LEDA – A First Step in ESA's Lunar Exploration Initiative

D. Kassing & M. Novara
System Studies Division, European Space Research & Technology Centre (ESTEC),
Noordwijk, The Netherlands

The proposed ESA Moon Programme is based on a phased approach. The current end goal is the establishment – in Phase 4 – of a lunar outpost to serve science and the utilisation of lunar resources. The first phase of this programme of lunar exploration would make a survey of unexplored regions on the lunar surface and an inventory of lunar resources by means of remote sensing and by in-situ measurement. It would also develop a range of technologies of direct benefit for the later phases of the lunar programme. This article summarises the initial results of an ESA study being performed in cooperation with CNES (F) and ASI (I).

Why to the Moon?

The first International Lunar Workshop held in June last year in Beatenberg, Switzerland, defined the overall objectives for a staged, but evolutionary Moon Programme. About 140 representatives of space agencies, scientific institutions and industry from around the World considered plans for the implementation of internationally coordinated programmes for robotic and human lunar exploration. It was agreed that the time is right – scientifically, technologically and financially – to initiate the first phase involving Moon orbiters and landers with roving robots to prepare for 'Science of the Moon' (illuminating the history of the Earth – Moon system), 'Science from the Moon' (for astronomical projects) and 'Science on the Moon' (biological reactions to low gravity and the unique radiation environment). The details are to be found in ESA Special Publications SP-1150 and SP-1170 (available from ESA Publications Division).

The enthusiasm expressed in Beatenberg about the rich opportunities offered by the exploration and utilisation of the Moon was really the trigger for LEDA, ESA's study of a 'Lunar European Demonstration Approach'. It includes a series of in-house and external activities to define an exploration mission consisting of a spacecraft that would soft-land, in the year 2002, on the lunar surface after having been put into orbit by Europe's Ariane-5 launcher. This spacecraft (Figs. 1 & 2) would carry a payload consisting of a rover, a robotic arm, a soil-processing test facility and a number of instruments for making in-situ measurements in the lunar environment (Table 1). All of this must be accomplished within the budget of a medium-sized ESA mission.

A range of mission options, landing sites, spacecraft/rover design concepts and technologies are presently being assessed by a working team of experts from ESA, the French Centre National d'Etudes Spatiales (CNES) and the Agenzia Spaziale Italiana (ASI).

Mission design

Lander missions to the surface of the Moon require a total velocity increment (delta-V) of 3 km/s or more from the initial orbit into which the launcher delivers the spacecraft. Ideally, this initial orbit is a Lunar Transfer Orbit (LTO) with its apogee in the vicinity of, or beyond the Moon. However, the need to transport a significant useful payload to the Moon, combined with the high velocity increment required, implies that relatively large launch masses are needed for this kind of mission (in the order of 3 t or more). One way of containing the launch cost for such spacecraft is to share a launch with a commercial payload bound for geosynchronous orbit; this permits a saving of one third of the cost in the case of an Ariane-5 launch. The lunar lander would be delivered into a 620 x 35 883 km Geostationary Transfer Orbit (GTO) inclined at 7° to the Earth's equator. The available payload mass with a standard Ariane-5 launch, assuming 58% of the total were allocated to LEDA, would be 3330 kg.

Depending on the relative orientations of the apsidal line of the GTO and the line of nodes of the Moon's orbit, the delta-V required for the subsequent transfer varies over a year, as shown in Table 2 (where the corresponding velocity increment for a direct LTO injection is also indicated). Under the most unfavourable conditions, the duration of the transfer is also

Table 1. LEDA mission summary

Objectives	- Europe to soft-land a spacecraft on the lunar surface using ARIANE 5 - Carry a payload to undertake investigations pertinent to future phases of ESA programme - Budget of a medium size mission
Spacecraft	- Mass: 3330 kg in GTO, 1007 kg on Moon surface - Size: diameter 4.1 m, height 2 m - Propulsion: 7 × 400 N, 8 × 10 N thrusters, pulsed-mode operation for thrust modulation during descent - Power: 300 W bus power from 5 m^2 GaAs fixed solar panels (207 W/m^2), 16 kg $Ni\text{-}H_2$ batteries (60 Wh/kg), 5 kg RHUs - Thermal Control: passive + active (radiator louvres) - GNC: 3-axis stabilisation, coarse sun sensor, Inertial Measurement Unit, radar altimeter, Doppler radar, camera vision system - Data: 8 Gbit MMU (video sequence storage) - Communications: 20-W S-band transponder, omni antennas for orbit and landing, 0.5 m high-gain antenna for surface operations - Landing: 4 legs, 0.5 m stroke, 5 m/s vertical speed, <5 g landing shock
Payload	- Payload mass: 200 kg - Payload may include rover, robotic arm, soil processing test facility - In situ measurement payload: soil characterisation, imaging, operational environment evaluation
Launch & Orbit	- Shared ARIANE 5 into GTO (58% of launch mass capability) - Manoeuvres to LLO: perigee, mid-course, lunar orbit injection (total ΔV = 1734 m/s) - Duration 81 days from launch to landing (including lunar orbital phase) - Lunar polar orbit at 100 × 100 km altitude, period 2 hours - Orbit lowering to 15 × 100 km, 1-2 orbits prior to landing, for site survey - Descent & landing (ΔV = 2000 m/s) in Moon South Pole region, 83-85° S, 0-20° W
Operations	- Communications: S-band (2,076/2,255 MHz) - Data volume: 44 kb/s to 4.4 Mb/s, on-board 1:4 video data compression, 2 ESA 15-m ground stations - ESOC operations centre - Operational lifetime: 4 lunar days on Moon surface - No orbital relay, direct communications to Earth (<73% of time)
Programmatics	- ESA cost <350 MAU - Phase C/D start in January 1998, launch in November 2002 - Based on European capability alone (except RHUs) - ESA provides shared ARIANE 5 launch - Payload contributed by National Agencies

