



QASCOM
AEROSPACE & DEFENCE

Robust Integrated Navigation for Launcher AFTS and GNC Applications

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Rome

UNCLASSIFIED - COMMERCIAL IN CONFIDENCE

QASCOM

■ Roadmap:

- Historical Launch Failures
- Navigation in Launchers Applications
- Flight Termination System
- Autonomous Flight Termination System
- Challenges in Launcher Navigation
- Baseline Launcher Navigation Engine
- Robust Launcher Navigation Engine
- FDIR & FDE Algorithm
- Simulation Scenario & Test Results

- **Long March 3B — February 1996:** Investigation traced the failure to a short-circuit in the vehicle's inertial/guidance platform at liftoff, which deprived the guidance system of valid attitude/acceleration data.
- **Ariane 5 — June 1996:** software error in the inertial reference system, guidance info was lost and the vehicle was destroyed by range safety ~37 s after engine ignition
- **Ariane 5 — Jan 2018:** vehicle's inertial reference units were misaligned, giving erroneous attitude/trajectory data; the rocket flew ~20° off its intended easterly trajectory. The failure stemmed from incorrect mission parameter specification (azimuth set erroneously) and inadequate checks of inertial reference alignment. The inertial system provided wrong orientation data from launch.

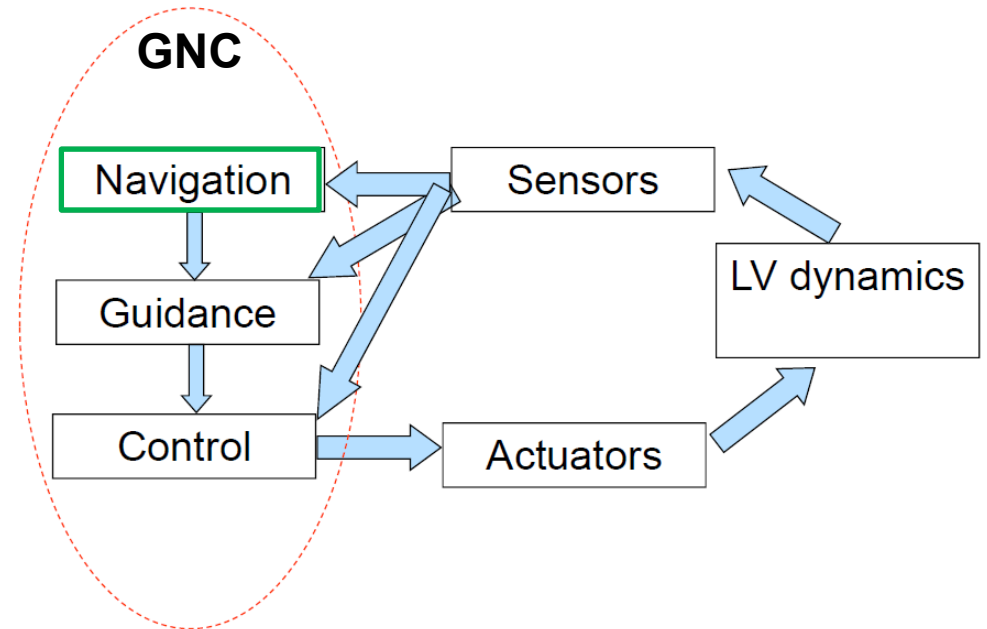


- **Proton-M — July 2013:** improper installation/orientation of angular-rate sensors on the first stage (redundant yaw sensors were all misoriented). The guidance computer received wrong attitude rates and could not control yaw — vehicle tumbled and was lost seconds after liftoff.
- **SSLV — August 2022 :** during second-stage separation, shock inputs saturated the accelerometers in the vehicle's inertial navigation system. The guidance system misinterpreted this as sensor failure and switched to a “salvage mode” (open-loop guidance) which led to significant velocity shortfall (~56 m/s) and loss of desired orbit.



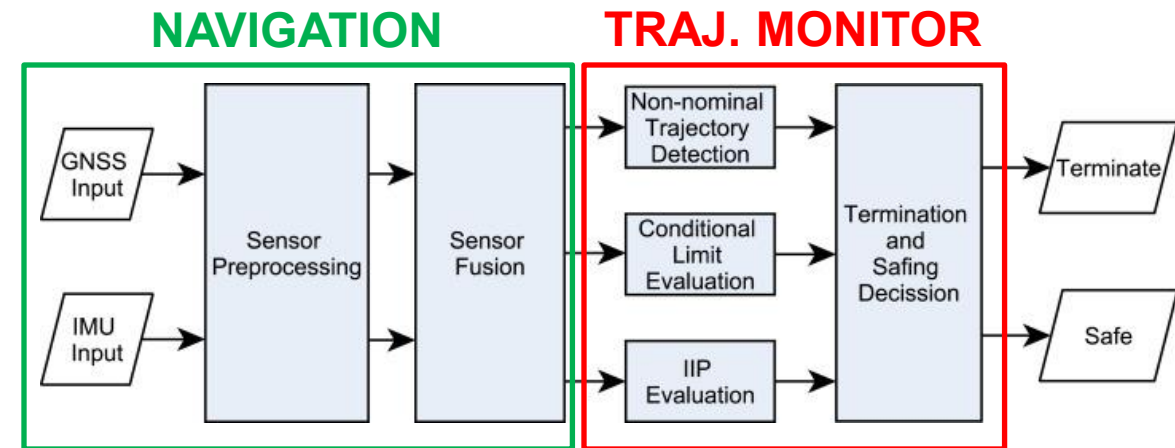
■ Navigation for GNC

- Support flight control and trajectory guidance.
- Strict real-time state estimates for the **Guidance and Control** algorithms.
- Tightly Integrated with the control loop
- Optimized for **real-time performance** and **control stability**.
- May run at a high rate (e.g. 100–500 Hz)
- Attitude estimation is the most critical part



■ Navigation for Range Safety

- Support the launcher **flight safety**
- Provides position and velocity data to a **trajectory monitoring unit** that checks whether the vehicle remains within safety corridors
- Must be **independent** or **functionally isolated** from the main GNC navigation chain.
- Runs at lower frequency (e.g. 10 Hz), focused on **reliability** rather than control dynamics
- Output may trigger **flight termination** if limits are violated
- More focused on position and velocity rather than attitude

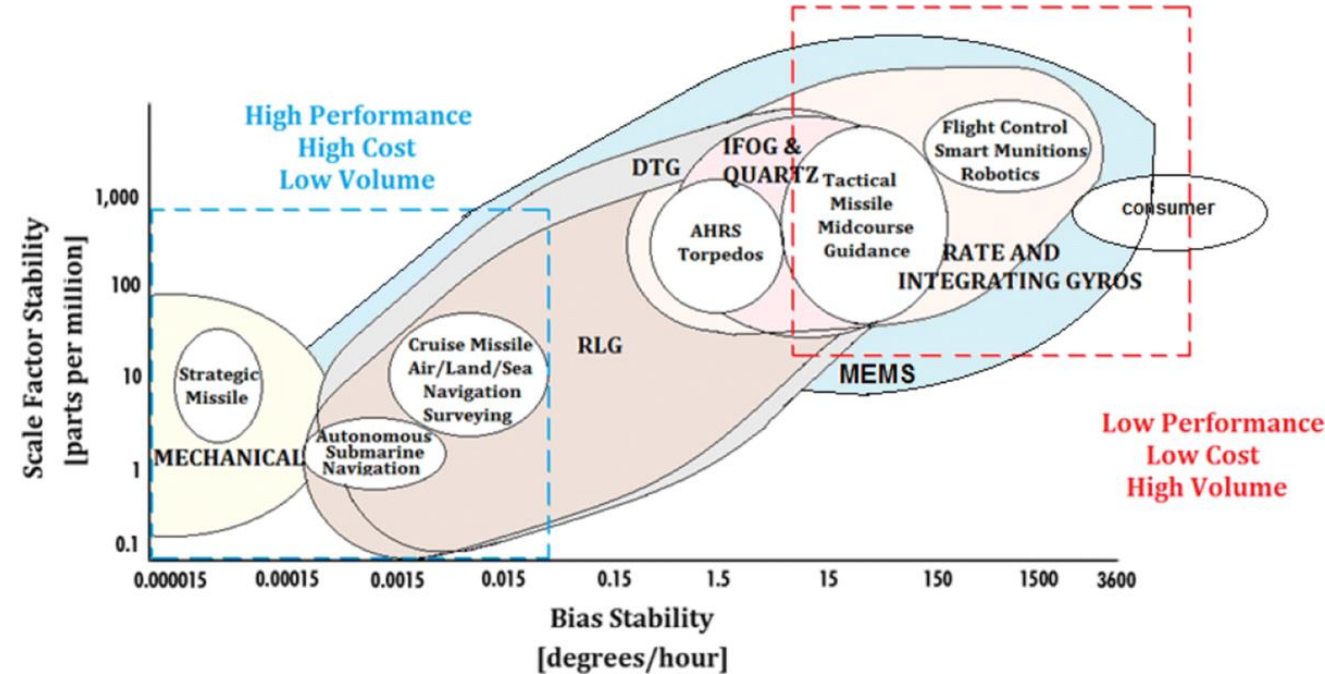


■ Old School Navigation

- ☐ Strategic/Navigation grade IMU (100K\$)
- ☐ Totally **immune to RF interferences**
- ☐ Position error directly related to gyro sensor quality
- ☐ In the long term the **system accumulate drift** and become useless
- ☐ High cost/weight system

■ Future Navigation

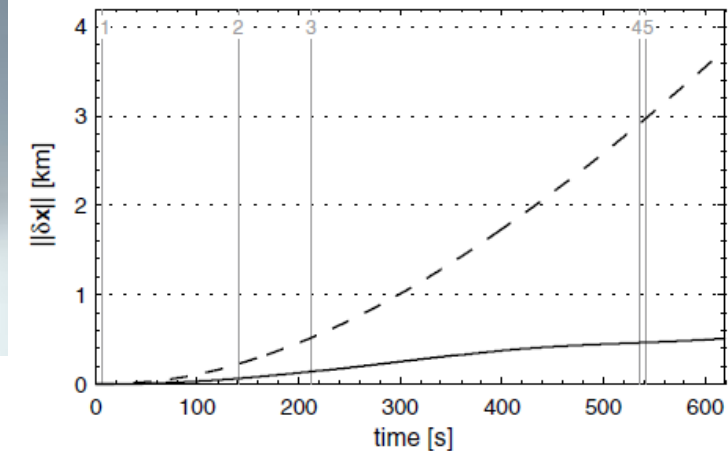
- ☐ Navigation/Tactical grade IMU (10K\$)
- ☐ Integration with GNSS receiver
- ☐ Drawback of INS long term drift is compensated by the GNSS long term stability
- ☐ Susceptibility to RF interferences of GNSS receiver is compensated by the INS short term stability
- ☐ Can be used for longer orbital phases
- ☐ Lower cost/weight system



