End-to-end GN&C for the Powered Descent and Safe, Precise Lunar Landing

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Agenda

-Background and Motivation

-Mission Analysis

-Navigation

-Guidance and Control

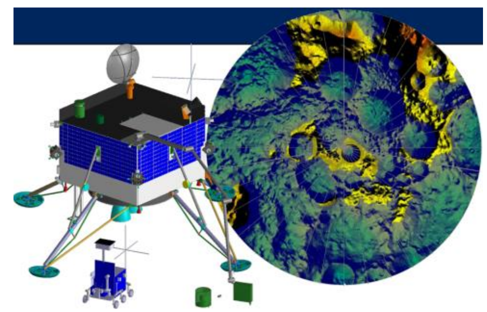
-Monte Carlo Simulations

-Conclusions

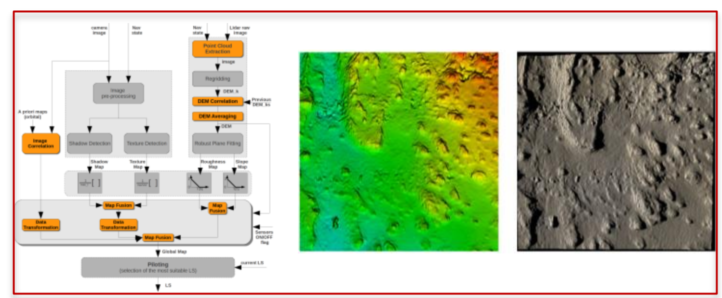
Background: Who we are

- **Spin.Works S.A.**
  - Aerospace and Defence Company based in Lisbon, Portugal
  - Founded in 2006

Some Background Work

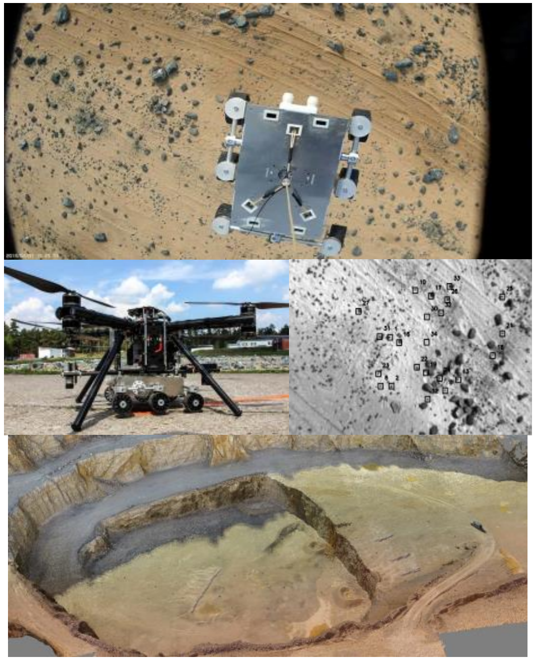


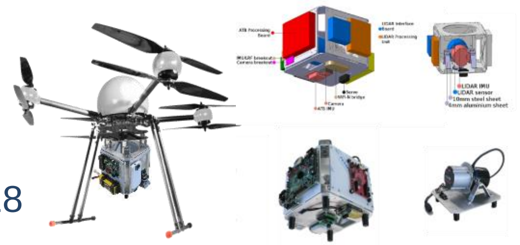
- **NEXT-Moon (2007-2010)**
  - Part of Consortium led by OHB (Germany)
  - Elaboration of Hazard Avoidance Strategies for Lunar Landing
  - Initial Implementation of G&C, Data Fusion algorithms (CAM + Lidar)
- **FUSION (2011-2014)**
  - Prime contractor
  - Development of Intelligent Decision Making for HDA
    - Fuzzy Reasoning, Probabilistic Reasoning, Evidential Reasoning
  - Enhancement of original HDA, G&C, Data Fusion algorithms
  - Application to Mars + Phobos landings



Background Work (cont'd)

- **StarTiger Dropter (2013/2014)**
  - Part of consortium led by Airbus D&S Germany
  - Implementation of Visual Navigation + HDA on RTSW
  - Construction of 40m x 40m Mars-representative terrain
  - Limited flight-testing using visual camera multi-copter
- **AVERT (2015-2018)**
  - Prime contractor, supported by Uninova (PT), Ruag (SE), Irida (GR)
  - Hardware acceleration (w/ FPGA) of VN&HDA, impl. in space HW
  - Construction of new 120m x 120m Mars-representative terrain
  - New copter for 100s of flight tests (validation of VN&HDA approach)
- **ANPLE (2017-2018)**
  - Prime contractor, supported by DLR
  - Development of pinpoint landing techniques for the Moon & Mars
  - Basis for present work, G&C is less detailed
  - GNC for Mars pinpoint landing w/ Supersonic Retropropulsion: IAC 2018





Motivation

- **Recent History of Lunar Landing Missions**
  - **Last 2 soft lunar landings:** Luna 24 (USSR, **1976**) Chang'e 3 (China, **2013**)
  - **…proposed until 2021:** China (Chang'e 4/5), India (Chandrayaan 2), Japan (SLIM), Russia (Luna-25)

- **Lunar X Prize (until March 2018)**
  - Inspired substantial investment in Lunar Landing technologies
  - 5 Teams confirmed launch contracts (SpaceIL, MoonExpress, Synergy Moon, TeamIndus, HAKUTO)
  - Prize not claimed

- **Post-lunar X Prize**
  - Several private teams have received funding for multiple Lunar missions
    - Typical: Lunar orbit in 2019, landing in 2020/21, commercial missions thereafter
  - Questions remain on feasibility (technical, cost, time)
  - NASA CATALYST, CLPS suggest a COTS-like enviroment for developing Commercial Lunar Landers is being established