Table 2. Comparison of velocity increments for various lunar transfer strategies

<table>
<tr><th rowspan="2">Manoeuvre</th><th colspan="3">Strategy</th></tr>
<tr><th>Via GTO
Short Transfer</th><th>Via GTO
Long Transfer</th><th>Direct to LTO</th></tr>
<tr><td>GTO to LTO Injection</td><td>720</td><td>750</td><td>0</td></tr>
<tr><td>Mid-Course Correction</td><td>120</td><td>310</td><td>0</td></tr>
<tr><td>LTO to LLO (100 × 100 km)</td><td>874</td><td>854</td><td>874</td></tr>
<tr><td>Lowering of Periselenum (15 × 100 km)</td><td colspan="3">20</td></tr>
<tr><td>Descent Manoeuvre</td><td colspan="3">35</td></tr>
<tr><td>Landing</td><td colspan="3">1965</td></tr>
<tr><td>Total</td><td>3734</td><td>3934</td><td>2894</td></tr>
<tr><td></td><td>[m/s]</td><td>[m/s]</td><td>[m/s]</td></tr>
<tr><td>Duration of Transfer to LLO</td><td><29 days</td><td><77 days</td><td>3-5 days</td></tr>
</table>

significantly longer. Up to 50 days may be required to compensate for the Moon's declination above the Earth's equator, plus up to one lunar sidereal period of 27.3 days for phasing with the Moon's angular position. A four-week window occurs just twice per year during which a 'short transfer' is possible (Fig. 3); the corresponding GTO launch mass can be reduced by 7%, and the transfer duration may be up to 50 days shorter, with a somewhat reduced choice of potential launch companions. It is presently considered that the LEDA mission should take advantage of this window.

Other strategies have been considered to optimise transportation to the Moon, including:

- A dedicated launch directly into LTO. Although technically sound, this alternative would be quite expensive, unless a cheaper launcher, such as a Russian Proton, were to be made available.
- A shared launch into GTO with the upgraded Ariane-5 Evolution vehicle (Ariane-5E), which would allow two 3.7 t spacecraft to be delivered to GTO for the same target cost as a basic Ariane-5.
- A shared Ariane-5 launch directly into LTO, together with an exploratory spacecraft bound for the Moon or its vicinity (e.g. for a lunar swingby manoeuvre).
- A shared Ariane-5 launch into Low Earth Orbit (LEO), with a companion bound for the International Space Station, e.g. by sharing a ride with an Automated Transfer Vehicle (ATV).

None of the above options is currently a clear-cut winner, since the most promising ones in terms of performance and cost rely on other, as yet unapproved, Agency programmes (e.g. Ariane-5E or one of the M3 scientific missions). The basic Ariane-5 launch into GTO has therefore been analysed in detail as the reference mission model.

Having reached the vicinity of the Moon, the currently foreseen strategy for LEDA would be to enter a 100 x 100 km polar Low Lunar Orbit (LLO), which would provide the best opportunities for remote sensing and landing-site access. The landing-site area must be known within a given uncertainty (typically, an ellipse of 5 x 10 km). Once the ground track of the spacecraft's orbit comes close to, or crosses this area, the periselenum could be taken down as low as 15 – 25 km. Overflying the landing area at this altitude for the last one or two orbits before descent would allow an onboard vision-based navigation system to assess the morphology of the terrain to a resolution of better than 1 m, so that an obstacle-free spot could be targeted for the landing.

