FTSnext

Next Generation Flight Termination Systems for Launchers

Kick-Off Presentation for Final Review

October 04, 2023

Agenda

1. Introduction
2. Project Goals
3. Project Overview
4. Project Results
5. Outlook

INTRODUCTION

Flight Termination Systems (FTS)

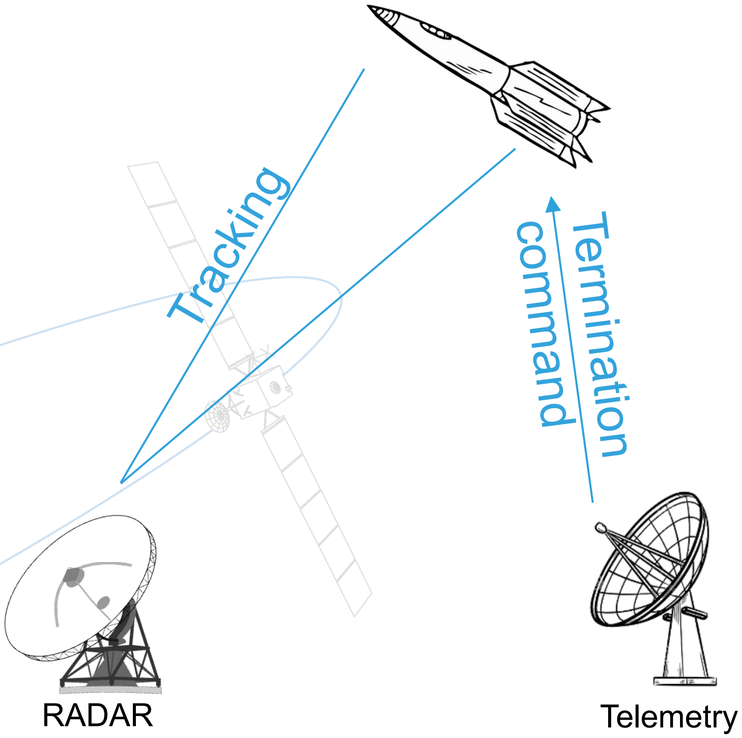
Cause:

- Leaving safe trajectory
- Observable system failure

➡ Increased risk to humans or property

Termination

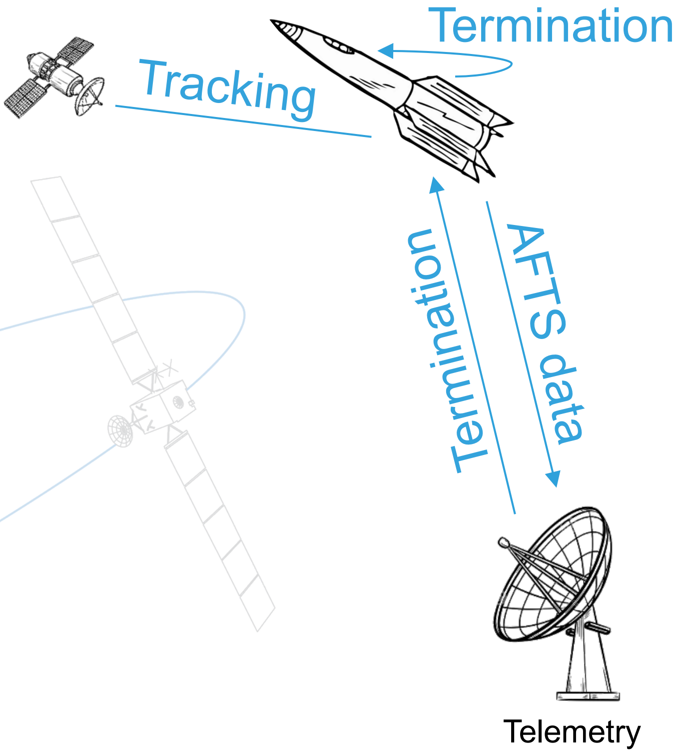
- Destruction of the launcher
- Engine shut-off



Flight Termination Systems (FTS)

Autonomous FTS (AFTS)

- Onboard tracking, monitoring and termination rules
- Optional termination from ground



Advantages

- Cheaper infrastructure
- More flexible trajectories possible

PROJECT GOALS

FTSnext project

FTSnext

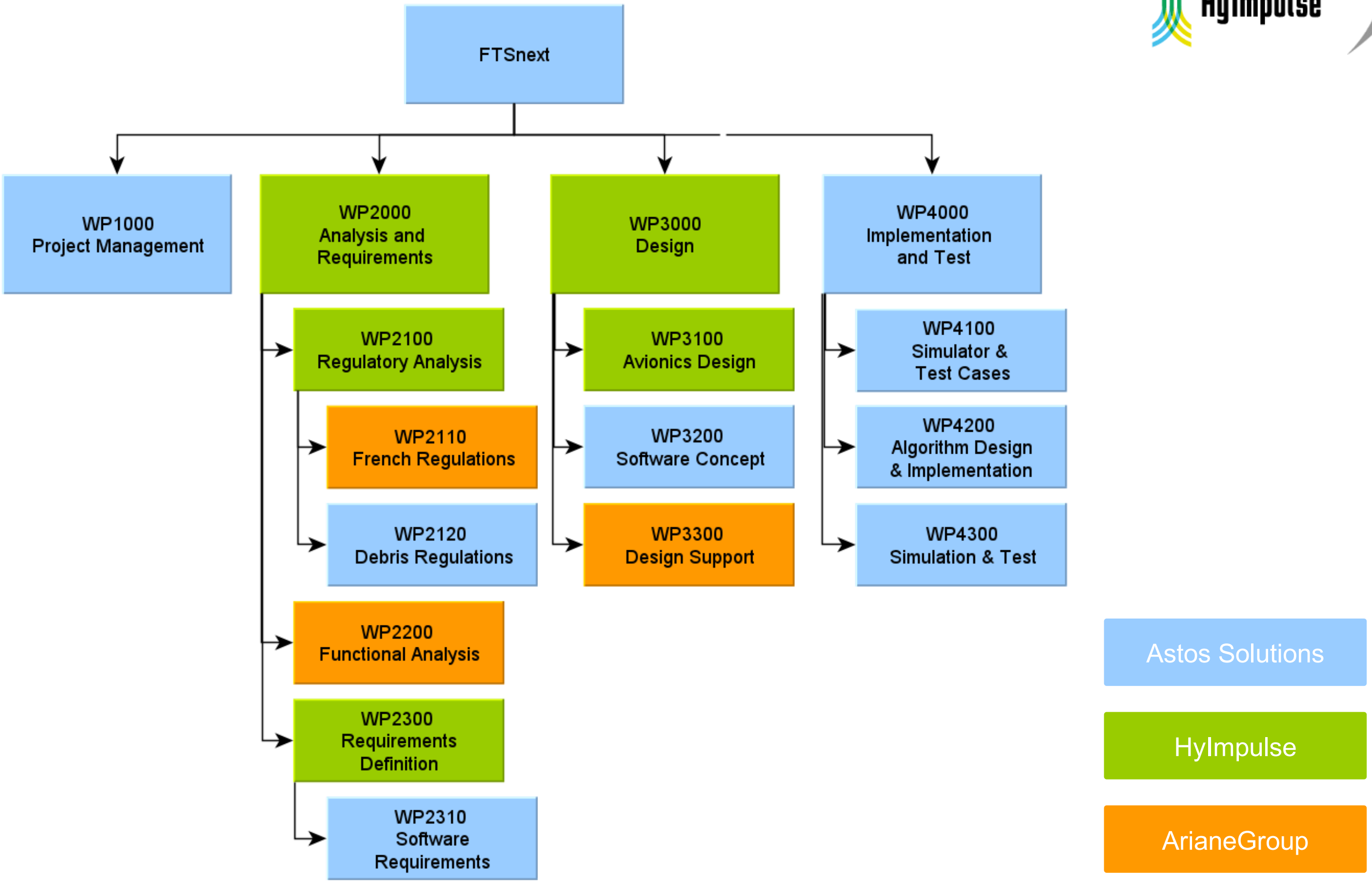
- AFTS development for international market
- Easy reconfiguration to launch sites, launchers and regulations
- Team: Astos Solutions, HyImpulse and Ariane Group

