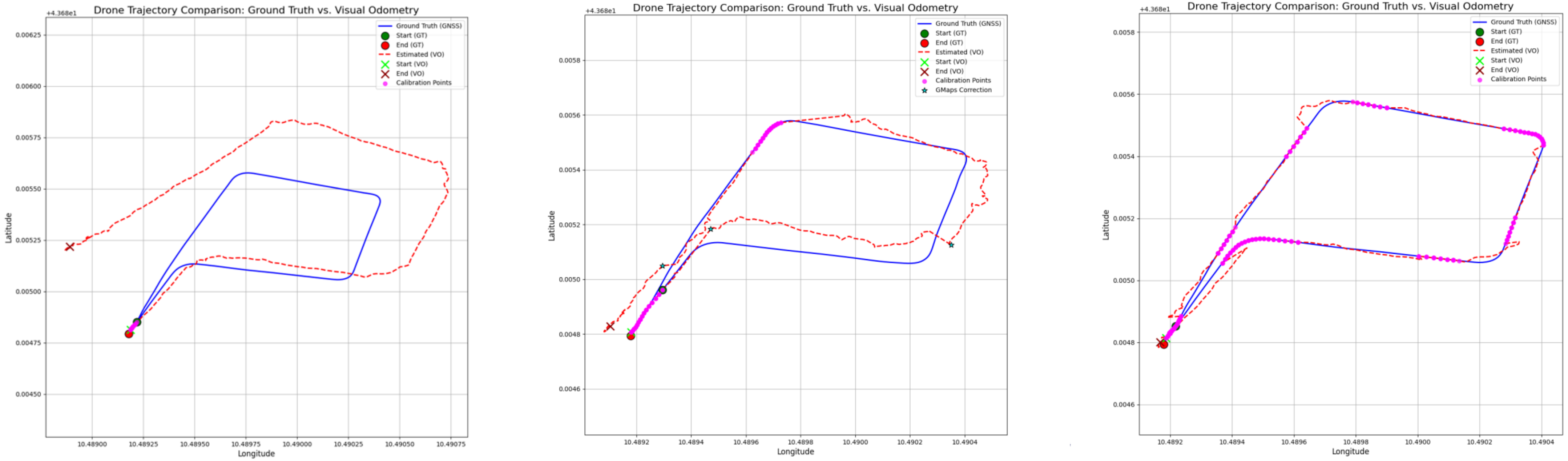
Way forward

- improvement of the vertical information in Take off and landing by adding sensors (Radar, etc.)
- Integrity problems may be related to poor reference trajectory

3 – Demonstrator Design Verification and Validation (26/26)

> Results vision based algorithm UPT side

- Position recalibration of the visual navigation algorithm on every 1, 5, 10 20 and 40 seconds, with and without Google Maps positioning.



a) Scenario 2 Altitude 25 m, Speed 6 m/s, no calibration

b) Scenario 2 Altitude 25 m, Speed 6 m/s, GNSS and Gmaps calibration every 40 sec

c) Scenario 2 Altitude 25 m, Speed 6 m/s, GNSS and GMamps calibration every 5 sec

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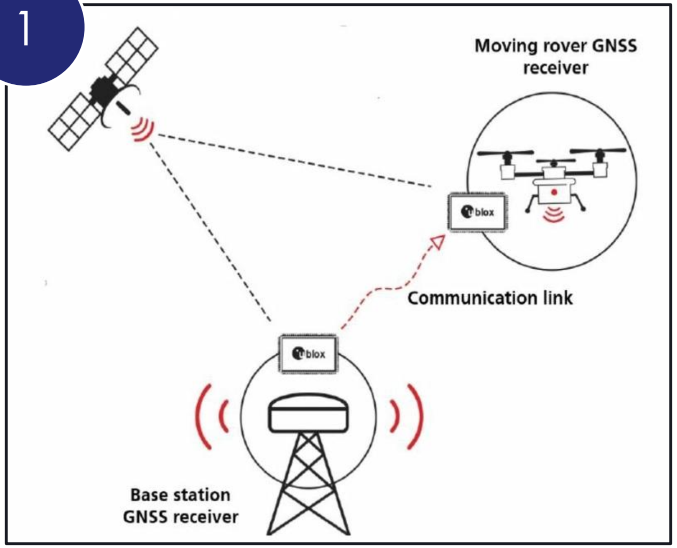
4 – Conclusion (1/4)