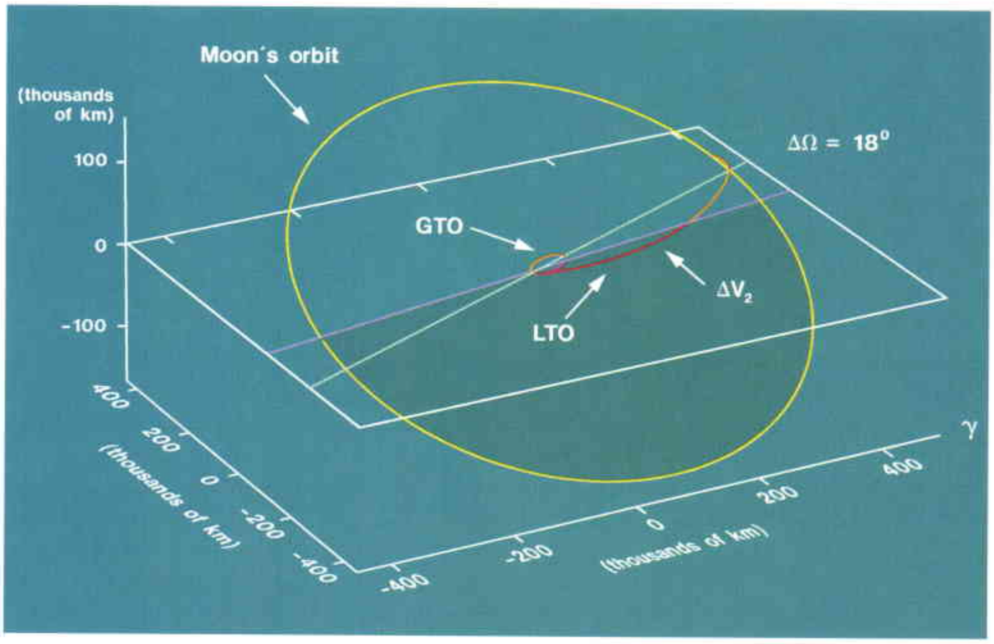

Figure 3. Orbital transfer manoeuvre from GTO to the Moon. When the angle between the GTO apsidal line and the line of nodes of the Moon's orbit is small (18° in this figure), the delta-V required for the manoeuvre is minimised. This condition occurs twice per year for periods of about four weeks

A further burn would initiate the descent trajectory, bringing the spacecraft down to within a few kilometres of the landing site. A terminal burn phase would then begin, during which the spacecraft could be steered towards the target site by the onboard cameras, matching their images against the landing-site images previously stored from orbit. When objects as small as 0.5 m or less are discerned, some hovering could take place, allowing the lander to avoid such obstacles (Fig. 4). Finally, the engines would be cut and the lander dropped from a height of a few metres for a soft landing, with a vertical speed of less than 5 m/s and a shock of no more than 5 – 10 g contained by the landing-gear design.

Landing-site selection

The Moon was extensively visited during the 1960s and 1970s by both automatic and piloted missions. Nevertheless, there are still many sites which were not, or were only summarily investigated and are deemed to be of great interest to the scientific community. For example:

- The polar areas are little known. No lander missions were ever flown at high or polar latitudes, and even orbiter data are scanty for those areas; the Clementine imagery, for example, is limited to a resolution of 100 m and no altimetry data were obtained. Scientific interest in these areas is manifold, ranging from the search for water ice, residue from cometary impacts, which may have survived in the permanently shadowed areas that are likely to exist near the lunar South Pole, to the possibility of installing infrared interferometry devices in these same shadowed, and thus extremely cold, areas. Access to unique geological features, such as the Aitken Basin (covering a large portion of the south polar region) is also a highly regarded opportunity.

- Research into the Moon's volcanic history, radiometric age, and heat flow are areas of investigation not previously pursued, and ones for which the lava-flooded areas to be found at medium/high lunar latitudes (up to 70°) are ideal sites.

Besides the scientific and exploratory interest, technical and operational considerations affect the choice of landing site. The south-polar region, which is of the highest interest, is not very well known, but it appears to be considerably rougher, in general, than lower-latitude sites. Such morphology has several consequences:

- The risk of not finding a suitable, obstacle-free landing site is higher.
- Both the Sun and the Earth will be visible at very low elevations from the landing site, so that both the availability of sunlight and communications with Earth will be very much impacted by local features (peaks, valleys, etc.).
- Operation of a mobile payload (a mini-rover) on the surface will be constrained by the difficult local terrain (slope, size of boulders), and also by the fact that sight of the lander maybe lost very soon after moving away from it.

In particular, it has to be remembered that the regions around the Moon's poles (beyond approx. 83° latitude) periodically disappear from sight for an observer on Earth (the so-called 'optical libration phenomenon'). This phenomenon lasts for half a lunar day, i.e. about 14 Earth days, at the pole itself. Given that the lunar night also has a comparable duration of 14 Earth days, there is an annual periodicity pattern during which the Earth can be seen from the Moon's polar regions during local daytime, as shown in Figure 5. The best conditions only occur for about four months per year, and this would seem to determine the maximum duration for a surface mission to the poles, as well as imposing a 'landing window' at the beginning of the four-month period. Given that there is already a launch-window constraint for a shared launch to GTO, a waiting time in lunar orbit for phasing purposes would thus be necessary.

The low elevation of the Sun also means that solar generators would be required to cope with the full 180° azimuth variation of sunlight direction in order to receive sufficient energy (while at lower latitudes a simple, flat, horizontal solar array may suffice). Also, long shadows reduce visibility, implying that a vision-based landing could only take place around local noon, thereby losing surface-operations time during the preceding morning.

The fact that no high-resolution mapping of polar regions is available to a sufficient level of detail is also a concern. Imaging to better than 10 m resolution will be required to select the areas that are of highest exploratory interest. A digital elevation model, from either stereoscopic imaging, laser or microwave altimetry, is required to assess the safest landing-site conditions. If the mission is to include a search for particular chemical

