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Space Rider Parafoil: Validation and Verification Process

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Introduction
Space Rider Mission

- The ESA SPACE RIDER (SR) is a user-oriented program building as a follow-up to the IXV mission. It is an unmanned space transportation system integrated with VEGA C launcher, to enable routine access and return from space in a cost-effective, autonomous, and reusable way.

- The SR Re-entry Module (RM) is being developed by Thales Alenia Space Italy (TASI) for ESA.

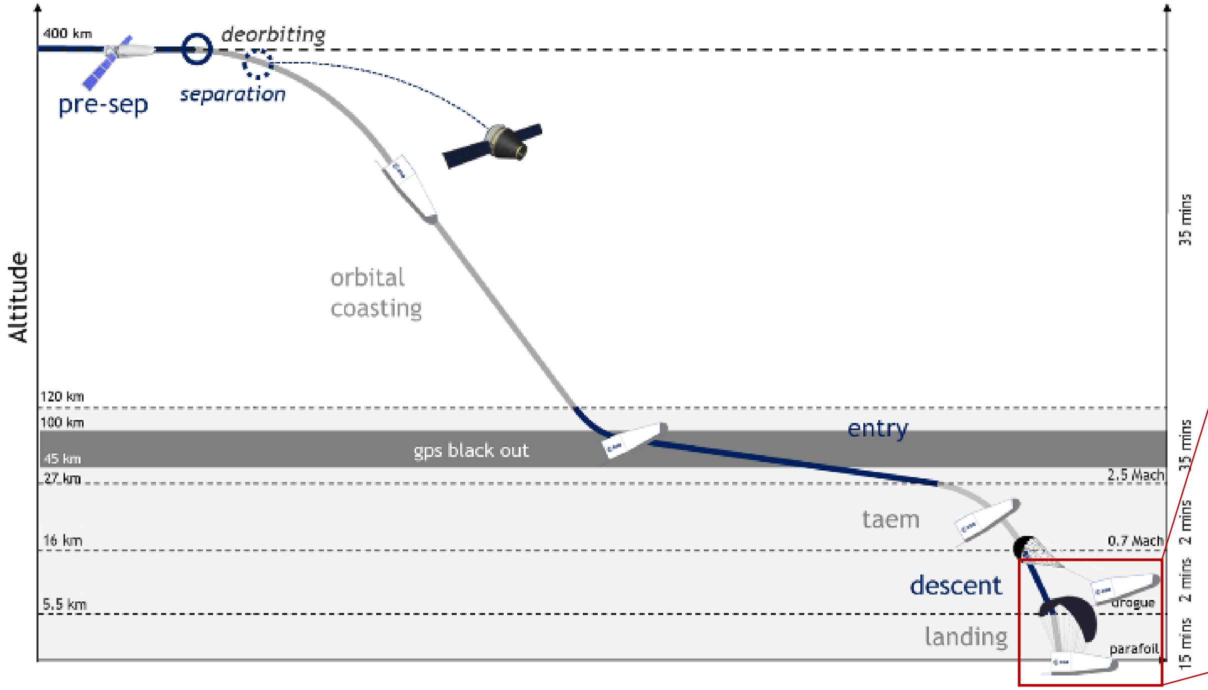
- Sener Aeroespacial is part of a consortium of companies (Sener + TASI + Deimos) working on the design of the GNC subsystem of the RM.

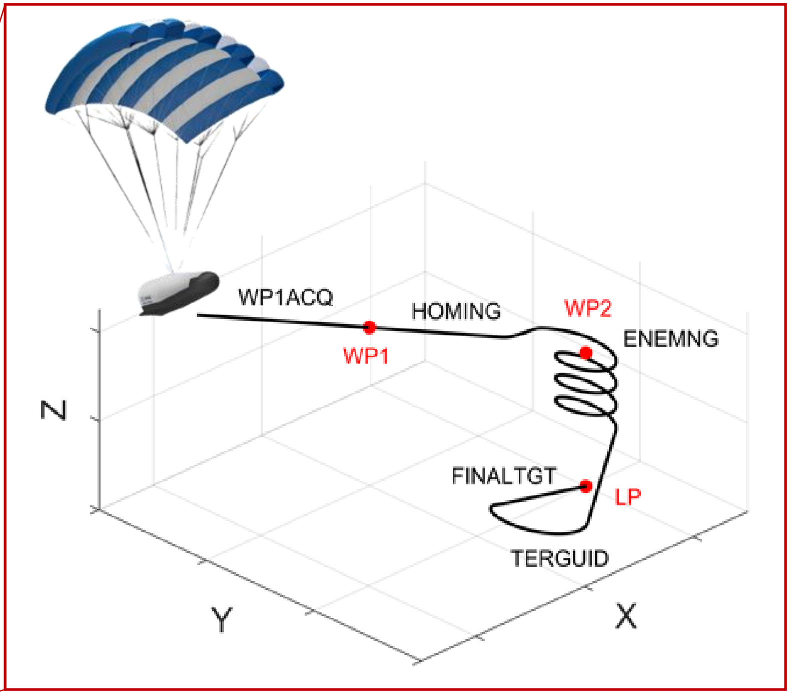
- Sener is the design authority of the RM GNC algorithms and the developer of the new Parafoil GNC (PGNC).

Introduction

Space Rider Re-Entry Module - Mission

- The Re-entry Module consists of a lifting body that performs a controlled hypersonic re-entry, transonic flight, and a final precision approach and landing under parafoil.
- The SR RM uses a guided parafoil during descent and landing phases.
- Waypoint based guidance with terminal guidance phase to land upwind.





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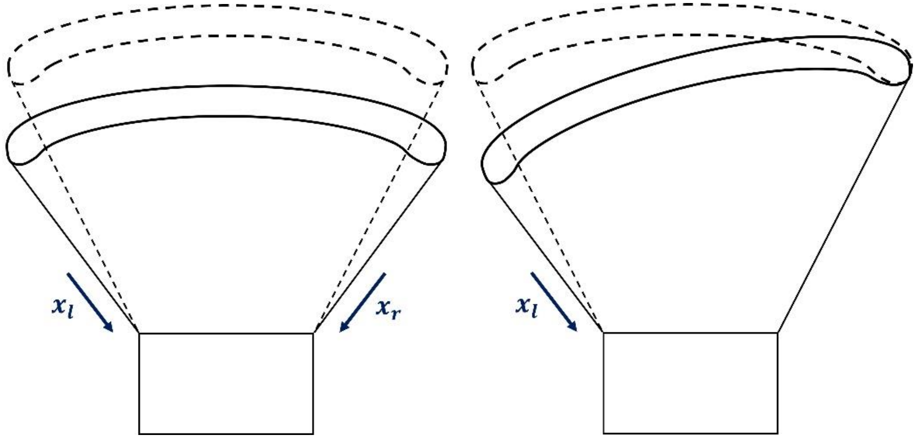
Introduction
Space Rider Re-Entry Module - Sensors and Actuators

Sensors
- x2 SIGI (hot redundancy)
  - GNSS+IMU
  - 2xGNSS antennas
  - Integrated Kalman Filter
- x2 Radar Altimeter (hot redundancy)
- AOM Star Trackers (used to initialize the RM SIGIs)

Actuators
- x2 Flaps
  - IXV heritage + improvements
- RCS
  - 4x400 N blowdown (IXV heritage)
  - Lower tank pressure: 166 N (BoL), 104 N (EoL)
- x2 Winches: Parafoil control lines