QASAR 3000



Gyro Bias 0.01 °/h



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IMU

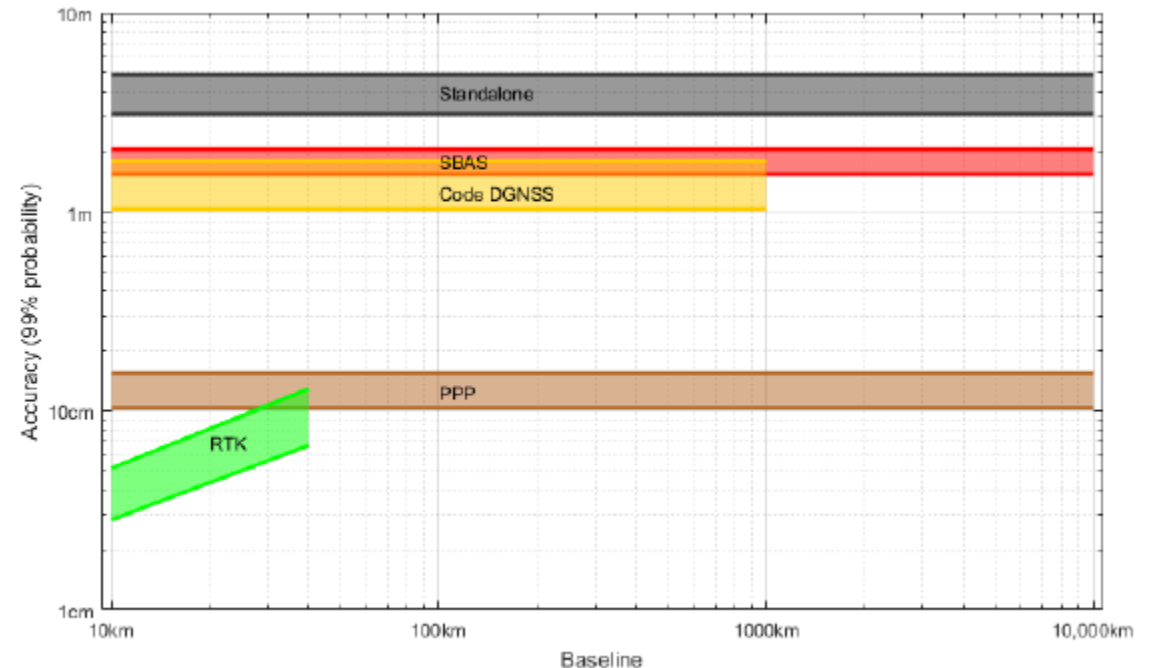


GNSS Receiver

+



Gyro Bias 6 °/h

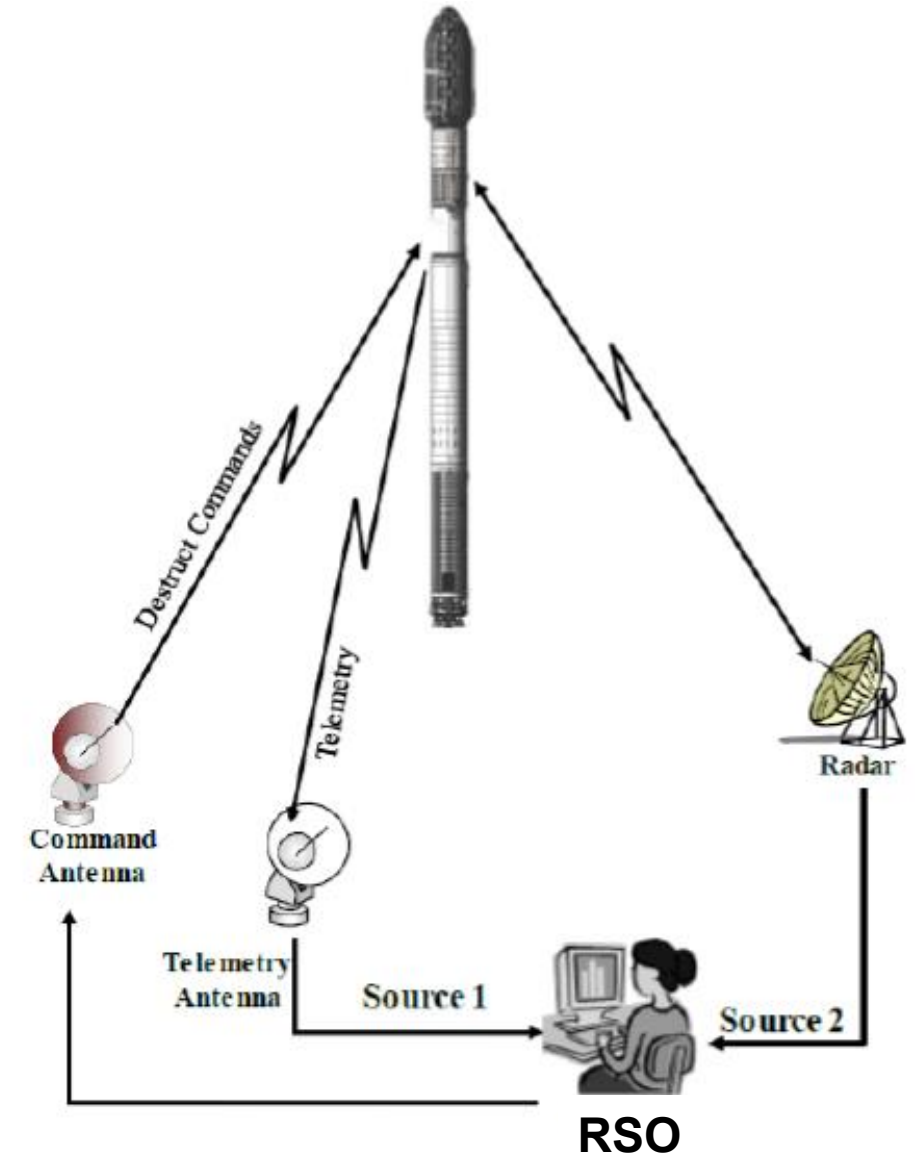


■ Purpose

- Ensures **public safety** in case the launch vehicle deviates from its planned trajectory.
- Provides a means to **rapidly neutralize** a malfunctioning vehicle (usually by destroying it or shutting down propulsion)
- Operated under **Range Safety** authority

■ Command Path

- **Range Safety Officer (RSO)** monitors real-time telemetry and radar tracking.
- If the vehicle leaves the **safety corridor**, the RSO sends coded “ARM” and then “DESTRUCT” signals via UHF or S-band uplink.
- The onboard Command Receiver Decoder (CRD) validates the signal
- If valid, the system transitions from **SAFE** → **ARMED** → **FIRE**, triggering the **termination command**.
- The **vehicle disintegrates**, stopping the propulsion.



■ Modern Updates respect to FTS

- ☐ Uses onboard INS/GNSS navigation
- ☐ Preloaded flight rules to make real-time decisions
- ☐ Eliminates reliance on ground command links and operator
- ☐ Provides faster response and **lower the operational cost.**
- ☐ Used by SpaceX (AFSS), Rocket Lab, and others.
- ☐ It's a **segregated** independent system in the launcher w.r.t. GNC

■ In the near future

- ☐ Regulatory and range-safety policy is moving strongly in the direction of using only AFTS for launchers.
- ☐ For U.S. Department of Defense ranges, AFTS is **planned to be mandatory** starting from 2025.
- ☐ Europe is moving in the same direction.

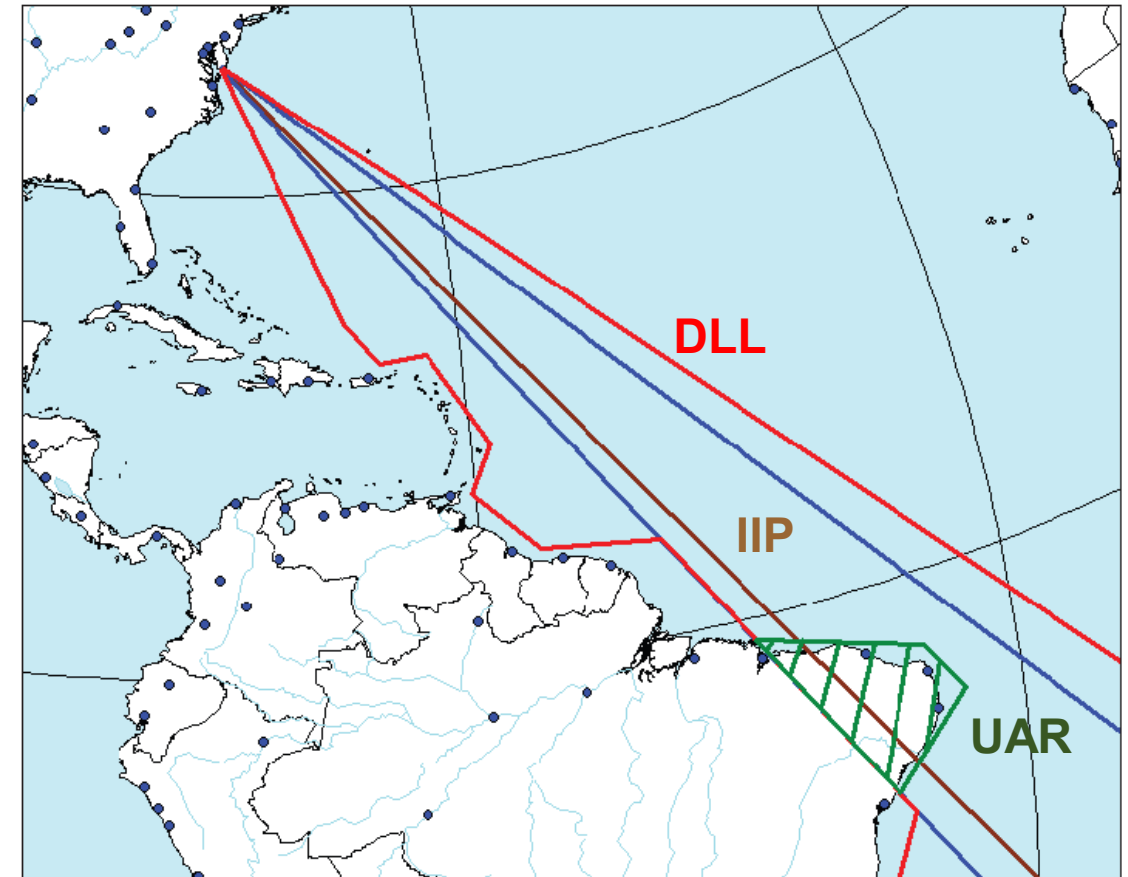


■ Trajectory Tracking Function

- ☐ By default: provide **position and velocity** with the associated accuracies (e.g.: EPE, EVE)
- ☐ In addition: provide the attitude, angular rates and accelerations
- ☐ Mandatory: high level of system **reliability**

■ Trajectory Monitoring Function

- ☐ Compute the Instantaneous Impact Point (**IIP**)
- ☐ Verify Boundary Limit Violations
 - Destruction Limit Line (**DLL**)
 - Uncontrolled Area Regions (UAR)
- ☐ Verify Parameter Threshold Violations:
 - Left/Right Azimuth
 - Min/Max Altitude Vs Downrange
 - Min/Max Flight Path Angle Vs Downrange
 - Maximum Accelerations
 - Maximum Angular Rate



