Safety and Reliability aspects of Planetary Descent and Landing (from a GNC Perspective)

3rd European Optimisation in Space Engineering Workshop

Glasgow, UK

September 17, 2015

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Overview

-Key factors affecting the design of Descent and Landing strategies for Planets+Small Bodies

-Case Studies (and corresponding dominant factors in design)

- -Lunar landing – NEXT-Lunar Lander mission
- -Mars landing – Mars Precision Lander mission
- -Small Body landing – Phootprint mission
- -Binary Asteroid landing – Asteroid Impact Mission

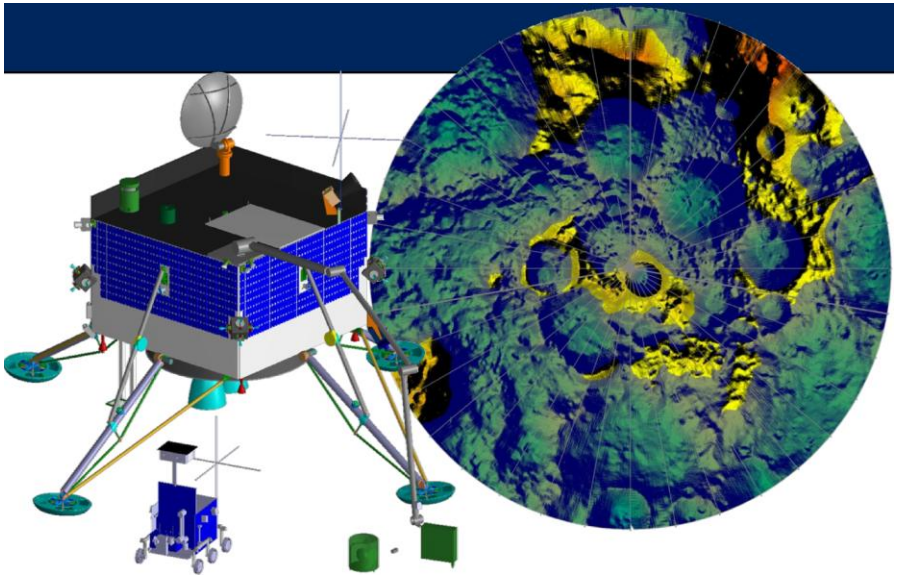
-Conclusions

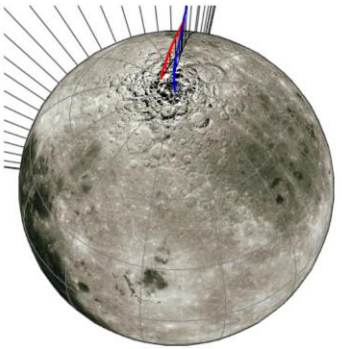
Key Factors

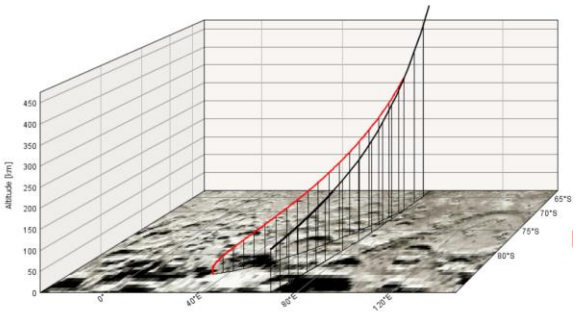
- Spacecraft Design and Orbital dynamics
  - Descent from planetary orbit, after atmospheric entry, from quasi-orbit, from co-orbit…
  - Achievable landing dispersions (different orders of magnitude depending on target)
  - Spacecraft size and landing system design (“Skycrane”… and the rest)
- Landing Site selection
  - Quality of a priori images, terrain models (LRO, MRO, MEx)
  - Pre-selection of suitable landing areas w.r.t. hazards
- Hazards considered
  - Illumination – Time of “year” (Ls), latitude
  - Slopes, craters – long base length (more observable)
  - Rocks, holes – short base length (generally less observable)

NEXT-Lunar Lander Mission

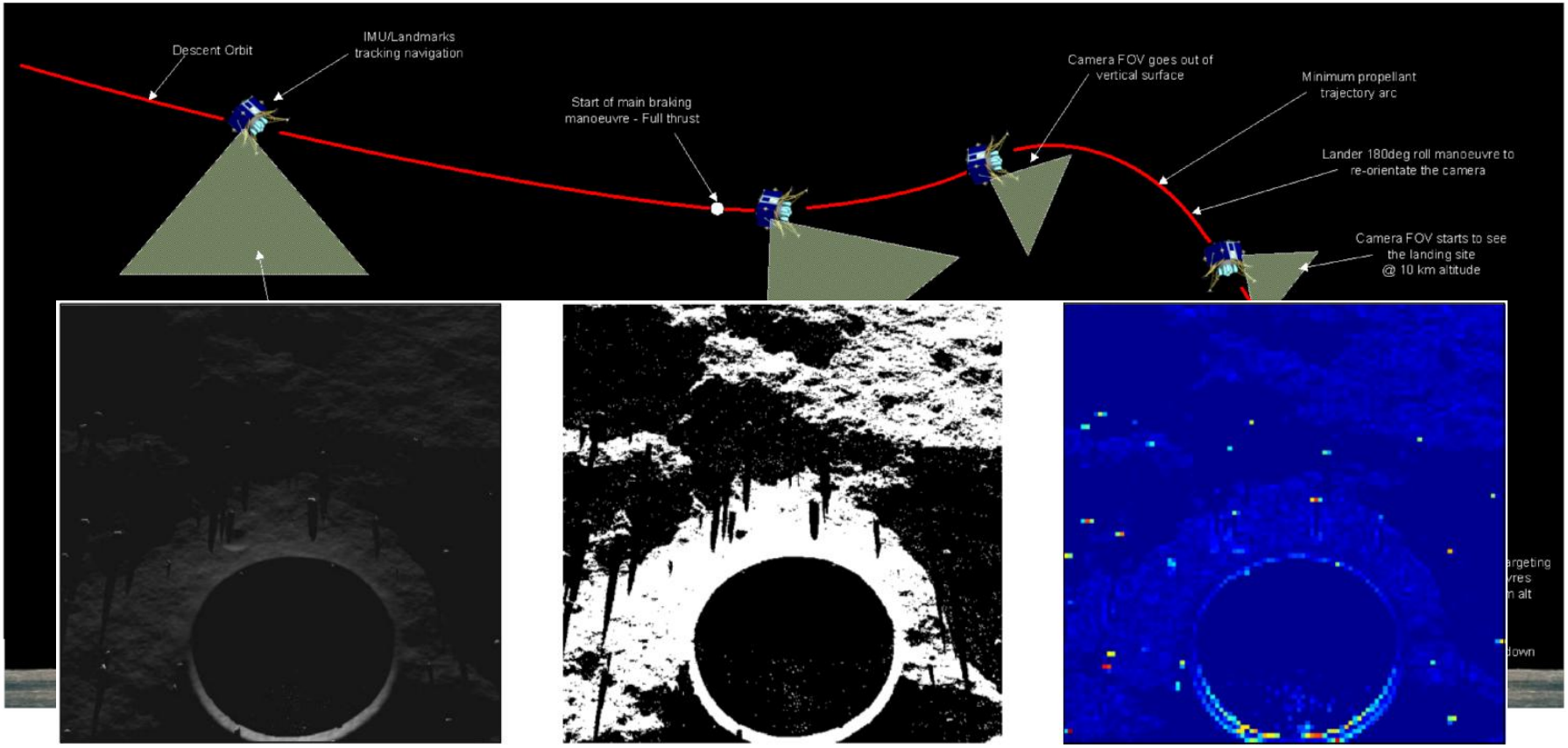
- **Mission Goals**
  - Development of a lunar lander with in-situ mobility
  - Soft precision landing
  - Preparation for future Lunar Exploration
- **Mission Overview**
  - Launch with Ariane-5 in 2018
  - Trajectory: WSB transfer to the Moon from GTO
  - Wet mass at launch: ~4t (@TD: ~900kg)
  - Autonomous powered landing with hazard avoidance
  - Phases A-B1 completed (2008-2011)
  - Follow-up: ESA-Roscosmos Joint programme