End Goals

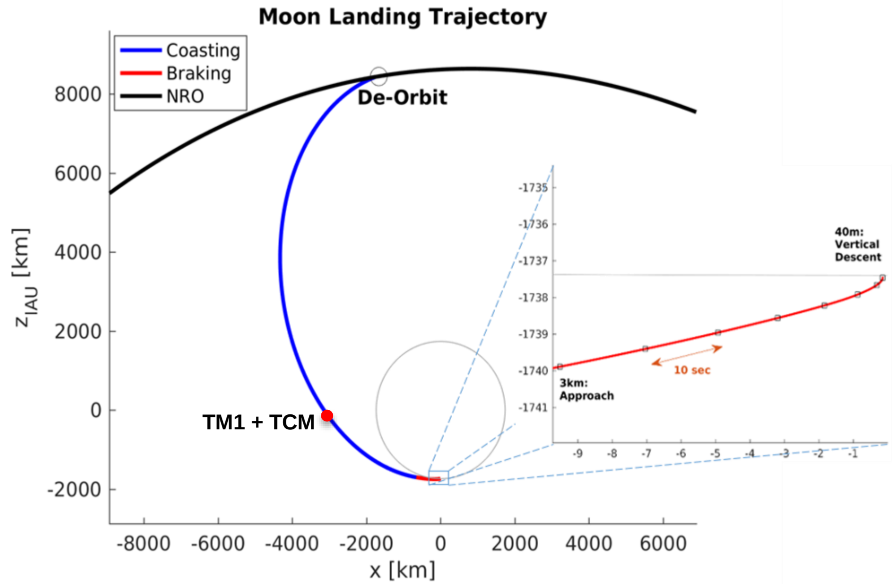
- Demonstrate a feasible GNC Design for a Precise, Safe Lunar Landing mission:
  - **Trajectory Design:** Descent and landing from a Near Rectilinear Orbit
  - **Orbit determination + control:** included in design cycle (reference timelines and clear separation between ground + onboard functions)
  - **GN&C:** 6DOF system applicable to all mission phases from de-orbit to touchdown
  - **HDA:** Camera-only, specific phase included in trajectory design, automated real-time divert trajectory generation & tracking assessed
  - **Validation:** via MC sims, targeting <10m landing accuracy (using terrain-relative navigation)

- Mature Avionics + GN&C technologies
  - **Design to Real-time Implementation:** considers real, available sensors + processing units, computational costs, data acquisition + processing timing constraints, storage, etc.
  - **Performance, constraints and limitations** of vision-based algorithms as known **from AVERT flight test data** (accuracy of IP, FOV, frame rate and resolution, angular rate limitations, etc)
  - Designed for **Processor-in-the-loop compatibility**

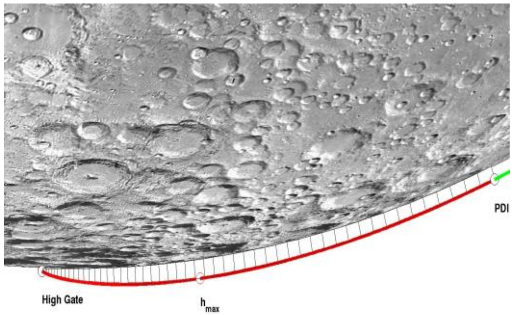
Mission Analysis – Trajectory Design

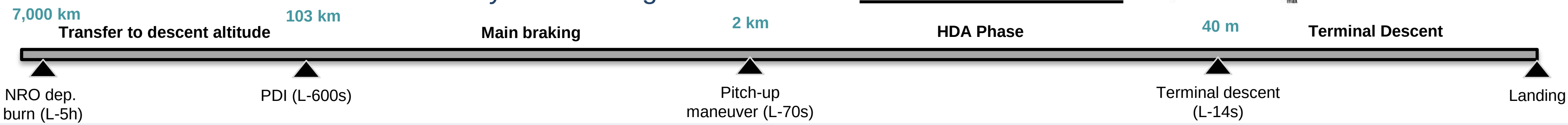
Trajectory Design

- Initial Point: along an NRO (optimized)
- De-orbit: impulsive manoeuver
- Powered Descent:
  - Phased: Main Braking, Pitch-up, HDA, TD
  - MB: Thrust@95% (allowing for corrections)
  - Pitch-up/HDA:
    - Thrust back to ~2/3 of original (2440N)
    - Restrictions: thrust mag., angular rates + acc., sensor offset from thrust vector, LS direction
  - Terminal Descent:
    - Pure vertical descent
    - Vertical attitude at 10m height
    - Zero horizontal velocity at 10m height



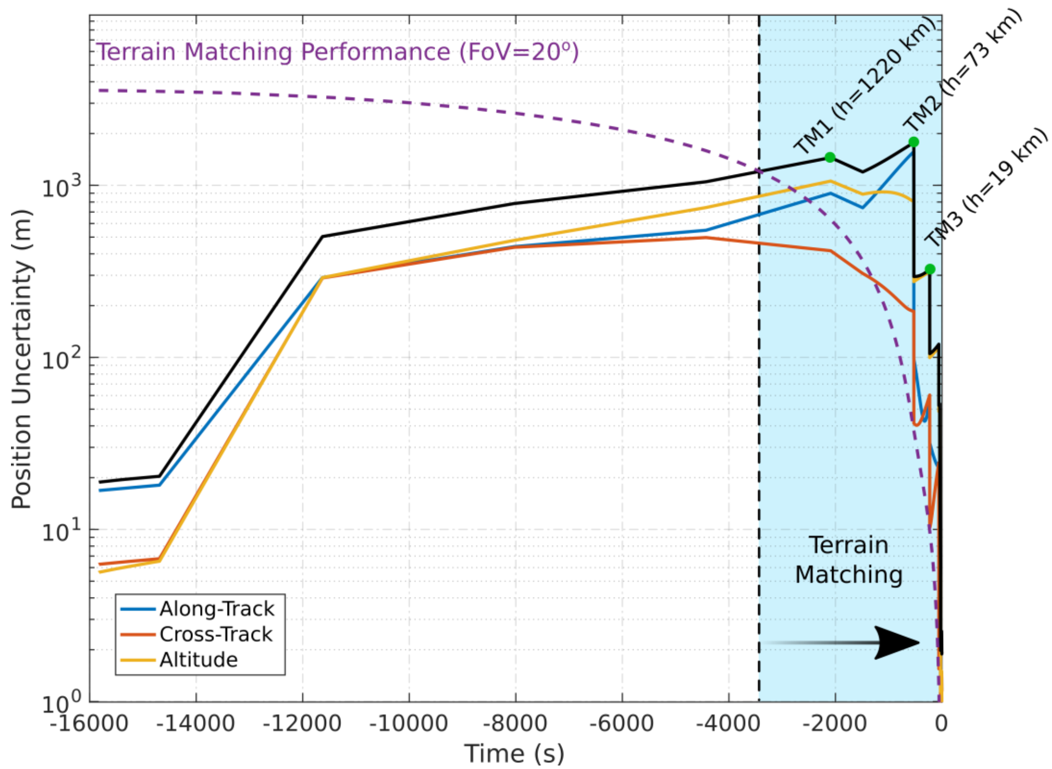
Spacecraft Parameters	
Mass	1,500 kg
Max. Thrust	3.5 kN
I_{sp}	311 s
NRO characteristics	
Periselene	7,000 km
Aposelene	61,500 km





