LunARSat
European Orbiter Mission to the Moon

The LunARSat Team*

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Abstract

LunARSat, the Lunar Academic and Research Satellite, is a micro-spacecraft that will be sent into an orbit around the Moon to perform scientific investigations concerning the lunar environment and its characteristics. However, the prime objective of the LunARSat mission is to serve as an educational and outreach project. LunARSat is designed by young engineers, scientists, and students from around Europe, with support from numerous institutions and space industry. It shall be launched as an auxiliary payload on an Ariane 5 ASAP platform and will have a mass of 100 kg in GTO. LunARSat will orbit the Moon on a highly elliptical polar orbit with its perilune above the lunar south pole area. This orbital strategy yields the possibility to obtain images of the lunar south pole region with a resolution never achieved before. Further measurements shall provide further evidence regarding the existence of water ice in the lunar polar craters.

Background

The origin of the LunARSat Project dates back to July 1996 when 52 students, young scientists, and engineers from 15 different European countries gathered in Alpbach, Austria, for the ESA Summer School "*Mission to the Moon*". At the end of this 10 day workshop, two groups presented their results to the Director of Science at ESA, Dr. Roger Bonnet, and other high-level representatives of the European space community. After these presentations, Dr. Bonnet challenged the participants of the Summer School to build a small lunar orbiter. The LunARSat Proposal was the answer to this challenge provided by the participants.

In October 1996, the LunARSat Proposal was presented to the ESA Long-term Space Policy Committee (LSPC) in Paris. As a result, the ESA Council and the ESA Director General recommended in December 1996 that a co-operation between LunARSat and the EuroMoon initiative should be investigated. During its December 1996 meeting, the ESA Council approved an initial study of the EuroMoon concept. The EuroMoon core team, based at ESA-ESTEC and consisting of representatives of the major European space companies, ESA-ESTEC, ESA-ESOC, and two LunARSat Team members, conducted the EuroMoon Feasibility Study between April 1997 and March 1998. The Institute of Astronautics of the Technische Universität München developed into the engineering center of the LunARSat Project. Supported by the local space industry, a growing team of up to 20 professors, research assistants, and students worked on LunARSat from early 1997. The Munich engineering group was supported by several members of the Alpbach group in different European countries. The LunARSat science efforts also involved several of the Alpbach participants, coordinated by the Swedish Institute for Space Physics in Uppsala which essentially became the LunARSat science center. In late March 1998 the ESA Council decided to stop the EuroMoon project. As a consequence, a continuation of the project is now being pursued by a team at the University of Surrey / Surrey Satellite Technology Ltd. in collaboration with the original LunARSat Team. A Phase B study is conducted between July and October 1998. The involvement of further European universities is foreseen.

Aims of the LunARSat Project

It is the goal of the LunARSat Team to design and build the micro-spacecraft LunARSat for a launch to the Moon by the year 2001 with the support of ESA, research institutions, and space companies from around Europe. The primary objectives of the LunARSat Project are:

- To serve as a vehicle for a variety of educational projects that will stimulate interest in space exploration and science amongst the younger generations.
- To provide young professionals from across Europe with an opportunity for academic collaboration and 'hands-on' experience with a real space mission.
- To demonstrate new methods by which the mission design and realization of a lunar polar orbiting small satellite can be accomplished providing education in micro-satellite technology and demonstrating access beyond earth orbit from GTO.
- To stimulate interest in the Moon (and space exploration) through the investigation of the suitability of the Lunar South Pole for a future extraterrestrial outpost, i.e., ice distribution, sun illumination, and other environmental effects.
- To encourage youngster's interest in space science by investigation of the lunar environment (plasma, exosphere, etc.)

The major scientific objectives of the LunARSat mission include:

- Obtaining high resolution, multispectral, and stereo imaging of the lunar south pole region and other selected areas.

- Monitoring the seasonal changes of the illumination in the polar areas.
- Studies of the lunar exosphere and plasma surroundings.
- Try to gather information regarding surface and subsurface materials and structure in lunar south pole region.