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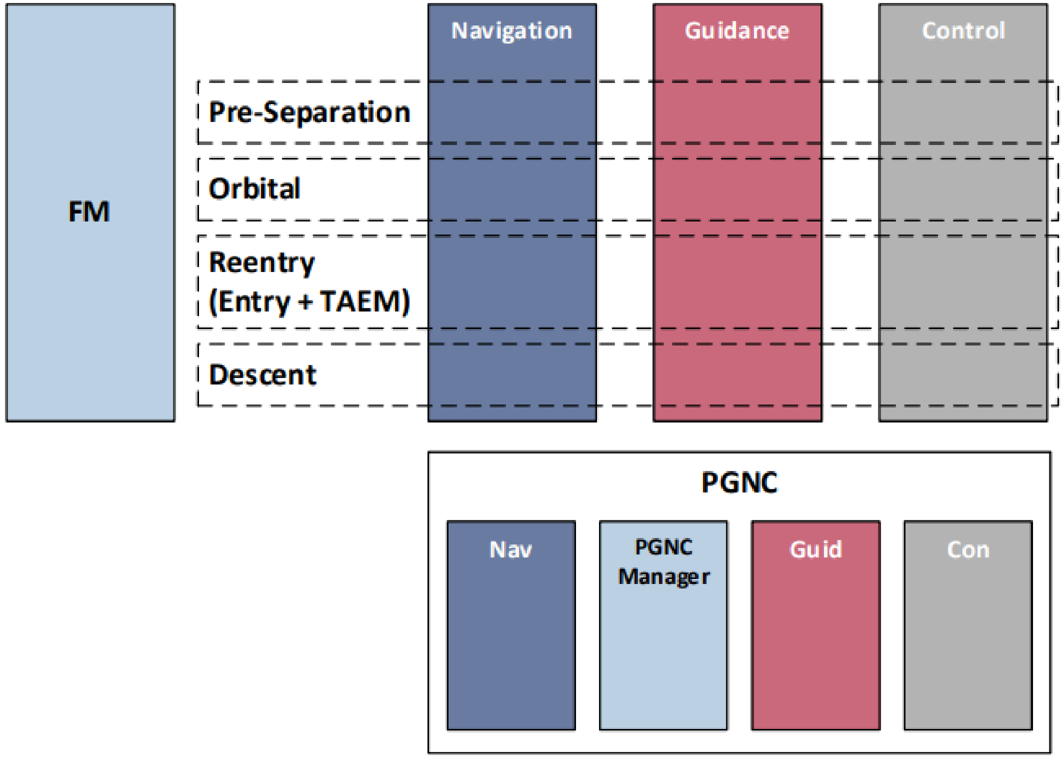
GNC Description
Overview

GNC Overview

- Maximization of IXV Heritage.
    - TAEM and PGNC completely new!
- Modular approach with reusability of low-level functions.
- High level manager for each functionality calling low level algorithms.
- Combination of external and internal mode and submode changes based on system/GNC reconfiguration.
- Independent Parafoil GNC (PGNC) module for easy extraction (flight test validation).



GNC Description
Guidance

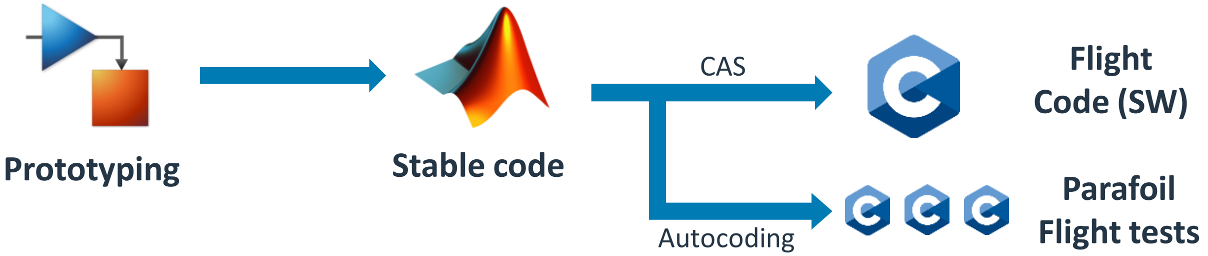
	Mission Phase		Guidance Strategy	Flight Regime	Sensor / Actuator
IXV Heritage	Coasting		NADIR pointing followed by 45deg pitch up manoeuvre	Hypersonic	Nav Unit // RCS
IXV Heritage	Reentry	REE	Reference trajectory tracking OL/CL (Drag/AoA-Mach)	Supersonic	Nav Unit // RCS + Flaps
NEW	Reentry	TAEM	Reference trajectory tracking CL (PosVel/ AoA-Mach)	Transonic	Nav Unit // RCS + Flaps
NEW	Descent		Drogue and parafoil deployment	Drogue and Parafoil Inflation	Nav Unit
NEW	PGNC		Waypoint based guidance with quasi-optimal approach to LP	Flight under Parafoil	Nav Unit + RADALT // Winches

GNC Algorithm Design
Implementation

- The design of SR GNC algorithms is carried out in Matlab/Simulink environment.
  - Reusability of IXV heritage in Matlab.
  - Preliminary design (up to PDR) carried out in Simulink due to flexibility and interactive debugging options.
  - Stable implementation written in Matlab due to change tracking and autocoding control.

GNC Implementation	Matlab function	Simulink model
Version Control	Full change traceability with GIT/SVN	Partial change traceability using Matlab tools
Implementation and debugging	High effort	Low effort
Autocoding	Direct traceability	Complex traceability

- Control Algorithm Specification (CAS) is released to the Software Team.
  - Final SR GNC flight code is manually written in C.
  - Unit testing to identify programming errors.



- De-risking flight tests use an autocoded C release.

GNC Algorithm Design
Code Instrumentation

- Matlab functions prepared to interact with tools for:
  - Automatic generation of **Control Algorithm Specification (CAS).**
  - Automatic generation of GNC **System Data Summary (SDS).**
  - **Housekeeping** and **Reference Test Data** generation (HK/RTD).

- <u>Matlab function structure</u>
  - Input/output/state definition (CAS, SDS).
  - Function key fields for version control (Traceability).
  - Declaration of persistent values and parameter processing.
  - Main algorithm.
  - Housekeeping generation using global variables/data store memory (CAS & RTD).

```
function [o_vVectorOut1,o_sScalarOut1] = ...
sr_rm_gnc_matfun_template(i_vVectorVariable,i_sScalarVariable,p_gncdb)
% FUNCTION_NAME short description
%
% Long description of what this function does.
%
% DEFINITION_START
%---------------------------------------------------------------------------
% i_vVectorInput:      'type',[sizeL,sizeR],<description>
% i_sScalarInput:      'type',[sizeL,sizeR],<description>
% s_vVectorState:      'type',[sizeL,sizeR],<description>
% s_sScalarState:      'type',[sizeL,sizeR],<description>
% o_vVectorOutput:     'type',[sizeL,sizeR],<description>
% o_sScalarOutput:     'type',[sizeL,sizeR],<description>
%---------------------------------------------------------------------------
% DEFINITION_END
%
% p_gncdb: gnc parameters database structure.
%
% @author  Name Surname
% @project Space Rider RM GNC
% @company SENER Aeroespacial
% @ver     $Id$
%---------------------------------------------------------------------------

% DECLARATION_START
%---------------------------------------------------------------------------

persistent s_sPersistent1
persistent s_vPersistent2

% This section is used to extract the parameters from the p_gncdb structure.
% Parameters in the CAS are defined directly as separated variables, not as
% fields of a structure, which is in turn required by the MATLAB execution.
p_vVarParam1 = p_gncdb.p_vVarParam1;
p_sVarParam2 = p_gncdb.p_sVarParam2;

% Initialize the persistent variables
if isempty(s_sPersistent1)
    s_sPersistent1 = 0;
end
%---------------------------------------------------------------------------
% DECLARATION_END

% ALGORITHM_START
%---------------------------------------------------------------------------
%%%% Write the function body here
%---------------------------------------------------------------------------
% ALGORITHM_END

% HOUSEKEEPING_START
%---------------------------------------------------------------------------
global hk
hk.sVar1 = var1;
hk.vVar2 = var2;
%---------------------------------------------------------------------------
% HOUSEKEEPING_END
```