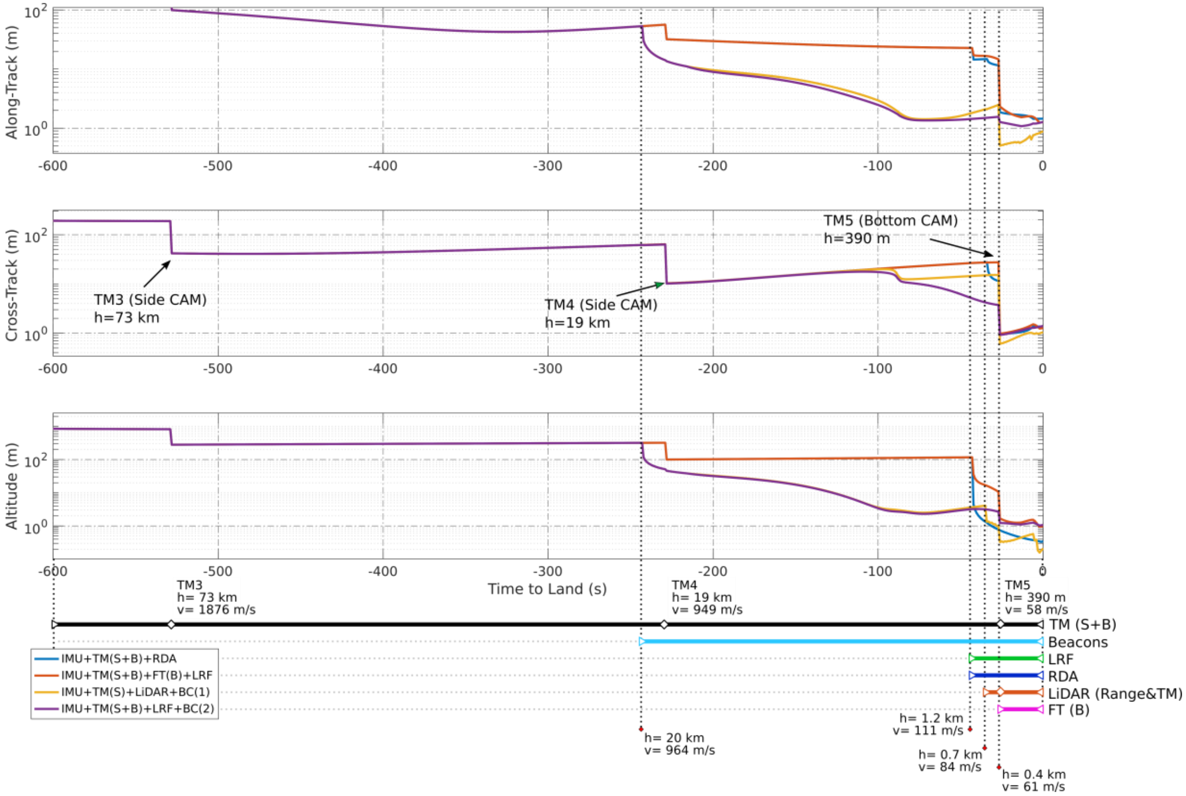
Covariance Analysis

- **Propagation of Onboard State Knowledge** (along reference descent trajectory from NRO)
- **Dynamic Model** includes gravity (Lunar, Earth), continuous thrust (incl. perturbations@2%, 3σ)
- **A Priori Knowledge** assumed ground-based, calculated via OD cycle while in NRO
- **Sensors and Actuators:**
  - **IMU:** LN-200 assumed
  - **RAD:** European PALT
  - **CAM:** 1024x1024 camera, 20/50º FOV (side/btm)
  - Airbus **220N+500N** thrusters (trajectory control), **22N** (attitude control)
- Optional sensor suite trade-off :
  - Side/bottom CAM (w/ terr. matching + ft. tracking)
  - Doppler radar
  - Pre-landed beacons
  - LIDAR (ranging, navigation)



Navigation Solution Trade-off

- **Side Camera** (Terrain Matching)
  - Essential to provide accurate absolute navigation information
- **Bottom Camera** (Terrain Matching+Ft. Track.)
  - Lighter alternative to Radar Doppler
- **LiDAR Imaging**
  - Enables the detection of hazards
  - Accurate ranging measurements
- **Surface Beacons**
  - Provide accurate observations during almost all the descent trajectory
- **Radar Doppler**
  - During the descent, provides accurate velocity and altitude measurements to enable soft landing



