THE MOONTWINS MISSION CONCEPT : AN AFFORDABLE AND SCIENCE ATTRACTIVE EUROPEAN MISSION TO VALIDATE MSR SOFT LANDING AND HAZARD AVOIDANCE TECHNOLOGIES

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ABSTRACT

In the context of ESA Aurora Next Science and Technology Mission (NEXT) programme, aimed at preparing the participation of Europe to Mars Sample Return (MSR), ASTRIUM – with the scientific support of the Institut de Physique du Globe de Paris (IPGP) and DLR, and with SENER and Deimos as industrial partners – has conceived an innovative, efficient, affordable and scientifically attractive mission: the MoonTWINS mission. This acronym stands for "Moon Technological Walk-Through and In-situ Network Science". It consists in launching on Soyuz-Fregat two identical soft landers to the Moon that would first demonstrate autonomous Rendez-Vous in-orbit GNC technologies and operations around the Moon, and then achieve a soft precision landing on the Moon surface with hazard avoidance. This would represent the first opportunity for Europe to validate vision-based and LIDAR technologies that ESA is currently pre-developing through its on-going TRP studies, for preparing future planetary probes missions. At science level the landers would carry each a valuable geo-science instruments package, including a high resolution seismometer developed by IPGP, and at least one lander would be targeted to a Peak of Eternal Light at the Pole, marking the first step for preparing the future manned exploration of the Moon by visiting a candidate landing site for a permanent lunar base.

1. INTRODUCTION

In the frame of its AURORA Exploration programme, ESA has initiated in spring 2007 several pre-phase A studies aimed at defining MSR precursor mission concepts, whose main objectives are to prepare Europe to take an active role in the future MSR international mission, through the early demonstration of key technologies required to bring back samples of Mars to the Earth in the 2020-2030 time-frame. In addition to the technology demonstration objective, the MSR precursor mission concepts must exhibit a real science interest, and be compliant with an overall cost budget within 400M€. ESA then intends to down-select the best mission concept and submit it for approval at the 2008 Ministerial Council, for a launch as early as 2015, two years after the ExoMars mission (see Figure 1). Technologies that should be focused on must complete the ones already endorsed by ExoMars, therefore Planetary Entry, Descent and Soft/Precision Landing, Planetary Ascent, autonomous Rendez-Vous and Docking / Capture are especially targeted. High speed Earth Re-entry was already covered in previous ESA studies. Low Earth orbits, the Moon, Mars, or even large Near Earth Objects or Phobos, are considered by ESA as appropriate mission targets.

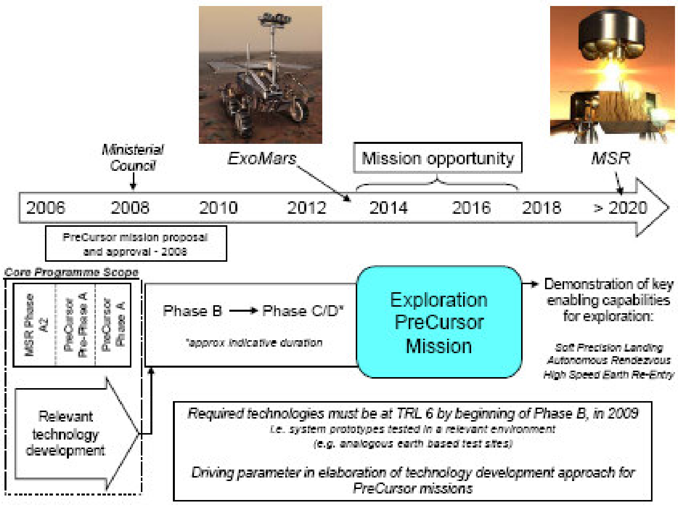

Figure 1. ESA Aurora Next Science and Technology Mission Programme

This paper first describes the rationale behind the MoonTWINS mission concept; in terms of technology demonstration goals, Moon science and exploration objectives. Then the mission architecture and system preliminary design is further detailed. The soft precision landing and hazard avoidance technologies demonstration concepts are especially highlighted, being relevant to a wide range of planetary landing probes.

2. MOONTWINS SCIENCE AND MSR TECHNOLOGY DEMONSTRATION OBJECTIVES

The MoonTWINS mission concept consists in two quasi-identical lunar landers launched on a single Soyuz-Fregat launcher from Kourou. It presents a great potential for enhanced lunar science and MSR technology efficient demonstration, as described hereunder.