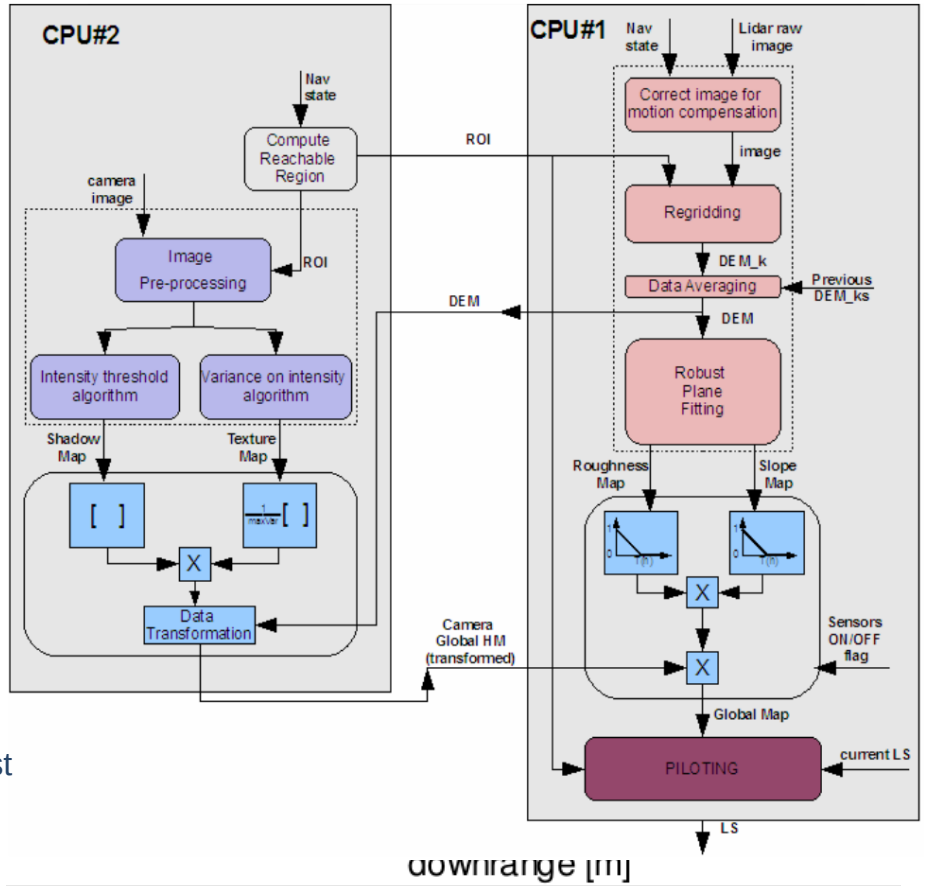
Descent and Landing Sequence



Hazard Detection + Avoidance

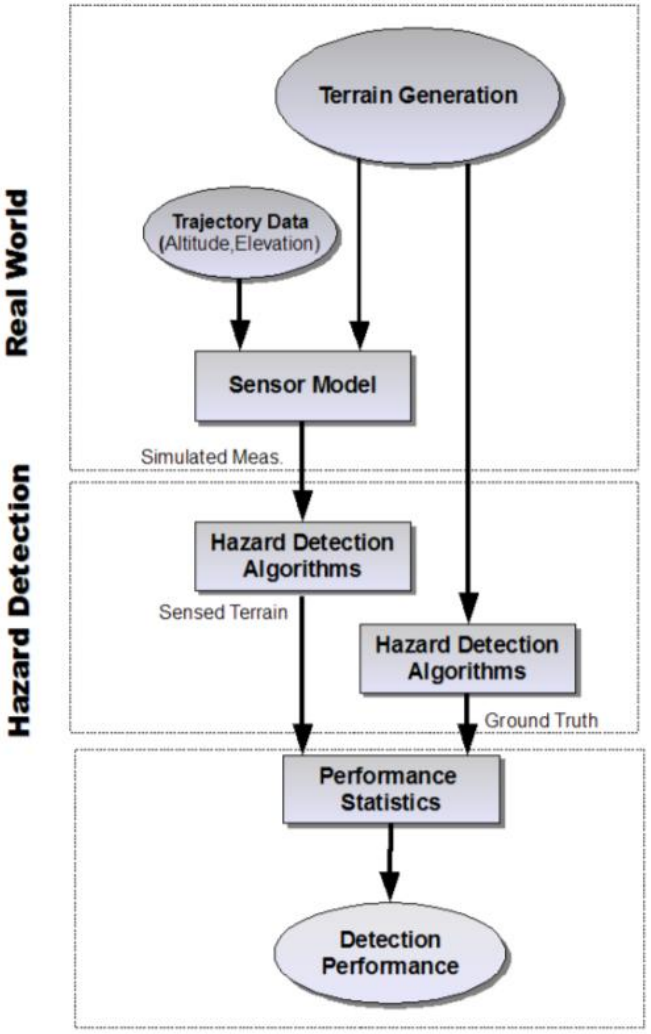
- **HDA Requirements**
  - **Obstacles** (rocks, holes) higher than 0.5m
  - **Slopes** <15deg
  - **Illumination** – LS fully lit at time of landing
  - **Touchdown speed** <0.3m/s (vert.), <0.9m/s (hor.)
  - **P_{sss}** > 99%

- **HDA concept**
  - **Instruments:** Camera and Lidar
  - **Hazards:** shadows, slopes and roughness
  - **Processing HW**: 2xLEON3-FT (100MFLOPs)
  - **HDA sequences**
    - **High altitude:** visibility over whole landing area, detection of slopes and large obstacles, selection of most appropriate area
    - **Low altitude:** map landing area in detail, detection of lander-sized patches of terrrain free of obstacles, selection of landing site