RM GNC V&V Process
Verification Roadmap

Algorithm verification executed against GNC Technical Specification

Challenges:

- Different flight regimes
- Large modelling uncertainties for flight under parafoil
- Novel Parafoil GNC

Solution:

- Stepped verification
- Flight test for flight under parafoil

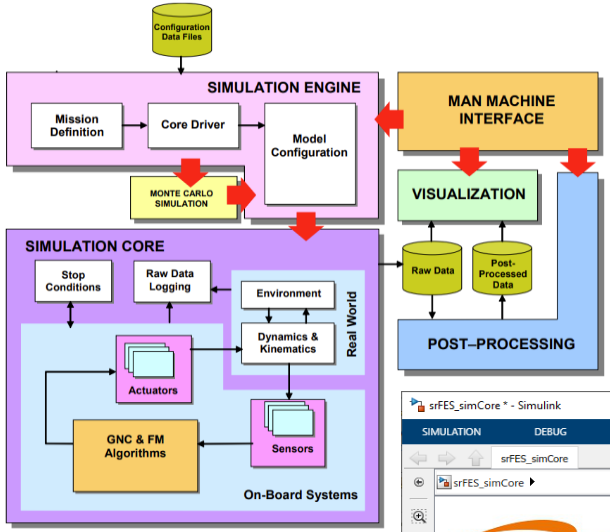
Element Under Test	Test Facility	Test Campaign	Scope/Objective
GNC SEP To DES	FES Re-entry Validated	MIL SEP To DES	Verification GNC Reentry
GNC PGNC	FES Parafoil No Validated	Prelim. MIL PGNC	Preliminary Verification PGNC
AUTOCODING	FES Parafoil No Validated	PIL PGNC	Validation Autocoding
AUTOCODING		Flight Tests	FES Models Validation PGNC Validation
GNC E2E	FES E2E Validated	MIL E2E	Verification GNC E2E
GNC FDIR	FES E2E Validated	MIL FDIR	Verification GNC FDIR

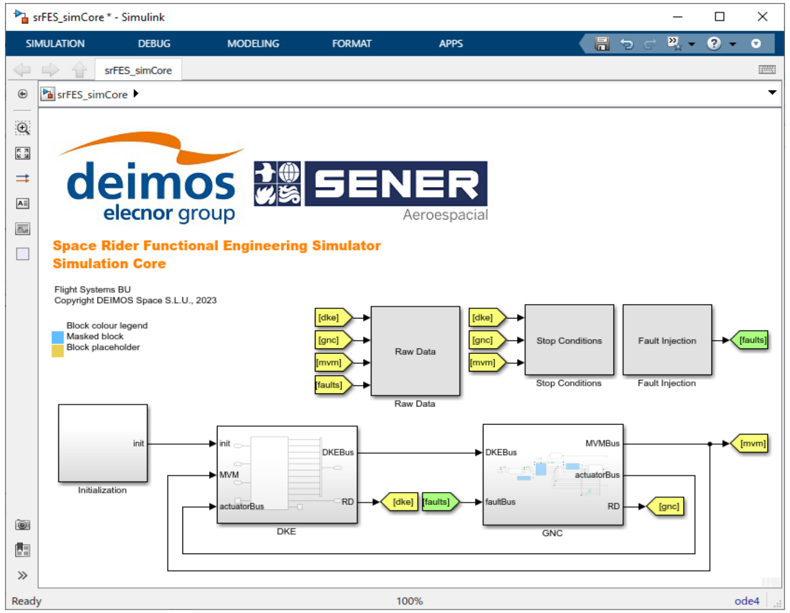
RM GNC V&V Process

FES Highlights

FES Features

- IXV GNC Functional Engineering Simulator heritage
- MATLAB/Simulink environment
- Based on Deimos's SIMPLAT reusable infrastructure
- From AOM-RM separation to touchdown
- RM 6DOF dynamics
- Parafoil dynamics
- Single run and Monte Carlo simulations
- Failure injection
- Environment models: atmosphere, winds
- GNC equipment models: SIGI, RCS, ACS, radar altimeter, winches
- SR Flight Code
- XML database
- Source for
  - Data Summary Tool
  - CAS RTD Tool





RM GNC V&V Process

FES V&V Campaign

Input: FES Technical Specification (derived from CFI)

Test Configuration: FES Software Verification and Validation Plan

Flight Tests

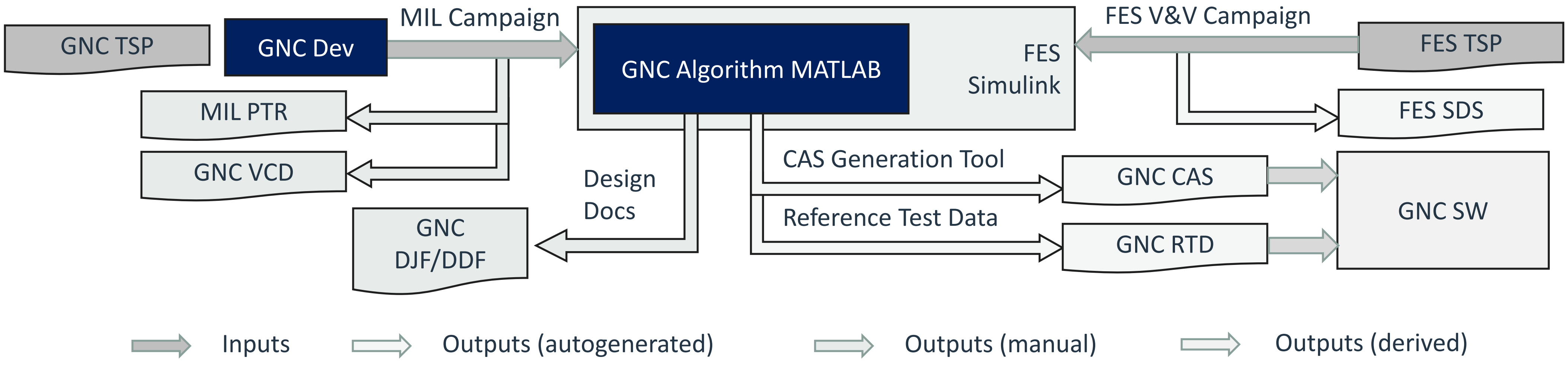
- FES V&V Levels
  - **Model Test:** covers the validation of the SR models:
    - Sensor & Actuators (model vs spec)
    - Dynamics (model vs data) ← Flight Tests
  - **Unit Test:** unit testing of the project-specific toolboxes (tool/libraries).
  - **Functional Test:** functional validation of the simulator with respect to the SR reference trajectory (simulator config).
  - **Integration Test:** aims to validate the correct integration of GNC-relevant SR models into the FES (isolated vs integrated).
  - **System Test:** system tests for the validation of the TS.

Output: FES Verification and Validation Report

RM GNC V&V Process

GNC Algorithm Verification - MIL campaigns

The objective of the MIL campaigns is to verify the behaviour and performance of the GNC algorithms in a simulated environment.