2.1. MoonTWINS Potential Science Objectives & Payload Instruments

At this stage of the project no science payload definition nor mission science objectives were specified from ESA. During the study, IPGP performed a detailed survey among the Moon European Scientific Community to define potential science objectives for MoonTWINS and corresponding payload strawman models in support of the spacecraft design. Three types of scientific objectives were retained :

- **Science of the Moon goal :** determination of the crustal and interior structure of the Moon, by a multi-parameter approach determining the heat flow, the seismic velocity and attenuation, the electrical conductivity and density. This will allow to determine in-fine the mineralogy and thermal state of the Moon interior and to better understand its formation and evolution.
- **Science on the Moon goal :** determination of the electromagnetic noise on the far side of the Moon in the LF frequency domain and radio-astronomy survey.
- **Exploration goal** : analysis of the Environment of the Moon near the area where a future permanent manned base might be located. The parameter to be measured is the radiation, frequency of micro-meteorites impacts and seismic hazards, with the corresponding payload elements being a radiation sensor, a micro-array of short periods seismic sensors and a very broad band seismometer.

All these different science goals could be achieved with the payload elements listed in Figure 2. However due to payload mass and power allocations constraints stemming from the mission concept, it is probable that prioritization would become necessary with the Agency and scientists at a later stage of the project.

Instrument	Mass (Kg)	Mean Power (W)	Science objectives	Comments
Moon geophysics (8.6-15.7Kg)				
3 axis Very Broad Band Seismometer (VBB)	4.2	0.7	Deep structure of the moon, analysis of the shallow moonquakes, crustal thickness lateral variations, detection of SQMs	20x more sensitive at the frequency of Apollo LP (0.5 Hz) and larger dynamic/bandwidth. Based on GEP instruments. Acquisition common to SP. Include I/F and cover
3 axis Short Period Seismometer in single (SP) or local Network (NSP)	0.4 or 3	0.2 *or* 0.5	Crustal and regolith structure in the vicinity of the landing sites, detection and characterisation of micro-meteorites *or* Subsurface and regolith structure in the vicinity of the sites, detection and characterisation of micro-meteorites	10x better at the peaked frequency of Apollo SP (8Hz, 0.5 10^{-8} $ms^{-2}/Hz^{1/2}$) and larger dynamic/bandwidth. Based on GEP instruments *or* 3 x 1kg micro-penetrators with SP micro-seismometers and telemetry. New development
Geodesy experiments (GEO)	1.5-5	0-5	Measure parameters of the dynamics of the Earth/Moon system, including Moon librations and tidal deformation with implications for Lunar deep structure.	10x-100x better than results from the Laser Passive detectors, depending on the technology. Possible technologies are Ka-band transponders, passive Laser reflector or Active Laser.
Magnetometer (MAG)	0.75	0.15	Interaction of the Earth magnetotail and solar wind with the Moon, magnetic sounding of the Moon	20x better resolution than Apollo (0.01 nT). Mass for dual magnetometers depending on the technology. Magnetometer put on the surface. Either single magnetometer plus dedicated deployment or dual magnetometers using the robotic arm.
Mole/Heatflux/densitoemeter (MOLE)	1.9	0.1	Measurement of the heat flux, determination of the bulk content in radioactive elements, heat conductivity and density of the regolith	5 meter depth penetration instead of 2.3 m (Apollo 17). Based on GEP instruments
Radio-astronomy (2.50Kg)				
Radio-astronomy Receiver/GPR (RAS)	2.5	1	Regolith structure beneath the landing sites, detection of radio flashes from ultra-high energy cosmic rays and neutrinos hitting the Moon	Passive/active mode in the 0.1-30 MHz bandwidth. Based on ExoMars WISDOM and GEP and Earth LOFAR technology
Sun/Mon Environment (2.55 kg)				
Radiation sensor (RAD)	0.55-0.75	0.75	Measurement of the radiation level on the Moon surface	Several Technology available, including those developed by GEP and for human mission
Context/deployment (4.25 Kg)				
Camera (CAM)	0.75	N/A	Verify landing site location and instrument deployments, study visual characteristics of rocks and soil at the site.	Micro-camera system based on previous ESA landers technology, in addition to those of the landing and RDV systems.
Deployment arm (ARM)	3	N/A	Deployment of the geophysical instruments on the Moon surface	From ExoMars GEP accommodation studies

Figure 2. Potential Science Payload Instruments for MoonTWINS

Among the potential science payload instruments, the VBB and SP seismometers are of special interest, because they would not only monitor the flux of meteoroides and micro-meteorides impacting the Moon, which is of importance for its future manned exploration, but they would also contribute to solve unanswered questions about the Moon interior : what is the mineralogy of the mantle, how do crustal and mantle structures vary from one region to another, and what are the physical properties of the very deep interior. This will be made possible by recording with a high sensitivity the broadband seismic data of deep moonquakes at two different stations, thus extending the existing Apollo network, especially at high latitudes (see Figure 3).