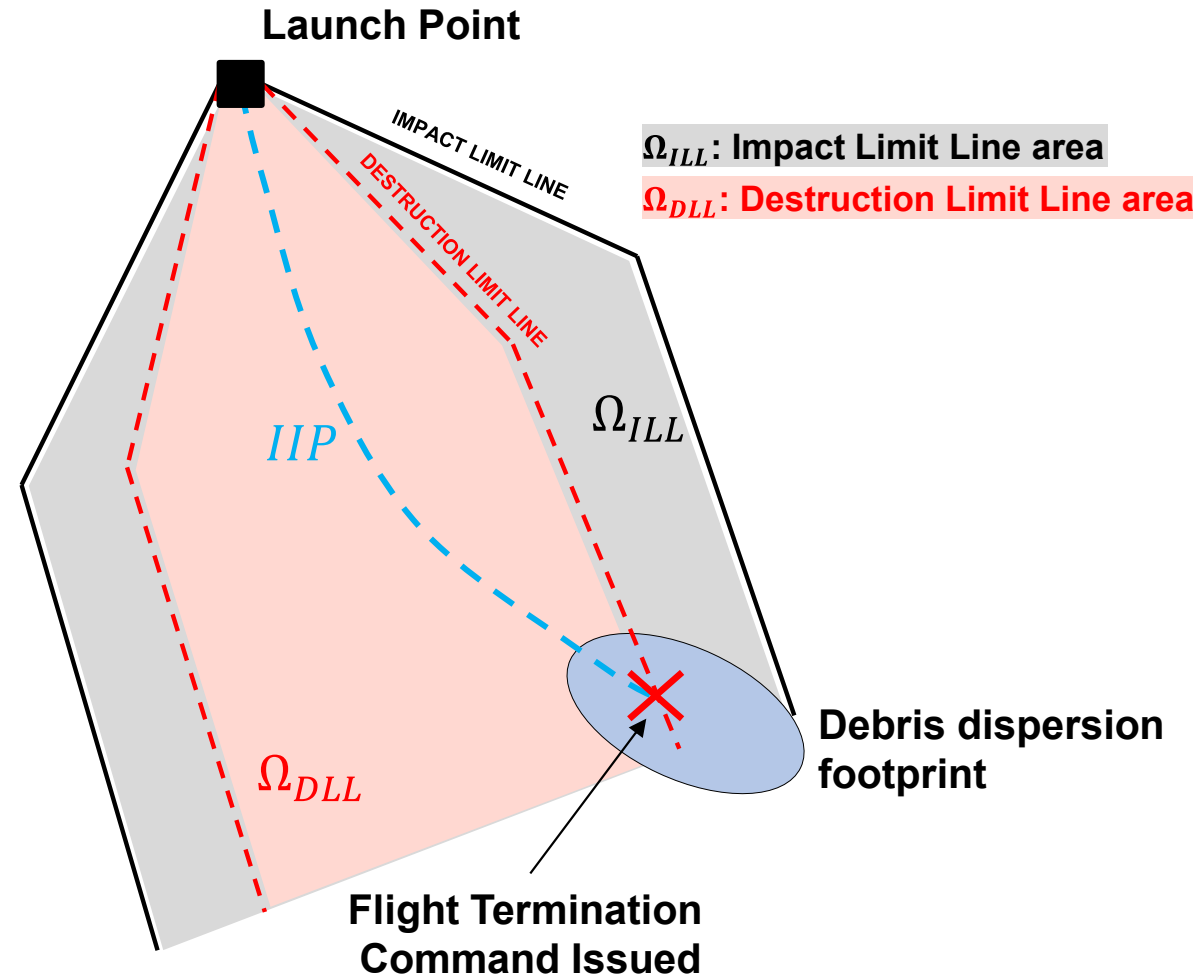
Autonomous Flight Termination System

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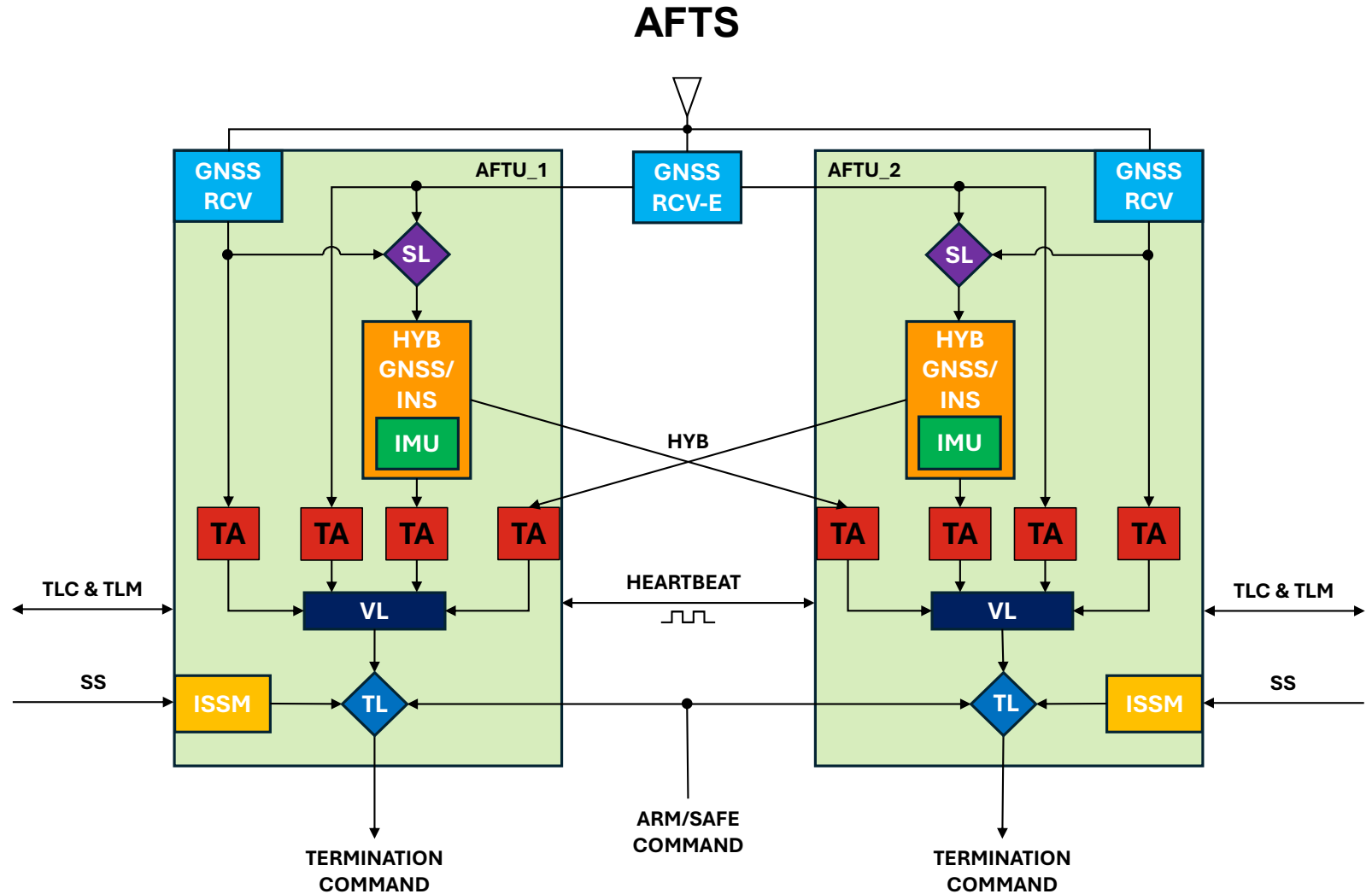


■ Trajectory Tracking

- ☐ GNSS – RCV (External/Internal)
- ☐ Hybrid GNSS/INS solution
- ☐ Switch Logic

■ Trajectory Monitoring

- ☐ Trajectory Analysis (TA)
- ☐ Voting Logic (VL)
- ☐ Termination Logic (TL)
- ☐ Inadvertent Separation Sensor Monitor (ISSM)