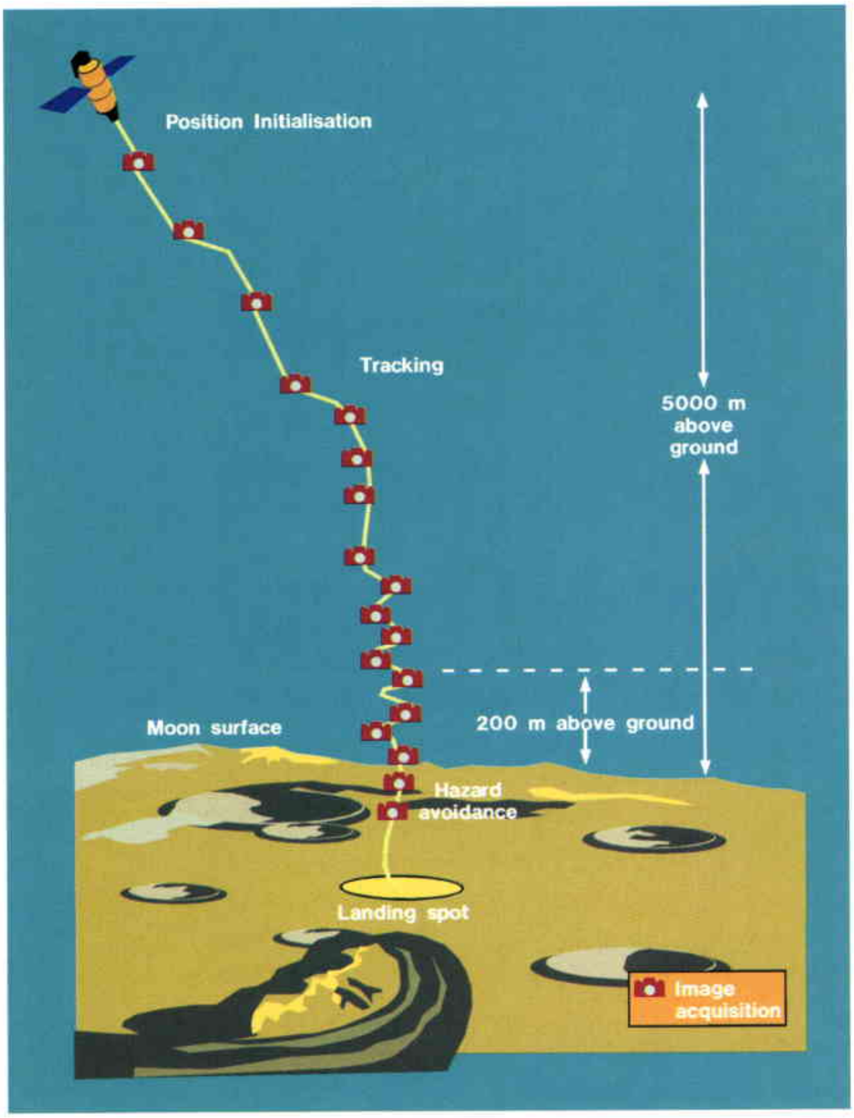

Figure 4. LEDA relies on a vision-based navigation system during the final descent phase. From an altitude of 5000 m, the onboard cameras track a pre-determined landing spot. At 200 m above ground, when obstacles as small as 0.5 m become visible, the navigation system steers the lander to a safe touchdown in a hazard-free area

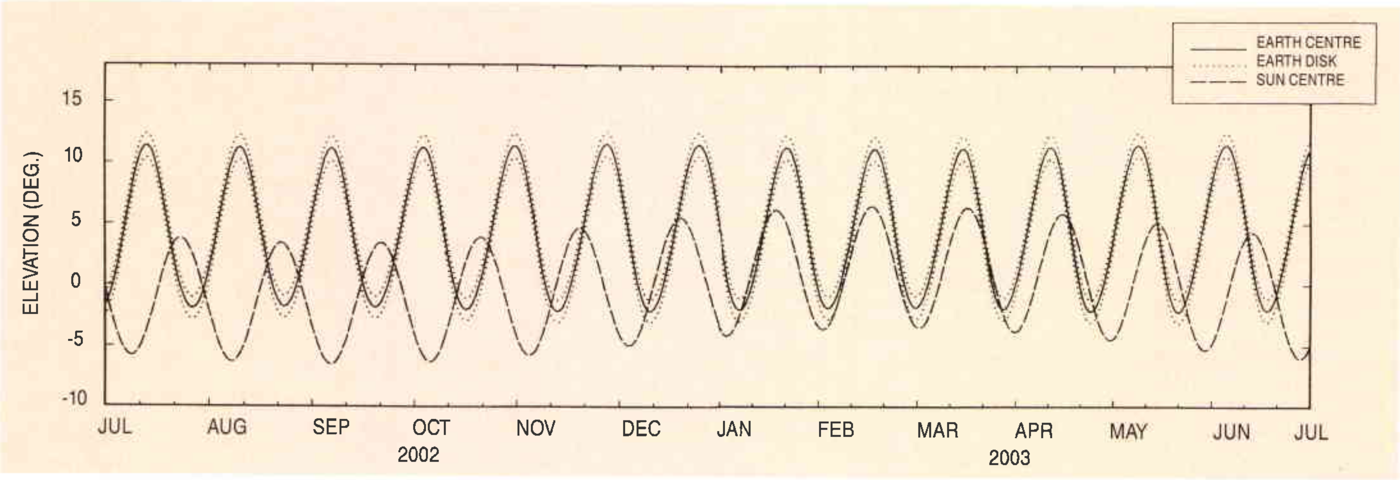

Figure 5. Visibility of Earth and Sun from a lunar landing site at 85° latitude. Elevation of both Earth and Sun over the Moon's horizon varies slightly in different periods, so that simultaneous visibility of both occurs for periods of about 4 months, once a year (e.g. January to April 2003)

species that are rarely found on the lunar surface (e.g. water ice), then remote sensing from orbit will be needed to pinpoint the locations of such species (e.g. neutron detection for the search for hydrogen). Otherwise, the probability of finding them within the limited surface mobility range of the LEDA mini-rover, which is expected to be just a few tens of kilometres, is unacceptably low.