> Lessons Learnt

- **From the payload and platform point of view**

1

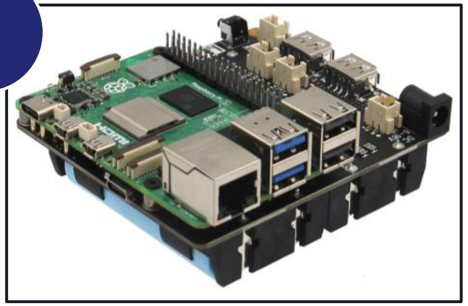


Regarding **positioning**, we found that the use of an RTK GNSS system is mandatory to achieve centimetric accuracy and to establish a reliable reference trajectory for validating visual algorithms.

2

Regarding **flight altitude**, the project results have shown that flying higher makes it easier to match UAV images with satellite based Google maps, as more details become visible.

3



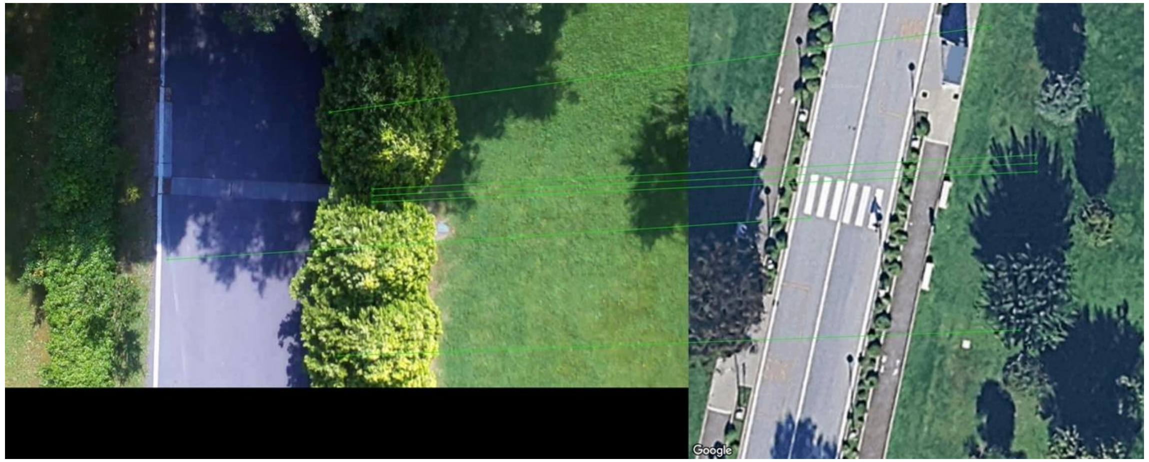
Regarding the **integration of the payload** and the platform, as expected, it is important to:

- ensure mechanical stability of the components
- design a payload that carefully considers power supply and the overall energy autonomy of the system

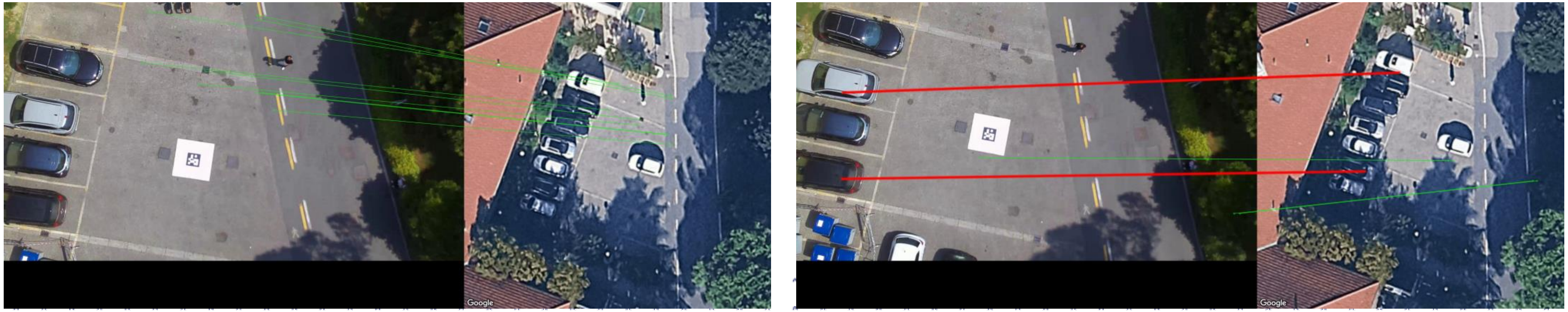
4 – Conclusion (2/4)

