Hazard Avoidance Techniques For Vision Based Landing.
Performance assessment and consolidation analyses

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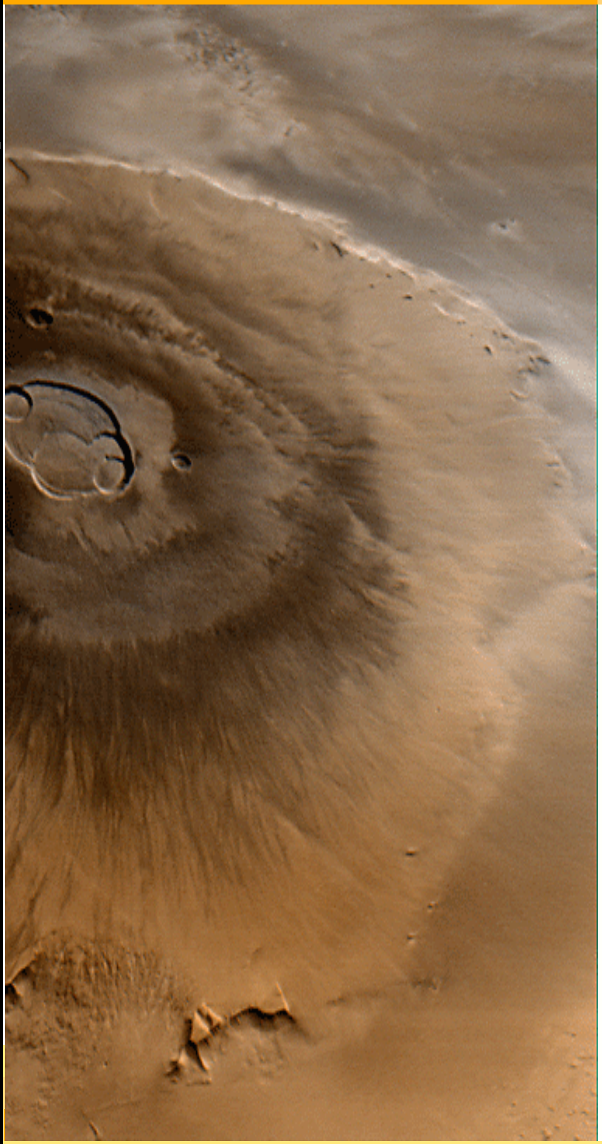

Hazard Avoidance Techniques For Vision Based Landing: Performance assessment and consolidation analyses

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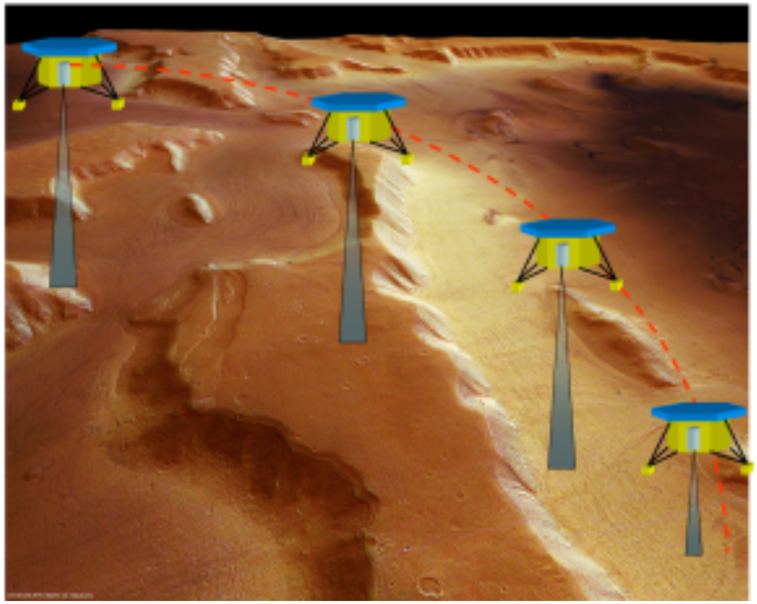
- **Hazard Avoidance**
  - Key technology for a safe landing of planetary landing missions.
  - Allows future landers (smaller, lighter and not so robust to surface hazards) to safely land on planetary surfaces that are not known *apriori* or in areas that are not flat and hazard free.
  - Requires a suitable sensor for hazard detection.
  - It comprises autonomous algorithms for:
    - Detection of any hazards (e.g. craters, rocks, boulders, high slopes, shadows, etc.);
    - Selection of most suitable landing region
    - Trajectory re-Planning to avoid the detected hazards;



- **Autonomous pinpoint soft-landing systems requires Hazard Avoidance(HA) capability to guarantee safe landing.**

Mission Overview

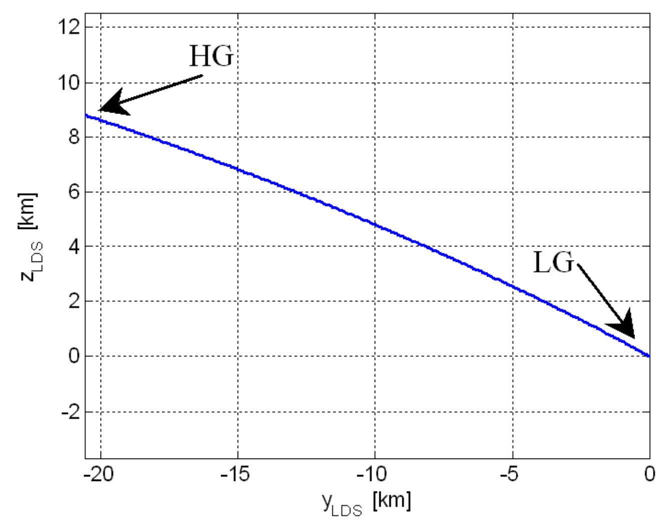
- NPAL mission scenario (Mercury landing), representative of planet without atmosphere (Moon).
- Landing during daylight with sun behind the spacecraft at low elevation angle.
- Landing Site (LS) is approached by south through a polar orbit.
- **Requirement: Landing on rough terrains with less than 10% of hazard free terrain.**