LunARSat Payloads

Camera System

The camera system consists of two optical systems, a high resolution camera and a wide angle camera. The electronics of the High-Resolution Multipurpose Camera will be identical to the GEMINI Camera proposed by DLR Berlin for the SMART-1 Project. The camera design is based on the ROLIS camera design for ROSETTA. A functional breadboard is already existing. Because the optics of the GEMINI are rather heavy, a catadioptric system with a focal length of about 400 mm and a mass of about 500g will be developed for LunARSat. The basic parameters of the High-Resolution Multipurpose Camera are:

- 1024*1204 CCD (THX 7888A)
- 14*14 micron pixel size
- 14.38*14.38 mm chip size
- 2*2 degree field of view
- 3.5m/pixel resolution at 100 km perilune
- Sensitive range 400-1000nm (visible to near infrared)
- 14 bit radiometric resolution
- TDI (time delay integration) capability
- Optics: 6 position filter wheel; 400mm f/8 catadioptrical mirror

To monitor a large enough field of the lunar south pole area at each perigee pass, an additional wide angle camera will be required. The LunARSat wide angle camera has a weight of 35g (including optics) and a focal length of 14mm, giving a field of view of 40 degrees. A functional model of this size and weight is already existing.

Radar and Plasma Experiment (REX)

The baseline Radar and Plasma Experiment (REX) comprises a radar antenna system with four 5 meter long elements spanning three dimensions (symmetrically mounted on LunARSat). The radar system can be operated both in a passive sampling mode and an active radar mode. A second element of the REX package is a classical Langmuir probe system *(LP)* on top of a 1 meter long boom. With the LP measurements of the local plasma density and electron temperature can be conducted. Using the REX passive mode plasma irregularities, emissions, and electric fields can be monitored. In the active mode REX can be used either as a coherent radar versus plasma irregularities and sharp density gradients, or as an "ionospheric" sounder. Together with a third and fourth element, a magnetometer and a sodium counter, a comprehensive plasma / exospheric package is formed. REX can also provide measurements of spacecraft charging, dust impacts, and solar UV flux. Furthermore, it can possibly carry out radar ground penetration and altimetry of the lunar surface and sub-surface.

The REX instrument package will be a piece of art in lightweight construction, which is necessary for integration on LunARSat with its low payload mass limit.

For instance, the specific antenna mass will be about 10 g/m and the LP system (incl. boom) will have a mass of only a few hundred grams. The overall mass and power characteristics of the REX package are:

Mass:
REX Antenna system (four or six 5 meter antenna) 1.2-1.8 kg, REX LP system (incl. boom) 0.2 kg, Central Electronics (digital) and box 0.5 kg, total in baseline 1.9-2.5 kg (will depend on integration with Sodium counter and Magnetometer).

Power
Passive operation 1-5 W, active operation <20 W (average), LP system 1-2 W.

Furthermore, the REX instrument package has the following performance characteristics:

Radar Antenna System

- Electric Field in the range 0.01 mV/m - 1 V/m, 0.05 kHz - 5 MHz
- "Magnetospheric" mapping of plasma irregularities and density gradients / structures out to about 1000 km from the S/C
- Topside sounding of the Lunar "ionosphere", critical frequency 50 - 500 kHz
- Radar ground penetration and altimetry of the surface/subsurface of the Moon

Langmuir Probe

- Electron Density 1 - 10^6 cm^{-3}
- Electron Temperature 0.001 - 10 eV
- Electron density fluctuations, Dn/n 0.1 - 50 %
- Plasma oscillations (near f_{pe}), 0 - 100 kHz
- Solar UV integrated ionizing flux
- Dust and micrometeorid impacts of mm sized particles on spacecraft
- Ion flow direction

Mission Design

LunARSat will be launched on an Ariane 5 into a standard GTO which is almost placed in the Earth equatorial plane. The GTO's apogee is always oriented towards the Sun. Since the orbit of the Moon is inclined to the Earth equator by about 22° in the year 2001, the angular difference of line of nodes of the GTO and the Moon's orbit turn out to be a critical parameter for the decision on the lunar transfer strategy. If the Moon can be directly reached at one of its nodes and thus in the Earth equatorial plane, a transfer strategy can be selected which comes close to a Hohmann transfer orbit. In the other case a bi-elliptic transfer orbit turned out to be a more effective solution.