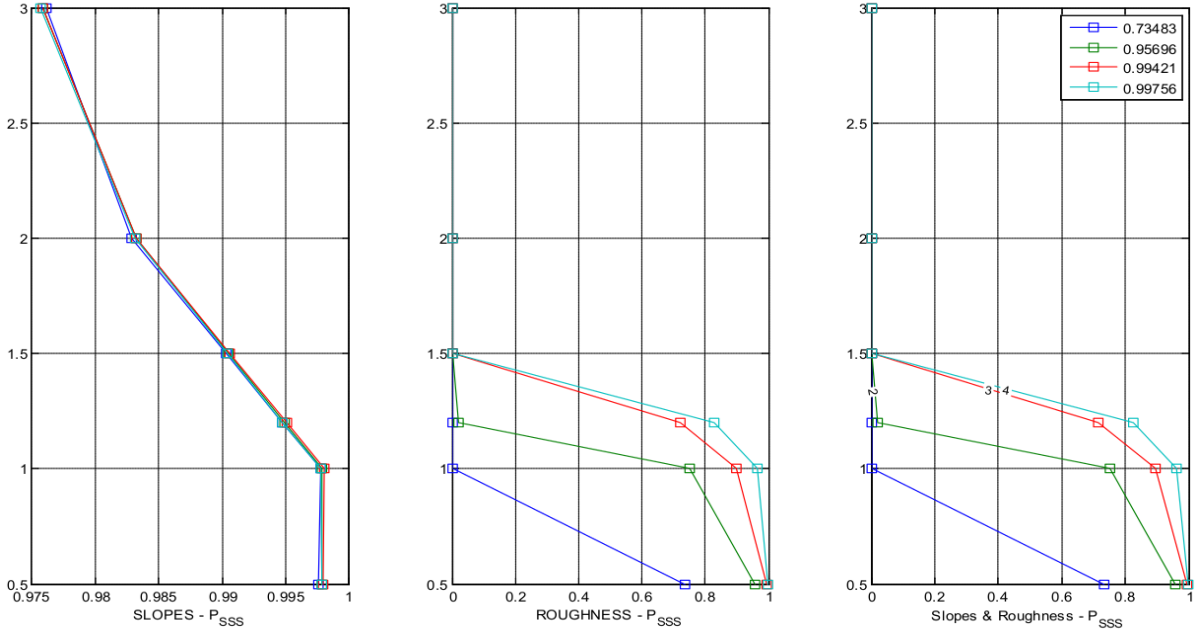
HDA Performance Assessment

- **Performance metrics**
  - **Detection** – "raw" hazard detection capability**:**
    - **hazard measurement errors**
    - **detection errors**
    - **false alarm rates**
  - **Probability of Safe Site Selection (P_{SSS})** – overall HDA performance metric, excl. GNC
- **Method**
  - **Artificial terrain** generation (PANGU-based with realistic hazard distributions)
  - **"Ground Truth"** calculation (roughness,illumination,slopes)
  - **Trajectory generation** (nominal + dispersed, alternative geometries)
  - **Sensor model** implementation – hazard detection performance
  - **HDA Algorithms Execution**
  - Aggregation of statistics
    - Terrain-based
    - Trajectory-based



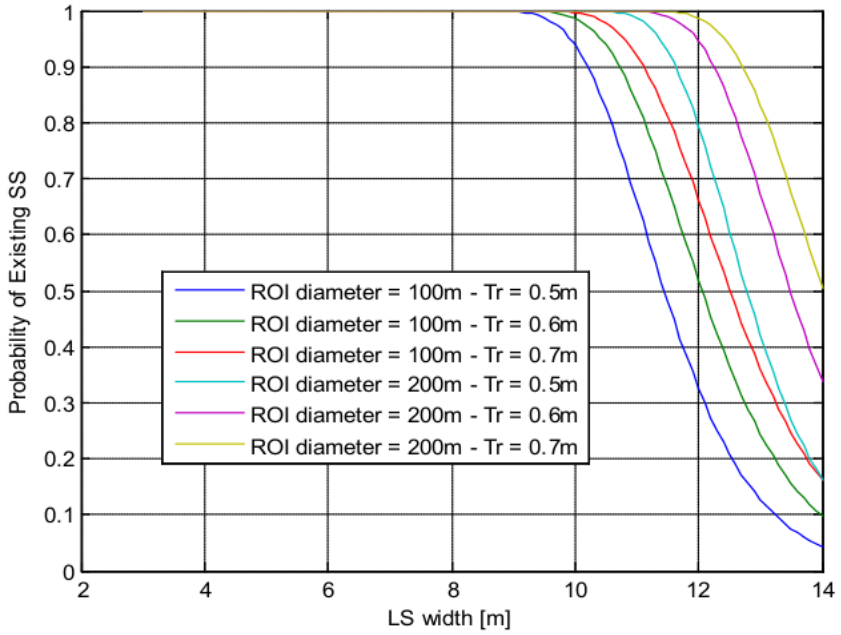
HDA Performance Analysis

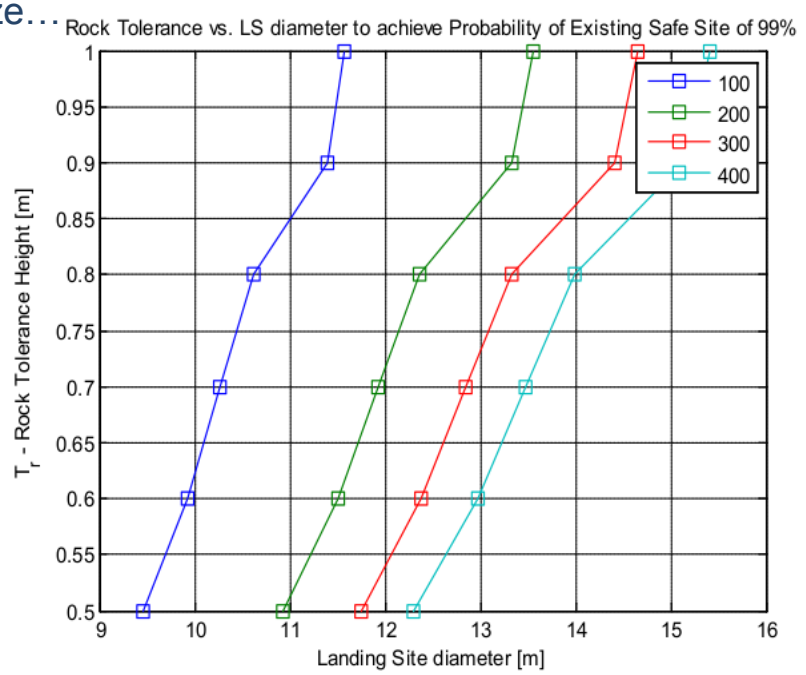
- **Dependence with Ground Resolution (fixed lander size, search area, rock tolerance)**
  - **Slopes** – not very significant (information about slopes in lander-sized patches available early enough)
  - **Roughness** – P_{SSS} highly dependent of resolution (assumes rock height = 0.5x diameter)
  - **Joint P_{SSS}** (slopes+roughness) – >99% success prob. with 0.5m/pixel, 3-4 images (for noise reduction)



HDA Performance Analysis (cont'd)

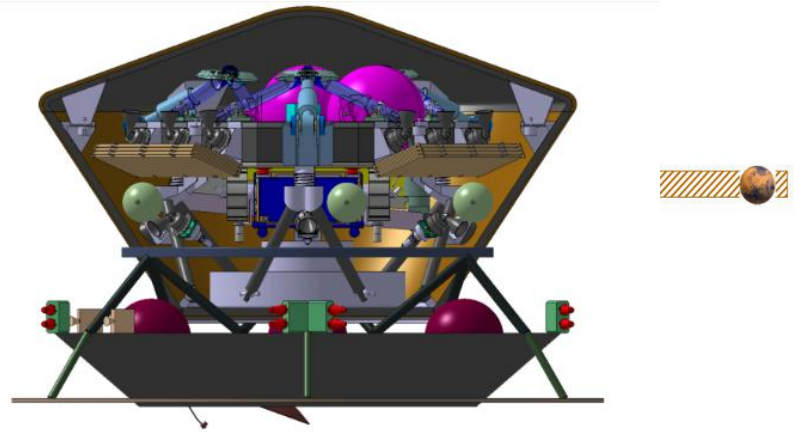
- **Dependence with Lander Size, Search Area (ROI) and Rock Tolerance (Tr)**
  - **Lander Size** – probability that a safe LS exists improves **very** significantly w/ smaller footprint
  - **Search Area (ROI)** – for sufficiently small lander size (say, 2x2m such as in a "Skycrane"), can be **very** small
  - **Rock Tolerance (Tr)** – for sufficiently small lander size…