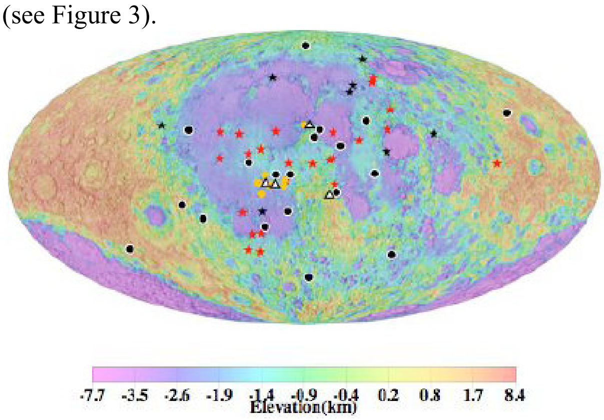

Figure 3. Seismic events recorded by Apollo stations (white triangles)

Furthermore, the seismometers already exist at a breadboard development level for Mars applications (Figure 4) and can operate continuously with a very low power consumption, which is an important asset for MoonTWINS, especially during the lunar night.

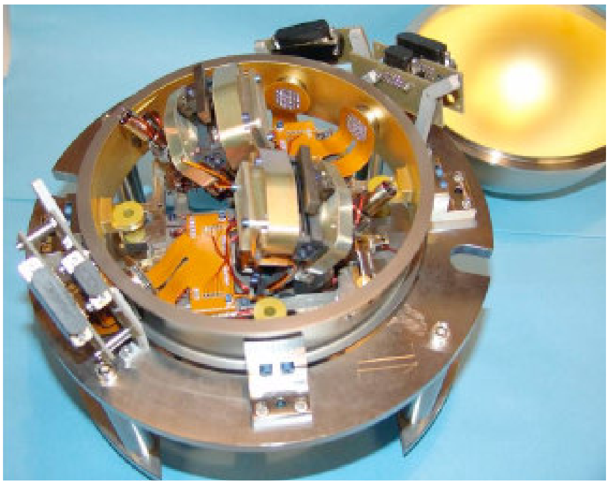

Figure 4. 2-axis VBB Sensor Sphere Breadboard

A radiation sensor would also cover the exploration goal, through the assessment of radiation hazards, and science objectives, especially the interaction of the Moon with the Sun.

Finally, a heat flux mole and a magnetometer would efficiently complete the payload for fulfilling geophysics science objectives, again with a modest power consumption and a good technology readiness level (see Figure 5).

Figure 5. Heat Flux Mole DLR Breadboard Model

Passive reflectors could also be easily accommodated on MoonTWINS landers in order to enhance the Moon Geodesy science currently limited to measurements to the near-equatorial Apollo landing sites.

A Radio-astronomy experiment installed at a lunar pole or near the limb (to be partly hidden from the Earth) would also be very attractive to prepare larger scale payloads for future missions, but the state-of-the art technology for the receivers and antennas deployment devices is probably less advanced than the other instruments.

For what concerns candidate landing sites, there is a consensus for targeting a Peak Of Eternal Light at a lunar pole for one of the two landers, because not only this has a scientific interest on its own (especially for seismic measurements, radio-astronomy and geodesy), but also because it will most probably be the preferred site for the future manned lunar base. MoonTWINS could therefore be a pioneer mission to characterize such a landing site and properly assess the hazards and technological constraints for future Moon exploration vehicles and crews. The rim of Shackleton crater at the South Pole shown on Figure 6 is a good candidate.