The recently announced NASA 'Lunar Prospector' mission, planned for a 1997 launch, may provide lunar geochemical information crucial to LEDA mission planning. If no other orbital missions to the Moon can be flown to obtain the necessary high-resolution mapping beforehand, LEDA would be required to carry out its own remote sensing. This would have to be limited to the latitude of specific interest, since a global mapping would require a different spacecraft design (i.e. Moon-pointing, instead of Sun-pointing attitude). The 83 – 85° latitude band is currently being taken as a reference, this being the lowest at which access to permanently shadowed areas and to Aitken Basin features appears possible. The landing site would in any case be as close as possible to 0° longitude (near side) for best Earth-visibility conditions.

Should the South Pole landing site turn out to be too risky from an operational point of view, a less demanding site at latitudes lower than 70° could be chosen. It would allow the validation of technologies and operational capabilities required to perform complex tele-operated or automated robotic tasks. Landing on the far side of the Moon (in regions not visible from Earth) would require a Moon-orbiting data-relay satellite and is not financially realistic for Phase 1 of the Moon Programme.

The main characteristics and constraints associated with the various landing sites are summarised in Table 3.

It is therefore clear that, to cope with such a challenging landing site as the South Pole region, a thorough assessment of the technologies required for both survival and operations is a prerequisite before committing to the mission. Whether LEDA would be able to tackle the hurdles posed by the prime landing area near the South Pole, or a safer approach should be taken in a first mission, is an issue central to the current investigations.

Table 3. Comparison of lunar landing-site characteristics

	Thermal Environment	Earth Visibility	Sunlight (Energy)	Landing Opportunities	Exploration Opportunities	Required Data Base
Polar Regions (80°-90° N/S)	-230°/-40° C	Intermittent (50% -100% of the time)	Very low elevation (affected by topography)	14/28-day intervals 4 months per year	Geology Environment Water ice	Mapping Thermal Chemical
High-Latitude Regions (70°-80° N/S)	-160°/+60° C	Direct	Low elevation	14/28-day intervals from polar orbit	Geology Volcanism Environment	Mapping (Clementine)
Equatorial Regions (0°-10° N/S)	-160°/+130° C	Direct	Near zenith (no shadows)	Continuous from equatorial orbit	Geology Environment Historical	APOLLO
Limb/Farside (>80° E/W)	Function of latitude	Intermittent/ Indirect	Function of latitude	Function of latitude	Geology Environment Access to EM-quiet cone	Function of latitude

Payload

The need for a large velocity increment in order to land on the lunar surface implies that the mass available for the useful payload – whether of a scientific, exploratory or technology-demonstration nature – is thereby limited. Choices therefore have to be made and the hardware that is flown should have the maximum possible performance-to-weight ratio.

A mini-rover (Fig. 6) weighing 100 to 200 kg is regarded as the primary LEDA payload, essentially because:

- a range of a few tens of kilometres from a safe landing site is necessary, in order to explore more difficult but interesting terrain
- surface mobility constitutes one of the most important technology demonstrations in preparing for subsequent Moon Programme phases.

The main mission requirements for the mini-rover are highlighted in Table 4. A typical payload to be carried by the rover has been defined as a reference for the study, as shown in Table 5.

Depending upon the available payload mass, additional hardware may also be installed on the lander itself and operated in a stationary mode. Candidate facilities include:

- Instruments for geochemistry, environmental measurements and imaging, some of which could be back-ups to those carried on the rover, mass allocations permitting.
- A robotic manipulator, which may be used in support of other payload items (e.g. pick-up/deployment tasks, soil-sample feeding), but which would be flown primarily to demonstrate the technology needed for tasks for later missions, such as structural assembly.
- A drilling unit, able to penetrate 0.5 – 1 m (and possibly 2 – 3 m) beneath the surface for thermal-probe installation.
- A soil-processing test facility, aimed at evaluating the critical technologies (e.g.