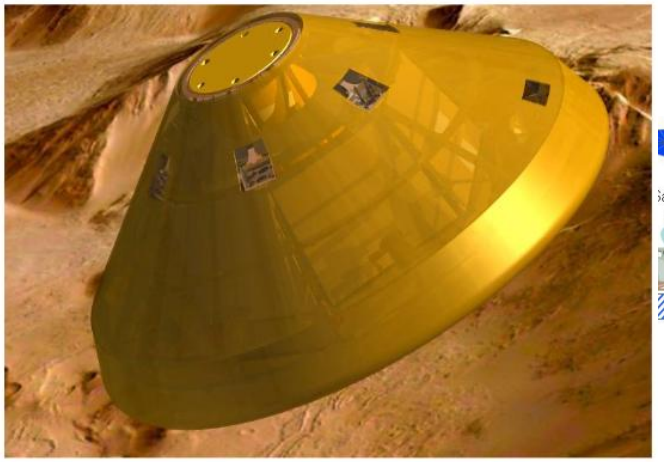




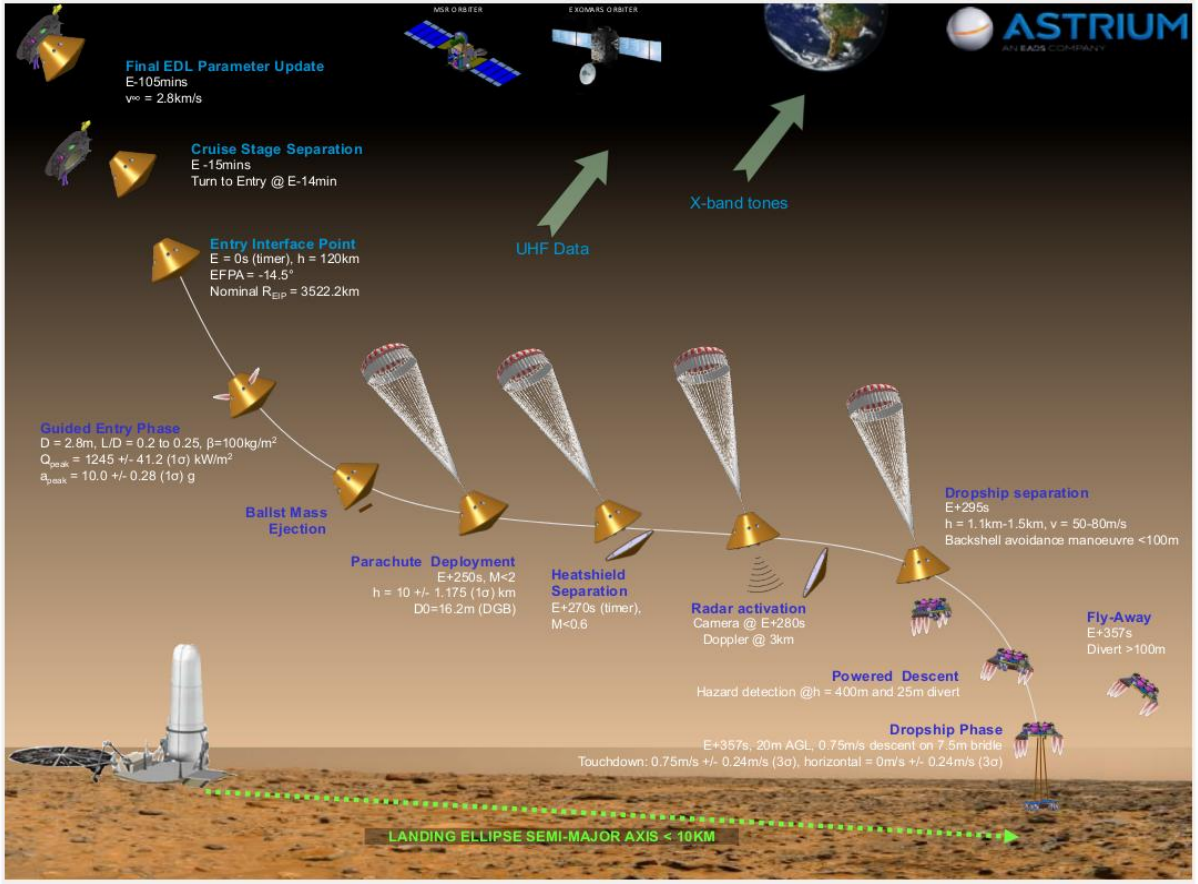
Mars Precision Lander

- **Mission Goals**
  - Optional element of the Mars Sample Return (MSR) architecture
  - Precise delivery (<10km of target) of small rover to collect sample cache
  - Hazard Detection and Avoidance
  - Sample transfer to Mars Ascent Vehicle (MAV)
- **Mission Overview**
  - **Launch** in 2022-2026 with a Soyuz 2.1b
  - **Direct transfer + Lander release** from hyperbolic arrival trajectory
  - **Guided entry**
  - Parachute-assisted + powered descent
  - **Landing site**: 15S < δ < 30N, -1 < alt < 0 km