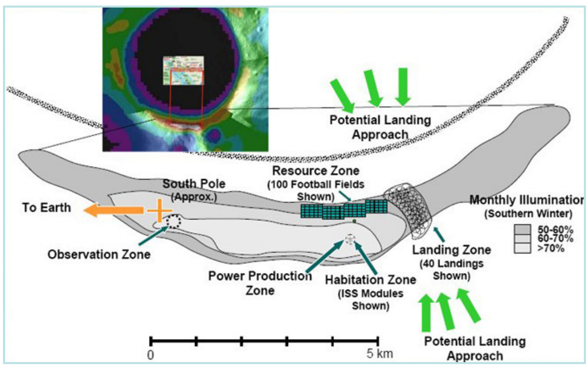

Figure 6. South Pole Peak Of Eternal Light

For the second landing site, scientists expressed the interest to place the lander near the limb, well away from the Apollo sites, in order to optimize the science return.

2.2. MoonTWINS Potential for MSR Technology Demonstration

The MSR technologies potentially deserving a flight demonstration in the frame of the ESA NEXT MSR Precursor missions are the following :

- Planetary Entry, Descent and Soft Precision Landing
- Planetary Ascent
- Autonomous Rendez-Vous and Docking or Capture
- Sample Collection
- High Speed Earth Re-entry
- Sample Recovery

The last two technologies are obviously linked to a Sample Return leg which can definitely not be part of the MoonTWINS mission concept due to an insufficient launch mass performance. Planetary Entry, Descent and Soft Precision Landing on the Moon can of course not be fully representative of a Mars landing mission because of the absence of an atmosphere, however the powered descent phase, following the separation of the lander from the parachute, can be efficiently demonstrated with a Moon lander. For the same reason, the MSR Mars Ascent Vehicle technology can not be fully demonstrated on the Moon, although a Moon lander hopping manoeuvre could partially validate operational aspects of an autonomous launch.

Sample Handling, Transfer and Collection can probably be demonstrated on a Moon mission but also partly on the Earth or in zero-g conditions, in the International Space Station for example. Furthermore accommodating such a technology on MoonTWINS landers would probably take away too much mass resource from the actual science payload.

Therefore it makes no doubt that the best MSR technology demonstration opportunities for MoonTWINS are the autonomous Rendez-Vous and the soft precision landing.

- **Soft Precision Landing** : since the MSR landing platform will be probably much heavier than the MoonTWINS lander, the descent propulsion system will not be similar. Only the trajectory Guidance, Navigation and Control system can be common between the two missions, and therefore demonstrated by MoonTWINS. Although nothing is definitive yet, the baseline navigation system pre-selected for MSR is based on a LIDAR (LIght Detection And Ranging), which is therefore retained as a nominal navigation sensor on MoonTWINS. This technology is currently being pre-developed by ESA to a Technology Readiness Level (TRL) of 4-5 through two studies including breadboard models. In addition, it is proposed to validate with the second MoonTWINS lander the other planetary landing technology currently in development by ESA, the vision-based navigation. The two navigation technologies are compatible with hazard avoidance and precision landing, that will also be operationally tested on MoonTWINS
- **Autonomous Rendez-Vous** : .the baseline MSR Rendez-Vous scenario relies on a capture mechanism to catch the free-flying Sample Canister after its release from the MAV. The far range detection of the Sample Canister by the MSR orbiter uses an RF proximity link system and an optical camera, while a LIDAR is used for proximity operations. On MoonTWINS however, the mass of the MSR RV technology demonstration must be minimised in order to reserve enough mass allocation to the science payload, and it has been assessed that the capture mechanism and the RF system can not be part of MoonTWINS. As a consequence the MSR Rendez-Vous technology demonstration will be limited to the far range target detection with an optical camera and the close proximity operations with a LIDAR. In order to save mass, the LIDAR and optical camera used for the Rendez-Vous demonstration will be the same sensors as those used during the Moon descent and landing phase. The MoonTWINS Rendez-Vous demonstration will include a touch-and-go manoeuvre through the landing legs of the two landers, in order to demonstrate the GNC performance at contact, to which the capture mechanism shall be designed for. If associated to a flight qualification of the capture mechanism in zero-g conditions (for example in parabolic flights or on-board the ISS), this could be considered as a complete validation of the MSR Rendez-Vous system.

3. MOONTWINS MISSION ARCHITECTURE

The MoonTWINS mission architecture has been optimised from launch and trajectory analyses results. The candidate launch strategies are a Soyuz-Fregat direct injection in a Lunar Transfer Orbit, or in a GTO-like orbit, or a shared Ariane 5 commercial GTO launch. The applicable transfer strategies are either a direct 5-day conjunction type transfer or a Weak Stability Boundary transfer that can save up to 100m/s on the overall ΔV budget, but adds three months more to the mission duration. All these options were considered in the mission architecture trade-off, with in addition the inclusion or not of a LISA-Pathfinder like propulsion stage, to reduce the propellant loads on the landers (see Figure 7).