RM GNC V&V Process
GNC Algorithm Verification – MIL campaigns

Input: GNC Technical Specification

Test Configuration: MIL Test Specification

- Item under test & FES config defined in CAS and SDS
- GNC Verification Methods
  - Analysis – Evaluation of simulated results
  - Inspection – Item identification on algorithms
  - Review of Design – Code and DDF/DJF review
  - Test not considered (algorithms do not have a reference to compare against)

- **Output:** Verification Control Document +
  MIL Test Report

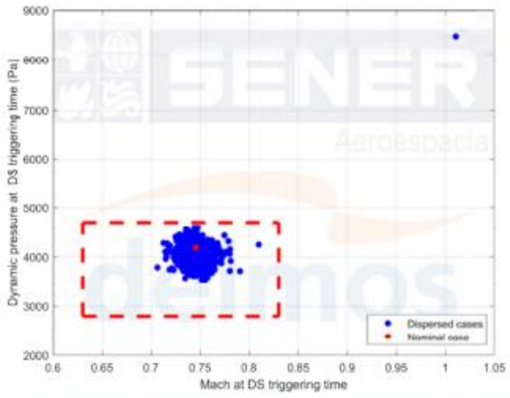
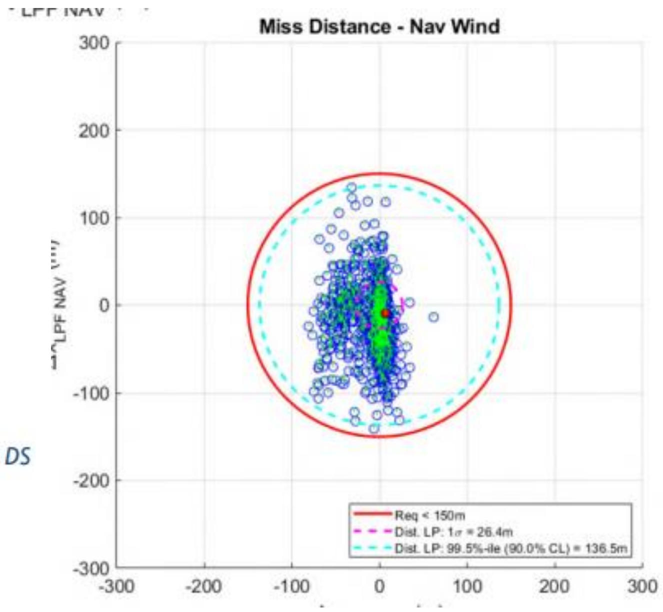


Figure 7-22 Dynamic pressure vs Mach dispersion at target DS event (Mach est 0.73)



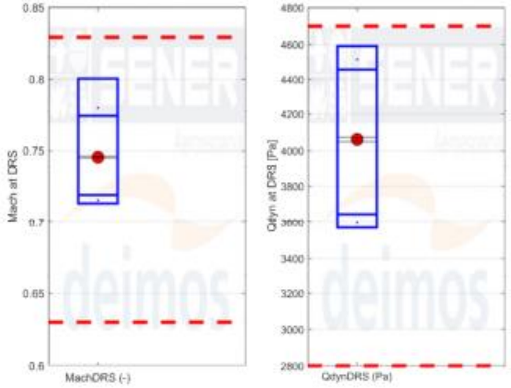


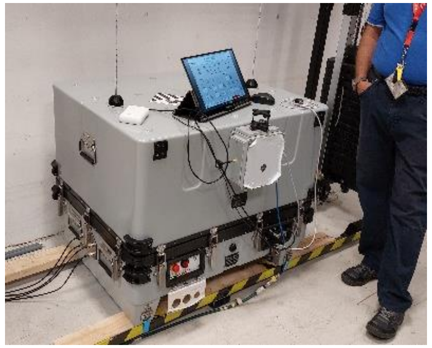
Figure 7-24 Mach and Dynamic pressure at Drogue triggering statistics

PGNC V&V - Flight Campaigns

Motivation

- GNC algorithms for the parafoil phase are brand new and not covered by IXV heritage.
- A dedicated drop test campaign has been set up for validation purposes, with an incremental approach

Scaled Down Flight Tests



Open Loop Drop Tests

Closed Loop Drop Tests

System Drop Tests

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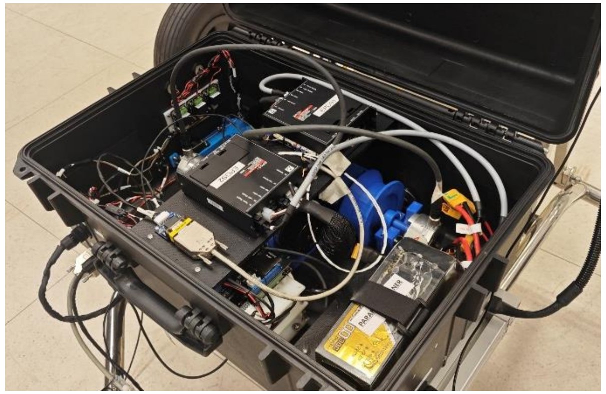
PGNC V&V - Scaled Down Flight Tests (SDFT)

Description & Objectives

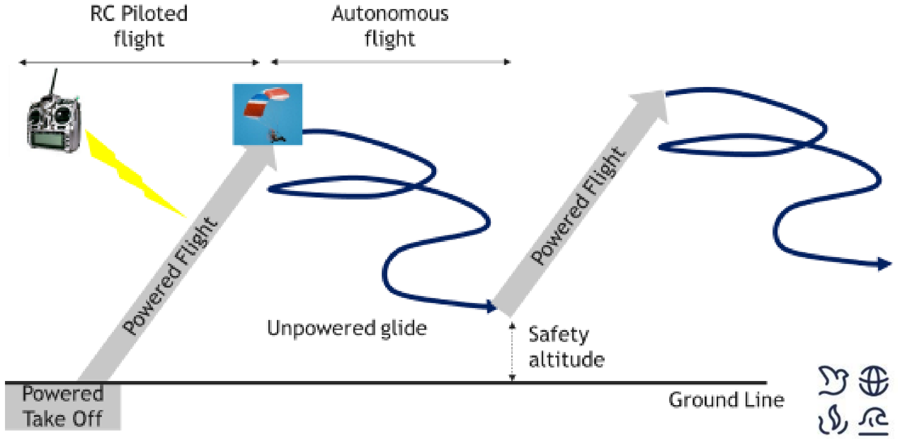
Configuration

- COTS paramotor ~150 kg
- IMU+GNSS unit, Radar altimeter, Custom Air Data System
- Remote and Autonomous control
- Possibility of open loop and closed loop maneuvers
- Isolation of safety critical elements
- Flight Termination System



Main Objectives

- Possibility to perform more tests than open loop and closed loop drop tests
- Test PGNC algorithms
- Test tools for the estimation of the parafoil AEDB parameters from flight data