The LunARSat mission analysis clearly indicated the feasibility of lunar missions departing from GTO. If a stringent constraint on the launch window can be accepted, the transfer from a GTO is quite competitive to lunar dedicated launch scenarios having a transfer time of 4-5 days. If no constraint can be allowed on the launch window, the mission becomes more complicated and several constraining effects result. These are:

- Transfer times of up to 50 days
- About 200 m/s increase in the total velocity increment
- Large distances from the Earth, up to 1 million km
- Large range in the arrival parameters such as the right ascension of the ascending node of the lunar orbit
- More complicated mission design
- Increase of the mission operations complexity

Overall, the mission analysis shows that:

- The total velocity increment from the injection into the phasing orbit to the insertion into the elliptic lunar polar orbit ranges between 1170 m/s and 1390 m/s
- The total time of flight ranges between 4 days and 70 days
- The argument of perilune of the lunar orbit ranges between 305° and 330°

Apart from science and mission operations aspects, the selection of the operational lunar orbit must be mainly based on stability considerations. In order to reach the proposed lifetime of 180 days, only a 4 hour lunar orbit appears to be reasonable. The velocity requirement estimate for orbit maintenance is 140 m/s for the entire operational lifetime and has been calculated taking into account third-body perturbations imposed by the Earth and the Sun. The investigations of the lunar eclipse phases for the selected orbit result in maximum eclipse durations of 65 minutes.

Mission Operations

Originally, it has been assumed that all LunARSat operational activities would be performed by the European Space Operation Center (ESOC) in Darmstadt, Germany. A "LunARSat Mission Assumptions Document - Operations and Ground Segment Concept (MAD)" has been compiled which describes a mission operations and ground segment concept. This MAD has been prepared according to the guidelines given in the ESOC Ground Segment Management Plan. It will serve as a basis for a Mission Implementation Requirements Document (MIRD).

In the meantime, a new operations philosophy has been considered. The main drivers of this new operations philosophy have been identified during a 10-day workshop at the University of Surrey, including:

- Availability of appropriate communication links whenever required
- Operations Cost
- Accessibility of spacecraft communication to a number of involved small ground station providers

The proposed Operations and Ground Segment Concept is to conduct low data rate operations from the Surrey 2.5 m ground dish and other small ground stations, which still have to be determined, and to use ESOC 15 m S-band antennas for high data rate transmissions like payload data acquisition.

The LunARSat Spacecraft

Spacecraft Structure & Configuration

The maximum allowed satellite size defined by the ASAP manual is 600x600x800 millimeters. This aspect is in conflict with the required tank volume. If all tanks are mounted at the same level, it is not possible to use spherical tanks. The tanks would touch or even penetrate each other. To overcome this problem, several spacecraft designs have been investigated, including a truss design. (see figure 1) This design allows to raise the tank sizes by 5 mm in diameter, but it showed that this is not sufficient to ensure mission success. Therefore, special tank configurations are necessary. One possibility would be an 'oil tank-like' shape (a cylinder with two spherical caps). This allows the tanks to be mounted on one level.

Figure 1: Example of a 4+1 Tank Configuration

Another configuration option is to raise the number of tanks from 4+1 to 6+1. This means that a second mounting level has to be introduced – three tanks on each level. Because of symmetric considerations this design may induce a cylindrical spacecraft shape. (see figure 2)

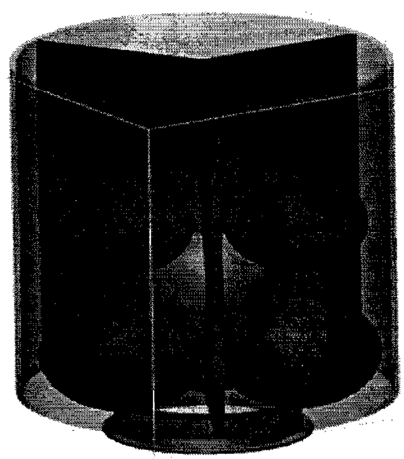

Figure 2: Example of a 6+1 Tank Configuration

According to first FE-analyses both configurations are able to meet the mechanical requirements given by the ASAP manual. The total satellite mass is 101 kg (including ASAP interface). According to results from the Surrey workshop, the mass of the structure contributes with about 12.5 % to the total S/C mass. The 6+1 design requires about 5 kg for the main structure which leaves 7,5 kg for inserts and secondary structures. The truss design is more critical in this aspect due to the fact that there are many nodes, which are made out of titanium or similar materials.

Propulsion System

Three principle solutions for the LunARSat propulsion system have been investigated. These three options are:

- Monopropellant propulsion system
- Bipropellant propulsion system
- Dual mode/Unified propulsion system

The results of the analysis indicate that, from a mass point of view, a monopropellant system is the worst possible propulsion system for the given mission scenario. The advantage of the monopropellant version is the need of only one fuel system (pipes, valves, tanks). This has its affect on the mission risk factor, which is lower because there is only one fuel system. The two other propulsion system options have more than one fuel system, which increases risk of failure and, thus, overall mission risk.