Initial Conditions at High Gate

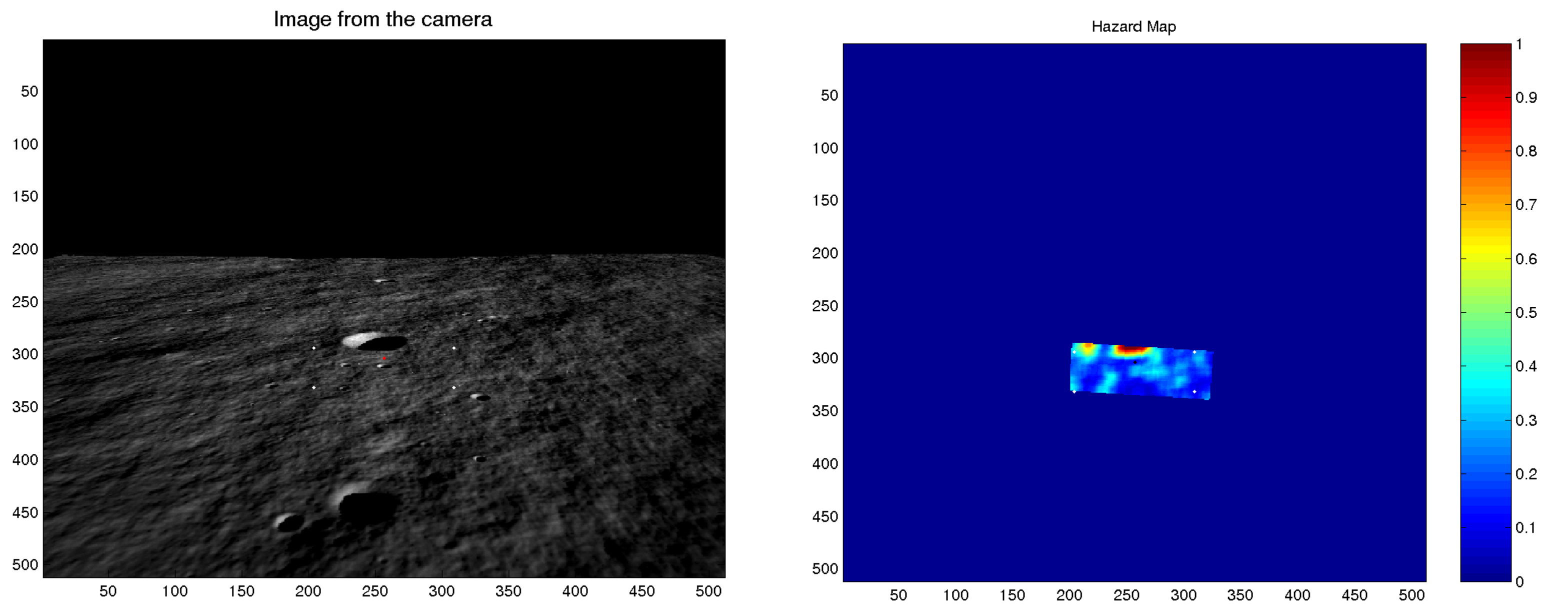
Range	21.9 km
Ground range	20.1 km
Altitude	8.46 km
Velocity	746 m/s
Horizontal error	571 m (1 σ)
Altitude error	244 m (1 σ)
Velocity error	4.5 m/s m (1 σ)

- Sensors:
  - Inertial Measurements Unit
  - Mono-axis camera

- Actuators:
  - 12 RCS thrusters (strapdown with thrust modulation capability).
  - 4 TCT thrusters (strapdown with thrust modulation capability).
  - 1 main engine (strapdown without thrust modulation capability).

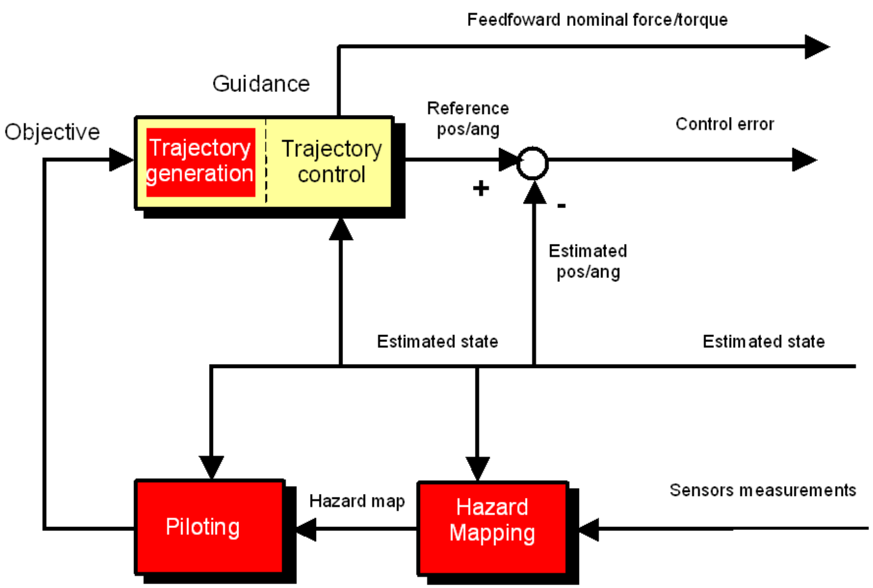


- **PANGU Generated Image and correspondent Hazard Map**



Hazard Avoidance functions

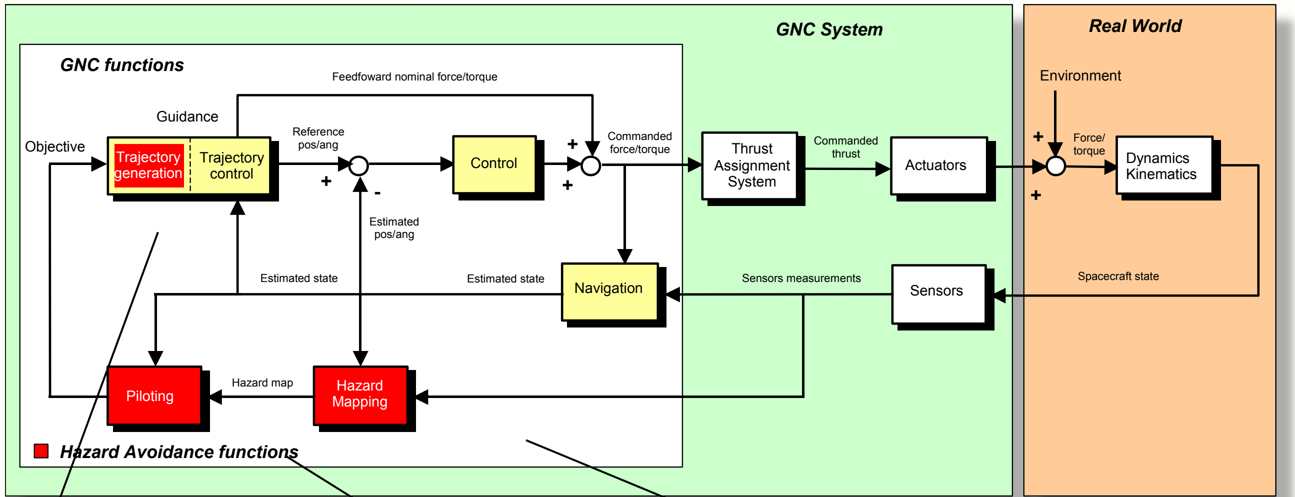
- HA is responsible for hazard detection and path-planning to avoid the detected hazards with constraints on fuel and spacecraft control authority.