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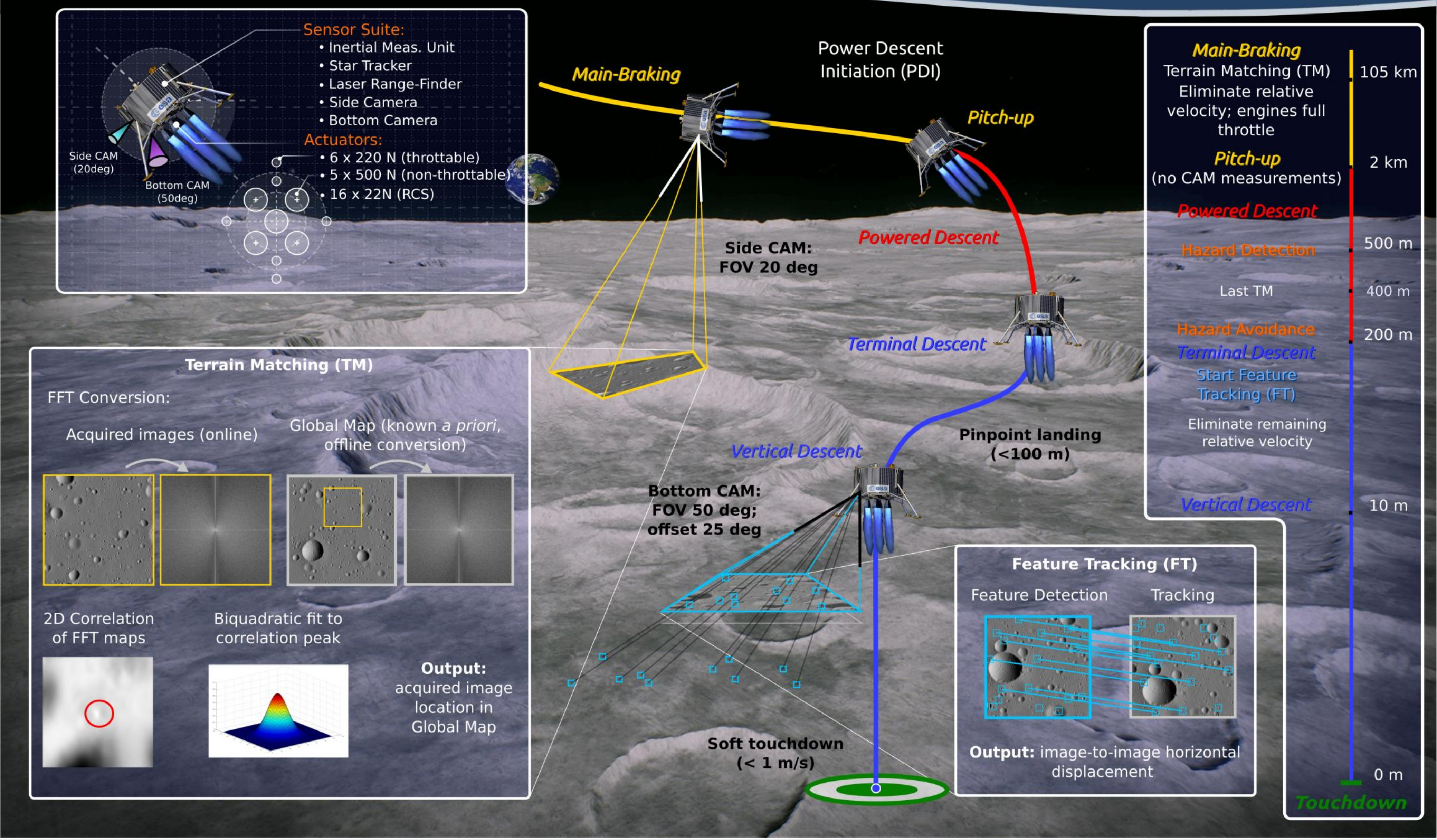
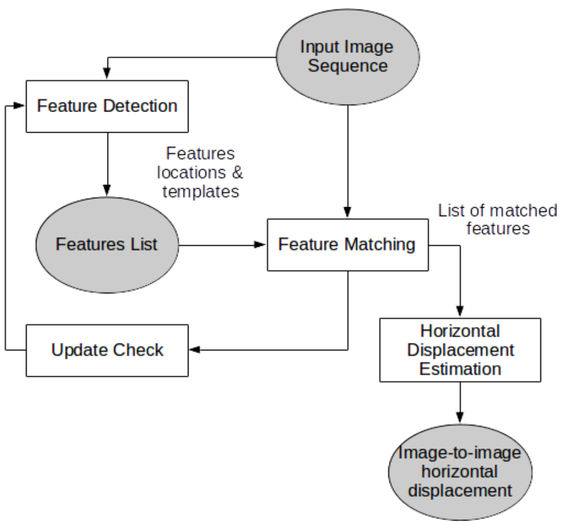

Sensor Suite:
• Inertial Meas. Unit
• Star Tracker
• Laser Range-Finder
• Side Camera
• Bottom Camera
Actuators:
• 6 x 220 N (throttable)
• 5 x 500 N (non-throttable)
• 16 x 22N (RCS)
Side CAM (20deg)
Bottom CAM (50deg)
Main-Braking
Power Descent Initiation (PDI)
Pitch-up
Powered Descent
Side CAM: FOV 20 deg
Terminal Descent
Pinpoint landing (<100 m)
Vertical Descent
Bottom CAM: FOV 50 deg; offset 25 deg
Soft touchdown (< 1 m/s)
Terrain Matching (TM)
FFT Conversion:
Acquired images (online)
Global Map (known *a priori*, offline conversion)
2D Correlation of FFT maps
Biquadratic fit to correlation peak
Output: acquired image location in Global Map
Feature Tracking (FT)
Feature Detection
Tracking
Output: image-to-image horizontal displacement
Main-Braking
Terrain Matching (TM)
Eliminate relative velocity; engines full throttle
Pitch-up
(no CAM measurements)
Powered Descent
Hazard Detection
Last TM
Hazard Avoidance
Terminal Descent
Start Feature Tracking (FT)
Eliminate remaining relative velocity
Vertical Descent
Touchdown
105 km
2 km
500 m
400 m
200 m
10 m
0 m

Navigation (Image Processing)

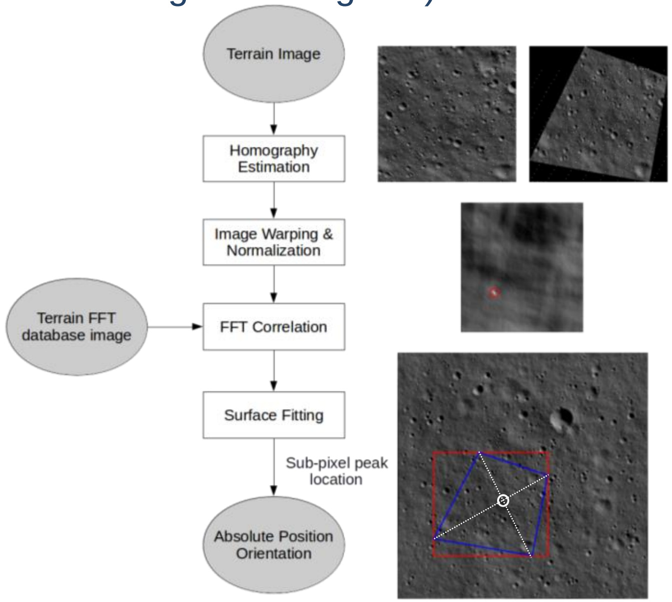
-Feature Tracking

- Produces observations of S/C terrain-relative velocity (expressed on camera sensor plane)
- Used from 390 m up to 20 m altitude (plume impingement on ground blinds sensor thereafter)