The bipropellant version appears to be the system with the lowest mass, due to the fact that it uses propellant with the relatively highest energy level. However, the dry mass of this option is higher compared to the dual-mode version. Also there would be the problem to fit this type of propulsion subsystem within the envelope of 600mm x 600mm x 800mm.

The dual-mode propulsion system has the lowest system wet mass and is thus the most promising propulsion system candidate, given the constraints. This result is only applicable for this mission scenario within the variation of velocity requirements for orbit transfer. If the requirements change to a much higher Δv requirement, the current results would have to be re-evaluated regarding mission feasibility and optimum propulsion system option.

Based on the analysis described in the previous sections, the dual-mode/unified propulsion system has been selected as a baseline for the LunARSat mission. This propulsion system uses a main engine with the following technical data:

- Propellant: Hydrazine / NTO
- Thrust: 110 N
- I_{sp}: 290 s
- Mass Flow: 40.3 g/s

For attitude control and orbit maintenance, hydrazine thrusters have been selected. These thrusters have following properties:

- Thrust: 1.32 N
- I_{sp}: 230 s
- Mass Flow: 0.61 g/s

Based on the results of the mission analysis, the required propellant mass will be between 42.80 kg (best case) and 47.74 kg (worst case). The tanks will have a fixed diameter of 0.2856 m (2 tanks) and 0.2583 m (2 tanks). This yields tank masses of 2 x 0.5545 kg and 2x 0.4535 kg, respective, using Al2219 as a tank material. Helium-pressurant system will be used for pressure-regulated propellant flow. The helium mass is about 0.2416 kg, the He-tank mass about 2.3629 kg. The He-tank will have a metallic core (Ti6Al4V) which will be reinforced.

Attitude Determination and Control System (ADCS)

The main task of the LunARSat ADCS is to control and measure the spacecraft attitude, to stabilize the spacecraft, and to orient it in desired directions during the mission, despite the external and internal forces acting on it. The following tasks and analyses have been conducted during the course of the ADCS design:

- Operational ADCS modes have been identified
- Subsystem constraints have been identified
- Hardware components and the subsystem architecture have been selected
- Preliminary power and mass budgets have been provided
- Interfaces with other subsystems and with the payload have been identified
- Required ADCS algorithms were identified

Due to the frequently required re-pointings and the complex mission goals, a 3-axis stabilization technique has been selected for the LunARSat spacecraft. The minimal ACDS hardware that is foreseen consists of:

- 3 Fiber optic laser gyros
- 1 Sun sensor
- 1 Star mapper
- 3 Reaction wheels
- Attitude thrusters

Attitude control and determination algorithms still need to be developed, as well as further investigations on the effect of the propellant sloshing in the tanks during the course of the mission and further analysis on the behavior of the control during the main engine firing need to be conducted..

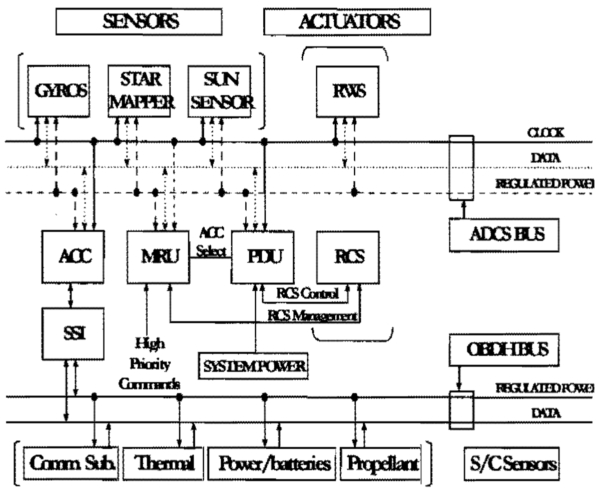

Figure 3: Principle Layout of the LunARSat ADCS

Power System

The LunARSat power system needs to produce and distribute electrical power for the spacecraft. Also, the produced power needs to be controlled and regulated.

LunARSat uses solar PV cells to produce power, rechargeable batteries to store energy and a power management and distribution system (PMAD) to distribute, control and regulate the electrical power. The LunARSat power system is based on an direct energy transfer approach, this means that always the complete available power is taken from the solar panels with the not required part being converted to heat by shunt resistors. The solar cells used for LunARSat are commercial off-the-shelf (COTS) Silicon-cells.