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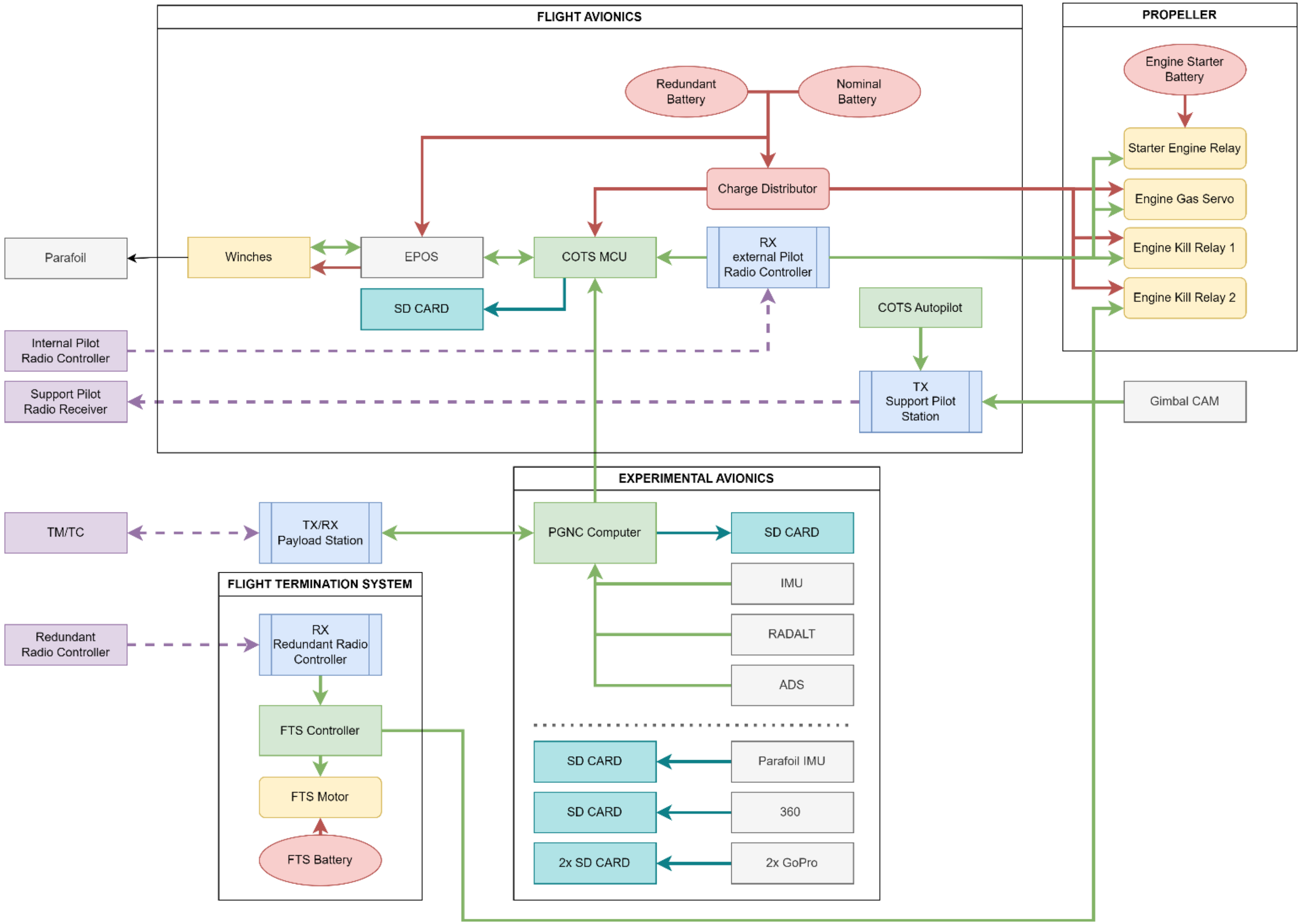
PGNC V&V - Scaled Down Flight Tests (SDFT)

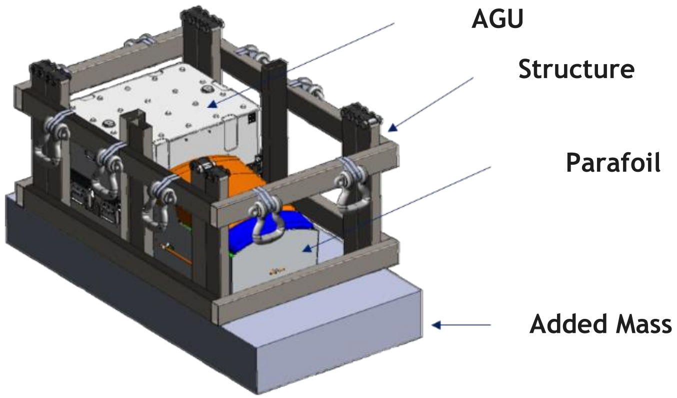
Air System Arquitecture



PGNC V&V - Open and Closed Loop Drop Tests
Description & Objectives

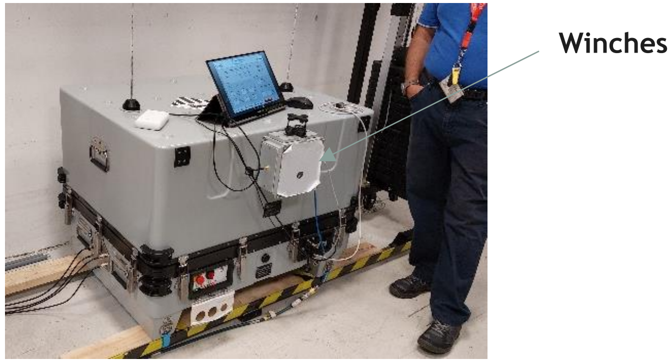
Configuration

- 5 drop tests from 2.4 km altitude (parafoil chain test)
- 5 open loop and 3 closed loop drop tests from 1.8 km altitude
- Crate with equivalent mass (3 tons), Size: 2000x1300x1000 mm
- AGU control unit and ground segment



Main Objectives

- Open Loop
  - Check parafoil and AGU behavior
  - Gather flight data for the validation of the parafoil model (response times, quantify relative oscillations)
- Closed Loop
  - Test behavior of the PGNC algorithms



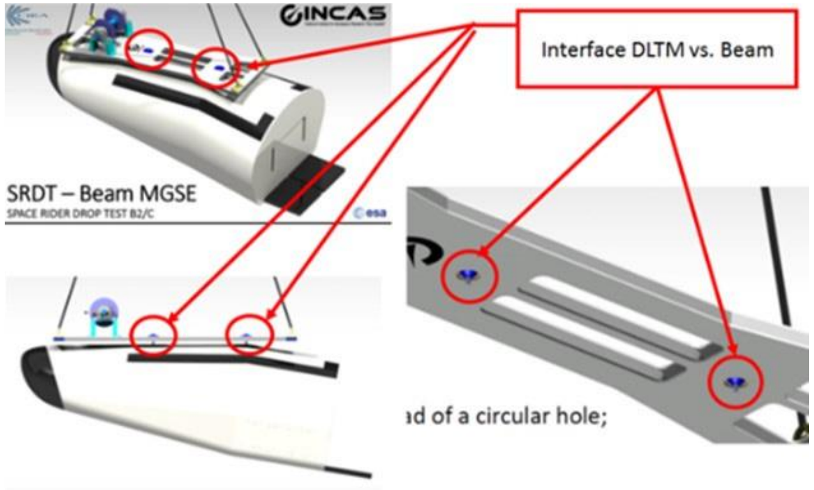
PGNC V&V - System Drop Tests
Description & Objectives

Configuration

- 2 drop tests from 3 km altitude
- Fully representative mockup (shape, mass, inertia, bridles layout)
- Separation system (BEAM) connected to a heavy helicopter
- Detachment commanded by the helicopter crew

Main objectives

- Test the complete extraction and inflation of the parafoil.
- Test the acquisition and transmission system of the wind profiles with weather-drones
- Test bridle cutting system
- Test the on-ground operations for spacecraft retrieval
- Validate PGNC algorithms



PGNC V&V - System Drop Tests

Original Sequence

SDFT Characterization flights
SDFT AEDB identification
Reproduce OL flight data in simulator
Validate SDFT simulator

Sensor, manoeuvres, procedures
Tools

OLDT
SR AEDB identification
Reproduce OL flight data in simulator
Validate SR simulator

Tune PGNC for SDFT

Tune PGNC for CLDT

SDFT Performance flights
Reproduce CL flight data in simulator
Validate SDFT PGNC