Focus

- Requirement Engineering
- System Design
- Simulation Environment
- Software Prototype

PROJECT OVERVIEW

WBS


FTSnext
WP1000
Project Management
WP2000
Analysis and
Requirements
WP3000
Design
WP4000
Implementation
and Test
WP2100
Regulatory Analysis
WP2110
French Regulations
WP2120
Debris Regulations
WP2200
Functional Analysis
WP2300
Requirements
Definition
WP2310
Software
Requirements
WP3100
Avionics Design
WP3200
Software Concept
WP3300
Design Support
WP4100
Simulator &
Test Cases
WP4200
Algorithm Design
& Implementation
WP4300
Simulation & Test
Astos Solutions
HyImpulse
ArianeGroup

Schedule / Milestones

Meeting	Purpose	Companies attending	Date(s)	Location
KOM	Kick-off of activity	Astos, HyImpulse, ArianeGroup	2023-11-03	Online
PM1	Progress Meeting 1	Astos, HyImpulse, ArianeGroup	2022-02-08	Online
DSR	Design Specification Review	Astos, HyImpulse, ArianeGroup	2022-07-22	Stuttgart / Online
PM2	Progress Meeting 2	Astos	2022-09-15	Online
FR	Finale Review	Astos, HyImpulse, ArianeGroup	2023-10-20 (TBC)	Online

Additionally, bi-weekly meetings with ESA

Deliverables

Documents

SOW	Doc#	Title / description	Milestone
TN-01	TN-01	AFTS Reference Framework	DSR
TN-02	TN-02	FTSnext Requirements Specification	DSR
	TN-03	Functional analysis	DSR
TN-03	TN-04	FTSnext Design Specification	DSR
TN-04	TN-05	FTSnext Simulator: User Manual, Architectural Design and Model Reference	FR
TN-05	TN-05	FTSnext Simulator: User Manual, Architectural Design and Model Reference	FR
	TN-07	Test Plan and Test Report	FR
SRF	SRF	Software reuse File (content see SOW)	FR
TDP	TDP	Technical Data Package	FR
TAS	TAS	Technology Achievement Summary	FR
FP	FP	Final Presentation	FR
ESR	ESR	Executive Summary Report	FR
FR	FR	Final Report	FR
CCD	CCD	Contract Closure Documentation	Contract Closure
MOM	MOM	Minutes of Meeting	5 days
PR	PR	Monthly Progress Report with updated schedule, problem notification, AIL, DDL	Monthly

Deliverables

Software / Models

SOW	SW#	Title / Description	Quantity	Milestone
SW-01	SW-01	FTSnext Simulator Software and Environment	1	FR
SW-02	SW-02	FTSnext Simulator Runs and Results	1	FR
SW-01	SW-03	FTSnext Algorithms	1	FR
	SW-04	Capella files of functional analysis	1	DSR

PROJECT RESULTS

Regulatory Analysis:
Contacted Launch Sites

Country	Launch Site	Response
UK	SaxaVord	Yes
Sweden	Esrange	Yes
Japan	Hokkaido	Yes
Germany	GOSA	Yes
Kazakhstan	Baikonur	No
Portugal	Azores	Yes
France	CSG	No
Norway	Andoya	Yes
Brazil	Alcântara	No
South Korea	Naro	No
New Zealand	Rocket Lab	No
Australia	Whalers Way	Yes

General feedback

Esrange, GOSA, Azores

- Would liked to keep informed
- Open for further discussion

Regulatory Analysis

<u>Detailed regulations from United States:</u>

- *Title 14 Code of Federal Regulations (CFR)* 450.108 Flight abort
- *Range Commander Council (RCC)* Flight Termination Systems Commonality Standard 319-19

Regulatory Analysis

National regulations:

- The French Space Operation Act
- United Kingdom Space Industry Regulations
- Australian flight safety code
- Japanese Space Regulations

→ Flexible design of AFTS necessary

Model Based System Engineering

Operational Analysis

Functional Need Analysis

Logical Architecture

Physical Architecture

Functional Requirements

Architecture

System Requirements Analysis

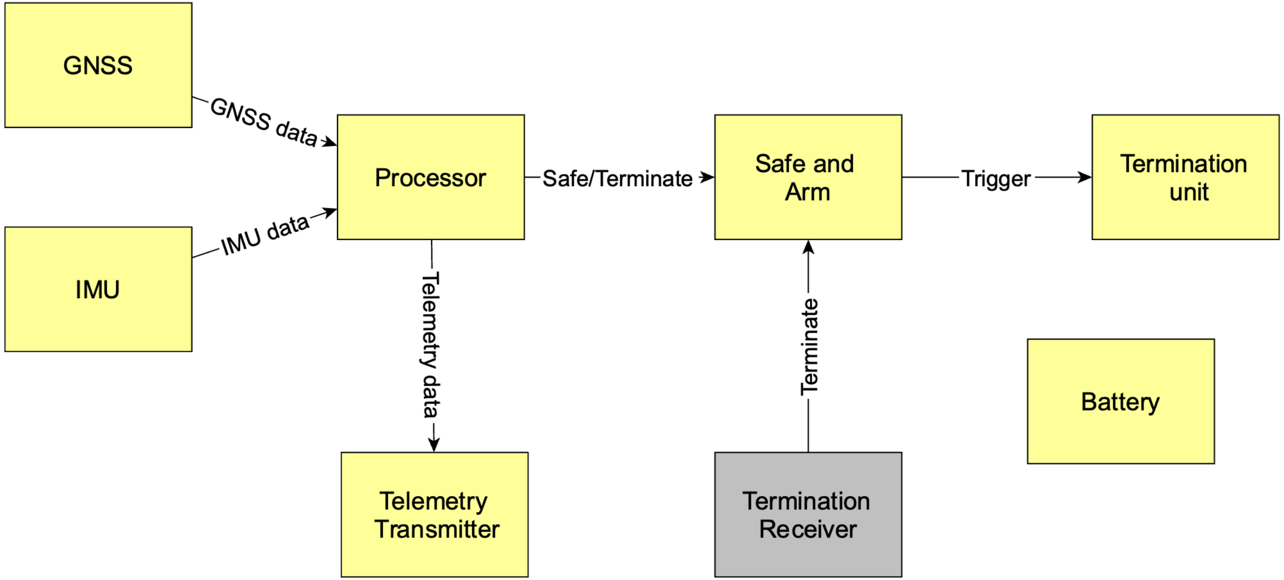
Input:

- Statement of Work
- Functional analysis
- Regulation survey
- ECSS-E-40 Part 1B and ECSS-Q-ST-80C

Outcome

- 137 system requirements
- 104 software requirements

High-Level System Architecture

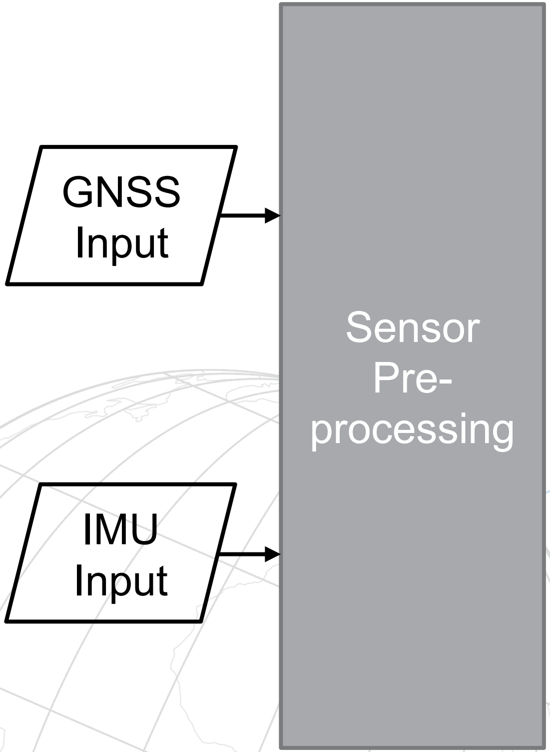


Redundancy for reliability

- Tracking: GNSS and IMU
- Two power units
- Cables and connectors
- Two processing units: Software

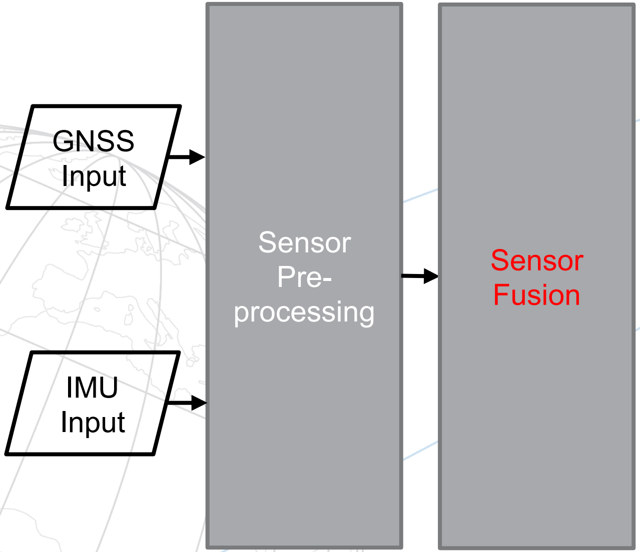
➡ Self-monitoring and fail-safe

Software Prototype



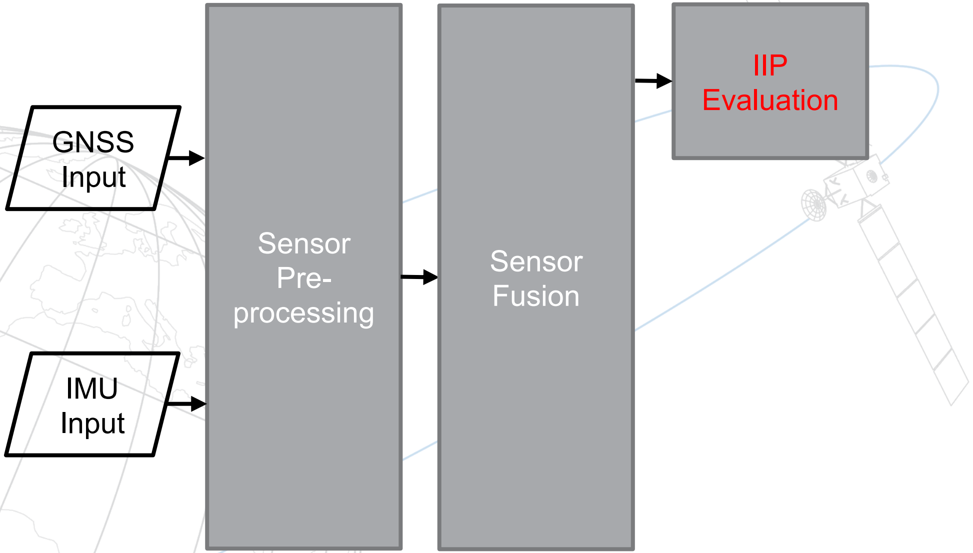
Software Prototype: Sensor Fusion

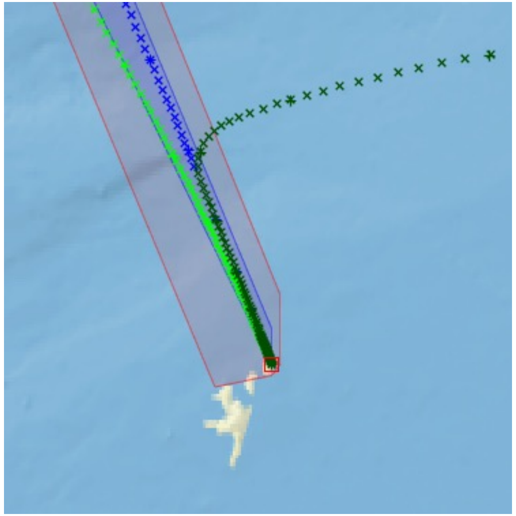
- Extended Kalman Filter
- Data Loss handling
- Sensor Cross Validation