> Lessons Learnt

- From the algorithmic point of view
  - Environmental impacts (UPT)
  - Phase of flights impacts (UPT/TAS)
  - Vision based algorithm (UPT)



Google Maps feature mismatching caused by tree shadow identified as tree.



Google Maps feature mismatching caused by wrongly identifying cars.

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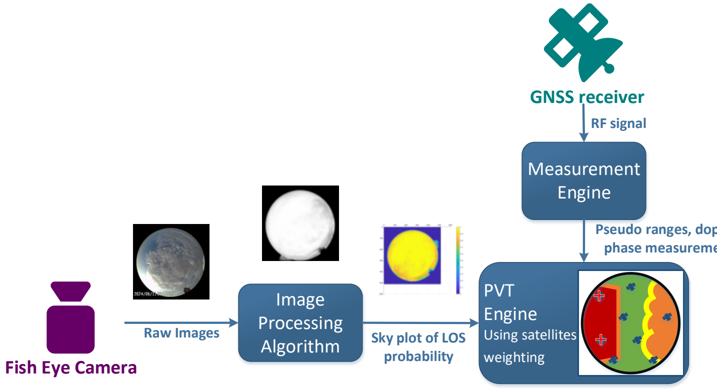
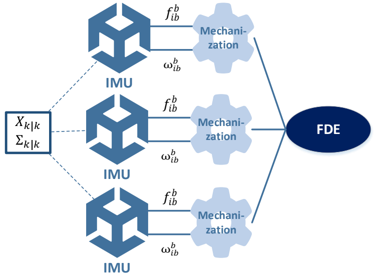
4 – Conclusion (3/4)

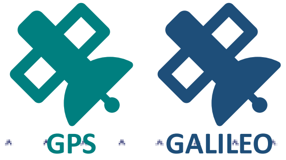
> Lessons Learnt and way forward for future studies

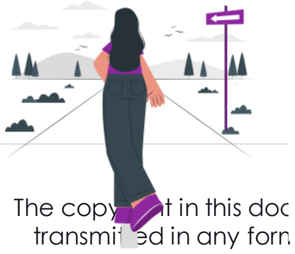


- **From the algorithmic point of view**
  - **Sensors Roles and Impacts (TAS)**
    - Fish eye camera:
      - low interest in open sky environment, but interest remains for take-off and landing and needs further studies
      - The integrity results improved (conservative approach)



    - Duplicated sensors
      - Results confirm that as expected, the redundancy scheme that has been put in place to create a "virtual sensor". is interesting for integrity purposes (or safety purposes). No accuracy improvements by using three sensors using the virtual sensors concept has been shown though.
      - To improve accuracy higher grade IMUs can be embedded inherently inducing higher cost
    - GNSS
      - Clear benefits of MFMC GNSS receivers: enhanced accuracy and robustness (more satellites in view).
      - RFI has not been studied in the TOPASE project, but high interest for further studies and MCMF Rx is one of the techniques to detect and mitigate RFI.