Preliminary tuning, procedures
Risk identification

CLDT
Reproduce CL flight data in simulator
Validate CLDT PGNC

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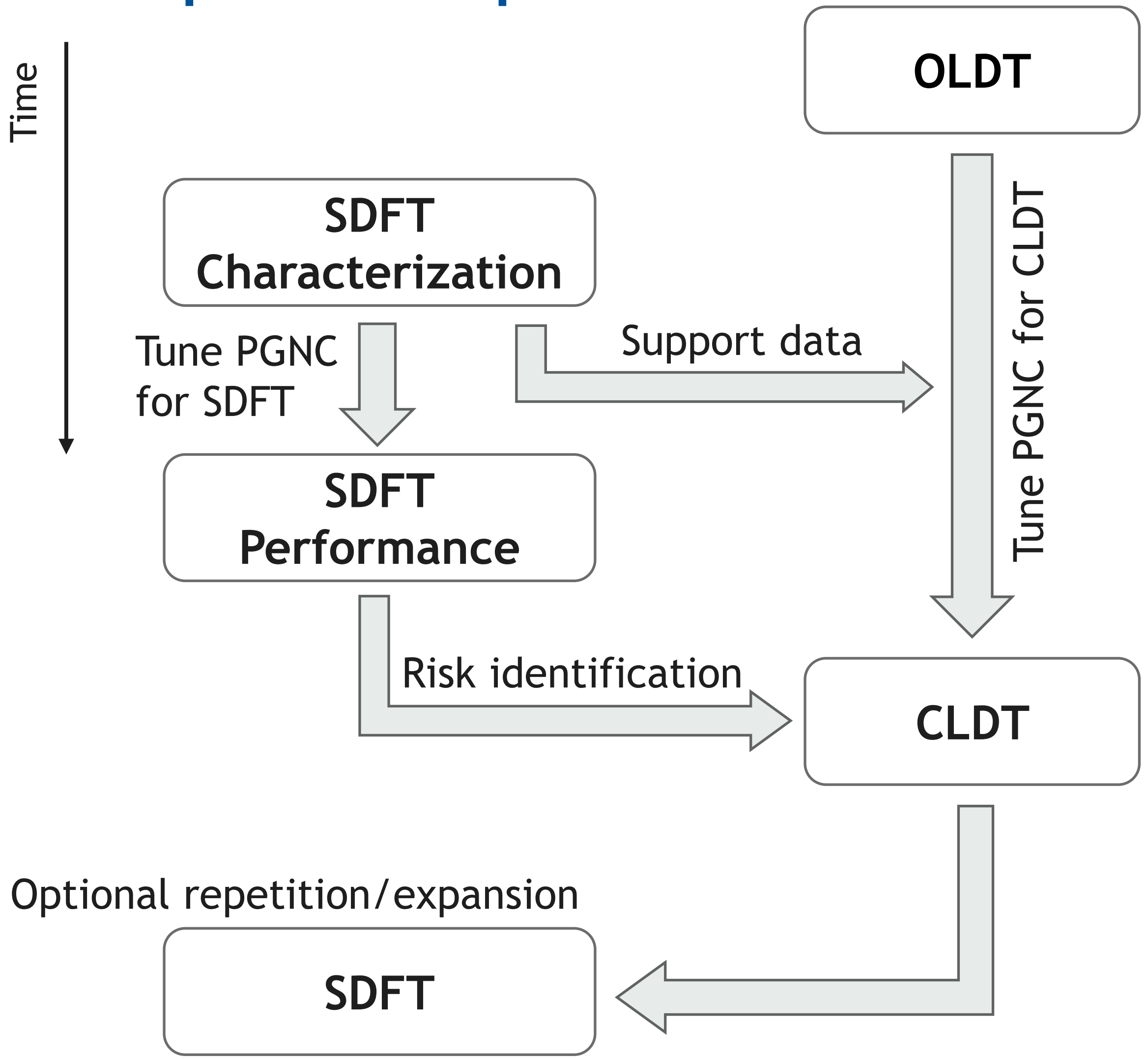
PGNC V&V - System Drop Tests

Updated Sequence



Current schedule pushes SDFT characterization after OLDT.

SDFT offers more flexibility for stepped PGNC testing, quick retuning and to test off-nominal/stress conditions.

SDFT objectives related to CLDT (de-risking)

- Evaluate leg-by-leg performance of PGNC
- Identify unmodelled effects affecting PGNC (relative motion, high frequency winds, …)

SDFT objectives related to MIL (system)

- Assess light rain impact on aerodynamics
- Obtain sufficient flight data to estimate uncertainty of AEDB estimation tool
- Support to OLDT open points

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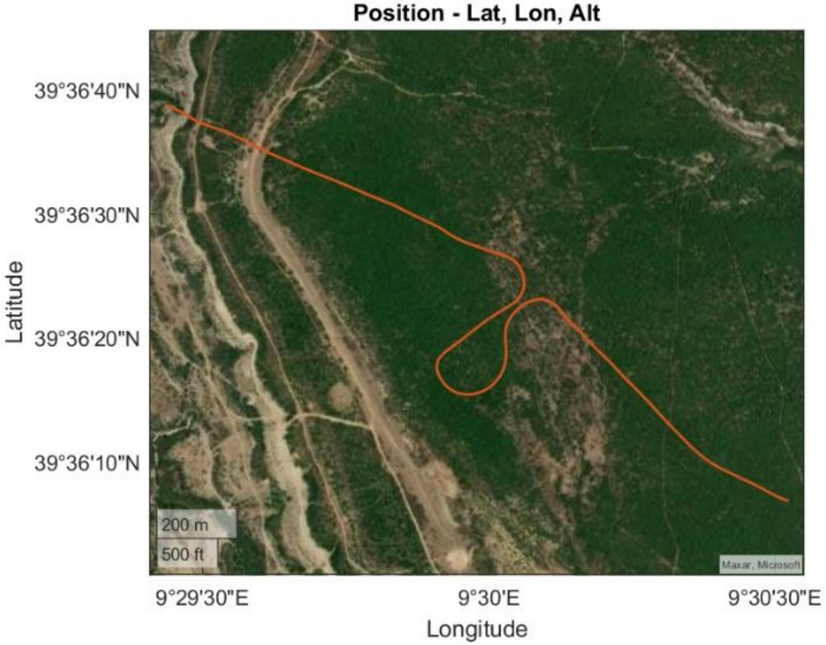
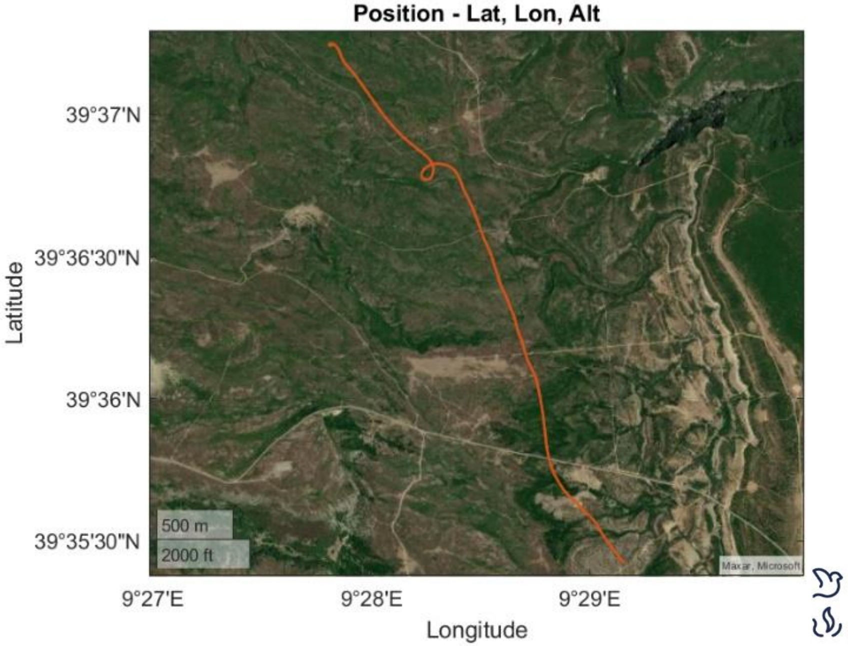
PGNC V&V - Flight Campaigns
Post Flight Data Analysis - OLDT

- **Input:** raw data from sensors and actuators.

