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THE LUNETTE SPACE MISSION: USING A NANOSATELLITE FOR HIGH RESOLUTION MAPPING OF THE FARSIDE LUNAR GRAVITY FIELD

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ABSTRACT

The farside gravity field of the Moon has so far been inferred through model-fitting based on Earth observations of farside entry and exit points of past lunar orbiters. The gravity model of the farside - currently 5 to 10 times less precise than the near-side model - could be refined significantly if two low-altitude satellites were to measure relative range rate while traveling over the far side of the Moon. This is the basis of the Lunette mission, a low-cost approach to high resolution lunar gravity mapping through the use of nanosatellite technology. Lunette has been selected as a payload for the European Student Moon Orbiter (ESMO). The Space Flight Laboratory (SFL) has recently completed a Phase A study. The Lunette concept is a 9 kg payload, including a "nanosatellite" that will separate from ESMO in Lunar orbit, a XPOD separation system, and a radio-tracking payload that will remain on the parent satellite. The nanosatellite will include a propulsion system with a 100m/s ΔV capability, along with a high-performance attitude control system. The main scientific aim of the Lunette mission will be accomplished by measuring the relative speed between ESMO and Lunette. Preliminary analysis suggests that using slightly modified SFL technology in a 100km circular orbit can achieve a *full-globe* precision of at least 20mGal, comparable to the near-side quality of the "LP75G" map. A reliable global map of this precision would be a major scientific accomplishment.

INTRODUCTION

The Lunette Space Mission was conceptualized by Dr. Jafar Arkani-Hamed (PI), Dr. Kieran A. Carroll and Henry Spencer. Lunette is realized through the involvement of the Space Flight Laboratory (SFL) founded and managed by Dr. Robert E. Zee. The goal of the mission is to create a full-sphere gravity map of the Moon of the same precision as the current near-side map. Currently, the standard used for lunar orbit planning is the "LP75G" map which was released at the end of the Lunar Prospector's mission which launched on January 6 in 1998. The reason for the discrepancy between the near- and farside precision of the gravity map arises from the method used to generate the data. Lunar Prospector employed Earth-based tracking in order to measure its orbit's perturbations due to the influence of the Moon's gravity. When the satellite was passing on the near side, the tracking was uninterrupted and quite accurate. However, the entire farside gravity map had to be inferred from the motion of the satellite as it entered and exited the far side of the Moon. Once the processing of the information was complete, the result was a farside gravity map 5 to 10 times less accurate than the near side.

The Lunette mission hopes to improve the knowledge of the Moon's gravity field by creating a full-globe gravity map as precise as the near-side map. This will be accomplished by supplementing tracking data obtained from Earth with intersatellite range rate data. A pair of satellites will orbit the Moon and the relative range rate of the satellites will be measured to a high degree of precision (1 mm/s) to generate of a full-sphere gravity field map.

The European Student Moon Orbiter (ESMO), being designed by the Student Space Exploration and Technology Initiative (SSETI) through the help and guidance of the European Space Agency's (ESA) Education Department, has chosen Lunette as one of its primary payloads. The other payload selected for the ESMO mission is a Narrow-Angle Camera (NAC) which will take high resolution pictures of the lunar surface for public relations reason. ESMO will not only serve as the second satellite with which to perform range rate tracking but will also carry the Lunette Mission Package from Earth to Moon. Currently, the mission is scheduled to launch in 2011.

The Space Flight Laboratory

Established in 1998, SFL has a full-time staff of professionals in addition to design, assembly, and test facilities to develop low-cost spacecraft. In the same year it was founded, SFL was contracted to build and test four of six critical subsystems for the MOST (Microvariability and Oscillations of Stars) microsatellite. These included the structural, thermal, computer and communications systems. SFL also played a major role in the integration of the satellite, launch and commissioning. Development efforts culminated in a successful launch of Canada's first space telescope at 14:15 UTC on the 30th of June in 2003.

In 2001, the Canadian Advance Nanospace eXperiment (CanX) was founded to further enhance SFL's research and educational offerings. The program engages small teams of graduate students, under the mentoring of the UTIAS/SFL staff, to build their own satellite in less than two years. Currently, the CanX group is developing four missions. CanX-2, scheduled to launch in late 2007, is a 10x10x34cm satellite designed to demonstrate technologies which will be employed on future CanX missions. CanX-2 also carries Canadian Science experiments from across the country. CanX-3 (also known as BRITE Constellation) is a set of four space telescopes with a mission similar, but complementary,to MOST. The constellation will photometrically observe the most luminous stars in the galaxy . CanX-4&5 is a precision autonomous formation-flying mission which uses two nanosatellites to demonstrate the feasibility of such a mission to a level of precision that has never been achieved before. Lastly, AISSat-1 is another mission under development at SFL which will study the use of satellites to track ships in Norwegian territorial waters.