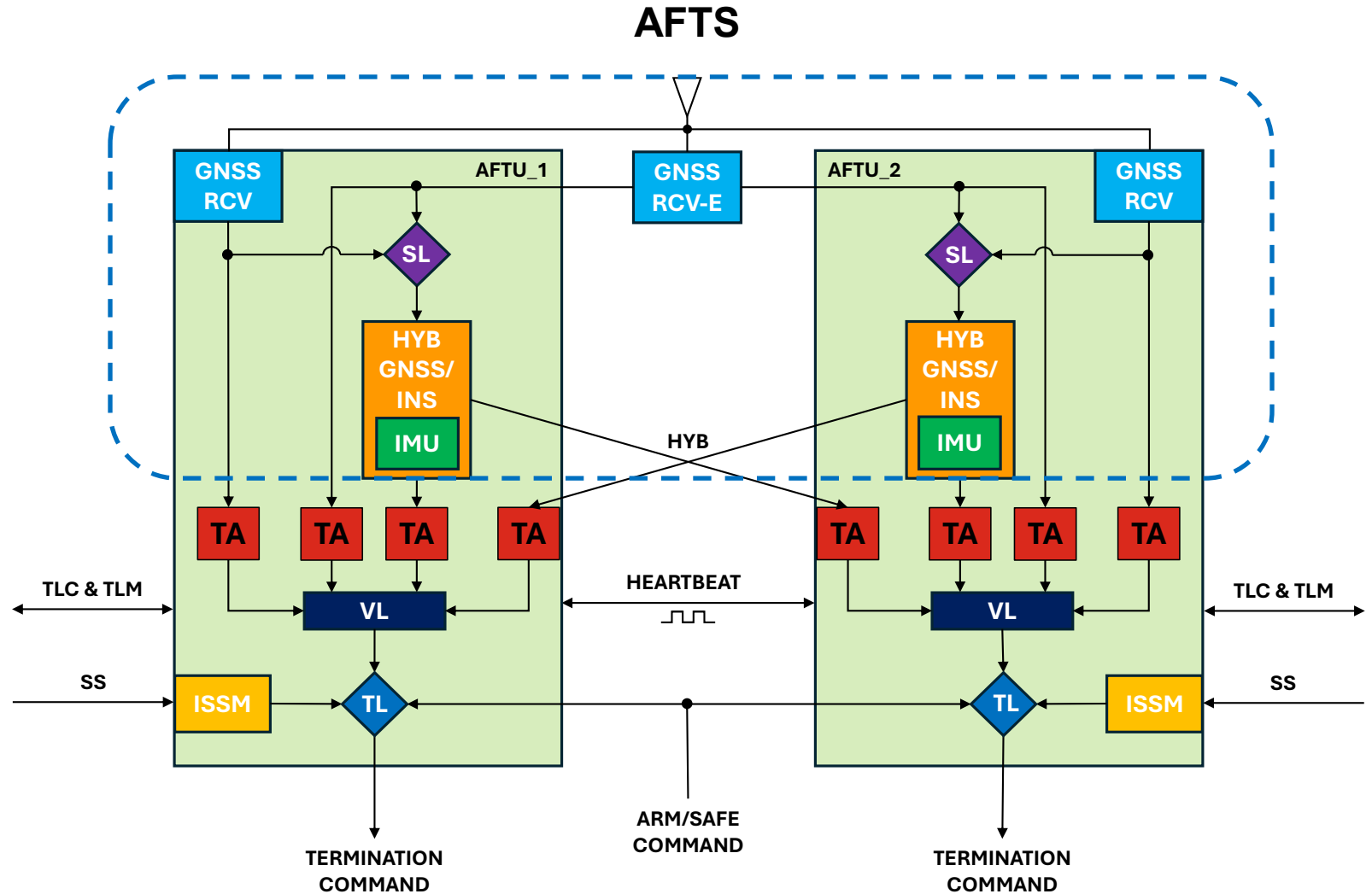


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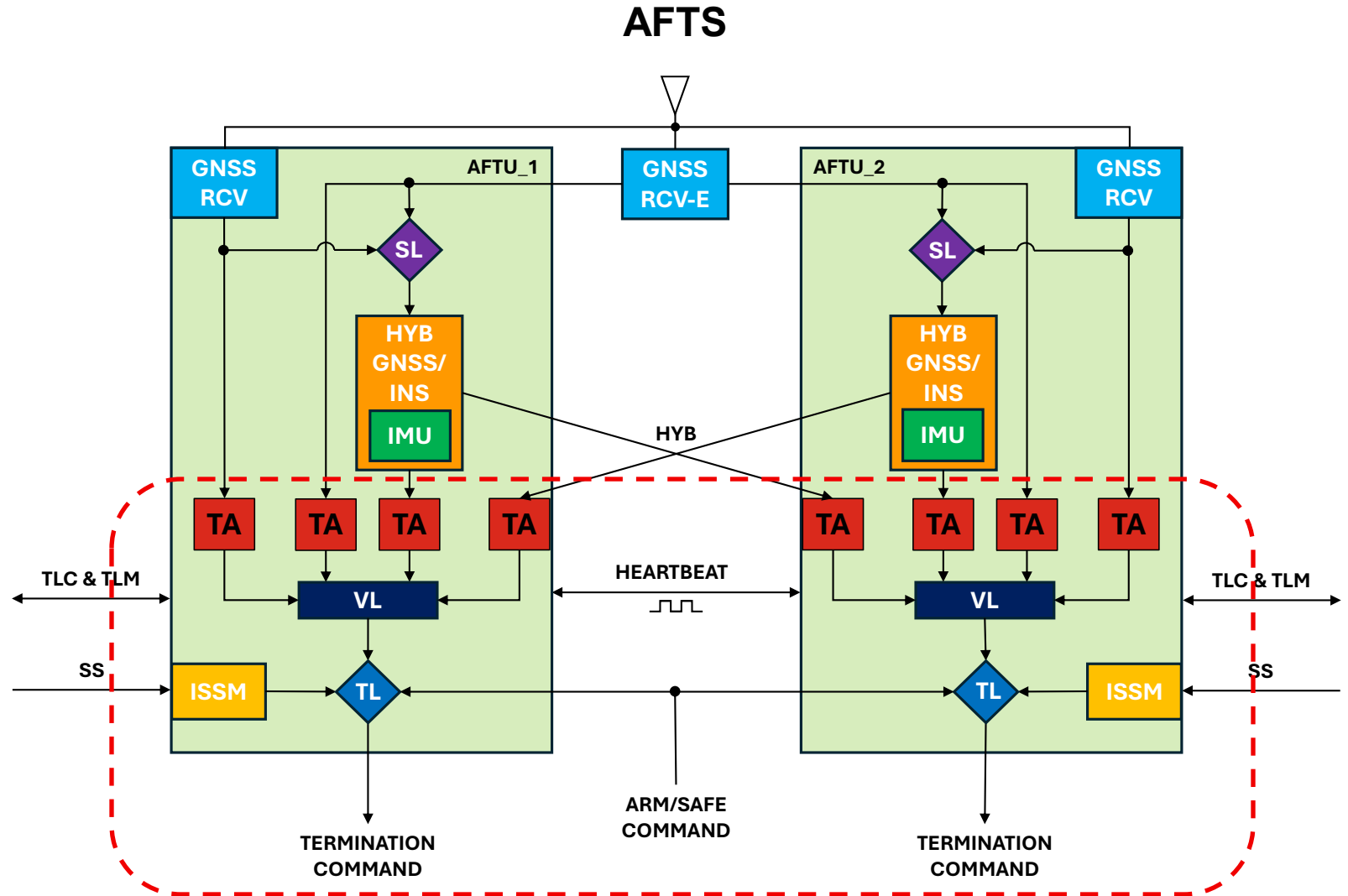


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Other Features:

Configurable based on IMU grade:

- Low/Tactical grade IMU
- Tactical/Nav Grade IMU



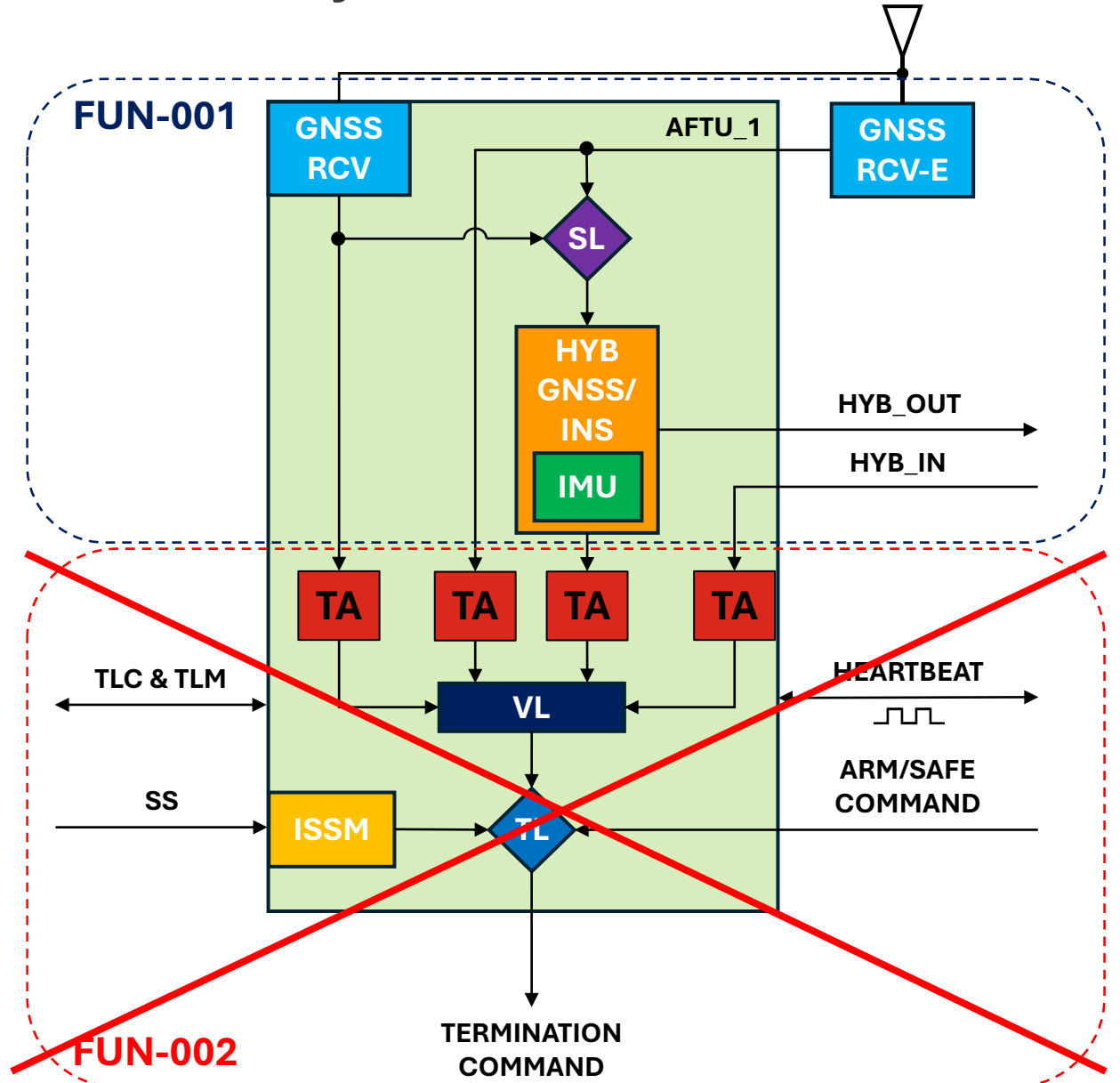
250 °/h



6 °/h

Can be used also as a navigation system for the launcher GNC

TARGET: dual function in one single product with a high-level of robustness for launcher navigation



■ Extreme dynamics (high accelerations, vibrations)

- Loss of Lock in the GNSS receiver tracking channels
- Rectification errors in the IMU
- Coning and Sculling phenomena

■ Stage separation and ignition shocks

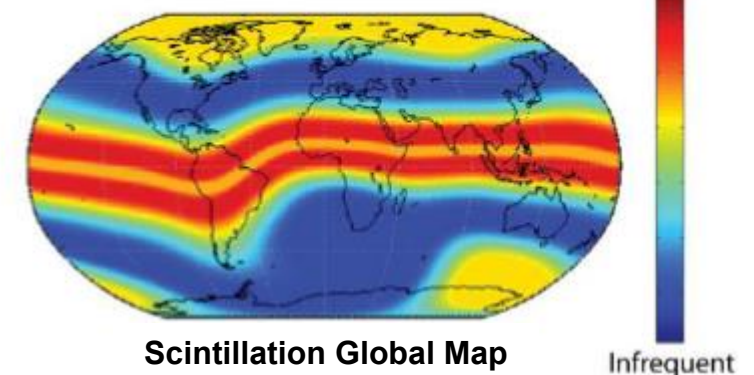
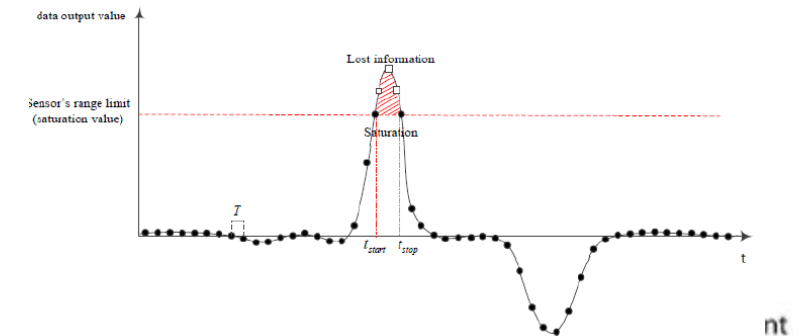
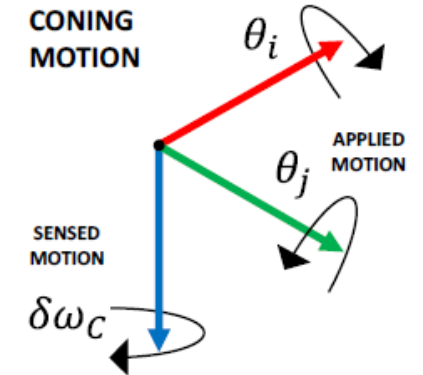
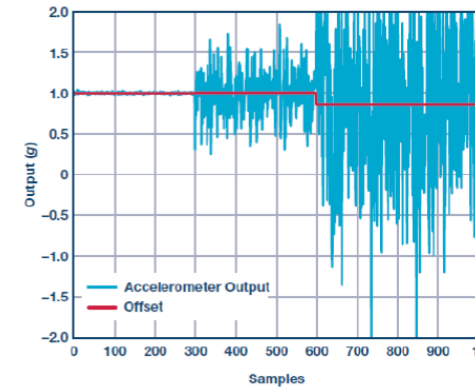
- IMU accelerometer saturations
- Clock discontinuity due to receiver oscillator g-sensitivity
- Temporary antenna blockage caused by fairing separation

■ RF interferences

- Ionospheric Scintillations (nav-bit errors, cycle slips, loss of lock)
- Jamming
- Electro Magnetic Interferences (EMI)