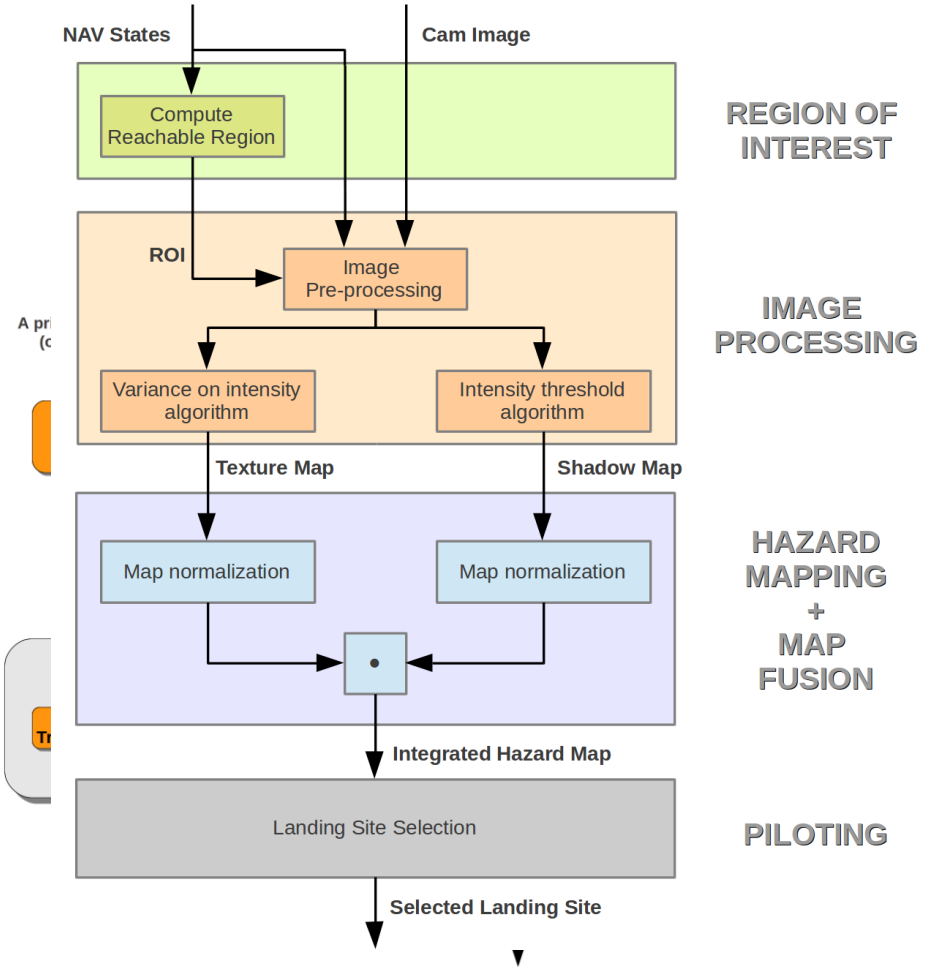


Descent and Landing Sequence



Hazard Detection + Avoidance

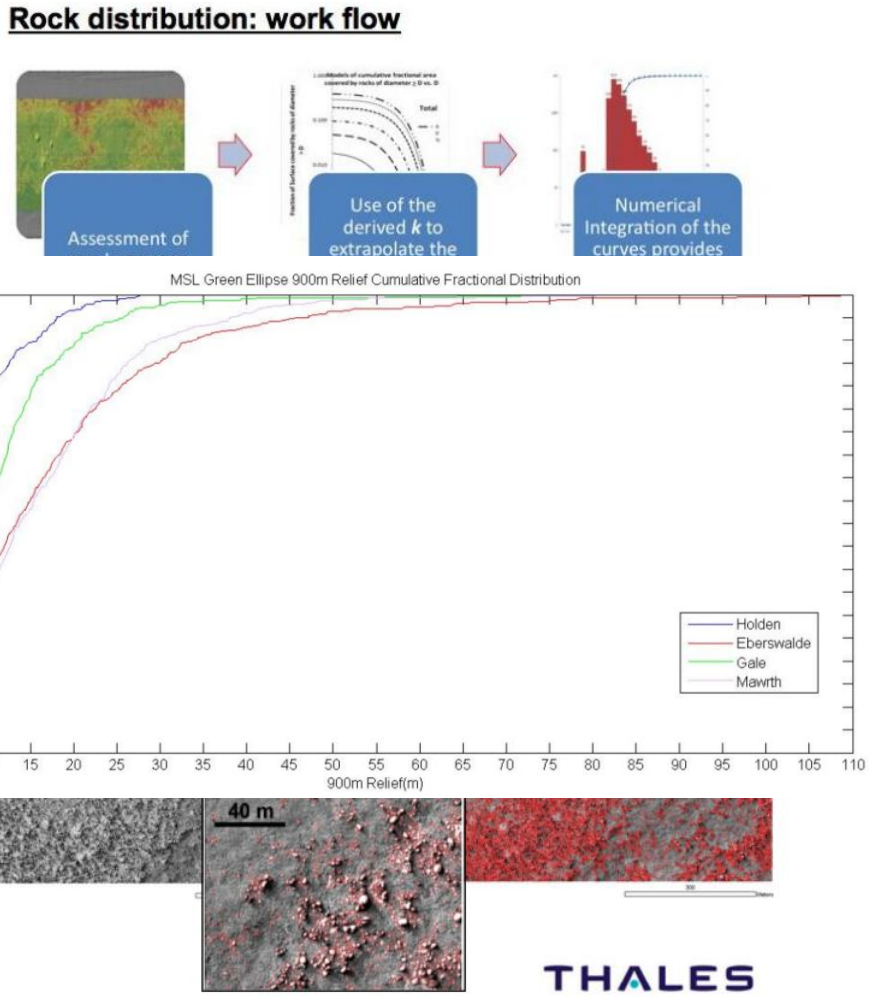
- **HDA Requirements**
  - **Obstacles** (rocks, holes) larger than 0.3m
  - **Slopes** <15deg
  - **Illumination** – LS fully lit at time of landing
  - **Craters (using the LiDAR)**
  - **P_{sss}** > 99%
- **HDA concept**
  - **Instruments:** Camera and LiDAR (backup: Camera)
  - **Hazards:** shadows, slopes, roughness, craters
  - **Processing HW**: 2xLEON3-FT (100MFLOPs)
  - **HDA sequence**
    - **Single decision point:** when sufficient ground resolution is achievable, two visual + flash LiDAR images are taken, and a decision is directly produced
    - **How does this affect HDA performance?**



Landing Site Analysis

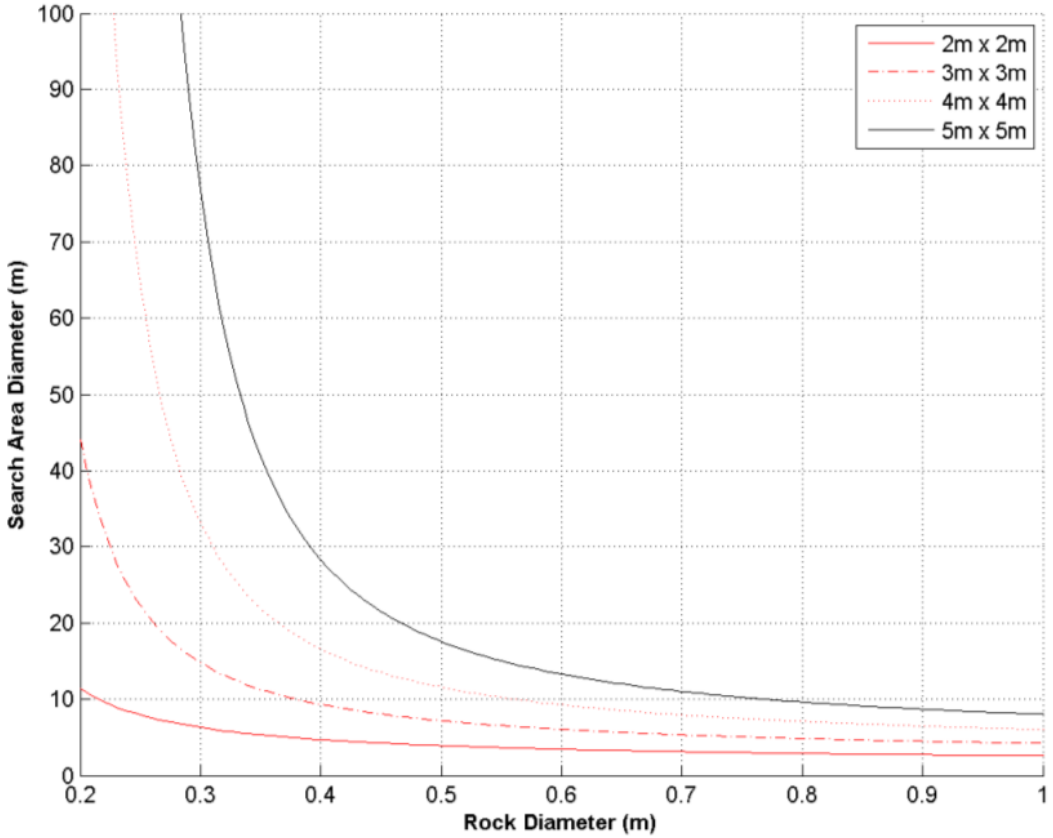
- **Landing Site Constraints**
  - **Slopes** limited by design
    - **Landing ellipse** should avoid rough terrain
    - **Observation:** “slopes” on km-scale represent low-end of “slopes” on m-scales. Therefore:
      - For NASA MSL, landing areas with 100m relief on ~1km-scale deemed unsafe
      - For ESA Mars missions (e.g. Exomars): <2º on base-length of 2km, and <8.6º on base-length of 330m
  - **Roughness distribution**
    - Rock Height/Diameter = 0.5
    - Logarithmic law of number-size distribution
    - Smaller rocks are exponentially more likely than larger rocks
    - Overall rock abundance regulated by simple expression