Hazard Avoidance functions

- HA comprises the following functions:
  - **Hazard Mapping**: refers to the process of analysing terrain topography and detecting hazards through image processing algorithms applied to the monocular optical images taken by the onboard navigation camera.
  - **Piloting**: refers to the concepts of data fusing, planning and decision-making used for the selection of a safe LS.
  - **Guidance**: refers to the concepts used to steer the spacecraft till the Landing Site (LS can change during flight).

Hazard Avoidance

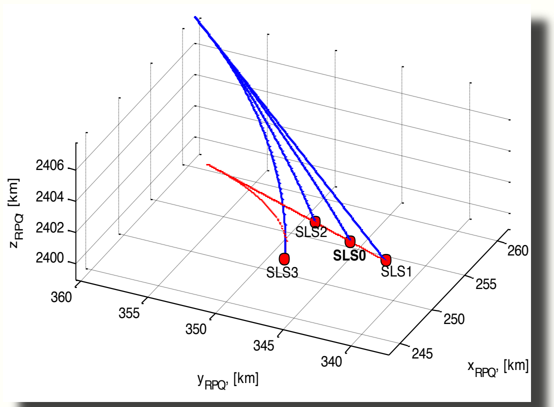


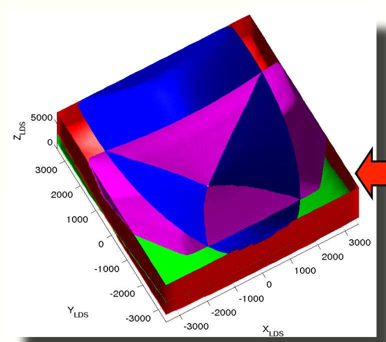
O/B Trajectory generation and control

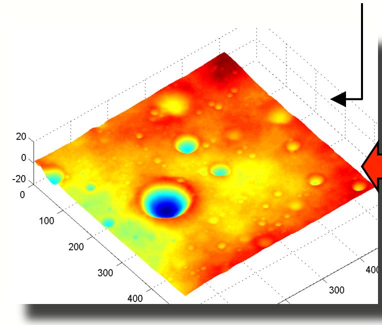
Piloting

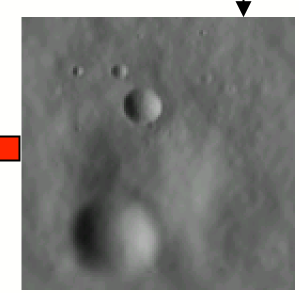
Image acquisition

Hazard Mapping



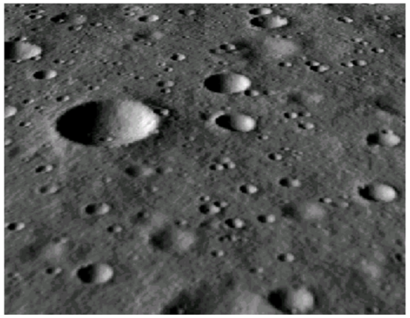






HA Design: Hazard Mapping

Courtesy of INETI

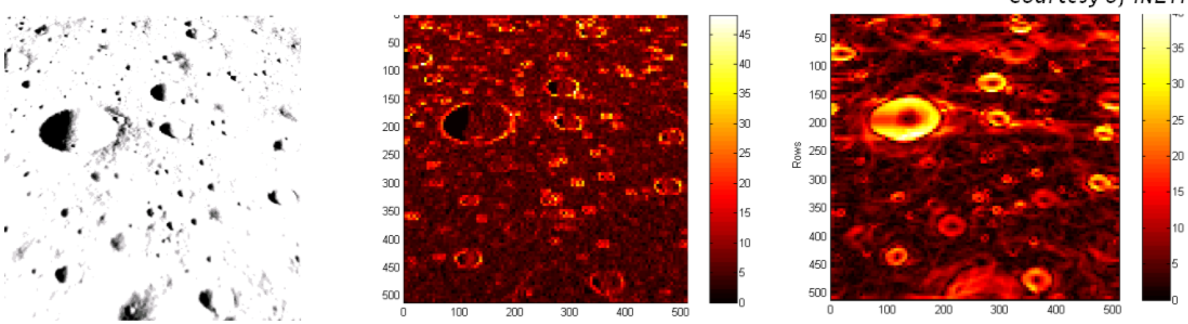


Camera image of landing area generated with PANGU

– Hazard Mapping (HM) assesses the landing risk associated to the morphological properties of the planetary surface that can be detected from panchromatic monocular optical images.

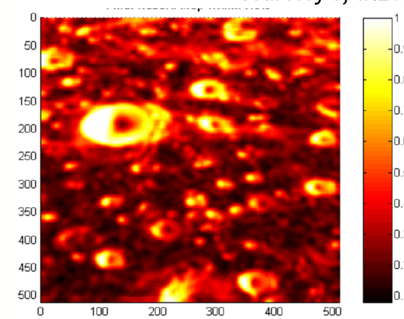
– **Shadow**, **Texture** and **Slope Maps** are merged into a final Hazard Map, which attributes a 'landing risk score' to each pixel in a region of interest surrounding the landing area.

Courtesy of INETI



Shadows, texture and slope maps

Courtesy of INETI



Hazard Map

- **Shadows** are extracted by automatic thresholding using the image grey level histogram.
- **Texture** is assessed using the grey level standard deviation within a square patch tuned dynamically with range.
- **Slope** is estimated by first building a digital elevation model using "shape from shading" techniques and supplemented by spatial filtering.