Software Prototype:
Instantaneous Impact Point (IIP)

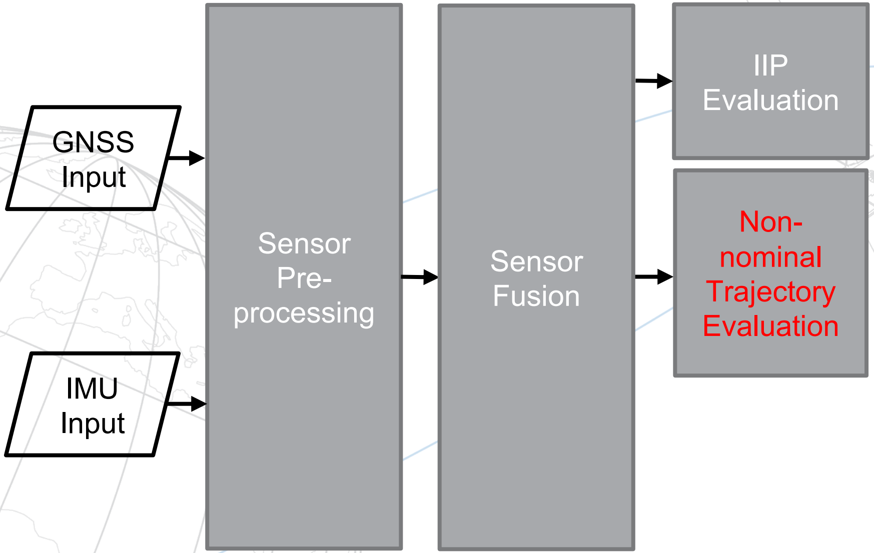
- Propagate trajectory to find impact point
- Keplerian algorithm
- Keep out zones defined by polygon areas

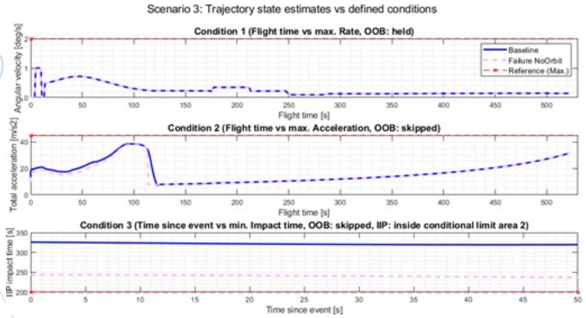




Software Prototype:
Non-nominal Trajectory

- Continuous state monitoring against limits
- Generic selection from all available observables (meas.* & derived**)
- E.g.: detect extreme acceleration or tumbling

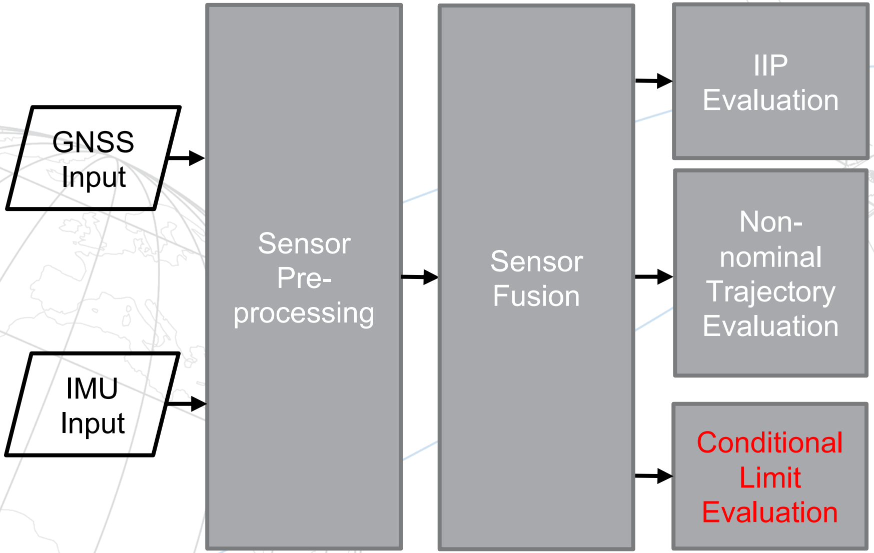


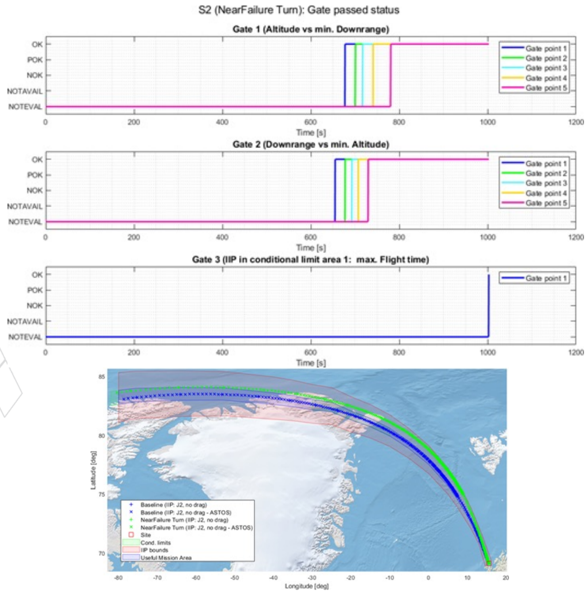


* position, velocity, acceleration, rate, flight time
** altitude, perigee height, downrange distance, IIP velocity, IIP impact time, event time