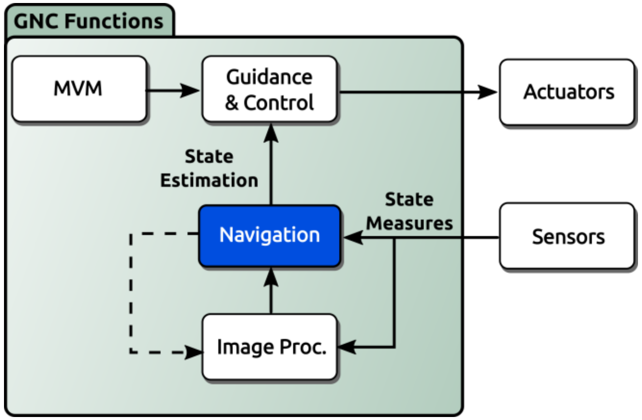
-Terrain Matching

- Produces observations of “absolute” S/C horizontal position (relative to a global map)
- 6 Images taken at 73 km, 40 km, 19 km, 8 km, 2.4 km, 390 m
- Altitudes selected iteratively (min # of maps, while achieving mission goals)

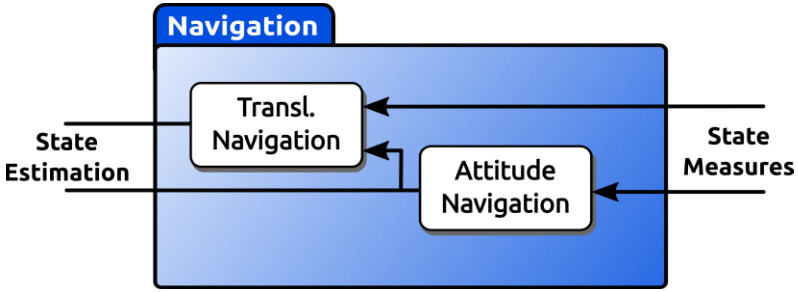


Navigation (Filters)

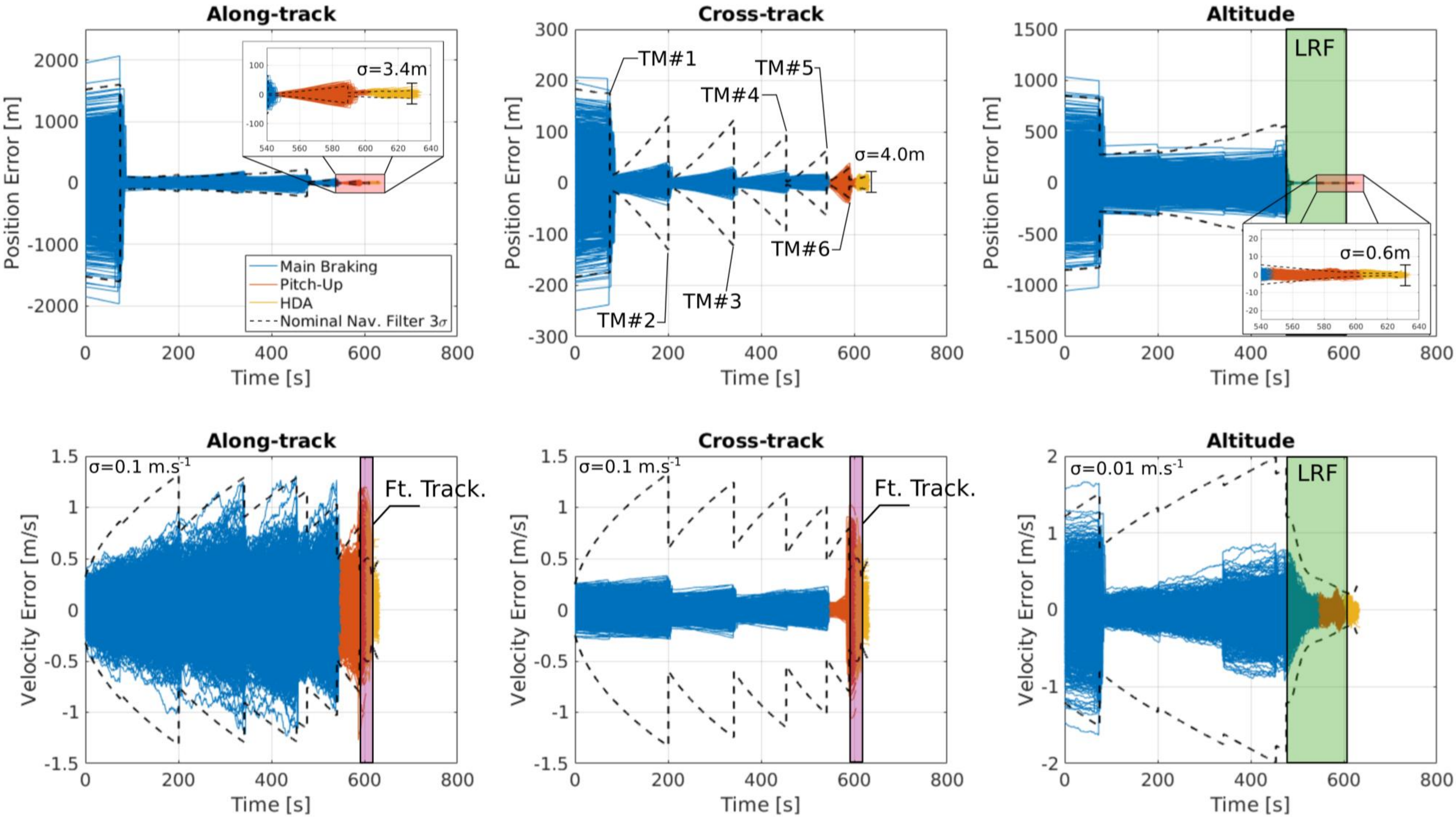
- **Translational Navigation filter**
  - **Type:** EKF-based discrete navigation filter
  - **States:** S/C position and velocity w.r.t. to the target body (inertial reference frame)
  - **State Propagation:** Accelerometer meas. and (simple) gravity model
  - **State Update:** Optical measurements