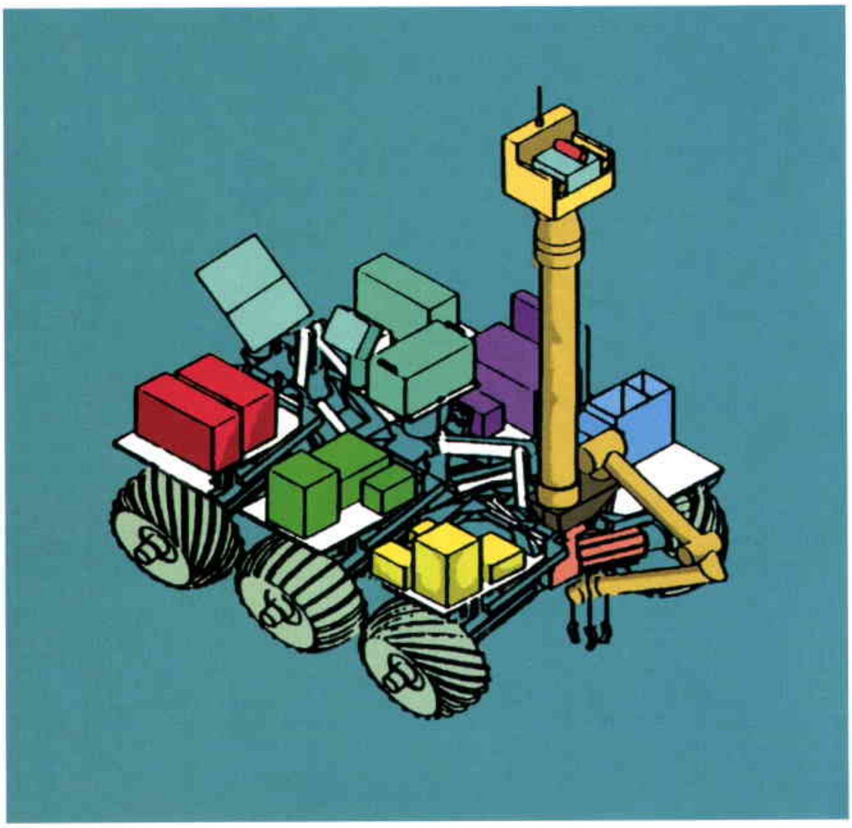

Figure 6. The ground demonstrator IARES (Illustrateur Autonôme de Robotique Mobile d'Exploration Spatiale), a programme by the French Agency CNES, which will help develop some of the critical technologies needed for the LEDA mini-rover

Table 4. Summary of lunar-rover mission requirements

Exploration	Over 4 lunar days, about 50 km radius off the lander
	Including the (presumed) permanently shadowed areas
In Situ Measurement Support	Mostly while rover is stationary
	Minimum of 6 stations per lunar day, minimum of 10 hours each
	Position instrument sensor heads
	Feed samples to analysis instruments
Technology Demonstration	Assess performance of critical subsystems (locomotion, communications, power, control)
	Test lunar survival skills (maintaining communications, use of natural or artificial shelters)
	Demonstrate key capabilities for future missions (assembly, maintenance, repair of infrastructure)
Information and Education	Allow teleoperated locomotion control, camera positioning, robot manipulation
	Downlink sufficient imaging data (not necessarily in real time) to reconstruct environment for "virtual reality" model on Earth (for scenario and path planning, simulation, training, public utilisation)

chemical reactions in hypogravity) needed for such future applications as oxygen production from lunar soil.

The application of virtual reality and tele-presence to lunar-surface payload operations is important for exploration, in-situ measurement, technology demonstration, and information coverage. It provides a powerful user interface to rover, robot and scientific-instrument operations. It offers 'sensory' feedback (images of environment and spacecraft, rover and robot states, instrument measurements), either on- or off-line (stored). It grants an interaction capability (commanding at various levels), either on-line (immediate execution) or off-line (planning in simulated environment, validation, later execution). In terms of public information and education, such tele-presence involvement can be offered on a worldwide scale to participants ranging from scientists and experts to students and the general public.

The constraints to be faced are essentially:

- the communications time delay (up to 10 s), which requires interaction at a sufficiently high level and the implementation of sufficient onboard autonomy
- limited telemetry bandwidth (less than 0.5 Mbit/s): only critical for image data, requiring on-board data compression, low refresh rate (but compatible with dynamics of scene and level of interaction!)
- rover operational limitations (power, control): very low speeds (less than 1 km/h), long pauses may cause operator boredom and fatigue.

Possible user interfaces to the payload in a tele-presence mode include:

- 'augmented reality' (virtual image of predicted rover position in real video image) for tele-operation
- fully simulated scenes (virtual rover in virtual world, alternative viewing points) for planning, supervision of autonomous execution
- offline replays of (condensed) real data in virtual environment (for analysis, planning, training, validation of new algorithms, simulation of future operations, research, teaching, entertainment, etc.)
- 'virtual dome' from real images for users to move around and explore ('hot spots' for interaction) as depicted in Figure 7.

A long-ranging result of tele-presence applications is the possibility of winning and maintaining public support, stimulating multi-disciplinary participation in lunar exploration and utilisation (exhibits, contests). Media products could eventually be derived from the development and operations tools and scientific data made available by a lander/rover mission, e.g. 'Moon Rover Rides' (like today's flight simulators) for education and entertainment.

Table 5. Potential complement of rover-mounted instruments

Rover-Mounted Instruments			Mass [kg]		Power [W]	Data Rate [kbit]
			Sensor Unit	Electronics		
Geochemical Analysis	APX	Alpha-Proton-X-ray Spectrometer	0.25		0.3	32 / sample
	GRS	Gamma-Ray Spectrometer	0.5	0.4	1.0	8 / sample
	NED	Neutron Detector	0.1	0.2	0.2	0.032 / sample
	EGA	Evolved Gas Analyzer	0.5	0.2	8.0	1000 / sample
	CPM	Complex Permittivity Meter	3.0		1.5	0.016 / min
	GPR	Ground Penetrating Radar	5.0		10.0	1 / s
	SAS	Sample Acquisition System	2.0		5.0	-
Environmental Measurements	TAP	Thermal Array Probes (2x)	0.15	0.2	1.0	0.05 / 2
	RDM	Radiation Dose Monitors (2x)	0.2	0.25	2.0	0.4 / meas.
Imaging	PCS	Panoramic Camera System	0.75	0.75	4.0	512/ image
	CUI	Close-up Imager	0.1	0.2	4.0	512 / image
Total			<15			