$$F_k(x) = k\ exp(-q(k)D)$$
$$q(k) = a + b/k$$



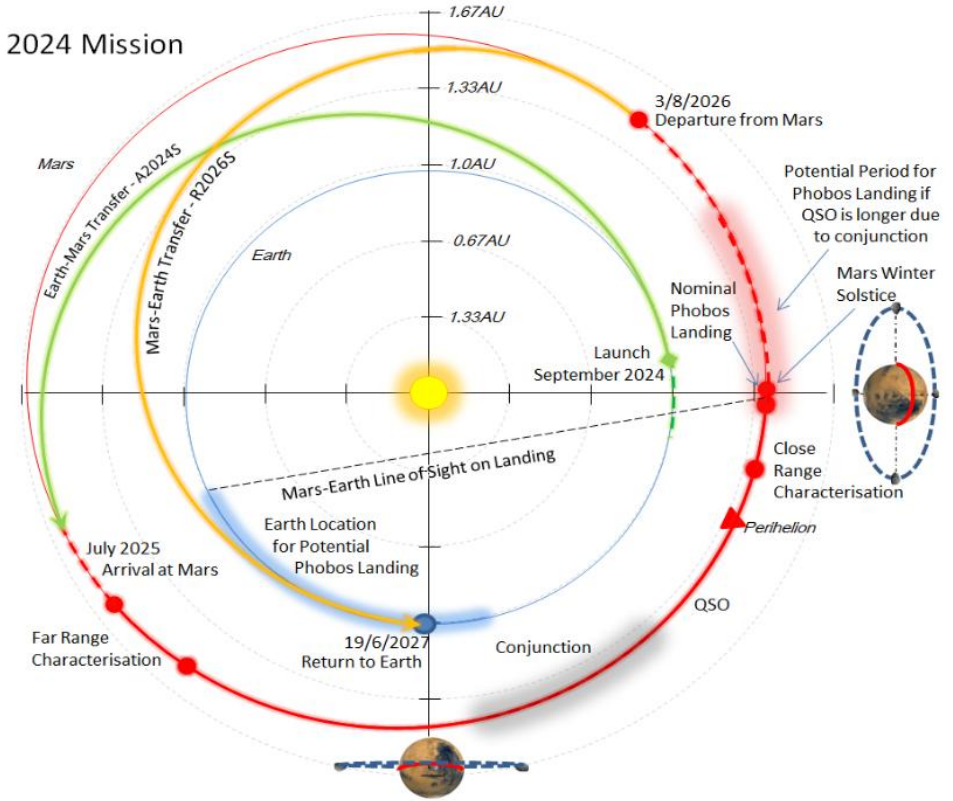
HDA Performance Analysis

- **Search area diameter (for >99% P_{SSS})**
  - Analysis applicable to **detection of terrain roughness** (rocks, holes) with given distribution
  - **Lander Size** causes exponential increase in search area requirement
  - **Better rock tolerance** (shown as higher "Rock Diameter" below) dramatically improves situation
  - Determination of 3 **key design parametres**:
    - **HDA altitude** (depends on sensor range, dynamics, timing of mission events)
    - **Ground resolution** (to allow identification of all hazardous rocks)
    - **Sensors Field-of-View** – minimum required to observe entire search area with given ground resolution, with margin



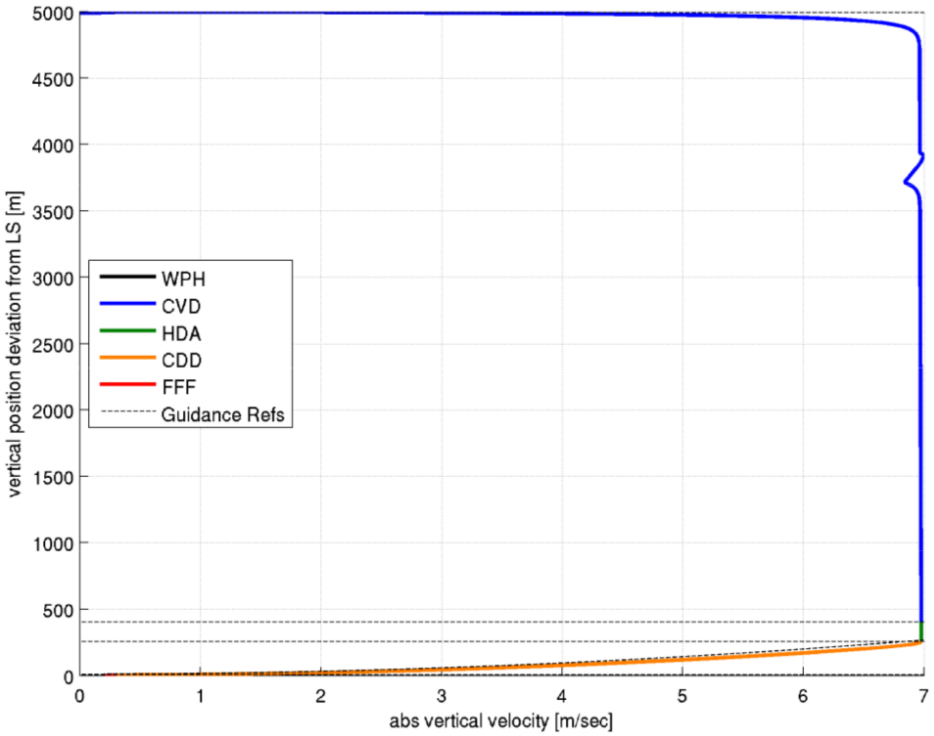
Phootprint

- **Mission Goals**
  - Understand the formation of Martian moons Phobos and Deimos
  - Constraints on evolution of Solar System (co-formation? capture? impact ejecta?)
  - Tech Demo for Mars Sample Return
    - High accuracy structural + spectroscopic analysis not possible in-situ -> **return 100g of samples**
    - Precise landing (<100m of target)
- **Mission Overview**
  - **Launch** in 2024-2026 with an Ariane ECA
  - **Direct escape** strategy preferred
  - **Insertion into highly elliptical** Mars Orbit for low-DV transfer to Phobos
  - Injection into Phobos **QSO**
  - **Static Landing** at Phobos
  - Return to Earth in 2026-2032 **(passive Re-Entry)**