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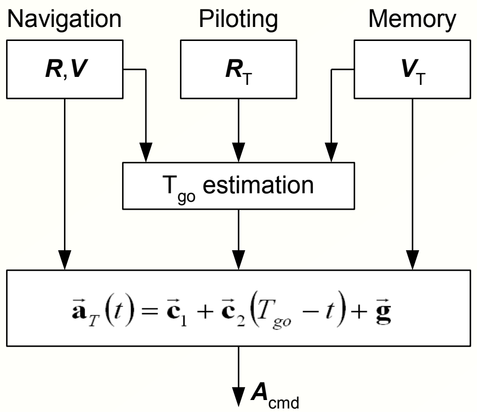
HA Design: Guidance

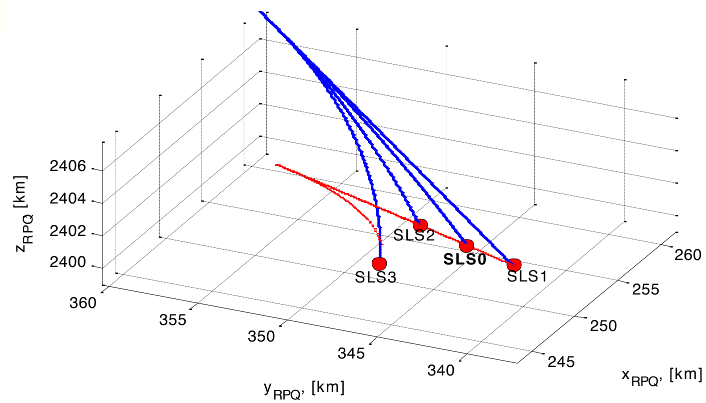
- The guidance algorithm is a terminal point guidance, based on the **E-Guidance** method, which solves a two-point boundary value problem to guide the vehicle from its current state to the desired target state (which can change during flight), in a specific time-to-go (Tgo).

$$\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} \frac{4}{T_{go}} & -\frac{6}{T_{go}^2} \\ -\frac{6}{T_{go}^2} & \frac{12}{T_{go}^3} \end{bmatrix} \begin{bmatrix} V_{Y_{LS}} - V_Y \\ Y_{LS} - \left(Y + V_Y \cdot T_{go}\right) \end{bmatrix}$$



- Tgo is computed to erode the vehicle's ground velocity with a constant horizontal acceleration. This acceleration is recomputed each time a retargeting occurs.

- Guidance commands the required spacecraft acceleration to attain the desired conditions at landing site.



Retargetings at high altitude

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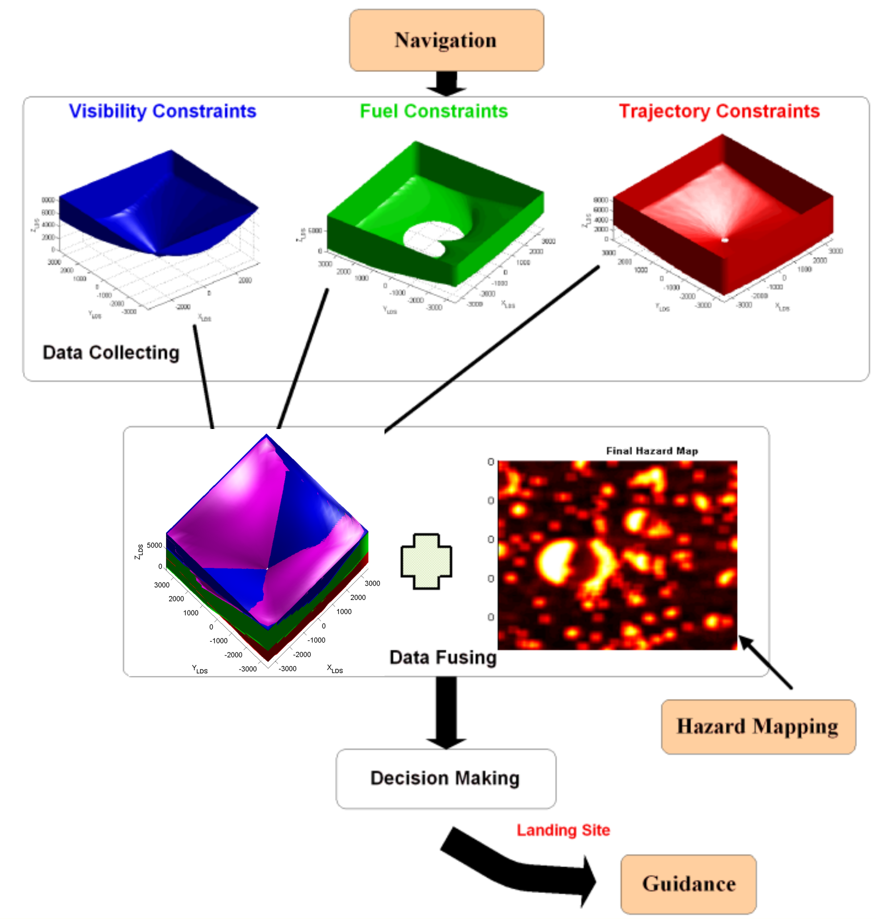
HA Design: Piloting

Piloting algorithm main phases:

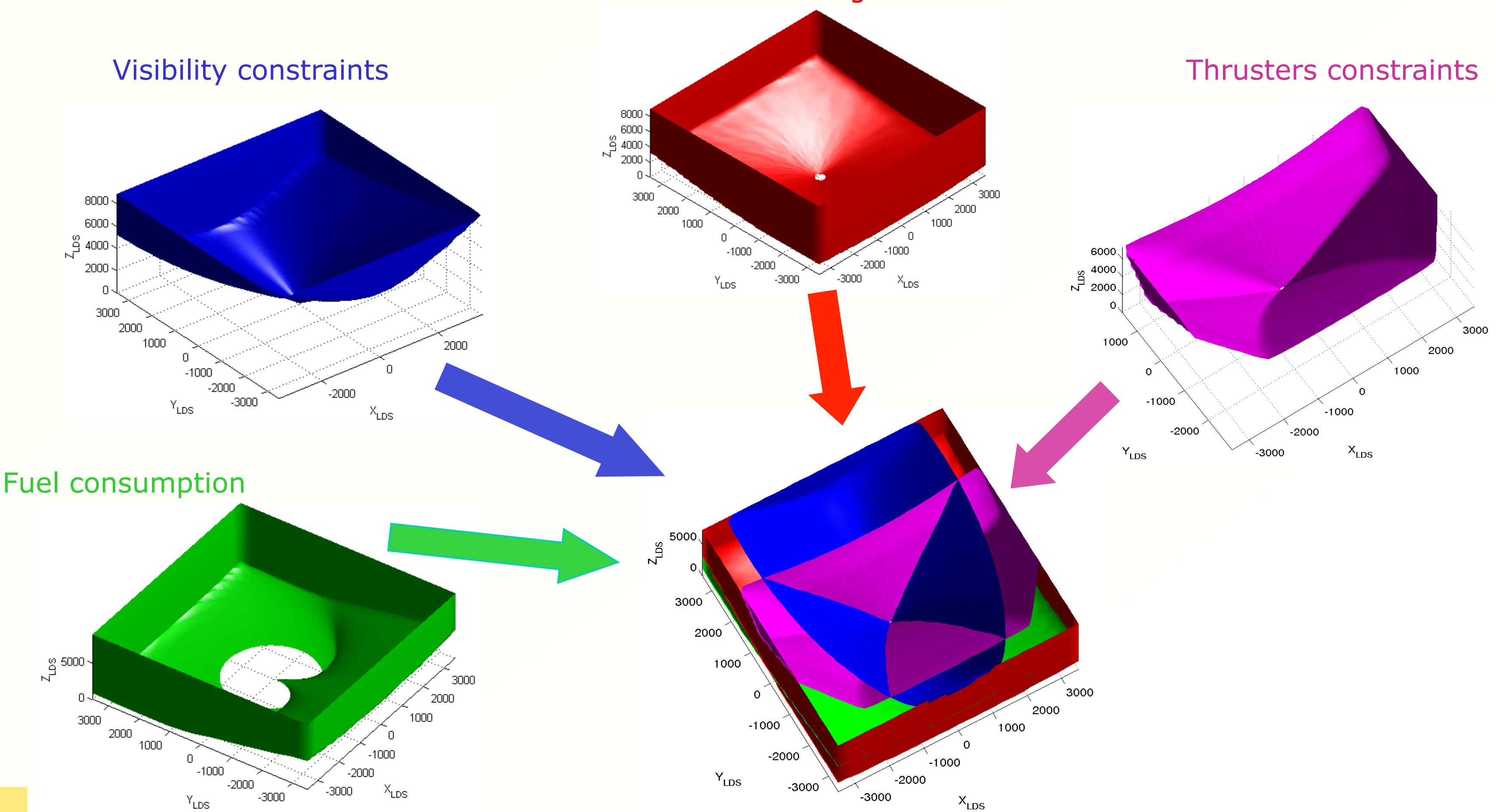


- **Data Collecting**: refers to gather all available information useful to assist the decision of a safer LS. Each candidate to LS is scored according to the following tests:
  - » Trajectory constraints test
  - » Propulsion constraints test
  - » Visibility constraint test
  - » Fuel constraints test
- **Data Fusion**: the previous scores are merged into a 'Global Score Map' also considering risks scores.
- **Decision Making**: when the current LS is considered unsafe, a retargeting occurs if:
  - » the candidate site is significantly better than the current target.
  - » the same candidate site is chosen for some iterations.

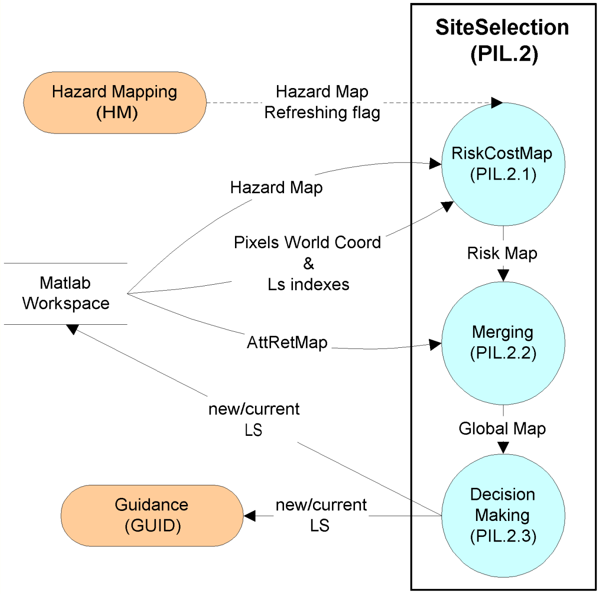
HA Design: Piloting

- **Considering the current guidance scheme the “Attainable area” around the nominal landing site can be evaluated in terms of:**

Crashing constraints



- **Site Selection function**
  - Risk Score Map
    - Determine the risk score for the current LS within the Hazard Map taking into account the GNC dispersion
    - If the current LS is found to be safe the SiteSelection function is terminated being its output the current LS
    - If the current LS is found to be hazard, the same computation is performed for each HM matrix element
  - Merging
    - Generate the global score map by merging the Attainable Retargeting Map and the Risk Map
  - DecisionMaking
    - Select a safe LS

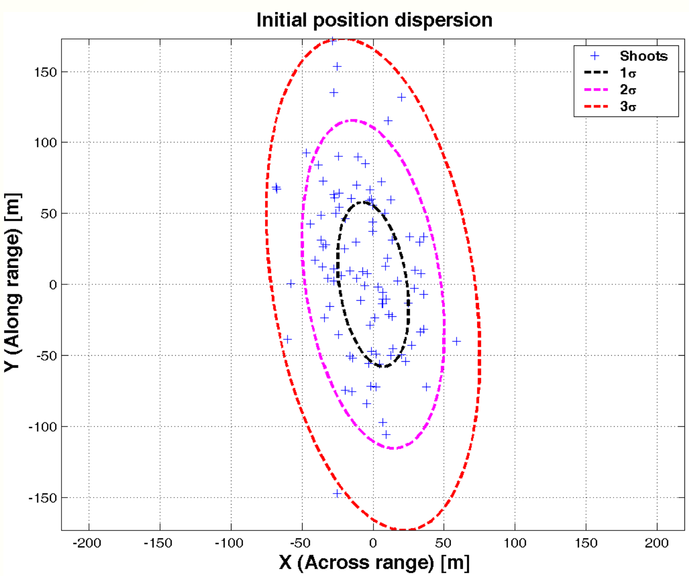


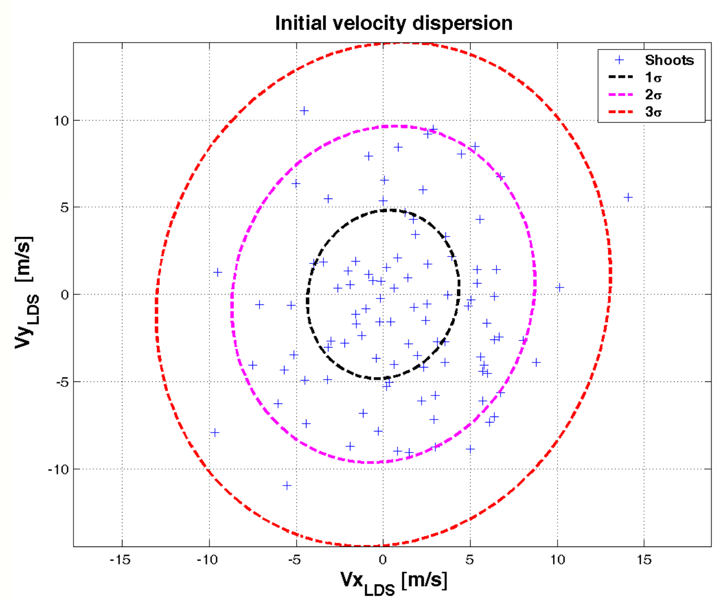
- **Methogology:**
  - G&C Validation with Navigation performance model
  - Piloting robustness
  - HA Closed Loop test
  - SW Profiling towards OB Implementation