	S-F launch in LTO	S-F launch in GTO	S-F launch in GTO	Shared Ariane 5 commercial GTO launch
Launch performance	~2100kg (incl adapter)	~3200kg (incl adapter)	~3200kg (incl adapter)	typ. ~4000kg (without adapter)
Staging approach	No propulsion stage	No propulsion stage	LISA-Pathfinder like propulsion stage	No propulsion stage
ΔV to Lunar Circular Orbit	~900m/s	~1600m/s	~1600m/s	~1600m/s TBC
Mass in Lunar orbit	2 x ~750kg	2 x ~900kg	2x ~800kg +200kg (LISA-PF)	2x ~1200kg
ΔV to Lunar surface	~1900m/s			
Lander dry mass allocation	**~350kg each**	**~450kg each**	**~400kg each**	**~600kg each**
Lander propellant capacity requirement	**~650kg each**	**~1050kg each**	**~400kg each**	**~1400kg each**
Useful Mass Performance	**4th**	**3rd**	**2nd**	**1st**
Mission Costs	**1st (cheapest)**	**2nd**	**3rd**	**4th (TBC)**
Mission complexity and risks	**1st (least complex & risky)**	**2nd**	**4th (more complex composite spacecraft)**	**3rd (more complex trajectory design)**

↑ Baseline

Figure 7. MoonTWINS Mission Architecture Trade-off

The selected MoonTWINS mission architecture baseline is finally a compromise between mission costs and useful mass performance, i.e. the ratio between the landers dry mass and their required propellant capacity. It consists in a Soyuz-Fregat launch in a GTO-like orbit of two identical landers with no propulsion stage (Figure 8). The two landers are separated right after launch (Cluster-like strategy) and raise their apogee altitudes before inserting into a direct Lunar Transfer Orbit. Five days later they achieve a Lunar Orbit Insertion and acquire through a multiple-burn strategy a 150km altitude circular orbit selected to reproduce the MSR Rendez-Vous orbit kinematics. The autonomous Rendez-Vous experiment is achieved on this orbit during the next two months, and then the two landers are targeted for their respective landing sites through a de-orbit manoeuvre.

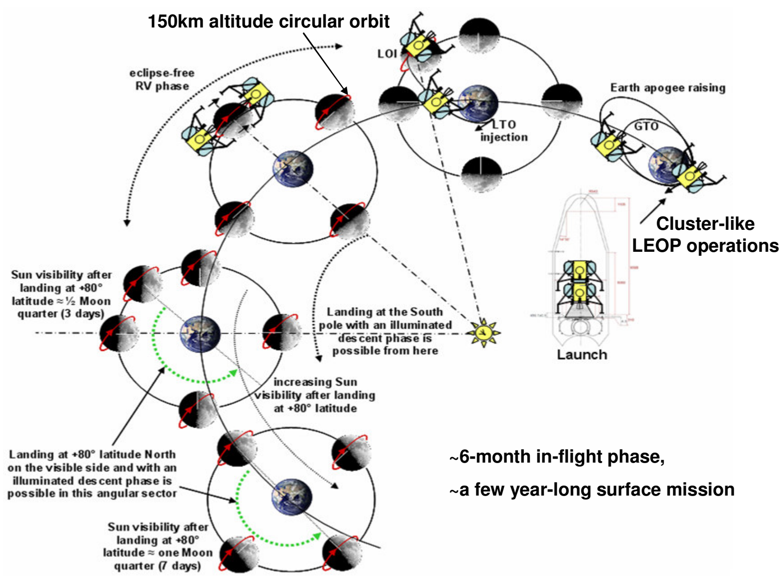

Figure 8. MoonTWINS Mission Baseline Scenario

4. SOFT & PRECISION LANDING TECHNOLOGY DEMONSTRATION

4.1. General Approach

The MoonTWINS mission concept supports an efficient demonstration of two soft landing technologies currently pre-developed by ESA for future planetary landing missions : the LIDAR and vision-based navigation. These two technologies can be tested in MSR-like kinematic conditions by tweaking the fuel-optimal lunar landing trajectory such that a vertical descent is initiated at a few km altitude (Figure 9). Along this trajectory the vision-based navigation can be initiated much earlier than the LIDAR, because the latter is limited by its operational range and adverse viewing conditions due to the low incidence approach. Precision landing can be supported mainly by the optical camera through image correlation techniques early enough in the descent profile. Hazard avoidance can be achieved with the two technologies in the final part of the descent.