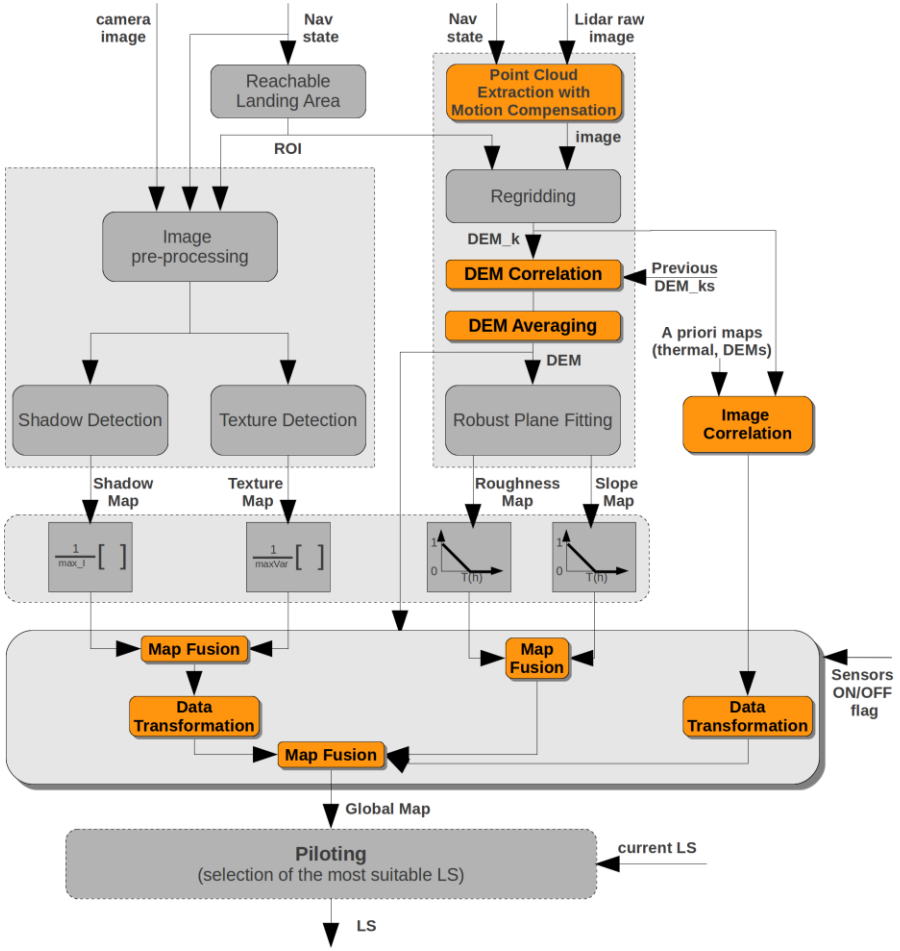
Descent and Landing Sequence

- **Descent Phasing**
  - **Descent from Waypoint to synchronization height** (WPH) – descent on a forced motion from 5km until about 10m height;
  - **Constant Velocity Descent** (CVD)
  - **Hazard Detection and Avoidance** (HDA) – with sufficient ground resolution, a safe landing site is selected
  - **Constant Deceleration Descent** (CDD) **–** decrease of descent velocity until nulling of relative velocity; attitude alignment w.r.t. surface;
  - **Free-Fall Phase** (FFP) **–** horizontal coordinates kept within a “dead band”, attitude control achieved through inertia wheels to avoid ground contamination w/ thrusters
  - **Touchdown.**



Hazard Detection + Avoidance

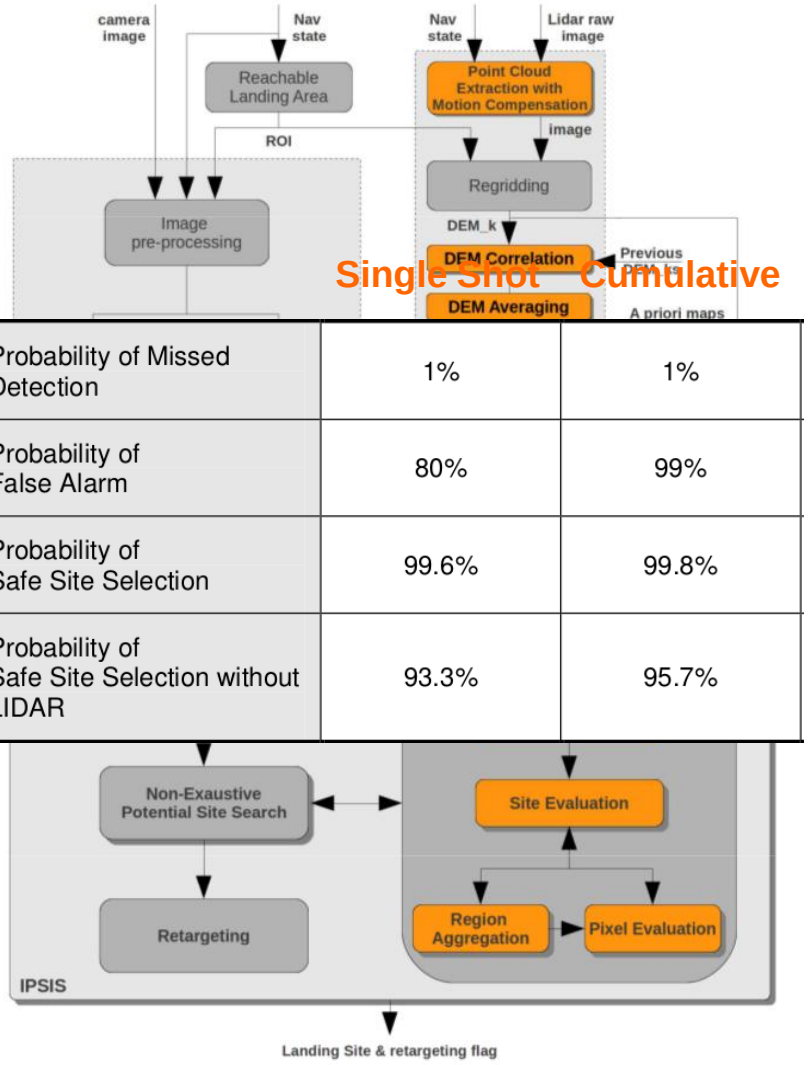
- **HDA Requirements**
  - **Obstacles** (rocks, holes) larger than 0.6m
  - **Relative Attitude (w.r.t. ground)** <10deg
  - **Illumination** – LS fully lit at time of landing
  - **P_{sss}** > 99%
- **HDA concept**
  - **Instruments:** Camera and Lidar (backup: Camera)
  - **Hazards:** shadows, slopes, roughness
  - **Processing HW**: 2xLEON3-FT (100MFLOPs)
  - **HDA strategy**
    - **Continuous monitoring of LS** during HDA phase (far longer descent – 720s – than for Mars case – 60s)
    - **Readjustment of target LS** (when required) to largest area which is sunlit and free of obstacles



Case Study 3: Phobos Landing

HDA Performance Analysis

- **Use of Cumulative Hazard Map Data in Safe Site Selection (IPSIS):**
  - **Process**
    - **Landing Site rating** (weighting of available hazard maps)
    - **Historical process** (use of past HMs of same regions for reinforcement learning)
    - **Retargeting process** (decision based on rankings + rules
  - **Advantages/Disadvantages**
    - **Heavier computationally** and more complex
    - Use of **more data for decision making** (when there's time!)
    - **Discard large proportion** of areas
    - Additional time could be used instead to take images at lower altitude
    - **Result: not necessarily an improvement in decision-making** over 'single-shot' approach