The Lunette Mission Package

The Lunette Mission Package consists of three major components. The first of these is the Lunette Satellite (sometimes also referred to as simply "Lunette"). This satellite is in large part based on the Generic Nanosatellite Bus (GNB) technology that was developed at SFL. The satellite is a 6.5 kg, 20cm cube that is ejected from ESMO using a SFL-developed XPOD separation system. The nanosatellite will include a propulsion system, with a 100m/s ΔV capability, along with a high-performance attitude control system with <3 arc-minute pointing stability. The propulsion system provides active formation flying, increasing the orbital life of the nanosatellite and permitting alterations to its orbit to increase science return. The attitude control system permits accurate maneuvers and prevents contamination of the range-rate data by satellite rotations. The main scientific aim of the Lunette mission will be accomplished by collecting the relative speed between ESMO and the deployed nanosatellite. To this end, Lunette will carry a communications suite, the core of which will be an S-band coherent radio transponder.

The second component will be the stay-behind electronic package housed on ESMO. It will consist of a tracking beacon, a receiver, and a return-signal analyzer. The beacon will transmit a tracking signal, which the transponder on the nanosatellite will receive, and re-transmit. The re-transmitted signal will be received and analyzed to measure the 2-way Doppler shift, from which the range rate between the two satellites can be inferred. In order to accomplish this to the level of accuracy necessary, an Ultra-Stable Oscillator (USO) will be required on the stay-behind package. The stay-behind electronics package will also serve as the sole link between ESMO and the Lunette Package in order to simplify the interface requirements of satellites being designed in separate countries.

The last major component will be the separation system which will house the nanosatellite during launch and the journey to the Moon. It will then separate Lunette from ESMO in order to begin the Lunar Gravity Mapping mission. The separation system will need to serve as a protective enclosure for thermal, structural and radiation environments.

THE LUNETTE MISSION

The Lunette mission is a low-cost, portable gravity-mapping mission designed at SFL to create high resolution full-globe gravity maps of high precision. The Lunette Mission package will be carried by ESMO to the Moon and will employ the microsatellite as the second data-gathering satellite in order to fulfill the mission.

The Gravity Field

Many practical methods of observation such as photography, altimetry, and radar imaging, are only capable of studying a thin layer at the surface of the planet. Even using gamma-ray or neutron spectroscopy will only allow the study of the first few meters under the surface. Meanwhile, studying the gravity field can yield information on subsurface features ranging from shallow depths to the core-mantle boundary.

The gravity field of the Moon is in fact quite different than the Earth's. While the Earth's gravity field is relatively smooth and uniform, the lunar gravity field is irregular with spatial variations in strength due to the presence of mass concentrations ("mascons"). It is believed these mascons arise from different geology present beneath the surface of the Moon and they appear to be concentrated in shallow basins that can be seen on the surface. There is hope that the knowledge of a precise gravity field will yield information regarding the nature of the mascons on the Moon.

Additionally, a precise, full-globe gravity map yields many benefits for future lunar missions. Local gravity maps are useful for manned exploration and can be used to locate subsurface mineral deposits for mining operations. Mission planning will be greatly enhanced as gravitationally-induced orbital perturbations can cause a spacecraft to waste precious fuel on orbital maintenance. Errors due to gravitational perturbations contributed to Apollo 11 overshooting its landing site on the Moon. Precise lunar landings will be made easier with the use of a full-sphere precise gravity map.

Lunette Science& Mission Profile

The Lunette science is unique in that it will be among the first to employ a nanosatellite to gather scientific data from around the Moon. Furthermore, the inclusion of a lightweight, inexpensive deployable satellite system is a portable concept that could be used on any lunar orbiter yielding a large return for little cost.

The course of the entire Lunette mission will occur over several stages. The profile of the mission is hoped to go according to the following sequence. The mission begins with Lunette contained within its separation system aboard ESMO for the launch. After launch, ESMO would be inserted into a transfer orbit around Earth and would proceed to the Moon under its own propulsion system. Currently, ESMO is still considering two propulsion system options: one chemical, one electrical. The choice of propulsion system will greatly affect the travel time to the Moon. ESMO would likely enter an elliptical capture orbit around the Moon. From this orbit, the NAC will be able to take pictures of the surface of the Moon. Optimally, ESMO would then perform an orbit alteration maneuver and be able to release Lunette in a 100km Circular Polar Orbit. The separation would need to occur following a lunar eclipse. The timing of the separation is important to ensure that Lunette will have enough time to perform the gravity mapping mission without encountering any prolonged eclipse periods. The entire mission should take approximately 4 months and eclipse periods are normally six months apart. If an eclipse occurs the survival of the nanosatellite cannot be guaranteed.