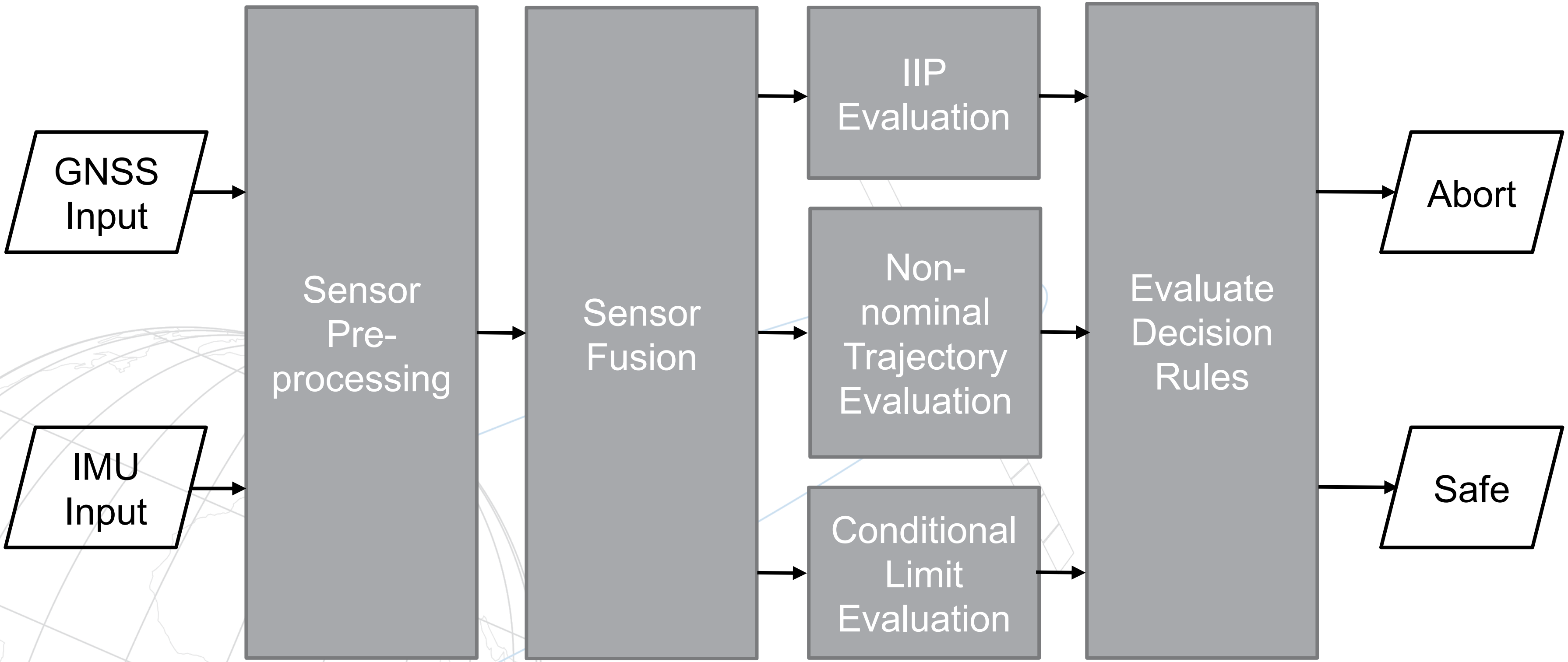
Software Prototype:
Conditional Limit

- Rules are evaluated after 'event' (predefined state condition)
- Generic selection from all available observables (meas. & derived)
- E.g.: detect if orbit is reached, populated area safely passed





Software Prototype



Data loss handling

Purpose

- Robust to short sensor outages → Reliability
- Self monitoring

Affects

- Fusion quality
- INS quality
- Sensor Fusion Algorithm
- Termination decision

Data loss handling

Sensor outages

- GNSS position
- GNSS velocity
- IMU angular rate
- IMU acceleration

Further influences

- Cross validation fails
- Launch pad vs flight phase

Outage limits

- GNSS
- Cumulated angular rate
- Acceleration

121 combinations

Adaptability

Goal: Adaptable to launcher, missions, launch sites and regulation

<u>Wrapper</u>

- Changes on functional level
- E.g. sensor interfaces

<u>Core</u>

- Parameters
- E.g. IIP boundaries

Qualification Approach

DO-178C: certification of aerospace software

- Test case for every line of code
- Test case for every possible state transition

→ Wrapper must be requalified after changes

→ Automatize qualification and document generation

Simulator

- ASTOS and Simulink
- 3 launcher scenarios
- 10 failure and near failure trajectories
- Prototype of onboard software

Simulator: Nominal Scenarios

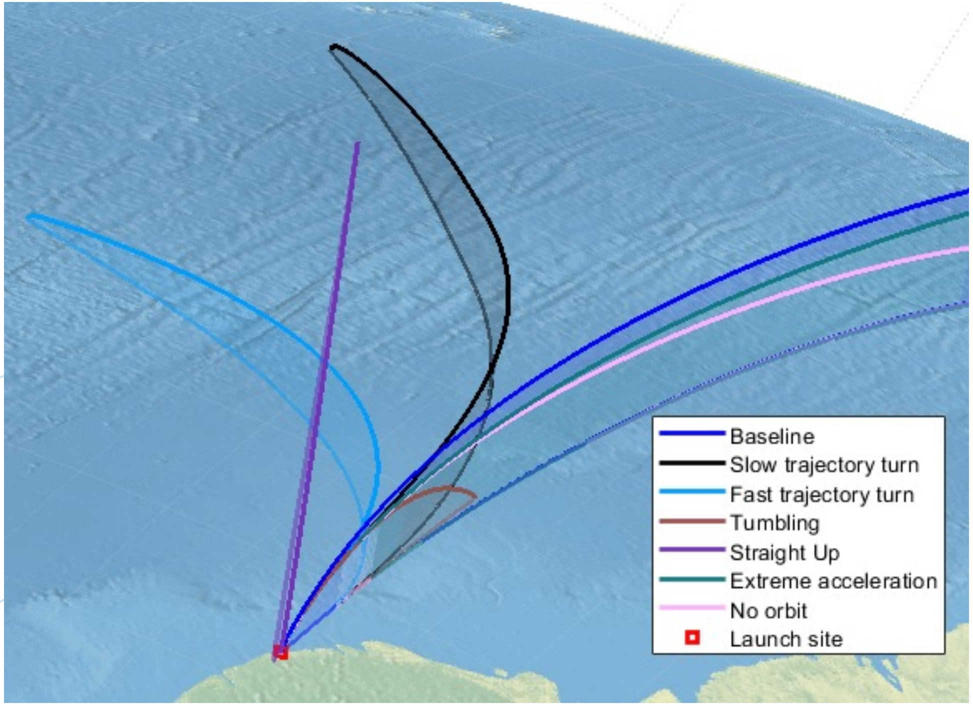
	Property	Scenario 1: Microlauncher A	Scenario 2: Microlauncher B	Scenario 3: Ariane 5
Trajectory	Launch site	SaxaVord Spaceport	Andoya Space Station	Guiana Space Centre
	Target orbit	500km SSO	300km SSO	200x35800 km GTO
Launcher	Number of Stages	3	2	2
	Length	27 m	27 m	50 m
	Diameter	2.2 m	2 m	5.4 m

Test Campaign

<u>Analyzed termination scenarios</u>

- Extreme accelerations
- Tumbling
- Outside of controlled area
- Not reaching orbit
- Straight up launch
- Data loss

(+ respective 'near-failure' cases)



Test Campaign

Robustness Sensor Fusion

- Monte Carlo: Uncertain parameters
- Monte Carlo: Outage handling
- High vibrations on IMU measurement
- High accelerations

Further requirements

- Cross validation
- Monte Carlo IIP: Accuracy
- Unit Tests

Test Results: Sensor Fusion

Requirements

- Position accuracy: Min 100 m (1 sigma)
- Velocity accuracy: Min 0.3 m/s (1 sigma) Outliers up to 8.66m/s
- Robus to sensor outages
- Robust to vibrations: White noise with spectral density 0.04 g^2/Hz
- Robust to high acceleration: 3 times highest expected acceleration