■ Surrounding Environment

- Multipath reflection (from launcher nearby structures)
- Spoofing or Meaconing (from an on-ground attacker)
- Plasma-induced RF blackout during re-entry phases



Baseline Launcher Navigator Engine Architecture

■ Flexible GNSS/INS architecture, adaptable to:

- ❑ Expandable Launch Vehicles & Micro Launchers (e.g.: Vega, Ariane-5, Shefex-2)
- ❑ Reusable Launch Vehicles & Re-entry vehicles (e.g.: Falcon-9, Space Rider)

■ Supported Initialization Strategies for Attitude:

- ❑ External Quaternion/Heading
- ❑ Star Sensor

■ Kalman Filter:

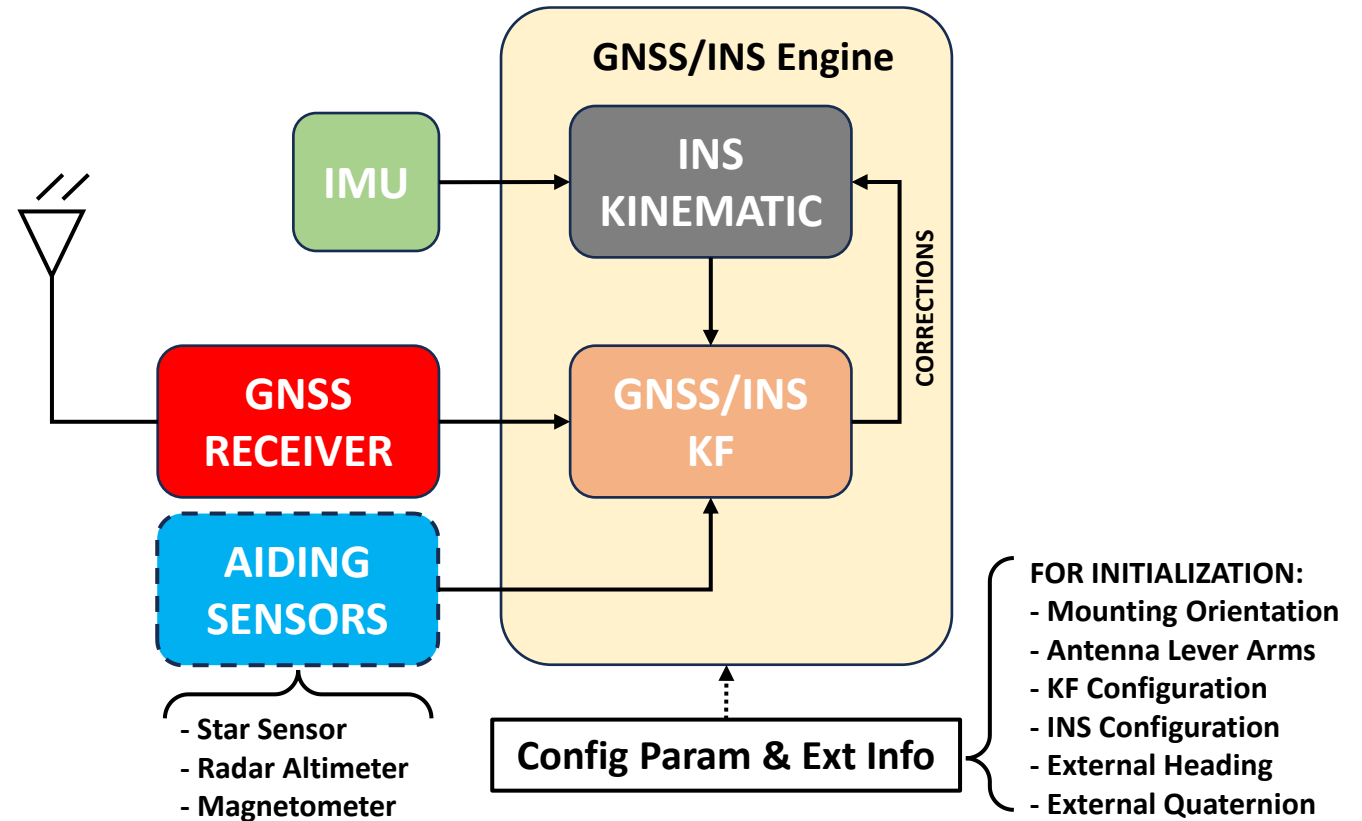
- ❑ Extended Closed Loop Form
- ❑ 35 Elements State Vector

■ Supported KF Measurement Updates:

- ❑ ZUPT (Zero Velocity Update)
- ❑ ZARU (Zero Angular Rate Update)
- ❑ GNSS TC (Tightly Coupled)
- ❑ GNSS LC (Loosely Coupled)
- ❑ Height Update (e.g.: Radar Altimeter)
- ❑ Attitude Update (e.g.: Star Sensor)
- ❑ Heading Update (e.g.: Magnetometer)

■ Easily Configurable:

- ❑ Enable/Disable Sensor Updates
- ❑ User Configurable KF/INS Parameters



INS Strapdown Kinematic

$$\dot{\mathbf{C}}_b^n = \mathbf{C}_b^n \cdot [\boldsymbol{\omega}_{ib}^b \times] - [\boldsymbol{\omega}_{in}^n \times] \cdot \mathbf{C}_b^n$$

$$\dot{\mathbf{v}}_{eb}^n = \mathbf{C}_b^n \cdot \mathbf{f}_{ib}^b - (2\boldsymbol{\omega}_{ie}^n + \boldsymbol{\omega}_{en}^n) \times \mathbf{v}_{eb}^n + \mathbf{g}_l^n$$

$$\dot{\mathbf{C}}_e^n = [-\boldsymbol{\omega}_{en}^n \times] \cdot \mathbf{C}_e^n$$

$$\dot{h} = -v_z$$

Kalman Filter

Time Update

$$\hat{\mathbf{x}}_k^- = \boldsymbol{\Phi} \hat{\mathbf{x}}_{k-1}^+$$

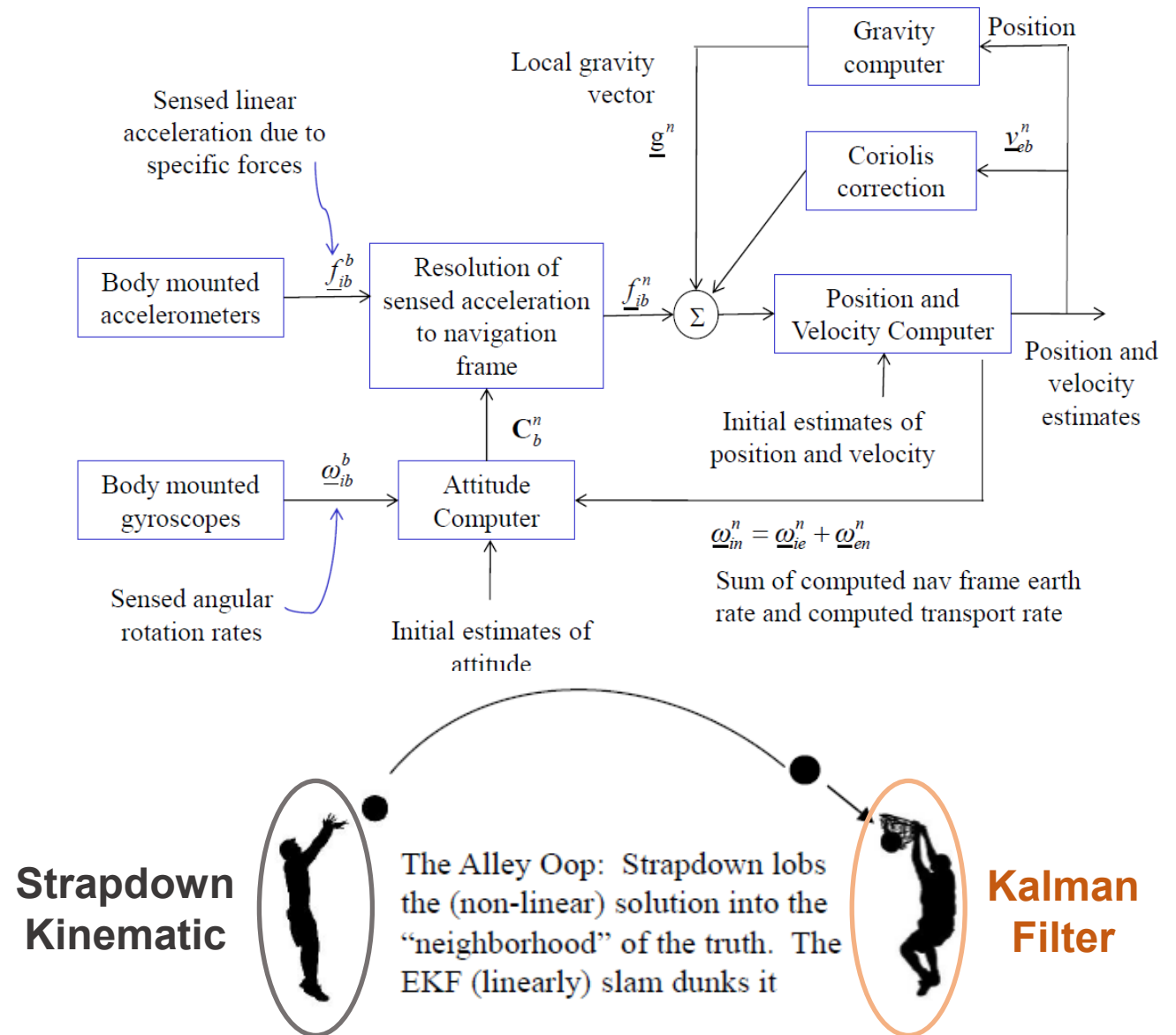
$$\mathbf{P}_k^- = \boldsymbol{\Phi} \mathbf{P}_{k-1}^+ \boldsymbol{\Phi}^T + \mathbf{Q}$$

Measurement Update

$$\tilde{\mathbf{z}}_k = \tilde{\mathbf{Z}}_k - \hat{\mathbf{Z}}_k$$

$$\hat{\mathbf{x}}_k^+ = \hat{\mathbf{x}}_k^- + \mathbf{K} (\tilde{\mathbf{z}}_k - \mathbf{H} \hat{\mathbf{x}}_k^-)$$

$$\mathbf{P}_k^+ = (\mathbf{I} - \mathbf{K} \mathbf{H}) \mathbf{P}_k^-$$



Robust Launcher Navigator Engine Architecture

■ Robustness at Hardware Level:

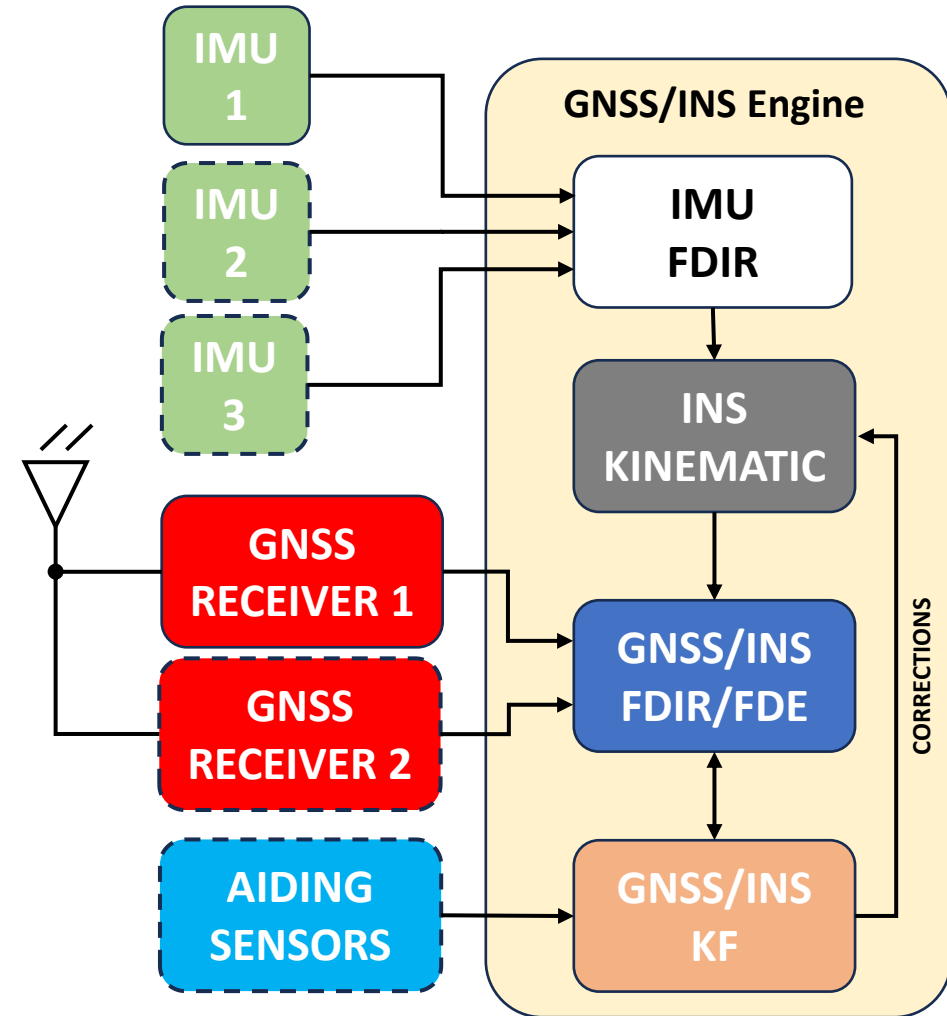
- IMUs Hot-redundancy
- GNSS receivers Hot-redundancy

■ Robustness at Software Level:

- 3x IMUs CBIT flag monitor
- 2x GNSS receivers CBIT flag monitor

■ Robustness at Filter/Algorithm Level:

- Covariance Monitor:
 - Positive semi-definite covariance check
- IMU FDIR:
 - Voting Logic available with 3 IMUs
- GNSS/INS FDIR/FDE:
 - Redundant Pseudo Ranges observables & INS
 - Redundant Pseudo Range Rates observables & INS



Robust Launcher Navigator Engine Architecture

■ Robustness at Hardware Level:

~~□ IMUs Hot-redundancy~~

□ GNSS receivers Hot-redundancy

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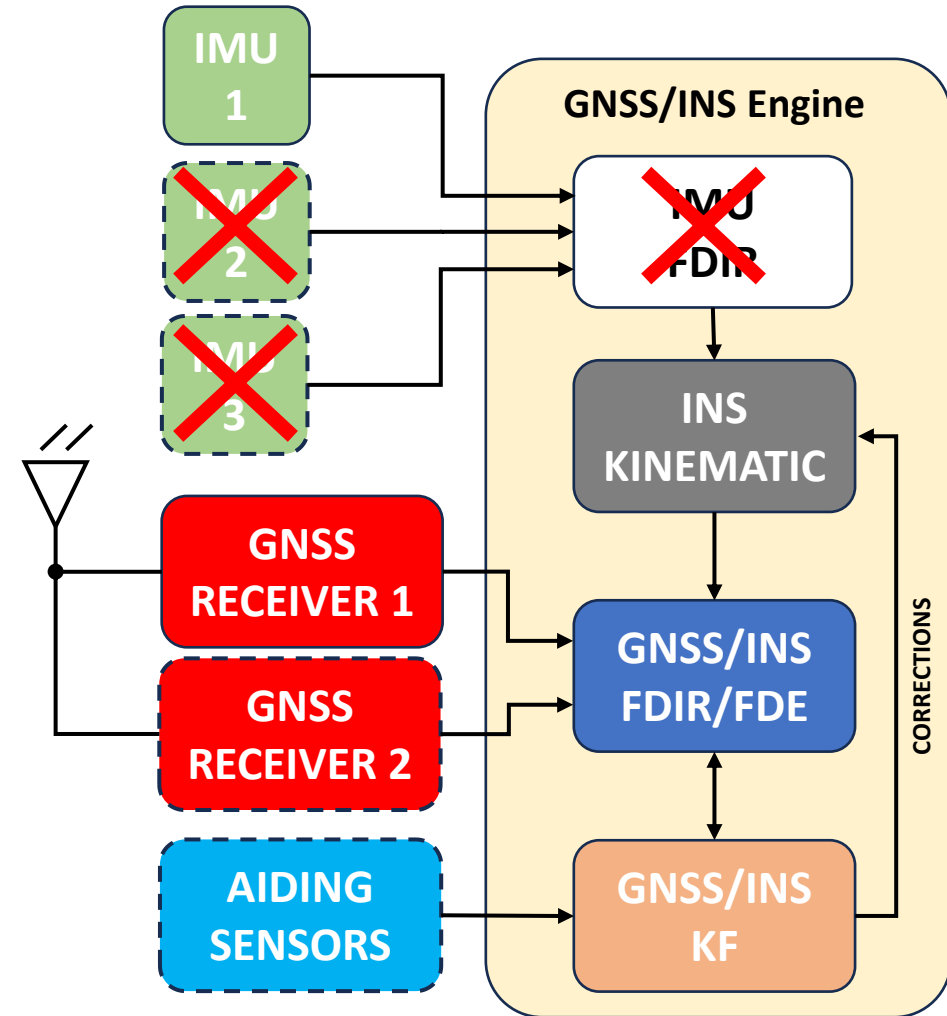
~~■ Voting Logic available with 3 IMUs~~

□ GNSS/INS FDIR/FDE:

■ Redundant Pseudo Ranges observables & INS

■ Redundant Pseudo Range Rates observables & INS

For AFTS Application

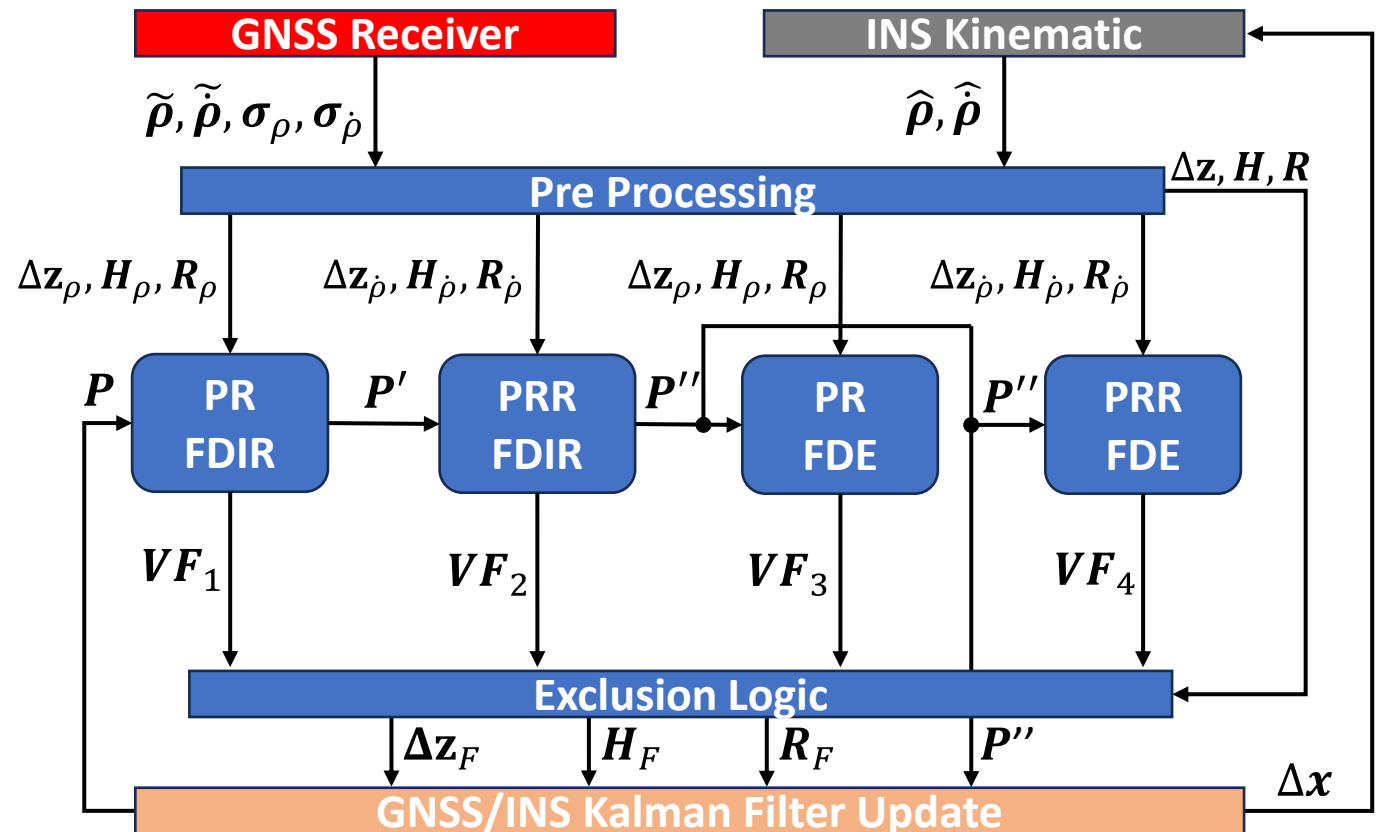


■ FDIR:

- Single Channel Inconsistency
 - Single Satellite Clock Failure
- Multiple Channel inconsistency
 - Multipath
 - Rough Spoofing Attack
 - Receiver Clock Step/Drift discontinuity
- Anomalous INS kinematic drift
 - IMU Unaccounted Error Dynamic
 - IMU Accelerometer Saturation
- Recovery:
 - Covariance pumping for the KF failed states

■ FDE:

- Single/Multiple channel slow drift
 - Sophisticated Spoofing Attack



■ Simulation Setup

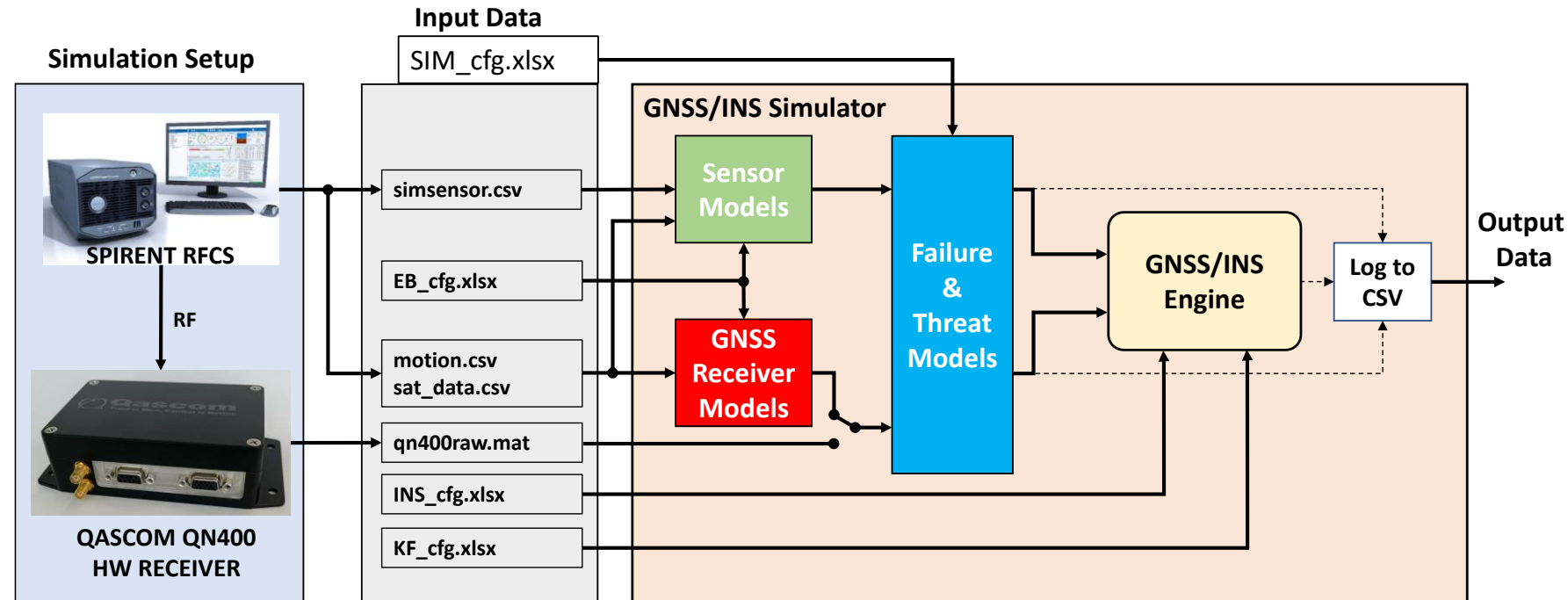
- ☐ Spirent RFCS (SimSENSOR)
- ☐ QN400 Space Receiver

■ Input Data Files

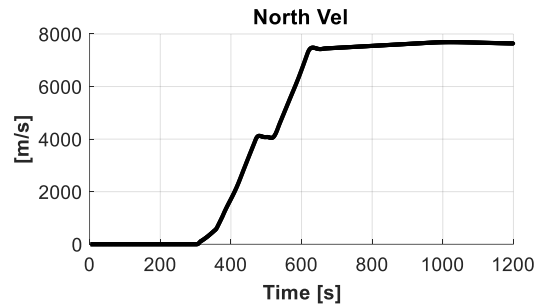
- ☐ Simulation Config. File
- ☐ Spirent Files
- ☐ Error Budget File
- ☐ QN400 Receiver Data
- ☐ INS Config. File
- ☐ KF Config. File

■ GNSS/INS Simulator

- ☐ Sensor Models
- ☐ GNSS Receiver Model
- ☐ Failure & Threat Models
- ☐ GNSS/INS Engine



- Vega insertion to LEO SSO
- Navigation Grade IMU (e.g.: HG2800)
- Threats & Failures introduction



ID	Threat & Failure	Description
01	SV clock bias & drift discontinuity	a) Single SV step error of 300 m b) Single SV drift error of 0.5 m/s
13	Spoofing	a) Spoofing of 4 SV with drift error of 0.2 m/s b) Spoofing of 4 SV with step error of 50 m
19	Receiver clock bias & drift discontinuity	a) Receiver clock step error of 1000 Km
22	Receiver HW failure	a) Zero-Hold measures for 50 sec
25	IMU saturation	a-b-c-d) Accelerometer x-y-z- axes saturation for 0.01 sec
27	IMU coning & sculling	a) 30Hz coning motion with 1 mrad amplitude on gyro X-Y-axes & 30Hz sculling motion of 1 mm amplitude on accelerometer X-axis
28	IMU HW failure	a) Zero-Hold measures for 15 sec
29	INS numerical failure	a) Introduction of negative value (-10) in the covariance matrix diagonal for tilt x state
30	Vibration G-rms	a-b-c-d) Vibration of 6 G-rms
31	GNSS signal outage	a-b) Signal outage of 15 sec

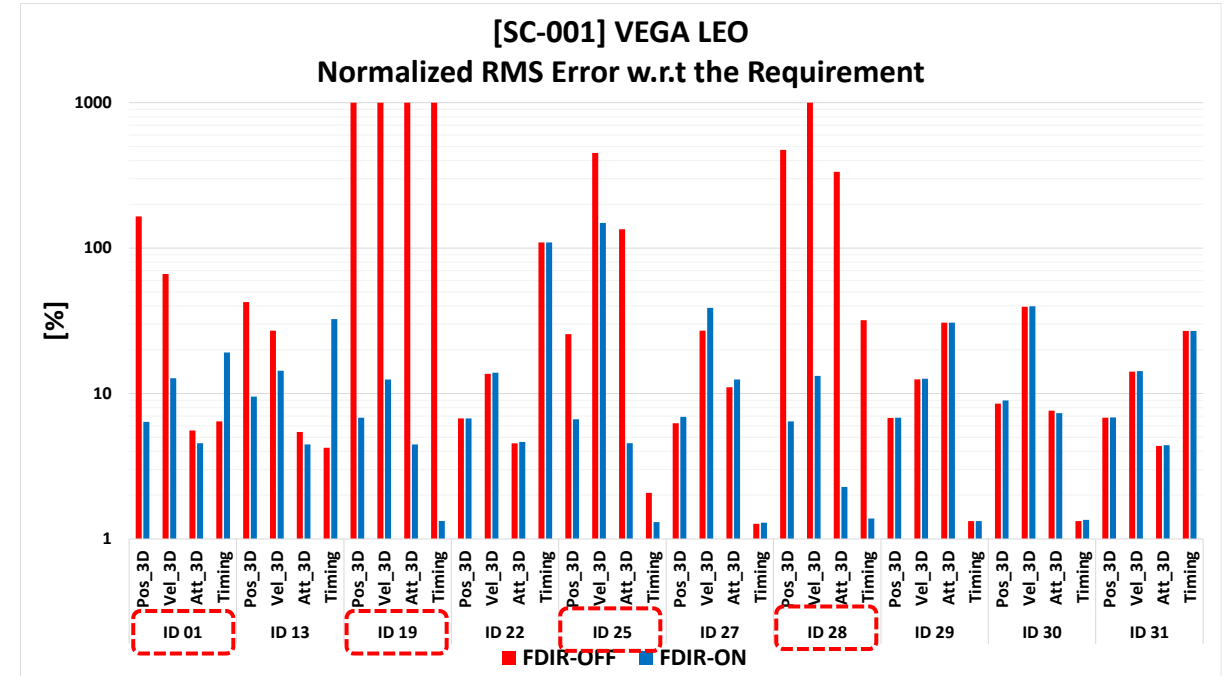
Table 1. Threat & Failure IDs for the simulation.

Time (s)	Flight Event	Threat & Failure ID									
		01	13	19	22	25	27	28	29	30	31
300	Fist stage ignition									a	
367	Max dynamic pressure						a				a
390	1 st stage separation		a			a					
407	2 nd stage ignition				a					b	
480	2 nd stage separation	a				b		a	b		
517	3 rd stage ignition			a						c	
522	Fairing Jettison					c					b
629	3 rd stage separation	b				d					
649	4 th stage ignition		b							d	
1024	End of first boost										

Table 2. Timeline scenario of Threat & Failure introduction.

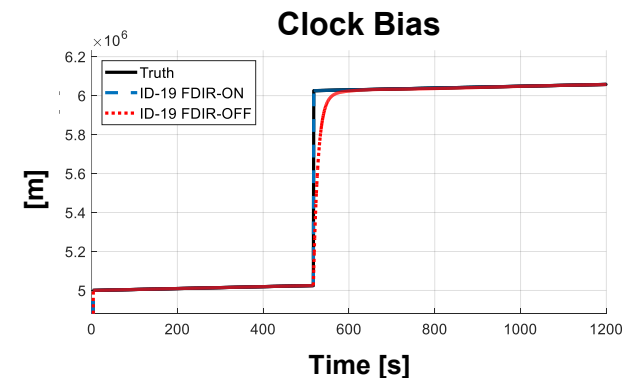
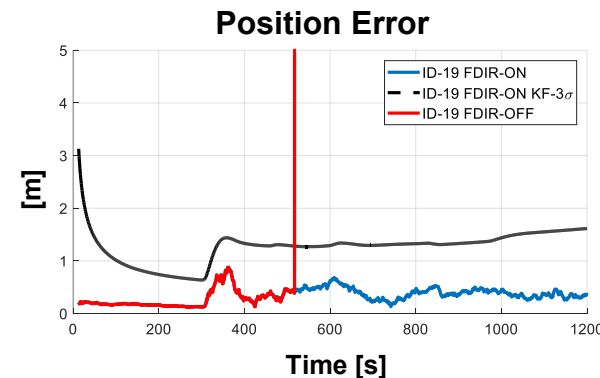
■ Identify Most Detrimental threats:

- ID-01: SV Clock bias/drift discontinuity
- ID-19: Receiver Clock Step
- ID-25: IMU Accelerometers Saturation
- ID-28: IMU Failure



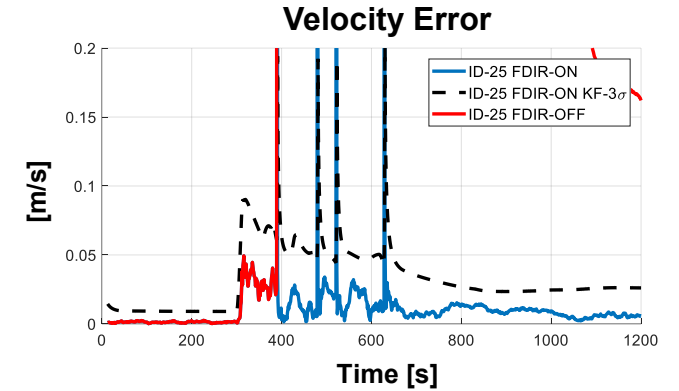
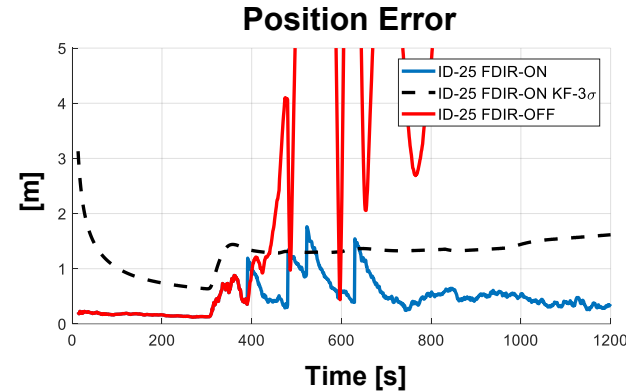
■ ID-19: Receiver Clock Step

- Position error restored to nominal values
- Covariance pumping for KF clock bias state
- Estimated clock bias fast adaptation during subsequent KF update