G&C Performance assessment (1/3)

- **Navigation implemented as vision-based navigation performance model (Astrium)**

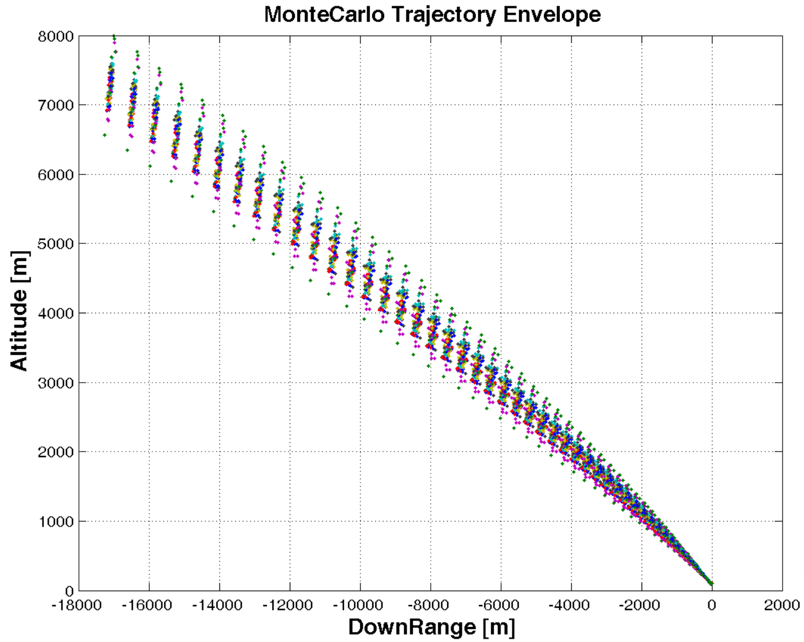
- **Guidance performances have been assessed with respect to Navigation error at the high gate**
  - X-Pos = 20 meters (1σ)
  - Y-Pos = 40 meters (1σ)
  - Z-Pos = 231meters (1σ)
  - Whereas the velocity knowledge error equal on the three axis:
    - Vx=Vy=Vz = 4.5 m/s (1σ)





G&C Performance assessment (2/3)

- **G&C Performance**




```
======================= M O N T E C A R L O   A N A L Y S I S =======================
=                                                                                   =
=   Test Case:                              GNC_100                                 =
=   Number of shoots:                           100                                 =
=                                                                                   =
=                                                                                   =
=                           GNC   DISPERSION STATISTICS                             =
= --------------------------------------------------------------------------------- =
= -      VAR                            MEAN                         3-sigma      - =
= --------------------------------------------------------------------------------- =
= -                                                                               - =
= - Pos X LDS [m]                      21.957                         4.629       - =
= - Pos Y LDS [m]                     -11.975                        15.906       - =
= - Pos Z LDS [m]                      -4.422                         1.915       - =
= -                                                                               - =
= - Vel X LDS [m/s]                    -0.818                         2.767       - =
= - Vel Y LDS [m/s]                    -0.036                         0.074       - =
= - Vel Z LDS [m/s]                    -0.203                         1.836       - =
= -                                                                               - =
= --------------------------------------------------------------------------------- =
=                              NAVIGATION KNOWLEDGE                                 =
= --------------------------------------------------------------------------------- =
= -      VAR                            MEAN                         3-sigma      - =
= --------------------------------------------------------------------------------- =
= - Pos X LDS [m]                     -22.355                         3.823       - =
= - Pos Y LDS [m]                       9.036                        16.655       - =
= - Pos Z LDS [m]                       5.201                         0.738       - =
= -                                                                               - =
= - Vel X LDS [m/s]                    -0.275                         0.080       - =
= - Vel Y LDS [m/s]                     1.364                         0.252       - =
= - Vel Z LDS [m/s]                    -0.147                         0.105       - =
=====================================================================================
```

G&C Performance assessment (3/3)

- **Apportioning of the different GNC functionalities to the overall dispersion**

SUMMARY OF GNC DISPERSION AND SUBSYSTEM APPORTIONING				
CASE	POSITION [m]		VELOCITY [m/s]	
	MEAN	STD	MEAN	STD
GNC	25.40	5.56	0.84	0.3
G	0.52	0.03	0.46	0.02
GC	0.56	0.27	0.62	0.05
GN	24.58	4.25	0.22	0.15

- **N: Performance model of vision based relative navigation (Astrium)**

HA closed loop performance assessment (1/3)

- **VBNAT+HA in closed loop with PANGU:**
  - PANGU used to generate an artificial planet surface.
  - Monte Carlo Analysis shooting on the initial dispersion on position and velocity
  - GNC error at landing 10 meters (1σ)

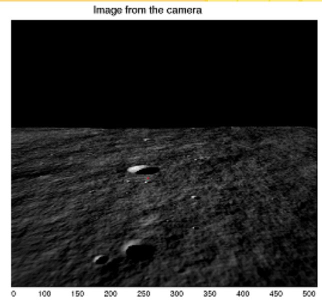


Figure 1 Moderate scene: at HG

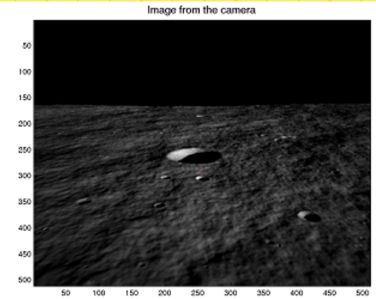
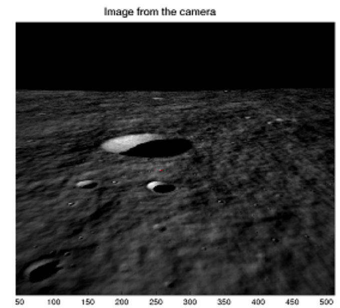


Figure 2 Moderate scene: 15s after HG



ure 3 Moderate scene: 25s after HG

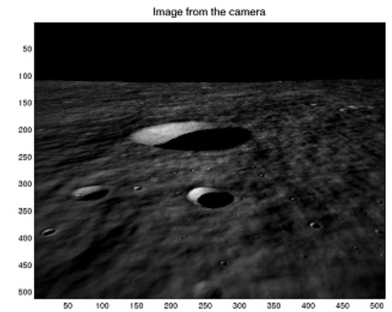
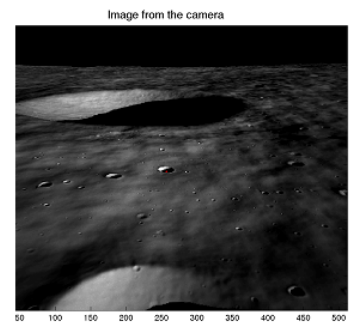