Test Results: Sensor Fusion

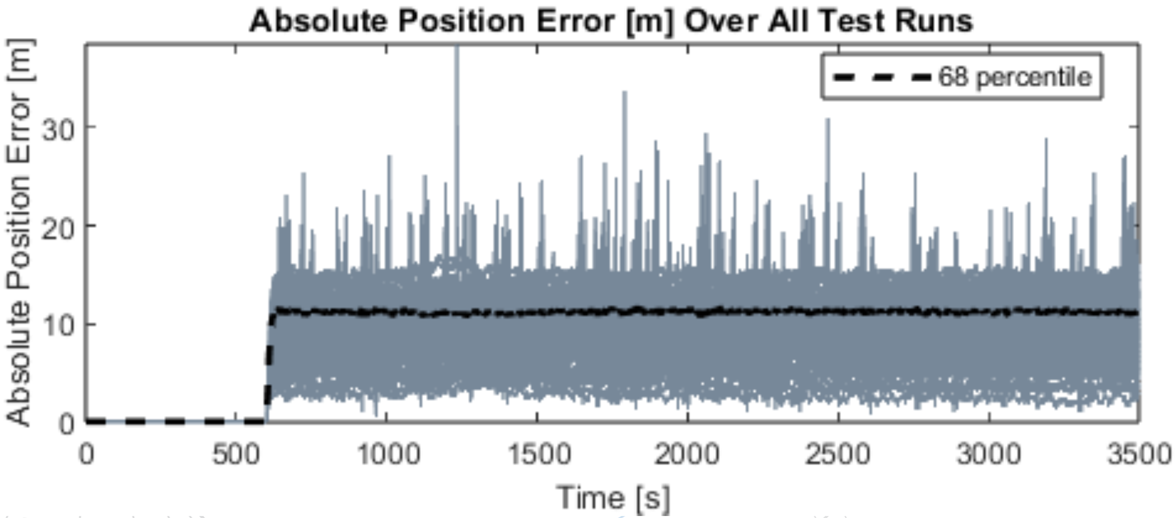
Monte Carlo Distributed Parameters

- Sensor noise and biases
- Initial estimate error
- Sensor position knowledge
- Earth model
- Gravity model

Sensor Outages

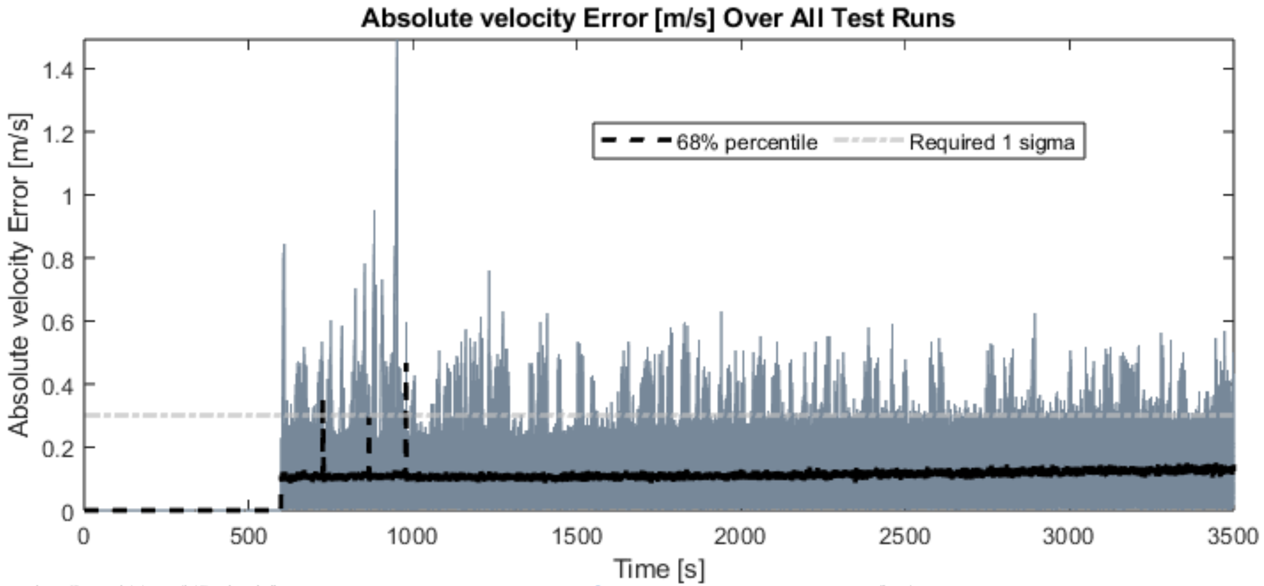
- GNSS of 10s
- Angular rate of 0.8s
- Acceleration of 10s

Test Results: Sensor Fusion



- Position accuracy: Min 100 m (1 sigma) ✓
- Robust to sensor outages ✓

Test Results: Sensor Fusion



- Velocity accuracy: Min 0.3 m/s (1 sigma) Outliers up to 8.66m/s ✓
- Robust to sensor outages ✓

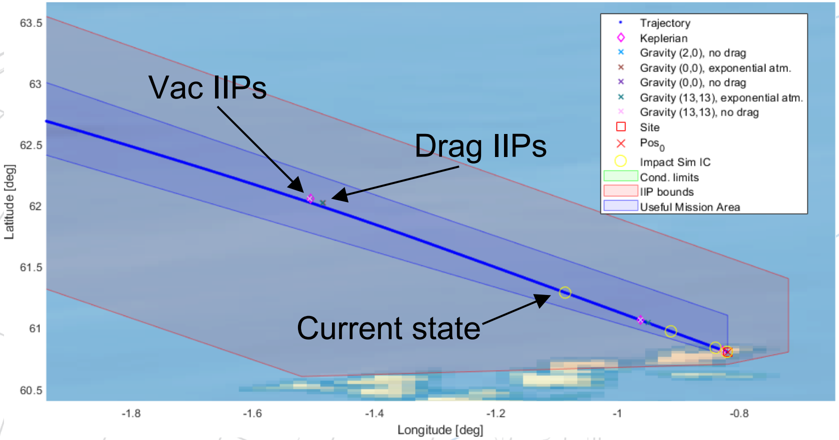
Test Results: IIP Accuracy

- Keplerian vacuum IIP vs IIP from 3-DoF simulation
- 3-DoF simulation for different gravity models with & w/o atmosphere