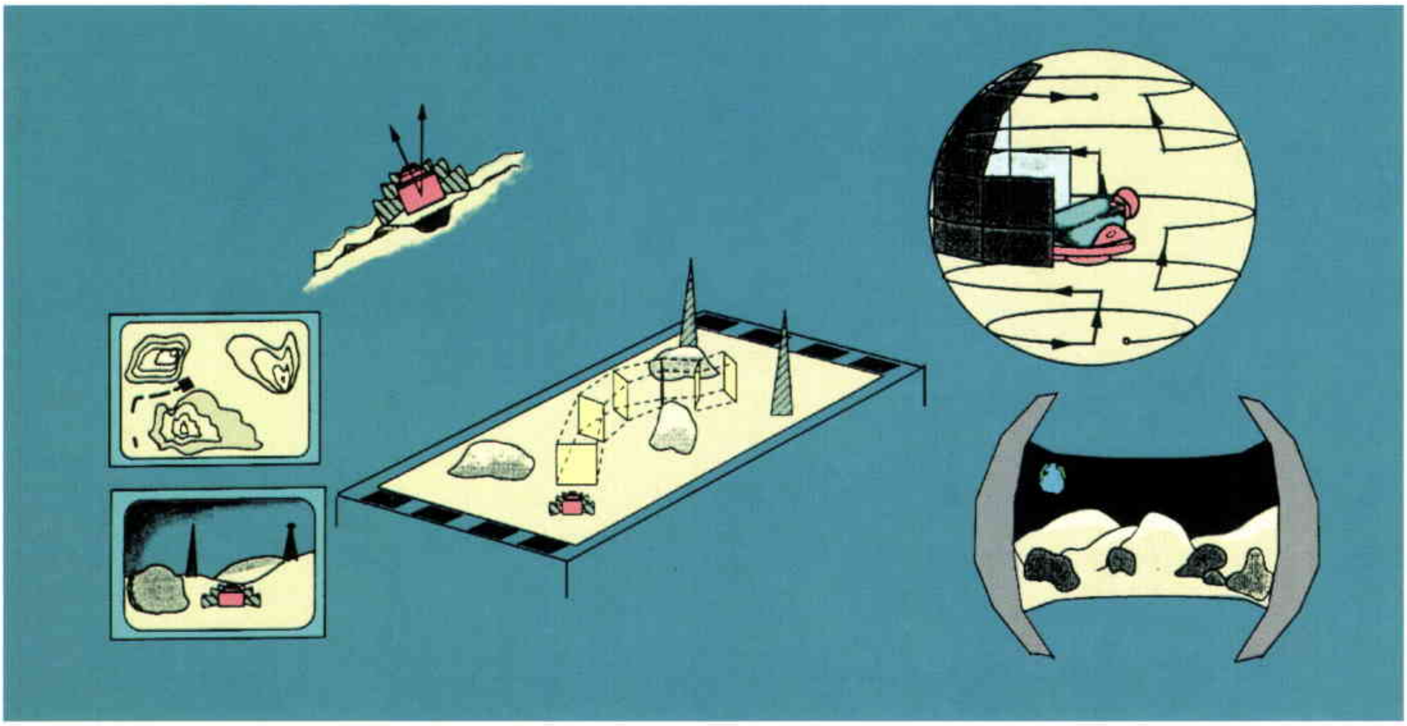

Figure 7. Virtual-reality applications to the rover mission on LEDA. Rover orientation and localisation can be performed by a ground operator by switching between various viewpoints in a virtual environment, and by adding 'widgets' (e.g. target points) to the landscape. The rover's path can be shown on conventional monitors, or on a horizontal planar screen with stereoscopic vision. A 'virtual dome' can be created by reconstructing the landscape observed around the rover by a movable camera

Technologies

A reference configuration for the LEDA spacecraft has been established (Fig. 2) to assess the critical technologies needed. The technologies will be driven by the two main phases of the LEDA mission, namely the transfer to the Moon up to the landing, and the subsequent lunar-surface operations.

Propulsion and landing technologies

The most critical subsystems for a successful landing are:

- propulsion
- guidance, navigation and control
- landing gear.

All three require innovative technologies in which Europe has no, or only limited experience to date. Other subsystems – such as communications, data-handling, power and thermal-control – are comparable to those of a more conventional satellite, apart from the process of landing.

The propulsion subsystem is the heaviest item on the spacecraft (consuming up to 27% of the total lander dry mass), because it has to provide such a large velocity increment. In addition, a wide range of thrusts are needed – a maximum at the beginning of descent from lunar orbit (minimum deceleration of 1.5 m/s^2), and significantly less (reduced by 50%) during final hovering. This calls for a propulsion system delivering in excess of 2.4 kN, but with the possibility of 'throttling back' to 1.3 kN. There is currently no such engine available in Europe, although a 3 kN non-throttlable engine developed previously may serve as a technology base for further development.

LEDA requirements could also be fulfilled by using a set of smaller engines (7 x 400 N) that are already available and space-qualified in Europe. Thrust reduction can then be achieved by a combination of switching off three or four engines during hovering, and operating the remainder in a pulsed mode (for which a small extra qualification effort is needed). This design is strictly applicable only to relatively small and unambitious landers such as LEDA, while further missions would require a newly developed system.

A number of other solutions are also still under investigation with a view to increasing the payload mass that can be landed by reducing the mass consumed by the propulsion plant, including:

- dual-mode propulsion (N_2H_4/N_2O_4), using hydrazine monopropellant for attitude control
- two-stage bipropellant (both lander and transfer stage)
- two-stage bipropellant lander and solid kick stage for trans-lunar injection.