<u>Post Flight Analysis Tool</u>

- **Output:**
  - Position, velocity, acceleration
  - Euler angles, angular velocity, angular acceleration
  - Airspeed, AoA, AoS
  - Wind speed, air density
  - Winches position





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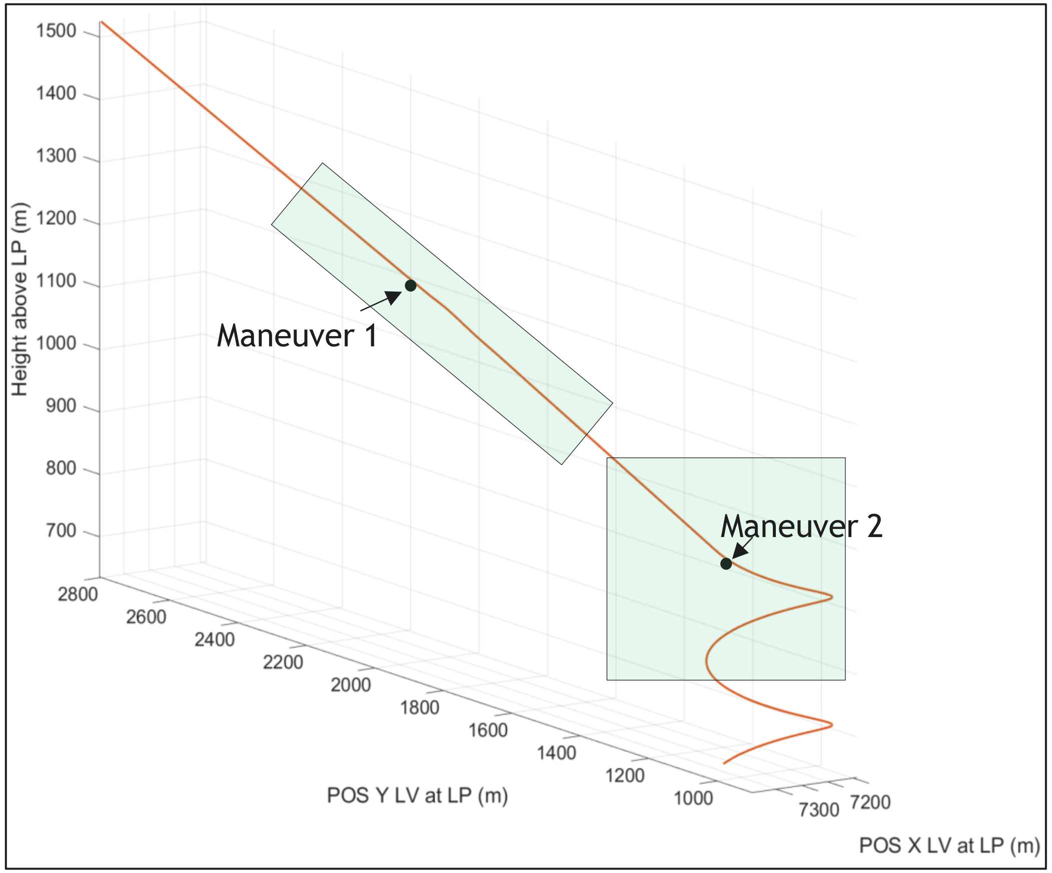
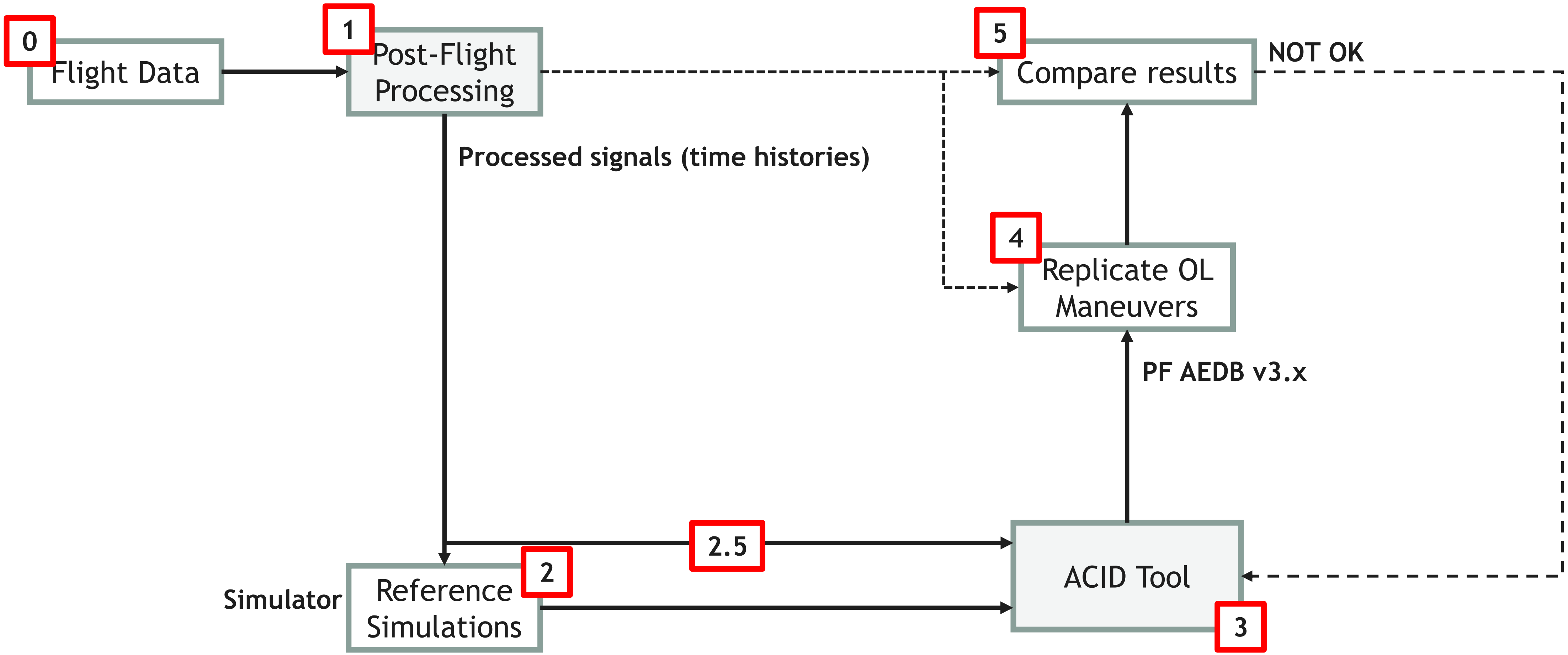
PGNC V&V - Flight Campaigns
AEDB Identification

SENER's ACID Tool

- Sener has developed a tool to estimate the parafoil aerodynamic coefficients from experimental flight data.
- Select different maneuvers as input to the tool.
    - Symmetric maneuvers
    - Asymmetric maneuvers
- The tool is based on Kalman filter for estimating a constant parameter.