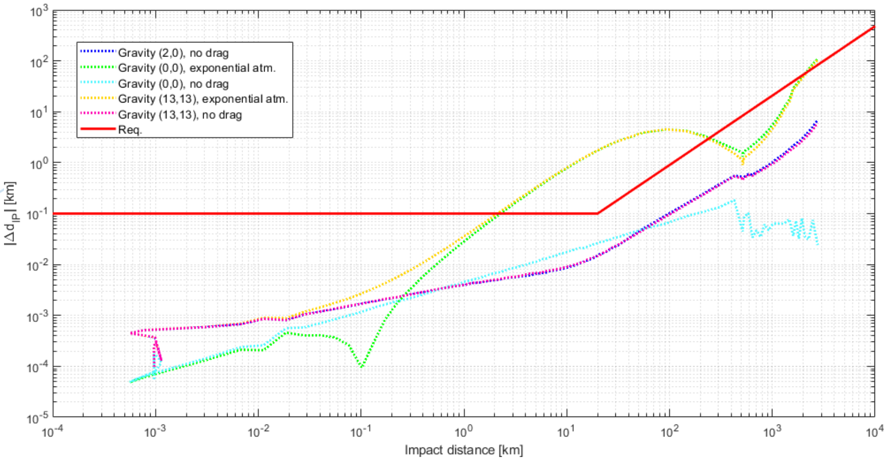
➡ Vacuum IIPs ‘ahead’ of drag IIPs, all vacuum IIPs close

➡ Estimation error safely within requirement (on Vac. IIP!)

S1 (Baseline): Latitude/Longitude map of IPs and estimated IIPs



S1 (Baseline): IIP estimation error over IIP distance from launch (Keplerian)



Test Results: Safe-Lock/Termination

- For all 3 launcher scenarios and all failure/near-failure cases

S1

Scenario Subtype	AFTS State (at end of sim.)	Trigger time (sim. time [s])	Indicator
Baseline	Safe-lock	949	-
NF: Turn	Safe-lock	948	-
NF: High Acceleration	Safe-lock	940	-
NF: Orbit	Safe-lock	951	-
NF: Low Thrust	Safe-lock	951	-
F: IIP Slow	Termination	677	IIP
F: IIP Fast	Termination	704	IIP
F: Tumbling	Termination	727	TRAJECTORY
F: Straight-up	Termination	645	GATE
F: Extreme Acc.	Termination	699	TRAJECTORY
F: No orbit	Termination	958	GATE
F: No lift-off	-	-	-

S2

Scenario Subtype ID	AFTS State (at end of sim.)	Trigger time (sim. time [s])	Indicator
Baseline	Safe-lock	1004	-
NF: Turn	Safe-lock	1003	-
NF: High Acceleration	Safe-lock	1003	-
NF: Orbit	Safe-lock	1010	-
NF: Low Thrust	Safe-lock	1010	-
F: IIP Slow	Termination	700	IIP
F: IIP Fast	Termination	668	IIP
F: Tumbling	Termination	756	TRAJECTORY
F: Straight-up	Termination	678	GATE
F: Extreme Acc.	Termination	675	TRAJECTORY
F: No orbit	Termination	1033	GATE
F: No lift-off	N/A	N/A	N/A

S3

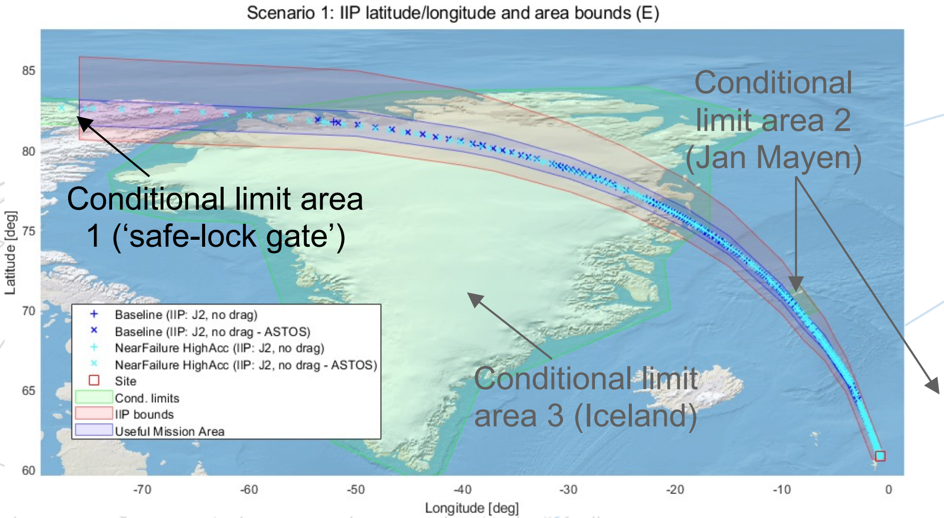
Scenario Subtype ID	AFTS State (at end of sim.)	Trigger time (sim. time [s])	Indicator
Baseline	Safe-lock	1062	-
NF: Turn	Safe-lock	1098	-
NF: High Acceleration	Safe-lock	1069	-
NF: Orbit	Safe-lock	1098	-
NF: Low Thrust	Safe-lock	1109	-
F: IIP Slow	Termination	847	IIP
F: IIP Fast	Termination	809	IIP
F: Tumbling	Termination	776	TRAJECTORY
F: Straight-up	Termination	636	GATE
F: Extreme Acc.	Termination	630	TRAJECTORY
F: No orbit	Termination	1121	GATE
F: No lift-off	N/A	N/A	N/A

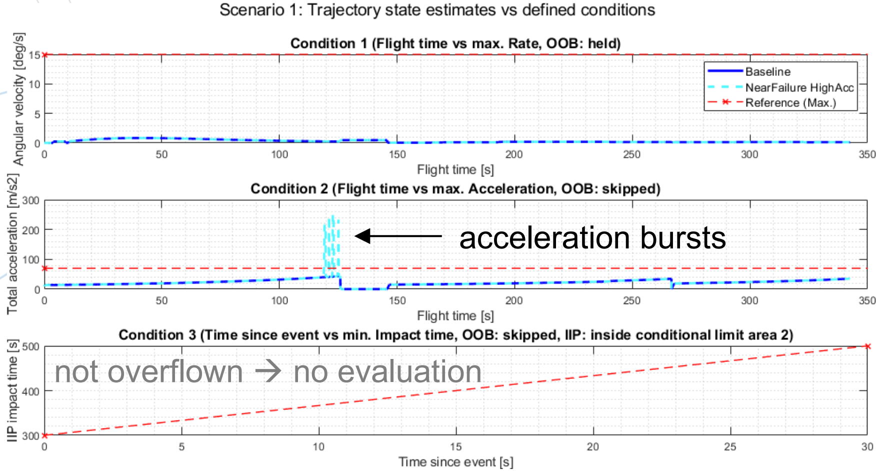
→ AFTS with expected behavior in all simulated cases