The landing gear has to ensure a stable landing in the correct orientation (within a given range), as well as keep the landing shock below a specified maximum. This essentially involves a trade-off between the maximum allowable residual shock and the length of the landing-gear stroke. The latter, in turn, may influence the overall lander configuration in terms of height of the centre of mass and payload accessibility to the lunar soil. The current baseline foresees four deployable hinged legs with crushable dampers, which have been traded-off against alternatives such as air bags and crushable cushions.

The guidance, navigation and control system controls the spacecraft's trajectory relative to the landing site during descent, hovering and landing, by means of a radar altimeter (range-to-surface measurement), a three-beam Doppler radar (three-axis velocity measurement) and an Inertial Measurement Unit (IMU) combining gyros and accelerometers (for attitude and position determination). Accuracy and safety in landing are accomplished by using a vision-based navigation system. Stability and pointing requirements allow concepts for attitude stabilisation and measurement relying entirely on the use, respectively, of a set of eight 10 N attitude-control thrusters, and of the vision-based navigation cameras as Moon horizon sensors (combined with a coarse Sun sensor). This synergy between the various equipment items has been devised to minimise both power and mass requirements.

The radar altimeter and the Doppler radar represent new developments for Europe for this application, although the radar experience with the Huygens project can be exploited to good effect. The vision-based navigation system also represents a new development, particularly in terms of onboard software required. Microcameras, which are already under development in Europe for other applications, will be needed. Fibre-optic gyroscopes are also an interesting new development that promises further mass reduction.

Technologies for lunar-surface operations

Two main critical issues immediately spring to mind in this context, namely lunar nighttime survival and surface mobility.

The lunar night of 14 Earth days (with a seasonal variation between 10 and 18 days at the LEDA target landing sites) constitutes a major challenge for the designer. No solar power is available during this period, and the temperature of the surrounding lunar-surface environment drops to well below –160°C (temperatures as low as –230°C have been predicted for polar locations, although these have never been measured). There are essentially three design strategies for facing this problem:

- highly efficient thermal control to dramatically reduce heat leaks during nighttime, a solution affected by residual uncertainties in terms of both system performance and the surrounding environment
- adoption of equipment that is qualified to survive, and even operate, at extremely low temperatures, typically in the range –50 to –100°C; availability of such equipment (especially electromechanical items such as motors) is currently quite limited and

Table 6. Comparison of energy-storage systems for nighttime survival

	Use for LEDA	Other Users	Technology Issues	Procurement
RFC	• Electrical power for nighttime survival • Possibly: electrical power for locomotion and operations in darkness (but mass appears prohibitive)	• Uncertain	• High mass (>150 kg for 100 W) increases launch cost • Power can be distributed by electrical heater system • Very complex, contains water, requires high operational temperature	• European technology available • No off-the shelf system (specific low-power adaptation to LEDA needed) • Alternative US and Russian suppliers
RHU	• Heat for nighttime survival • No use for locomotion or payload operations in darkness	• Used on GALILEO, CASSINI/HUYGENS, MARS-96 • Some interest for planetary missions	• Extremely mass efficient (5 kg for 100 W) • Simple technology • May give problems with unplanned re-entry • Concentrated heating source, requires heat distribution • Requires daytime heat rejection capability	• European development envisageable (large effort) • US source disappearing from market • Alternative Russian supplier
RTG	• Electrical power for nighttime survival • Electrical power for locomotion and operations in darkness • Rover only (excessive for lander application)	• Used on GALILEO, ULYSSES, CASSINI, MARS-98 rover • High interest for planetary missions	• Proposed PLUTO EXPRESS device (16 kg, 90 W) very interesting for LEDA • Power can be distributed by electrical heater system • Requires daytime heat rejection capability	• No European know-how • European development too costly, too long (>15 years) • US source disappearing from market, anyway high recurring cost • Alternative Russian supplier

considerable qualification efforts would be required

- use of highly efficient energy-storage systems appears to be the safest and most flexible solution, but no optimum system has yet been identified; conventional systems such as chemical batteries are too heavy, given the LEDA requirement of some 40 kWh per lunar night, and the most interesting candidates appear to be regenerative fuel cells or radio-isotope-based sources (Table 6).

The mobility issue will focus on the design of the mini-rover's chassis, including the locomotion, control and power subsystems. The availability of a suitable locomotion subsystem, able to cope with the terrain of the target South Pole landing areas, currently relies on a further development of the Russian Marsokhod rover chassis designed for the Mars-98 mission. However, the adaptations needed for lunar operations are numerous and drastic. The control subsystem requires critical developments in terms of miniature navigation sensors (cameras, Sun and star sensors) and onboard software for full, or at least partial, autonomy. The power subsystem faces extreme requirements in terms of low-mass energy storage.

Conclusions

The LEDA Assessment Study has shown that it is within the capabilities of ESA, working together with other European agencies, to undertake a lander mission to the Moon early in the 21st Century, and to demonstrate safe and effective landing and surface operations. A number of mission options and critical technologies, for which either a development activity in Europe or procurement from a foreign source is required (e.g. radio-isotope power systems), have not been finalised at this stage. However, the available information concerning the various options and technologies provided by the LEDA study should allow the managements of ESA and the national agencies to generate programmatic directives and to initiate the necessary agreements on cooperative undertakings.

Acknowledgement

The authors gratefully acknowledge the substantial contributions of a large number of specialists from ESA's Technical, Scientific, Operations and Administrative Directorates who have participated in the LEDA Assessment Study, and in particular G. Janin, M. Lang, P. Putz and J.-C. Salvignol for their contributions to this article.