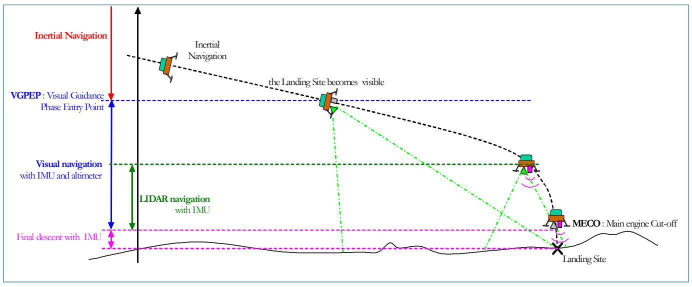

Figure 9. MoonTWINS Descent & Landing Trajectory

4.2. Vision-based Navigation

This technology has been developed by ESA from 2001 through the Navigation for Planetary Approach and Landing studies awarded to an industrial team led by Astrium. A technological break-through has been achieved with a breadboard camera and image processing / navigation algorithms qualified in a real-time environment up to TRL 4-5 (Figure 10). Next year ESA will bring this technology to TRL 5-6 by testing it in a real-world environment on-board a precision landing GNC test facility using a small helicopter. The vision-based navigation technique extracts features points on successive pictures taken at high frequency (20Hz), and processes them in a customized adaptive Kalman filter to derive position and velocity estimates. On MoonTWINS the optical camera will be completed by a simple radar altimeter to enhance the navigation convergence performance and robustness. The vision-based navigation is very attractive for its light-weight and low cost, its only drawback being its sensitivity to illumination conditions.

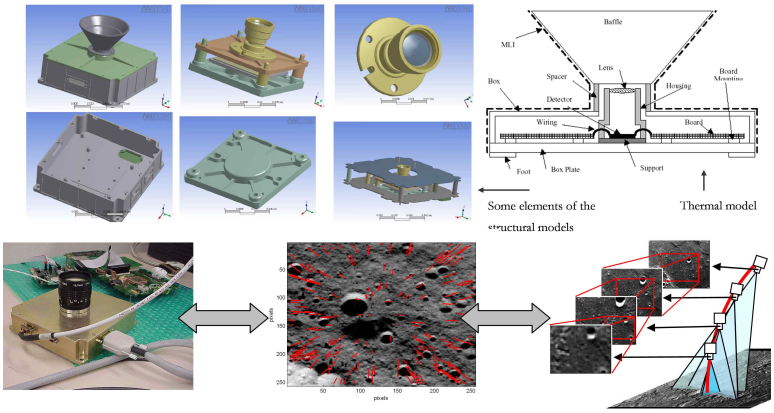

Figure 10. Vision-based Navigation (NPAL study)

4.3. LIDAR Navigation

The principle of the LIDAR navigation consists in measuring the time of flight of a scanning laser beam echoed by the surface during the descent, to construct Digital Elevation Maps and estimate the lander position and velocity vectors through a Kalman filter processing (Figure 11).