The design of the power subsystem is based on the following requirements and constraints:

- Mass: 4.3 kg
- Geometry: 60x60x60 cm^3
- Avg. Power Req. (Sunlight) 62.01 W

To use the available area in an optimum way, the solar cells will be placed on three sides of LunARSat with the middle corner pointing towards the sun. This leads to a sun incidence angle of about 35°. The steady state temperature of the cells in this configuration comes to about 62°C. Based on an efficiency of the Si-cells of 13.75 %, a total solar efficiency of 9.226 % results. In combination with the Sun incidence angle, this value leads to a required solar panel area of 0.86 m^2.

The resulting power production level of 66.08 W implies a power system design margin of 6.5%. The battery used for LunARSat will be a Li-Ion type of battery, as conventional batteries like Ni-Cd cannot fulfill the mass constraints. The achievable specific battery capacity for Li-Ion batteries is about 90 Wh/kg.

Communication & GNC System

The LunARSat communication system in its present configuration is based on a coherent transponder concept. Commercial off-the-shelf (COTS) components have been identified, as well as software / hardware components, and compatibility issues. The selected design offers relatively high data rates and ESA / CCSDS compatibility at low cost, low development risk and low mass. Implementation in a fast-track program is feasible.
The subsystem design is based on the use of 15m S-band ground stations. The downlink will provide data rates in the order of 75-150 kbits/sec; uplink will be in the order of a few hundred bps to a few kbps.

For telemetry data coding ESA / CCSDS compatible coding procedures will be employed. Basic options for coding implementation have been investigated; coding / decoding algorithms and commercially available chip sets and are under investigation. A number of available candidate antennas have been identified. The coherent transponder proposed for LunARSat will provide ESA/ CCSDS compatible ranging and tracking functions for the ground stations. The basic properties of the LunARSat communications and GNC systems is summarized in the following table:

Item	**Characteristics**
Low Gain Antenna	Omnidirect. crossed dipole / QF helix
Medium Gain Antenna	S-Band patch antenna array
Uplink Frequency	S-Band, ~2.05 GHz
Downlink Frequency	S-Band, ~2.2 GHz
Data Rate TC	500 bps min
Data Rate TM	75.000 – 150.000 bps
Uplink Coding	BPSK
Downlink Coding	BPSK, R-S + Convolutional
Transponder(s)	STX-95B/SRX-90 based
Size	~3500 ccm
Mass	~3.5 kg
Power [RX] / [TX + RX] DC	2.9 Watts / 34.9 Watts
RF Power	5 Watts

Thermal Control System

The preliminary design of the LunARSat thermal control system is based on the following assumptions regarding temperature requirements:

- Tanks: 20°C
- Electronics: 0 - 40°C

Within some limits, the desired nominal operation temperature ranges can be achieved just by tuning the MLI-performance in the TCS-design, i.e., if the power dissipation is less than 60 W (i.e., 40-45 W), the conductivity of the MLI on the radiator-side and the camera-side needs to be decreased (less conductivity through the MLI !). No thermostats are foreseen in the TCS design. Instead, the use of thermistor and computer controlled heaters is assumed. The required minimum number of thermistors comes to 30 (60 in case of redundancy). The total mass of the TCS is expected to be in the order of 1.8 to 3.2 kg.

Overall, the TCS analysis that has been conducted indicates that the desired temperatures can be achieved just by trimming the MLI performance, that radiators are probably not required, and that the lunar eclipse is not critical (80 percent average of Sun light during 2 h) if an orbit phasing strategy is used. However, postponing the LunARSat launch further into the year 2001 would have an impact on the TCS/Power system design. Assuming the current orbit design, the lunar-eclipse on 2001-07-05 is more demanding than the one on 2001-01-09.

Onboard Data Handling System

The system tasks of the LunARSat OBDH, well as the most critical design drivers have been identified. These include:

- Attitude control algorithms
- Timing of commands and initiation of operations
- Communication coding, command decoding etc.
- Compression of instrument data, especially images from the camera

Overall, the LunARSat OBDH system will require a high performance level. The OBDH also needs to take care of instrument data storage. The estimated memory is about 128 Mbytes, which should be enough for about 100 camera images per orbit. The estimated total mass of the system will be 3 kg (design limit). This mass requirement poses a major challenge. Also, it is most probable that no redundancy can be included. The baseline architecture of the LunARSat OBDH is shown in figure 4.