Single Shot Cumulative

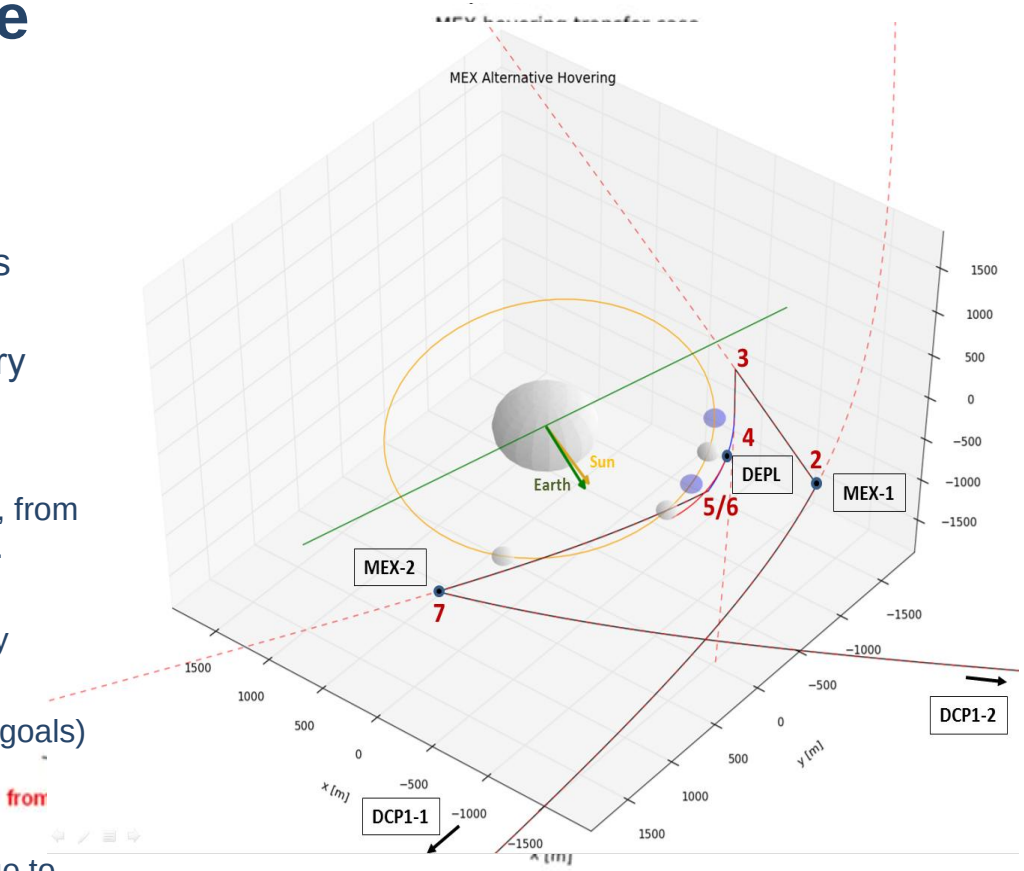
Robustness	Probability of Missed Detection	1%	1%
	Probability of False Alarm	80%	99%
	Probability of Safe Site Selection	99.6%	99.8%
	Probability of Safe Site Selection without LIDAR	93.3%	95.7%

Asteroid Impact Mission (AIM)

- **Mission Goals**
  - ESA/NASA mission to study binary object 65803 Didymos
    - ESA component – AIM
    - NASA component – DART (Double Asteroid Redirection Test)
  - Determine geophysical properties of ‘Didymoon’
  - Perform deep space laser comm experiment (TEX), asteroid landing (MEX), Cubesat-based deep-space payload operations
  - Determine momentum transfer after impact of DART spacecraft
- **Mission Overview**
  - Launch in October 2020 (earliest) with Soyuz 2.1b/Fregat M
  - Direct transfer, arrival at Didymos in May 2022
  - Stepwise approach to asteroid (Rosetta-like)
  - Deployment of Cubesats, passive Lander on ‘Didymoon’
  - Retreat to observe DART impact (October 2022)
  - Approach for detailed observation of results

Descent and Landing Sequence

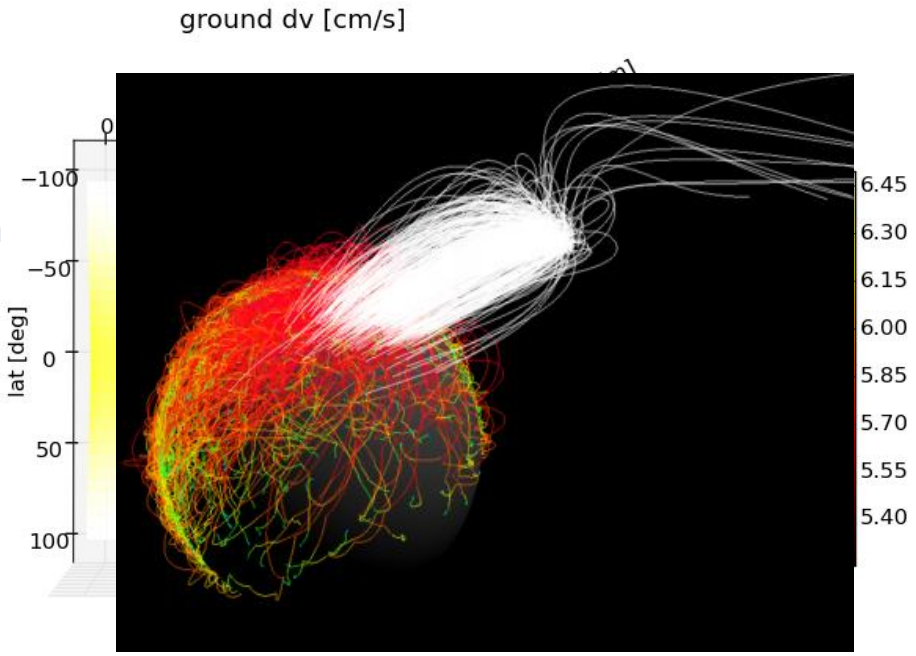
- **Main Requirement – Landing on Didymoon**
  - Trajectory in a three-body problem
  - **Many parametres only roughly known** (Didymos pole, Didymoon orbit, both object shapes)
  - **Passive lander** → likely requires delivery from very close approach, displacing risk onto AIM itself
  - **Study paths**:
    - **Several delivery options**: from hyperbolic trajectory, from temporary orbit, from hovering position, along WSB...
    - **Navigation strategy** (OpNav essential!)
      - Timing of landmark and shape model availability
    - **Sensor** and **Actuator models** required
      - Visual camera resolution (derived from science goals)
      - Lander deployment uncertainties
      - AIM thruster uncertainties
    - **Approach to model “Bouncing” on Didymoon** (due to very high coefficient of restitution - CR)



Delivery from Hyperbolic Orbit

Landing Performance Analysis

- **Rationale for delivery along System L2 line**
  - Touchdown velocity **minimized along L1-L2 line**
    - **20%** below maximum
    - Even with very high C_R the lander will stay on Didymoon
  - Delivery of MASCOT-2 along L1 line **risks landing on Didymos**
- **Sensitivity to deployment altitude**
  - Success achievable with deployment at 60m altitude
    - Assuming specific initial position, velocity uncertainties consistent with separate navigation analysis
  - **Threshold:** 65m altitude (at 70m, many cases escape the system)
  - **Lower altitudes:** lower bound on NAV accuracy, for each image resolution + FoV trade-off solution
    - Special radar observations or image processing techniques may be required



Release from 60m altitude, 60m fall

Conclusions

- Planetary Descent and Landing is a risky business
  - A priori risk mitigation (via landing site selection) can make a difference, but isn't always possible
  - Orbital dynamics, target characteristics can be very demanding (e.g. Mars, Didymoon cases)
  - Smart landing technologies have low TRL (flash LiDAR, "Skycrane", precision landing)
- GNC + HDA strategy must be tailored to improve success probability on case-by-case basis
  - Different targets pose different challenges
    - Lunar Pole → Illumination
    - Mars → strict timing
    - Didymoon → passive landing under the action of two bodies
  - Co-design crucial to success (Trajectory, Hardware, GNC strategy, HDA strategy)
    - Ideal solution: simplest solution without 'externalities'
  - If possible, exclude a hazard a priori
    - Alternative: use a priori data during descent

QUESTIONS?

FUSION + StarTiger Dropter

- **Technology developments**
  - Data fusion technologies for hazard mapping and piloting, up to Flight Demonstration (TRL4/5)
  - ESA contract s (TRP and StarTiger, 2012-2014)
  - Consortia led by Spin.Works, Airbus-D
- **Projects Overview**
  - Scenarios: Mars, Phobos
  - Camera and Lidar (FUSION), Camera (StarTiger)
  - Model-in-the-loop up to Real-Time Flight Test
  - **Real-Time Embedded GNC + Image Processing**
  - **Vision-based Navigation**
  - **Hazard Detection and Avoidance**
    - Craters (Lidar)
    - Shadows
    - Slopes > 15 deg
    - Rocks > 0.3 m