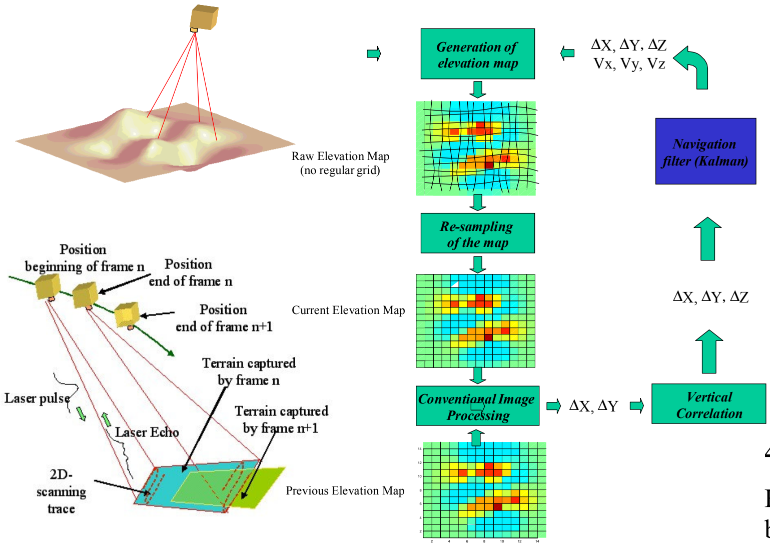

Figure 11. LIDAR Navigation Principle

ESA has initiated this technology first through the full simulation LiGNC study led by Astrium, and now through breadboard developments for Rendez-Vous and landing applications (ILT study). An end-to-end real-world demonstration will follow in 2009 using the same landing test facility as for the vision (LAPS study) to bring the technology to TRL 5-6. Compared to the vision navigation, the LIDAR is more robust to illumination conditions, but is also heavier and more power-hungry.

4.4. Precision Landing

Although not really applicable to MSR (because of descent and landing guidance and control constraints), vision-based precision landing is proposed on MoonTWINS to pave the way for future planetary missions, and because it might be required to land accurately at a Peak Of Eternal Light (for example on a crater rim). This might not be achievable with inertial navigation only, unless a high grade Inertial Measurement Unit is implemented, which is not affordable on MoonTWINS for mass and cost reasons. Vision-based precision landing uses image correlation techniques to match camera images with a 2D terrain model of the landing area stored on-board the spacecraft (Figure 12). Astrium is involved in the study (Optical Flow Navigation System for Landing) that ESA has initiated to master this technology, that will allow to achieve a landing accuracy better than a few tens of meters.

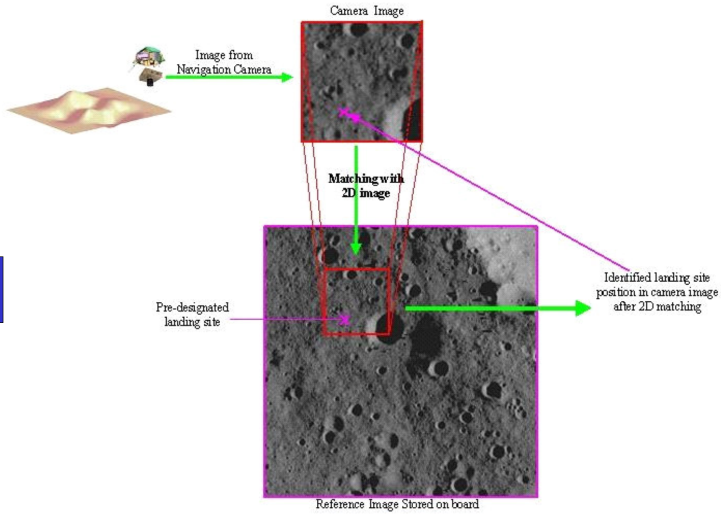

Figure 12. Vision-based Precision Landing Principle

4.5. Hazard Avoidance

Hazard avoidance is assumed to be mandatory on MSR because the landing platform has to land smoothly on an obstacle-free and flat surface area. As illustrated on Figure 13, hazard avoidance can be supported by the two envisaged soft landing technologies and consist in several steps : hazard mapping (identification of shadows, slopes and boulders), targeting (identification of safe and reachable site according to GNC constraints), and trajectory guidance (generation of a new trajectory). Grazing Sun incidence at the South pole will prevent vision-based hazard mapping, therefore the LIDAR is mandatory for the polar lander. ESA has initiated dedicated studies (VBRNAV) at Deimos Energhia to which Astrium has partnered for bringing vision-based hazard avoidance to TRL 5-6 through an ESA sponsored ground demonstration activity. On MoonTWINS hazard avoidance would be performed during the final vertical part of the descent trajectory.