    - The TOPASE project has paved the way for multiple studies:
      - Algorithm consolidation for multi-IMU multi-barometers systems
      - Cost and benefits trade-offs
      - Algorithm complexity
      - Radio Frequency Interference consolidation

4 – Conclusion (4/4)

> Lessons Learnt

- **From the algorithmic point of view**
  - **Performance analysis limitations**

› To assess the performance of a navigation algorithm, a **reliable reference trajectory is required.**

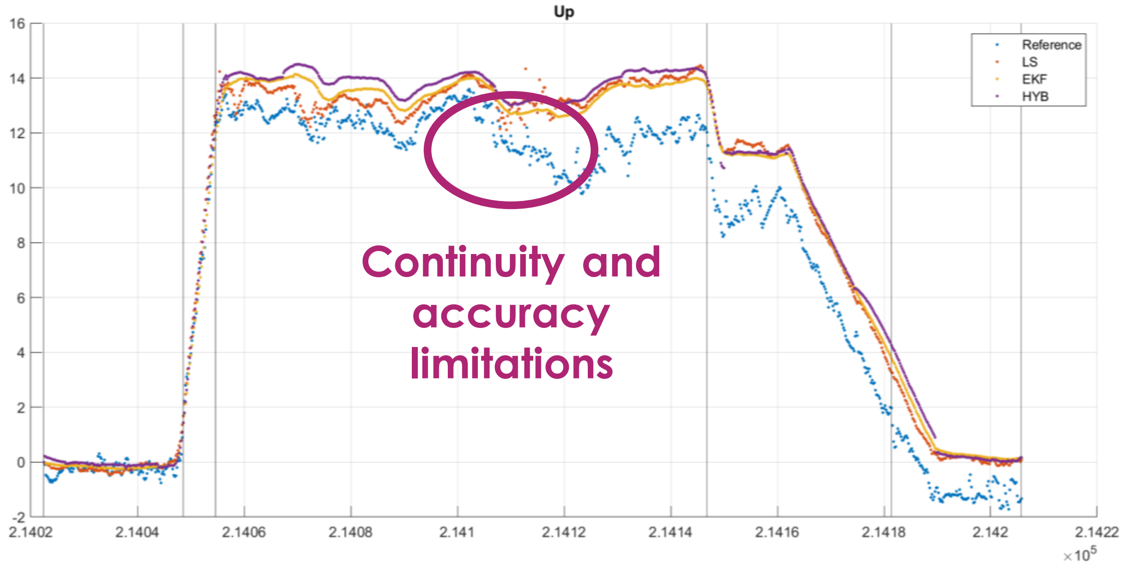
› Within the TOPASE project, the UAS was equipped with a **GNSS RTK receiver**, which, together with a base station, provided the reference data.

› An **independent** algorithm, **RTKlib**, was used to compute the reference trajectory.

› However, some results have raised concerns: continuity and integrity issue due to observability problems at the base station, altitude errors linked to the reference instability, among others.

› These observations highlight **the obvious need** to accurately evaluate the performance of the navigation algorithm**, the reference trajectory must be independent, highly precise and continuous**.

› However, in the UAV context, there are significant constraints on the embedded payload regarding weight and power consumption, which complicates the implementation of high-precision reference systems.



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5 – Next step (1/4)

> Way forward

- **Hardware evolution**
  - Using a more powerful computer instead of Raspberry PI to process all the algorithms needed on board of the drone
  - Implement a better way to synchronize the cameras (i.e. a software trigger instead of the optical trigger).