- **Attitude Navigation Filter**
  - **Type:** EKF-based discrete navigation filter
  - **States:** S/C attitude quaternion, w.r.t. to the inertial frame
  - **State Propagation:** Gyroscope measurements
  - **State Update:** Star Tracker measurements (when available)



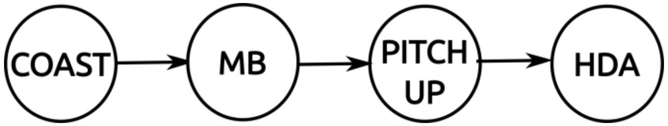
Navigation (Results)

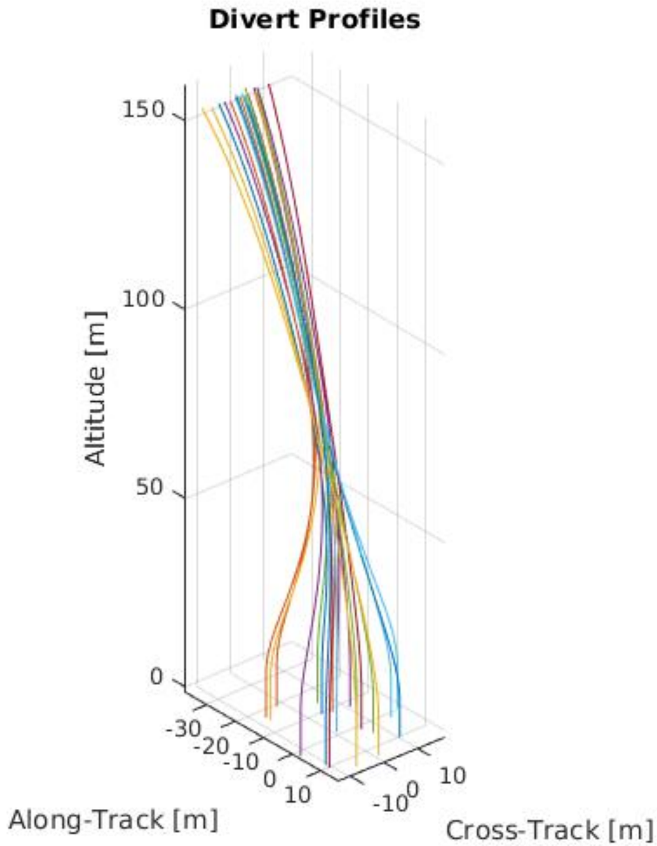


Guidance & Control

- **Main Braking and Pitch Up phases**:
  - Reference trajectory tracking w.r.t. estimated velocity (onboard-stored polynomials, using limited # of segments);
  - Trajectory control forces S/C to converge to reference trajectory from feasible initial state dispersions to within 20m, prior to HDA phase;
  - Sensor + actuator noise + misalignments considered;
  - Control gains tuned for fully closed-loop mission

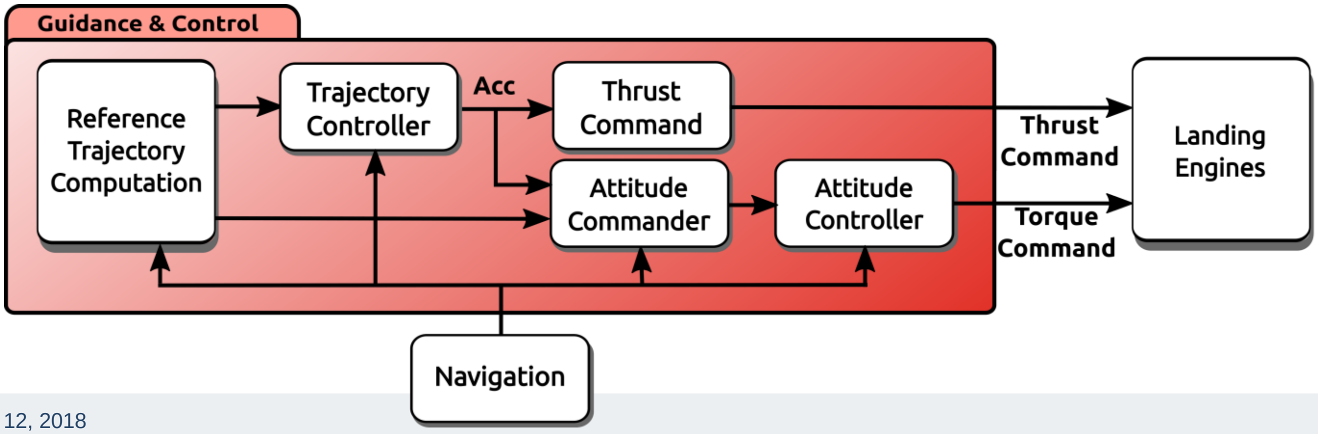
- **HDA phase**:
  - Piecewise polynomial divert maneuver generated online (acceleration + deceleration periods);
  - Maneuver timings kept fixed (while magnitude is tuned to allow for ~20 m diverts from 100 m altitude with reasonable angular rates and accelerations)