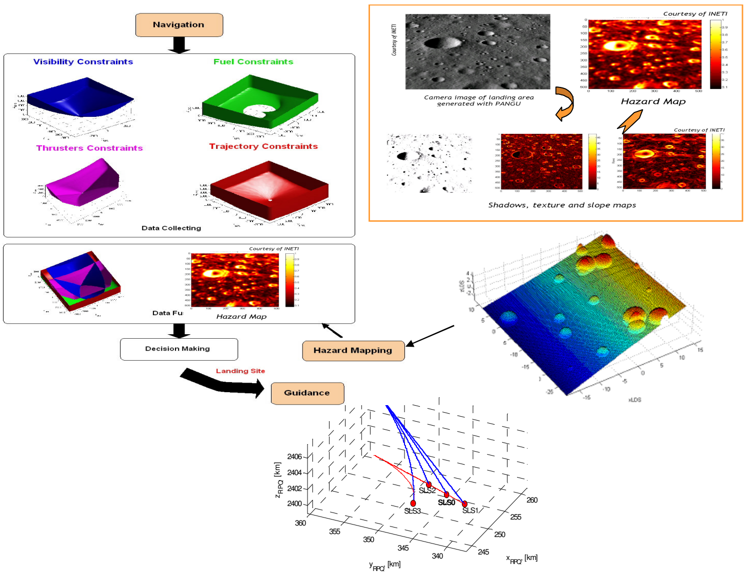

Figure 13. Hazard Avoidance Technique

5. MOONTWINS PRELIMINARY SPACECRAFT DESIGN

A preliminary spacecraft configuration and system design has been assessed during the pre-phase A study. The major system design drivers identified in this exercise are the following :

- launch mass constraint : the 3.2-ton Soyuz-Fregat performance in GTO is the major constraint that leaves no flexibility in the lander design and limits the payload mass allocation to less than 20kg per lander
- propulsion configuration : a highly efficient bi-liquid system is mandatory to support the descent and landing needs. The lander propulsion system relies on the new 500N European Apogee Motor from Astrium-ST (in development for Alphabus) as the central main engine, completed by eight ATV-derived 250N thrusters to enhance the thrust level and modulation capacity.
- power generation and storage constraints applicable to the on-surface phase impose the sizing of the solar array and the battery, designed to provide a few Watts for supporting minimum science operations during lunar nights. An all-around solar array is implemented on the polar lander to maximize the full science operational life-time on the surface.
- thermal control constraints on the surface, especially during the lunar night, impose the use of Radio-isotope Heater Units similar to those foreseen on ExoMars in order to minimize the heater power budget. Furthermore, Apollo-like parabolic radiators are necessary to dissipate the heat during lunar days despite the hot lunar surface

A candidate spacecraft configuration is shown on Figure 14. The spacecraft structure is based on a square box and four external propellant tanks, with payload and avionics equipment mounted on two side walls.

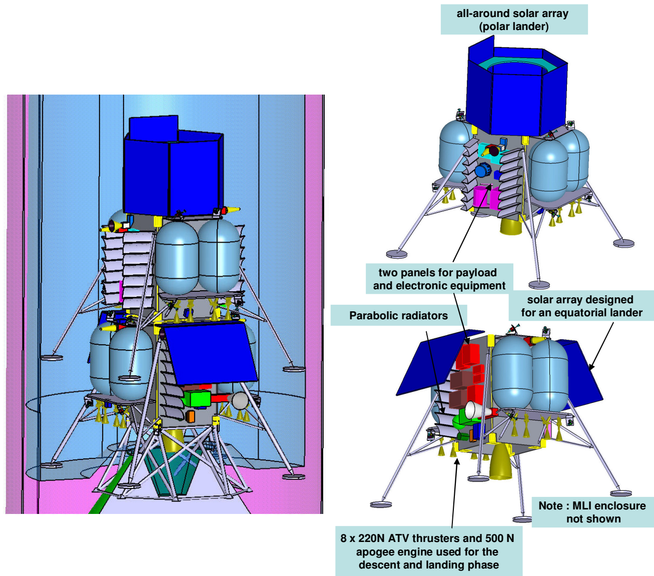

Figure 14. MoonTWINS Candidate Spacecraft Configuration

6. CONCLUSIONS

The MoonTWINS mission concept proposed by Astrium in the frame of the ESA MSR precursor pre-phase A studies would allow to solve several unanswered questions after the Apollo missions concerning the Moon's structure and history, and would provide the first insight on the Moon's deep interior (lower mantel and possible core). It would also represent a major step ahead for Europe in the global Moon exploration program, by potentially achieving the first robotic landing at the site envisioned for the future Manned base. On the technology demonstration perspective, it is a unique opportunity for ESA to validate the two soft landing technologies currently under development in Europe, the vision-based navigation and the LIDAR.

Furthermore, as demonstrated in the past by NASA with highly successful twin spacecraft missions (Voyager, Viking, MER), the presence of two spacecraft that can individually achieve part of the mission objectives is an insurance for mission success and a high value for money invested.