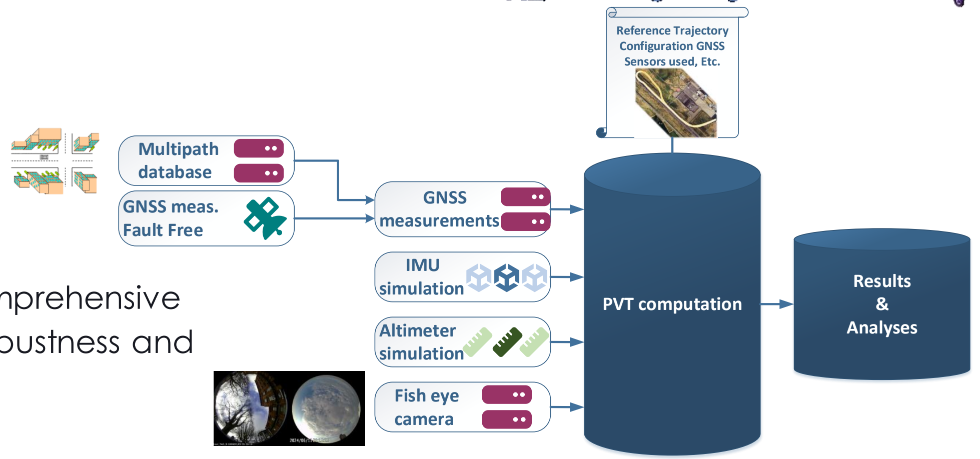
- **Software evolution**
  - UPT: Vision based algorithm
    - **Full 3D Visual Odometry/SLAM with Bundle Adjustment (VO/SLAM):** Instead of relying on a planar homography assumption, implement a full 3D visual odometry or Simultaneous Localization and Mapping (SLAM) system.
    - **Visual-Inertial Odometry (VIO) / Visual-Inertial SLAM (VI-SLAM):** Integrate an Inertial Measurement Unit (IMU) into the state estimation
    - **Deep Learning for Depth Estimation:** Replace the traditional stereo-based altitude estimation with deep learning models
    - **Semantic Understanding for Feature Selection and Localization**
    - **Hybrid Map Matching (Neural Radiance Fields - NeRF / 3D Gaussians)** Move beyond 2D image matching with Google Maps.

5 – Next step (2/4)

> Way forward

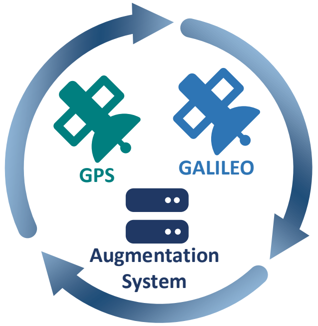
- **Software evolution**
  - **Hybrid GNSS, IMU, Barometer**
    - **Algorithm consolidation for multi-IMU multi-barometers systems**
      - The concept of redundant IMU has clear benefit for safety purpose even though Virtual IMU showed limited accuracy improvements in TOPASE. Its potential benefits in the presence of faulty sensor outputs requires further investigations.
      - Other state of the art algorithms for fusing multiple IMUs may be considered and compared.
    - **Cost and benefits trade-offs**
      - Depending on the application, users need to analyze the reliability and performance gains from using multiple low-cost IMUs versus a single high-grade IMU, focusing on metrics such as accuracy, update rate, latency, and integrity.
      - Introducing redundancy via multiple sensors can improve fault tolerance, but at the expense of higher complexity.
    - **Algorithm complexity**
      - Various multi-IMU fusion schemes are detailed in the literature; however, their additional algorithmic complexity must be carefully assessed.
      - The virtual IMU architecture proposed in TOPASE is among the simplest in terms of development effort. When evaluating alternative schemes, it is important to analyze the complexity alongside real-time processing constraints.
    - **Radio Frequency Interference consolidation**
      - Algorithm consolidation and complexity trade-offs must also be evaluated from an RFI perspective.
      - With RFI becoming an increasingly significant threat to navigation systems, designing solutions resilient to electromagnetic interference is of utmost importance.

5 – Next step (3/4)

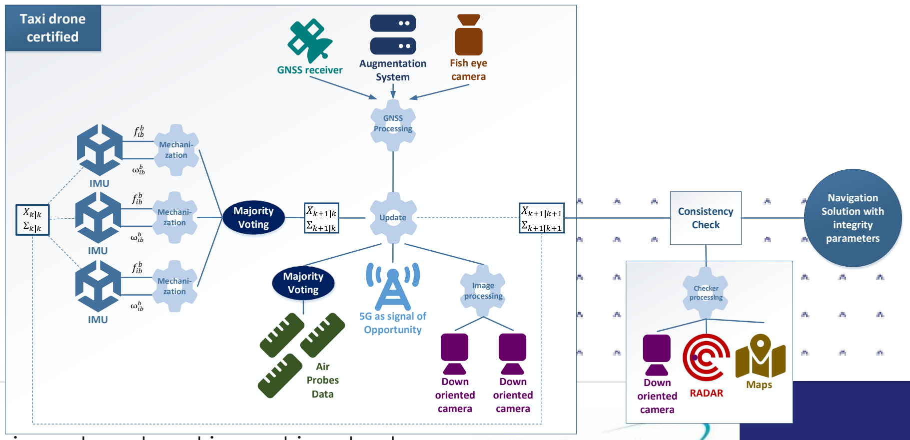


> Key technologies

- Powerful simulation tool
  - First validation step for the design of any architecture.
  - Can be improved by integrating failure modeling capabilities to offer a more comprehensive and realistic environment for system validation, ultimately leading to improved robustness and reliability of the final system design.