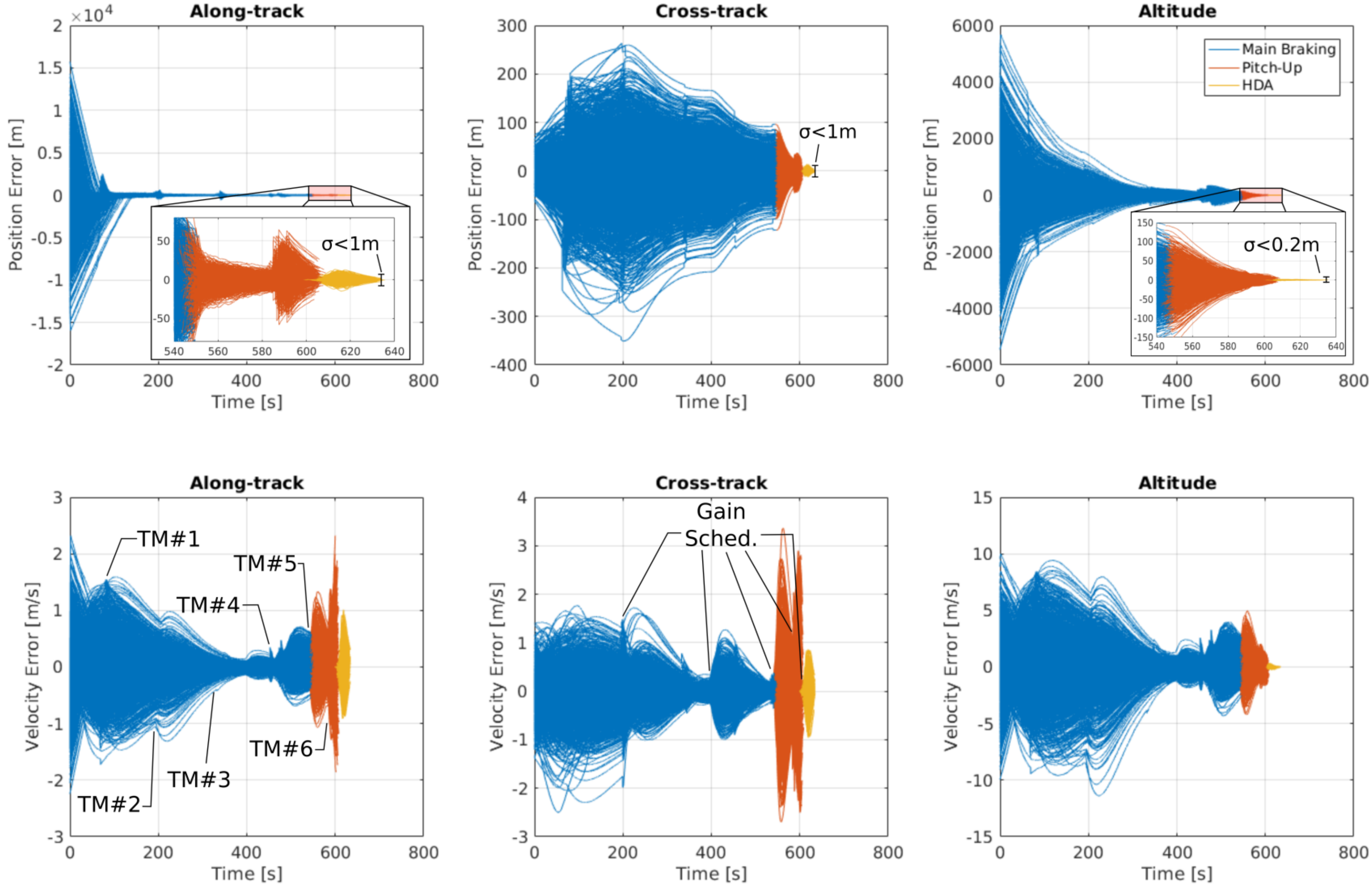


Guidance & Control

- **Reference Trajectory:** Interpolates the reference trajectory (position, velocity, acceleration and attitude) optimized offline using the estimated velocity;
- **Trajectory Controller:** Computes acceleration commands in order to track the reference trajectory based on a PD control law (with scheduled gains);
- **Attitude Commander:** Computes an attitude command that aligns the lander's thrusters with the commanded acceleration;
- **Attitude Controller:** Tracks the commanded attitude by issuing an appropriate torque command according to a PD control law (with scheduled gains).



Guidance & Control (Results)