Figure 4 Moderate scene: 30s after HG



ure 5 Moderate scene: 40s after HG

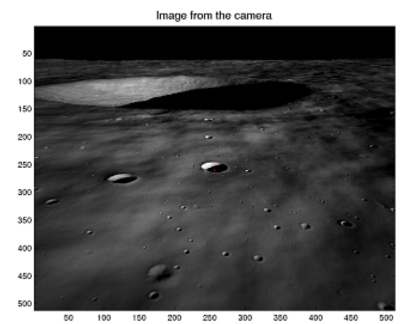
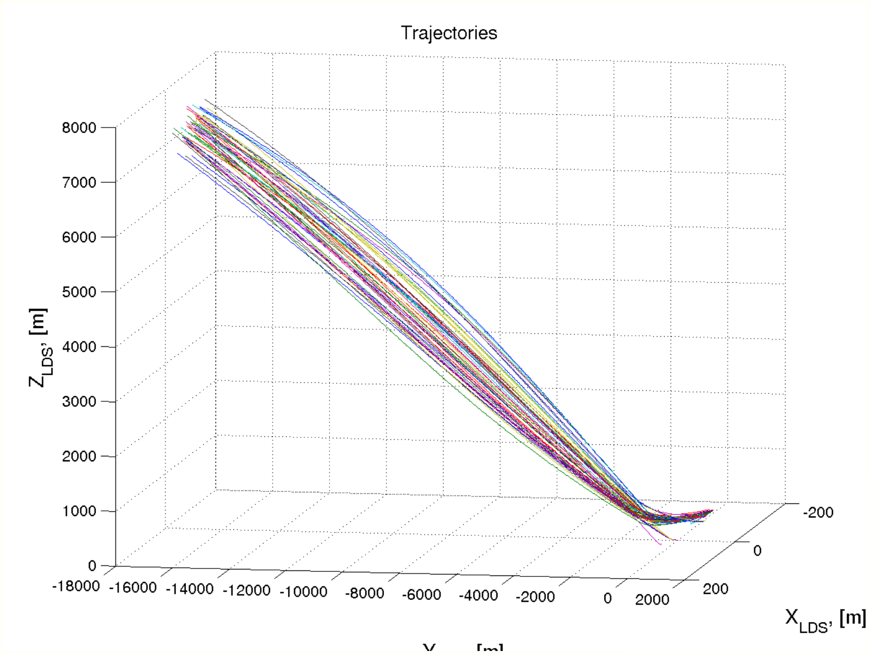
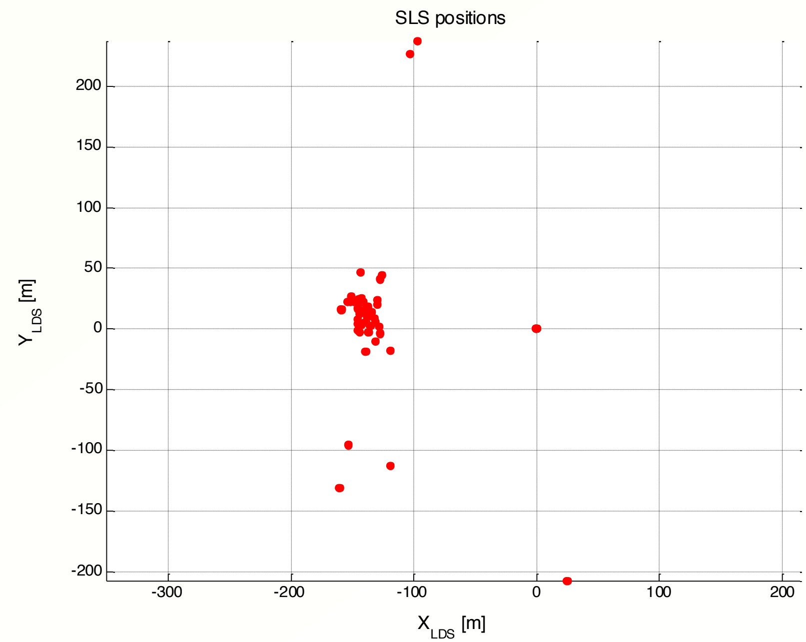


Figure 6 Moderate scene at LG

HA closed loop performance assessment (2/3)

- **Monte Carlo campaign for Piloting validation:**
  - GNC error at landing = 10m (1-σ)
  - LS Retargeting Dispersion is in the order of 50 meters (1-σ)