→ Termination cause indicated in telemetry

Test Results: Near-Failure Example

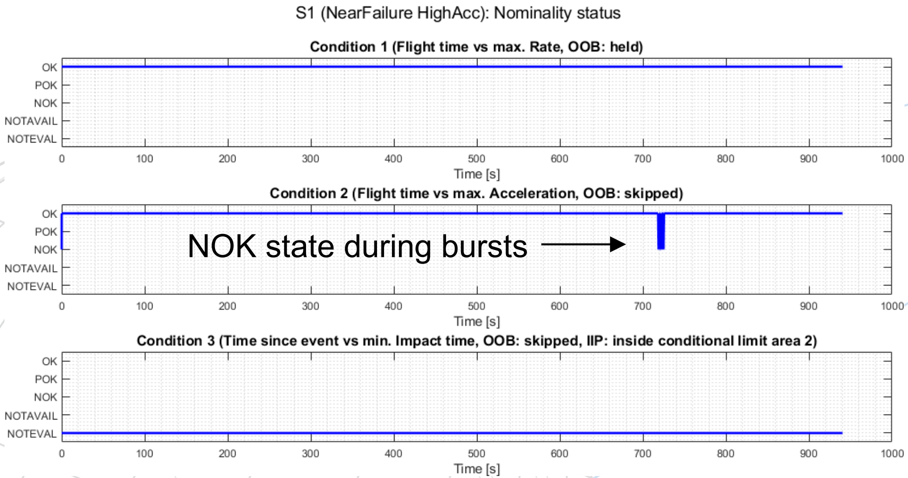
- Mainly nominal ascent trajectory for Scenario 1
- Sequence of short high-acceleration bursts before stage 1 burnout

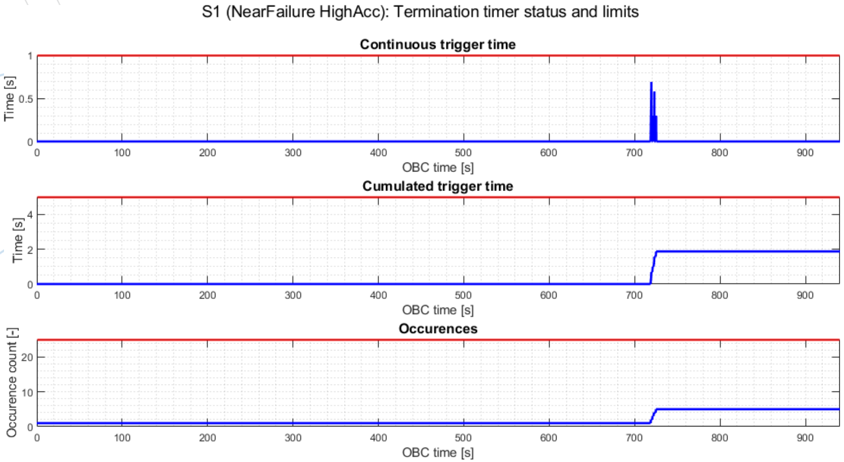




Test Results: Near-Failure Example

- Non-nominal trajectory conditions due to bursts correctly detected
- Increase of termination timers and occurrence counter during bursts (single-point failure avoidance)

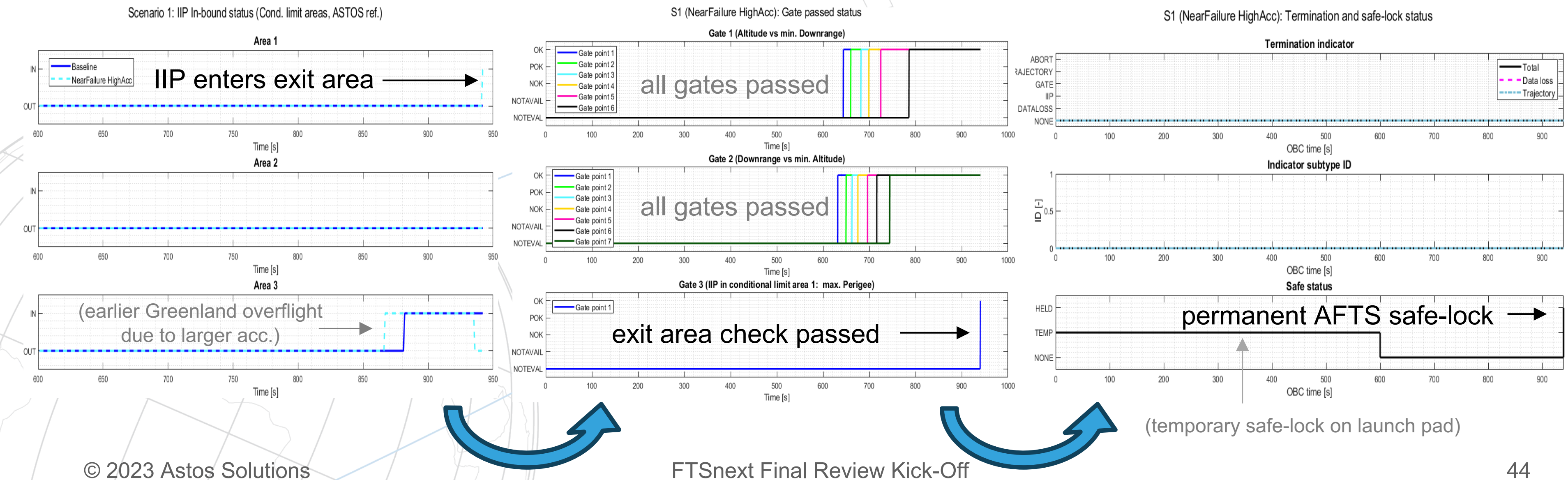




(lift-off after 600s → Time = Flight time + 600)

Test Results: Near-Failure Example

- All IIP and gate conditions remain fulfilled throughout ascent
- No termination indicated as timers/counter remain within threshold
- Safe-lock after IIP enters ‘exit gate’ 1 (and passing related check)



Feedback Conferences

Guiana Space Centre:

- Open for using FTSnext
- Recommend to include them in the development as early as possible

CNES

- New french space law is under development with more flexibility for AFTS

Avio

- Pushes for international regulations

Feedback Conferences

SpaceX

- Uses less complex termination rules
- Points out effort for missionization

Generally:

- AFTS was a popular topic at IAASS
- Be more flexible and need less infrastructure
- Workshop designated for this topic

Summary

- An adaptive AFTS design, potentially compatible with applicable regulations for many launch sites, countries and launch systems has been designed
- All identified requirements are covered by the AFTS design
- Prototype was implemented in Matlab/Simulink
- Test camping shows that the software behaves as expected

OUTLOOK

Outlook

- FMECA, Safety and Security Analysis
- Hardware development
  - Breadboarding
  - Hardware in the Loop tests
- Detailed definition of (re-) qualification process in collaboration with launching state authorities and launch sites
- Independent validation
- Outline proposal for next phase already sent to ESA
- Potential partners for next phase identified and contacted