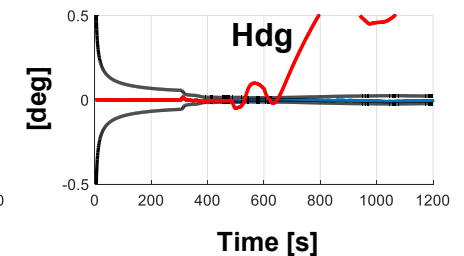
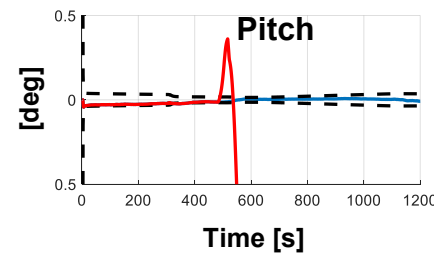
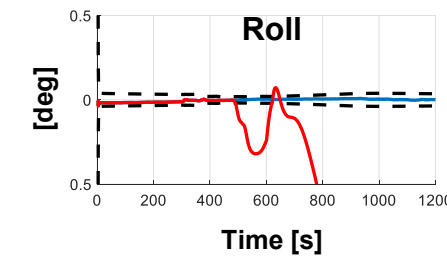
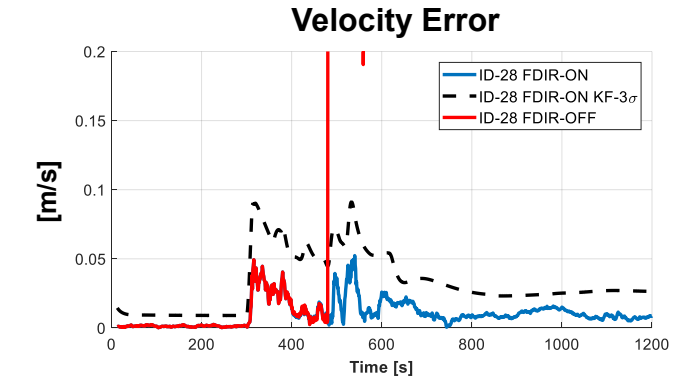
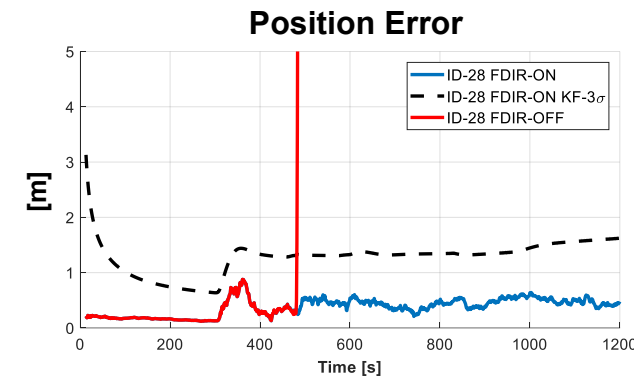
■ ID-25: IMU Accelerometers Saturation

- Covariance pumping for KF velocity states
- Restored Position & Velocity error coherence with KF covariance



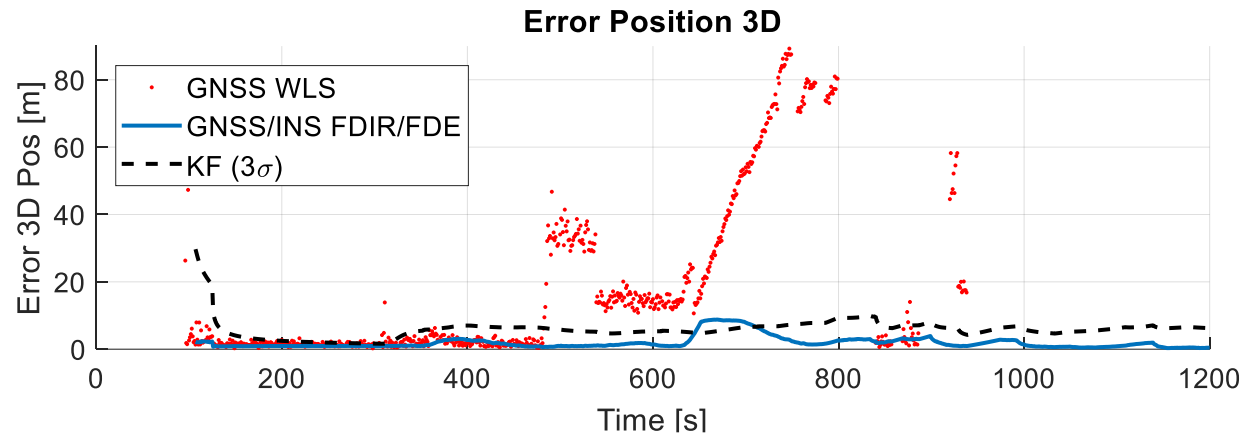
■ ID-28: IMU Failure

- Rapid identification of the IMU freezing
- Kinematic errors restored to nominal values
- Identification is performed before the error propagate to the attitude states
- KF estimated IMU errors and covariance states are then reset



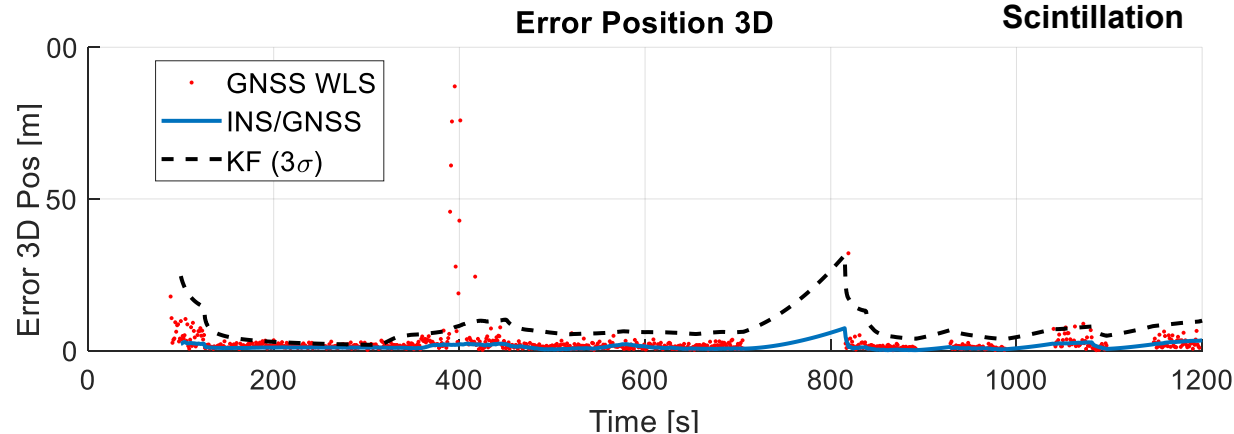
2 second steps errors with 50m magnitude every 10 seconds in the best GDOP satellites pseudo-ranges for both GPS and Galileo constellations.

Multipath

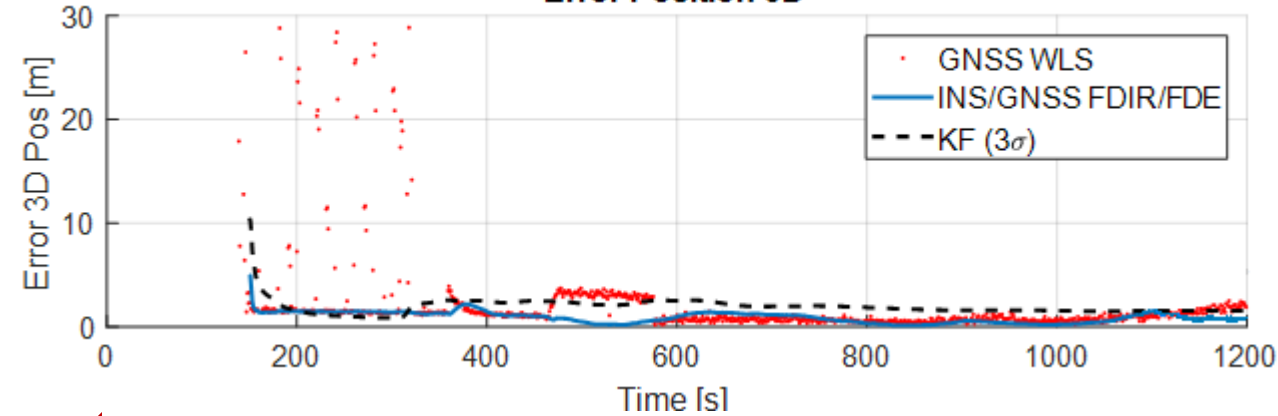


Cornell ionospheric model with $S_4 = 1$, $\tau_0 = 0.5$

Severe Scintillation



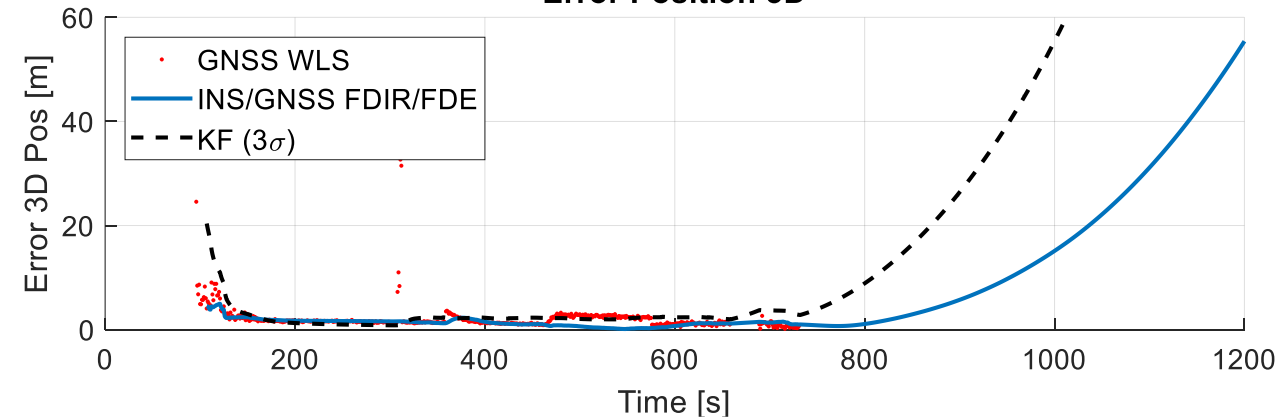
Error Position 3D



Sat. clock error

300 m pseudo-range step error in one SV
0.5 m/s pseudo-range drift error in one SV

Error Position 3D



RF Interference

Continuous Wave signal + Chirp Sawtooth + Continuous Wave Pulsed signal

Final Considerations & Next Steps

■ Achieved Goals:

- Design of a modular and scalable launcher navigation architecture for:
 - Navigation function (GNC)
 - Safeguard function (AFTS)
- Design of a flexible simulation environment:
 - User friendly (excel files to configure scenarios and INS/KF parameters)
 - Allow the use of real receiver data (Qascom QN400 SDR receiver)
- Robust navigation algorithms has been successfully implemented and tested:
 - FDIR at GNSS/INS level
 - FDE at GNSS/INS level
- Implementation of the navigation software for a real time target platform:
 - Porting the navigation software from MATLAB to C++ language
 - Test the C++ software in a Processor In the Loop (PIL) based on a Xilinx Zynq 7000 SoC and Cortex-H7 MCU

■ Next Steps:

- Test the robust launcher navigation engine integrated in the Qascom AFTU system
- Test the AFTU system in a real sounding rocket flight, in analogy with the SL15 mission



Thank you!