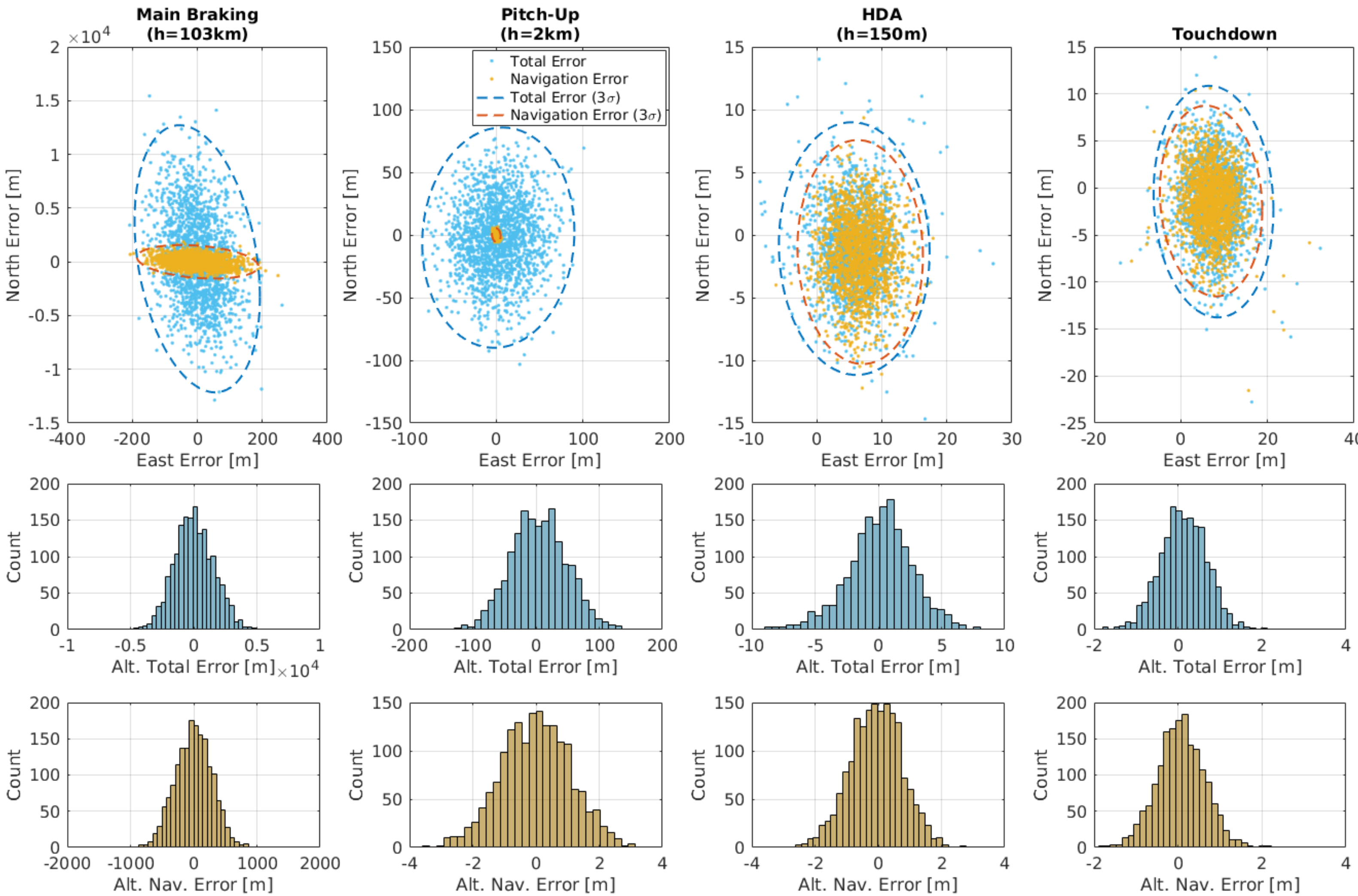
Monte Carlo

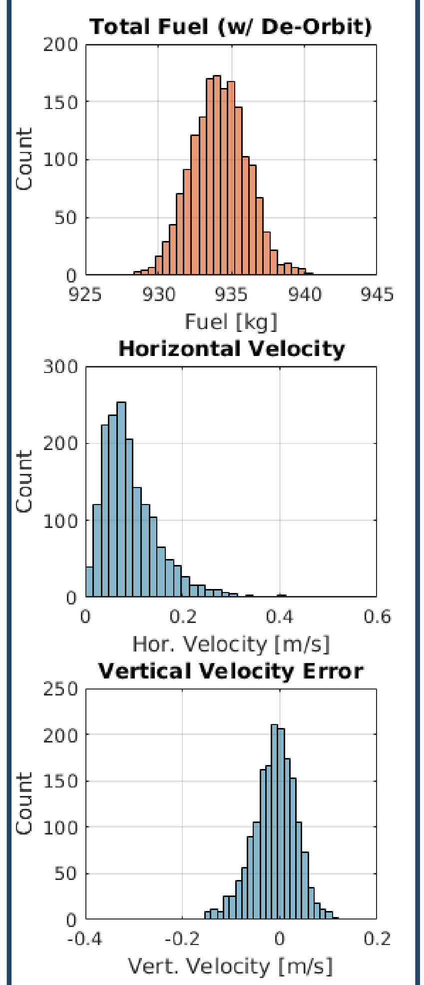
Block	Description	Parameter		Value
Initial Conditions	At the start of the Main Braking phase (from covariance analysis)	Mass		**Nominal:** 1219.4 kg, **3σ:** 1 %
		Position	Altitude	**Nominal:** 103.4 km, **3σ:** 4.3 km
			Along-Track	**Nominal:** 672 km, **3σ:** 11.1 km
		Velocity	Norm	**Nominal:** 2093.8 m/s, **3σ:** 2.98 m/s
			FP Angle	**Nominal:** -12.9 º, **3σ:** 0.21 º
Actuators	Idealized thrust along fixed in body direction and 3-axis torque. Both subject to constant random misalignment and multiplicative noise	Thrust	Noise	0.33 % (1σ, multiplicative)
			Misalignment	**Nominal:** 0 º, **3σ:** 1 º
		Torque	Noise	0.33 % (1σ, multiplicative)
			Misalignment	**Nominal:** 0 º, **3σ:** 1 º
Sensors	IMU model including white noise components and bias (used to model bias calibration error)	Gyroscope	ARW	0.07 º/√hr (1σ)
			Bias	**Nominal:** 0 º/hr, **3σ:** 0.3 º/hr
		Accelerometer	Noise	35 μg/√Hz (1σ)
			Bias	**Nominal:** 0 μg, **3σ:** 90 μg
	Models a small angle noise	Star-Tracker	NEA	2/3 arcsec (1σ)
	Outpus range to surface with a multiplicative error	Range-Finder	Noise	0.33 % (1σ, multiplicative)
			Bias	**Nominal:** 0 m, **3σ:** 2.4 m

Monte Carlo

Block	Description	Parameter		Value
Initial Navigation Error	Initial navigation error at the start of the Main Braking phase (from covariance analysis)	**Position**	**Altitude**	**Nominal:** 103.4 km, **3σ:** 851 m
			Along-Track	**Nominal:** 672 km, **3σ:** 1.52 km
		Velocity	**Norm**	**Nominal:** 2093.8 m/s, **3σ:** 0.56 m/s
			FP Angle	**Nominal:** -12.9 º, **3σ:** 1.83 ‘
Image Processing	Performance model parameters selected based on previous experience of algorithm performance	**Feature Tracking**	**Noise**	0.14 pix (1σ)
		Terrain Matching	**Noise**	0.5 pix (1σ)
			Map Tie Error	**Nominal:** 0 m, **3σ:** 40 m
HDA	Random HDA divert commanded at a specified rate	**Probability of Divert**		90 %
		Divert Magnitude		**Uniform in Disk of Radius:** 20 m

Monte Carlo Simulations





Summary & Conclusions

- A **complete mission design cycle** was carried out to frame the development of a realistic GN&C for Powered Descent and Landing of future Lunar Landing missions
- A **covariance analysis** was performed for the complete descent, to identify most suitable sensor suite (from a list of existing sensors & processing units).
  - A **dispersion analysis** was carried out to obtain **traj. dispersions → initial conditions**
  - **Navigation knowledge** is initialized using **knowledge covariance statistics**
  - Only onboard sensors contribute to trajectory knowledge after last OD cycle (at NRO)
- GN&C Algorithms were developed with **real-time implementation** in mind:
  - **Image processing performance** from **flight test data** of implemented algorithms
  - **Algorithm structure** designed for compatibility with stored & selected sensor data
  - **Communications**, **timing**, **storage** aspects taken into account
- A 6DOF Monte-Carlo simulation campaign was carried out to demonstrate feasibility
- **An End-to-End GN&C for Safe, Precise Lunar Landing has been validated**