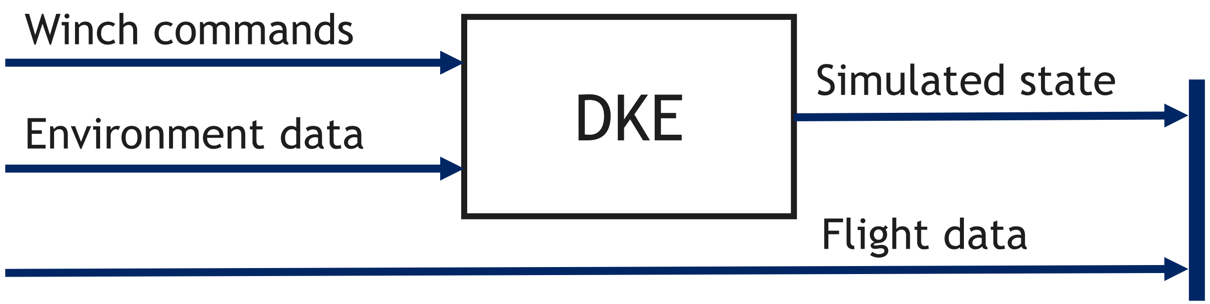


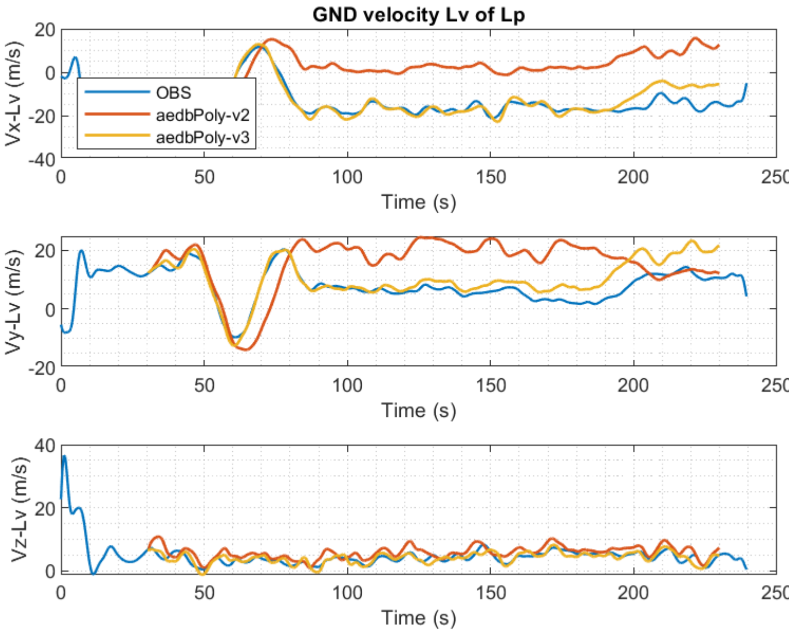
PGNC V&V - Flight Campaigns
AEDB Identification

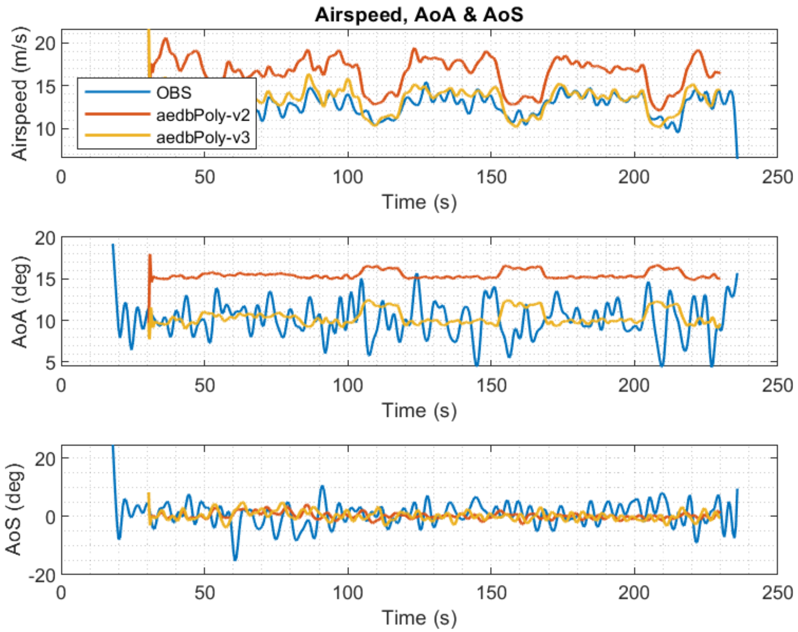


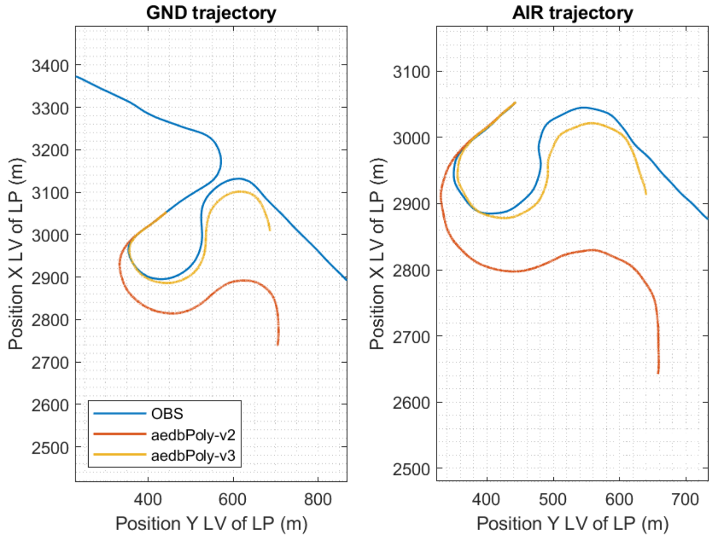
PGNC V&V - Flight Campaigns

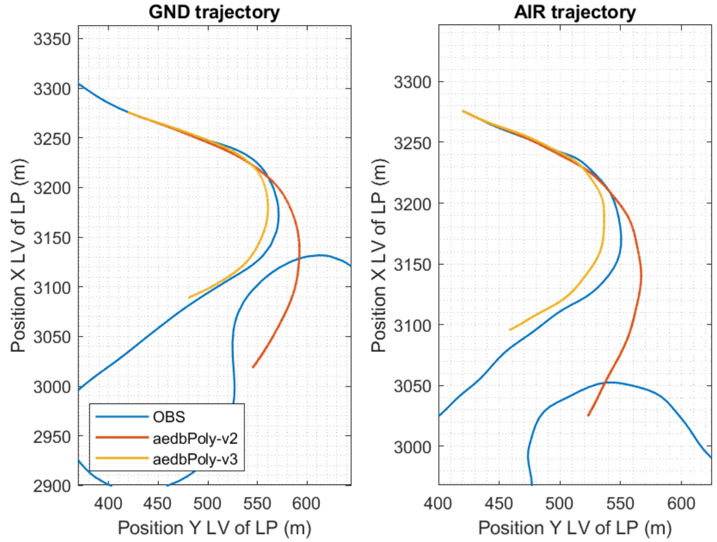
AEDB Identification











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RM GNC V&V Process
Roadmap - Next steps

- MIL campaigns:
  - MIL2: End-To-End
  - MIL3: FDIR

- Flight campaigns:
  - SDFT
  - CLDT
  - SysDT: PGNC validation

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AUTOCODING	FES Parafoil No Validated	PIL PGNC	Validation Autocoding
		Flight Tests	FES Models Validation PGNC Validation
GNC E2E	FES E2E Validated	MIL E2E	Verification GNC E2E
GNC FDIR	FES E2E Validated	MIL FDIR	Verification GNC FDIR

THANK YOU

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