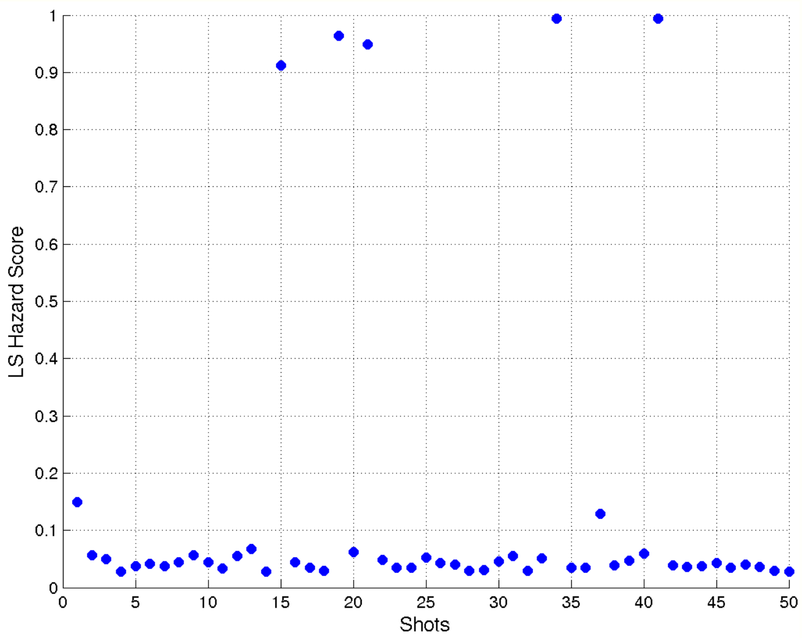




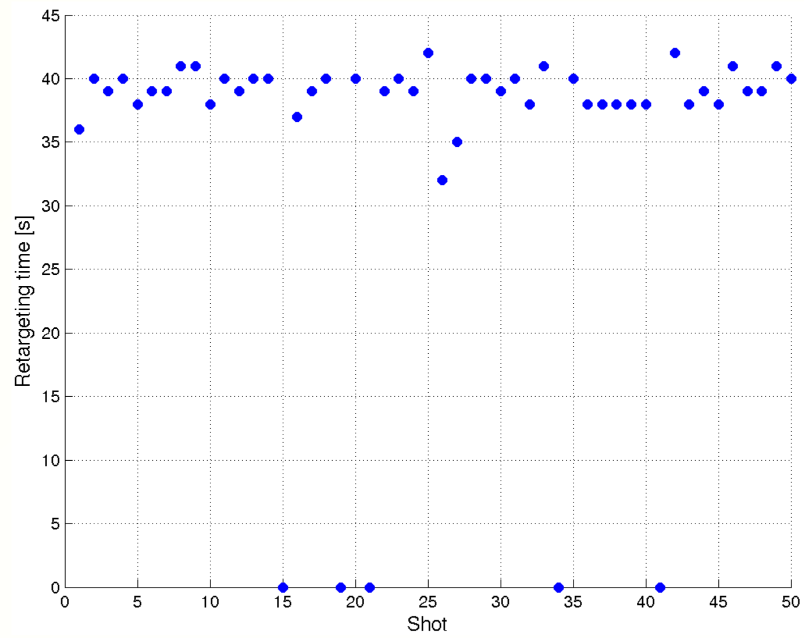
HA closed loop performance assessment (3/3)

– Retargeting Consistency Analysis:
  - Most of the retargeting are commanded with a minimum dispersion in Hazard Score and retargeting time

LS Hazard Map Score



Retargeting Time



- **Processing budget**
  - Assessment of computing resources required by camera-based Hazard Avoidance function including:
    - » Hazard Mapping
    - » Piloting
    - » Guidance
  - Estimated budget per run: 1.3×10^9 cycles in LEON processor.

HA function	Cycles	Ratio [%]	LEON (25Mhz) [sec]	LEON3 (250Mhz) [sec]
PIL.1	3.2×10^7	2	1.3	0.1
HM	9.9×10^8	75	39.6	4.0
PIL.2	3.1×10^8	23	12.4	1.2

  - Hazard Mapping constitutes the major bottleneck: ~75 %
    - » Very intensive image processing algorithms.
    - » Implementation in dedicated hardware or multiple processors would be recommended.

HA in a Mars Landing Scenario(1/2)

- **HA developed for Mercury scenario (similar to Moon)**
- **Applicability to Mars: major impact is on the Hazard Mapping component.**
- **The more relevant items are:**
  - Atmosphere: Dust, clouds, fog
  - Terrain
    - Topography, optical characteristics
    - Terrain requirements:
      - Boulders larger than 20 cm
      - High slope areas (20 deg)
      - Less than 10% of hazard free terrain
  - Trajectory: Terrain observation angle
  - Illumination conditions
    - Sunlight incidence angle
    - HA requirements:
      - Daylight: 5 - 87 deg incidence angle

- **HA tailoring needs for different landing scenarios**

	Moon	Mars	Impact on camera-based HM perfromance
Atmosphere	None	Present	➢HA availability limited by clouds and dust storms. ➢Atmosphere introduces a constant, additive component in the terrain illumination. The algorithms are reasonably insensitive to this component.
Terrain	Rougher	Smoother	➢HA perfroms better in smoother terrains. ➢Self-tuning nature of algorithms allows perfromance to be independent of albedo.
Trajectory	Shallower	Steeper	➢More vertical obervation angle improves performance. ➢Camera mounting angle on S/C can also be tuned.
Illumination	Daylight	Daylight	➢Worst-case illumination angles are shallow. Shadows have a very detrimental impact. ➢Higher angles (up to a point) provide better performance.

- **Apart from more limited availability of HA, when compared with Mars, the Moon/Mercury scenario is more demanding for the capabilities of the HA system.**

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Conclusions

- A complete Hazard Avoidance system has been designed, implemented and tested under realistic conditions in VBNAT in closed loop with PANGU.

- **Hazard Mapping**: The computed Hazard maps show that dark areas, rough terrain and boulders are well detected also with poor illumination condition (low sun elevation angle).

- An **E-guidance** law with a time-to-go formulation designed for retargeting purposes has been implemented while a simpler guidance scheme to provide realistic information for the piloting module is used.

- A simple but efficient **Piloting** algorithm has been conceived and implemented in straight relation with the guidance algorithm and available hazard maps. It has been successfully tested in scenarios with a high number of hazards on the terrain.

- No major modifications are required for the HA developed concept when migrating it to an atmospheric **planetary landing scenario** (e.g Mars). Most of the impact is expected at IP level to take into account the atmospheric scattering

Acknowledgements

– The work here presented was done under ESA/ESTEC contract for the study of Visual Based Relative Navigation Techniques Framework (VBRNAV).

– In this study, INETI – the Portuguese National Institute of Engineering, Technology and Innovation (LAER, Aerospace Laboratory) - was responsible for the development of the Hazard Mapping algorithms.

– Astrium provided a vision-based Navigation performance model.

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Backup slides

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HA in a Mars Landing Scenario

- **Atmosphere**
  - The presence of clouds, fog, severe dust storms, or other atmospheric phenomena that completely prevents the observation of the ground is a critical point.
  - Unfortunately, nothing can be done when in the presence of such obstacles, and therefore HA cannot be available during a landing with these conditions.
  - In a more benign atmospheric setting, the sunlight that is scattered in the atmosphere makes it behave as an additional illumination source that has a constant intensity. This additive bias is hard to estimate from the images.
- **Terrain**
  - Mars has a dynamic atmosphere and erosion has been playing a role in smoothing the surface.
  - Smoother surfaces are required for the Shape From Shading algorithm that is used by the Slope Mapping function to reconstruct the terrain topography from the camera image
  - Potential differences in optical terrain characteristics are probably not so relevant given the self-calibrating nature of the HM algorithms.

HA in a Mars Landing Scenario

- **Trajectory**
  - For all image-supported algorithms, the axis of the camera should be as vertical as possible in order to minimize distortion perspective and to reduce the variability between pixel areas. In fact, for pixels with widely different geometrical contents, the measured irradiance is an average of the cosine of the illumination angle with each individual pixel footprint.
  - Recovering slope is impossible, because $\langle \cos i \rangle \neq \cos \langle i \rangle$, where i is the angle between the normal to the surface and the Sun direction.
- **Illumination**
  - Landing must take place in day time. Shadows are a significant problem and the algorithm should not be used when shadows eventually dominate the image – as a along line algorithm, the integration of the differential equation is severely damaged whenever the signal drops to zero, discontinuously.