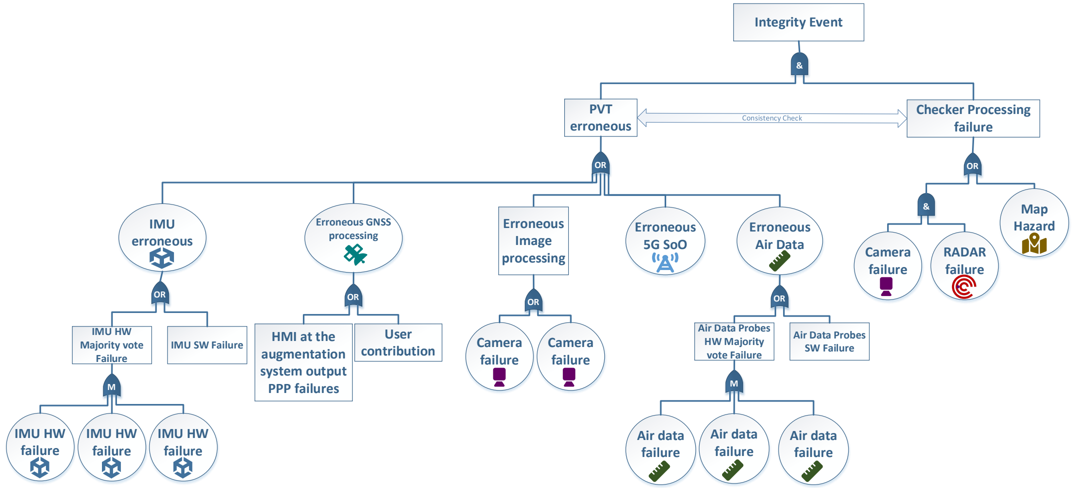
- High precision GNSS
  - GNSS is a key element, providing the UAS user with absolute positioning essential for safe navigation within the airspace.
  - The TOPASE project highlighted the necessity to embed Multi-constellation multi-frequency GNSS receivers.
  - PPP and RTK have been considered through the project and have shown their interest and limits
  - Improvement of resilience against RFI can be a next step
- Multi sensor fusion
  - Multi sensor fusion algorithm is essential.
  - Redundancy offers significant advantages in terms of integrity and robustness against sensor failures. However, further analysis is required to understand its impact on accuracy.
  - Laser sensor was explored in TOPASE but further validation is needed. Flight tests revealed that drone inclination and obstacle height hindered the provision of reliable data.
  - Additionally, a fisheye camera was integrated. Although its benefits are limited in rural, open-sky environments, it could prove highly valuable in densely built urban areas (as demonstrated in IMFUSING project).



5 – Next step (4/4)

> Key technologies

- Visual odometry
- Integrity architecture
  - Navigation sensors embedded need to be optimally combined to meet the stringent requirements
  - RAIM algorithms and multi-sensor fusion integrity concepts, incorporating conservative modeling of nominal errors, need to be implemented.
  - In TOPASE, several architectures have been proposed (consistency check architecture among other), they have shown encouraging results
- Drone trajectory design
  - Static phase at the beginning to ensure navigation solution convergence
  - Use of sensors depending on phase of flights



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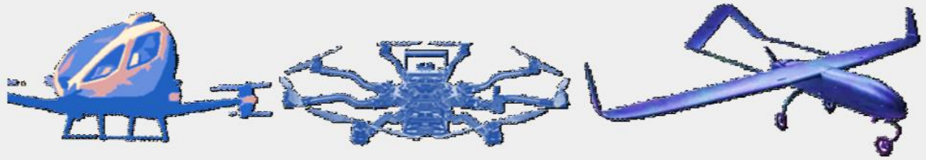

Thank you

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