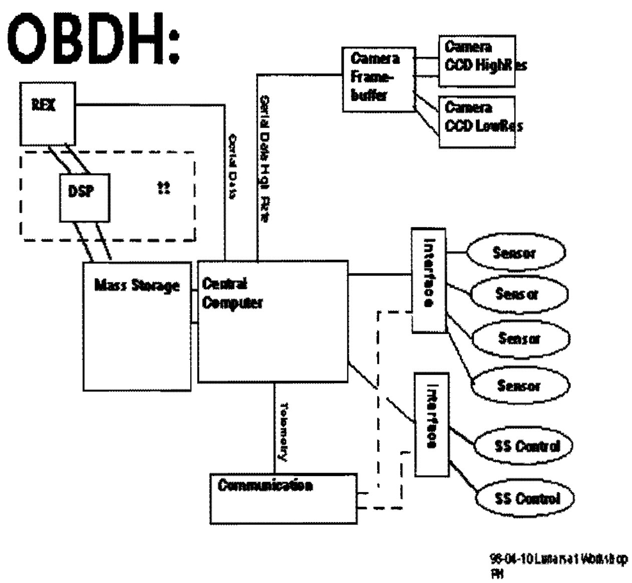

Figure 4: Principle Layout of the LunARSat OBDH

A central computer takes care of all tasks, reads the sensors, reads the instruments, talks to the communication system, etc. The internal computation of the REX payload will be done by a DSP (considered part of the payload subsystem). Candidate CPUs include the ERC32 or THOR2, as well as a 386ex used in previous SSTL missions. However, a single 386ex will not be powerful enough for doing all the tasks required. A final selection of processor and main architecture still needs to be conducted. Also, computer languages and operating systems for the onboard software needs to be identified. Programming language options are, not excluding others, C and ADA. ADA is a common S/C onboard language, and lots of experience and software libraries exists in Europe. VxWorks has been suggested as an onboard operating system, but if a real-time ADA kernel is used, an operating system might not be necessary for a small system like this.

Conclusions

The mission design & operations, as well as spacecraft design aspects present here will be further investigated during the LunARSat Phase B study between July and October 1998. A decision by ESA regarding funding of a Phase C/D is expected for late 1998.

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Born 1966 in Frankfurt (West-Germany), Peter is currently an Assistant Professor at the Institute of Astronautics (Fachgebiet Raumfahrttechnik) of the Technical University of Munich (Technische Universität München). At the TU he is lecturing on 'Space Stations' and 'Space Engineering'. His current main activity is the work on the microorbiter project 'LunARSat'. In parallel, Peter is lecturing on human space flight aspects within the Masters of Space Studies Program of the International Space University and within the 'Space Mission Analysis and Design' courses by Dr. James Wertz and Dr. Wiley Larson. Peter's first book 'Spaceflight Life Support & Biospherics' has been published in 1996 by Kluwer Academic Publishers / Microcosm Inc. Currently, he is working as a co-author on two chapters of the book 'Human Space Mission Analysis & Design' (editor: Wiley Larson, to be published in 1998), as well as on his second book, 'The Lunar Base Handbook', which is also to be published in 1998.

Andy Phipps

Graduated from University of Greenwich (London) in Electronic Engineering, and has been at Surrey Satelite Technology Ltd. since 1994. Andy worked in the team which started the research and development of Surrey Satellite Technology Limited's Minisatellite power systems. Having successfully completed his Master's program in Spacecraft Engineering at the University of Surrey, Andy started as a lunar mission researcher and was part of a small dedicated team which undertook a feasibility study of a low cost lunar orbiter mission 'Earthrise'. His interests led him to continue this research, specifically researching a low cost lunar lander. He is currently employed within the Projects Directorate at SSTL as the 'LunARSat' mission project manager.

Dr. Jan-Erik Wahlund

Born 1962 in Alingsas (South-Sweden), did his PhD in Space Physics in Uppsala 1992, and Jan-Erik is currently an Assistant Professor at the Swedish Institute of Space Physics, Uppsala Division, and is lecturing `Space Physics' at the Uppsala University. Jan-Erik has published more than 25 scientific papers in refereed journals in the subjects of auroral ion outflows, energization mechanisms with kinetic Alfven waves, and ion acceleration mechanisms cousing the escape of atmospheres to space. Jan-Erik have worked with data from the Swedish-German Freja mission and the European Incoherent SCATer radar (EISCAT), and is now a Co-Investigator on instruments onboard the Cassini and Rosetta missions. Jan-Erik also hold the ESA contracts regarding spacecraft charging and plasma environments effects on spacecrafts, and is one of the few in Europe competent in this field. Jan-Erik is currently managing the payload/science parts of the micro-orbiter project LunARSat and the development of a new Radar and plasma EXperiment (REX).