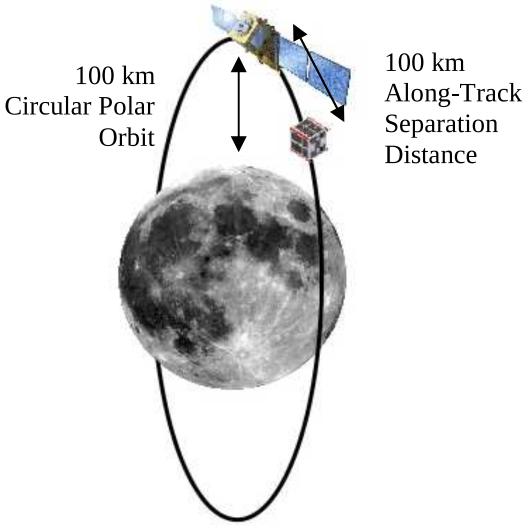

Figure 1: Optimal Lunette-ESMO Orbit

Once separated in the along-track orbit, Lunette and ESMO would proceed to drift apart to a distance of 100 km. The chosen orbital path would fully cover the Moon's surface in about 14 days, resulting in three full-sphere maps in the along-track orbit by the end of the minimum mission. The equatorial cross-track spacing of each map will be roughly 30km, with each subsequent map having a 10km cross-track offset from the previous map at the equatorial crossing. In order to minimize the impact of the satellites' orbital corrections on the data, maneuvers will be performed once a week and will occur over the poles of the Moon, where most of the overlap data will occur. Once the minimum mission is complete, a plane change of 1 degree would be performed in order to provide another three full-sphere maps that are slightly offset from the first three. This would enable verification of the data, and provide a better quality gravity map.

Mission Requirements

The mission goal is to provide a full-sphere map of the gravity field of the Moon of the same accuracy as the current near-side map. Currently, the LP75G map has an accuracy of about 20mGal. In order to accomplish its goal, the Lunette mission package will require a propulsion system capable of 100m/s Delta V. It will require a suite of ADCS sensors and actuators and a communications package on both the nanosatellite Lunette and on the parent satellite ESMO. The power system will be needed to provide enough energy to power all subsystems and the thermal system will be required to keep everything within operational temperatures.

Specific to Lunette, some of the mission requirements were listed to provide an overview of the conditions that drove the design of the mission package.

Selected Lunette Satellite Requirements	
Propulsion	• 100 m/s Delta V • Thrusts only once per week • Shall support Momentum dumping
ADCS	• 3-axis stabilized • Accuracy of 1° • Stability of 0.008 °/s
Communications	• Communicate with ESMO in any orientation • Measure range-rate peak to peak signature to 1 mm/s sensitivity

Table 1: Selected Lunette Satellite Requirements

Due to power limitations, the satellite will have several operational modes during the course of this mission, the most important of which will be the data-gathering mode. This is the time when Lunette will be in constant communication with ESMO, capturing the range rate data between the two satellites. In order to meet the signal-to-noise requirement as well as reduce the necessary power for this mode, Lunette's antennas will need to be 'aimed' at ESMO.

When in operation, the star tracker will be used to provide constant position updates to the Lunette satellite. Certain scenarios will require the Lunette satellite to spin in order to ensure a clear view of the stars for the star tracker, as both the sun and the lunar surface can occlude enough of the view to prevent a lock.

Generating the Gravity Map

In order to generate a precise gravity map of the Moon, the range rate of the two satellites must be tracked to a high degree of precision. The system will employ a number of S-band patch antennas between ESMO and Lunette in order to remain in constant communication. To begin with, the range of the satellites needs to be determined through the use of the communications systems on ESMO and Lunette. The position of the satellites is important in order to place the map on the surface of the Moon upon completion of the mission. ESMO can be tracked directly from Earth with a high degree of precision, but Lunette must obtain its position in relation to ESMO.

The stay-behind electronic package on ESMO will send out a specific bit sequence which is recognized by the Lunette hardware. It should operate similar to a firecode so that the signal is not required to pass through any software on Lunette, but rather be detected by the hardware and repeated directly back to ESMO. This will minimize time spent on Lunette by the carrier of the bit signal. The ranging bit sequence is detected by a ranging command detector located on the receiver. The detector sends a signal directly to the FPGA on the transmitter which halts its current job to send the ranging bit sequence to the analyzer. By bypassing the on-board computer and software, the delay of the hardware turn-around time can be predicted more precisely than the delays of the software turn-around. By completing the turn-around action using the hardware, the turn-around time is consistent and the analyzer can time the round trip of the bit sequence. By subtracting the turn-around time on the satellite, the distance can then be calculated.

The range-rate calculation must be derived by measuring the Doppler shift caused by relative motion on a carrier transmitted by ESMO which is in turn sent back by Lunette. As seen in the block diagram, a stable carrier at a given frequency f_1 is generated from ESMO and is sent out in a forward link to Lunette. A coherent transponder on Lunette is used to send the carrier back at a different frequency f_2 after imposing a frequency shift to avoid cross talk between the transmitted and received signals on ESMO. In the ESMO receiver, the return link signal is subtracted from a locally generated reference wave at frequency f_2 so that the Doppler shift f_D is detected. The resulting oscillation incorporates zero crossings at frequency f_D to be used to drive a counter that computes the time in a number of periods of the driving oscillation. Ultimately, the counter at the end of a 10 second observation window is proportional to the inverse of the Doppler frequency f_D, which includes the Doppler shift on the uplink as well as the downlink paths. From the resulting f_D value, the range-rate Δv can be derived. The Doppler frequency, f_D, can then be calculated using the following formula.

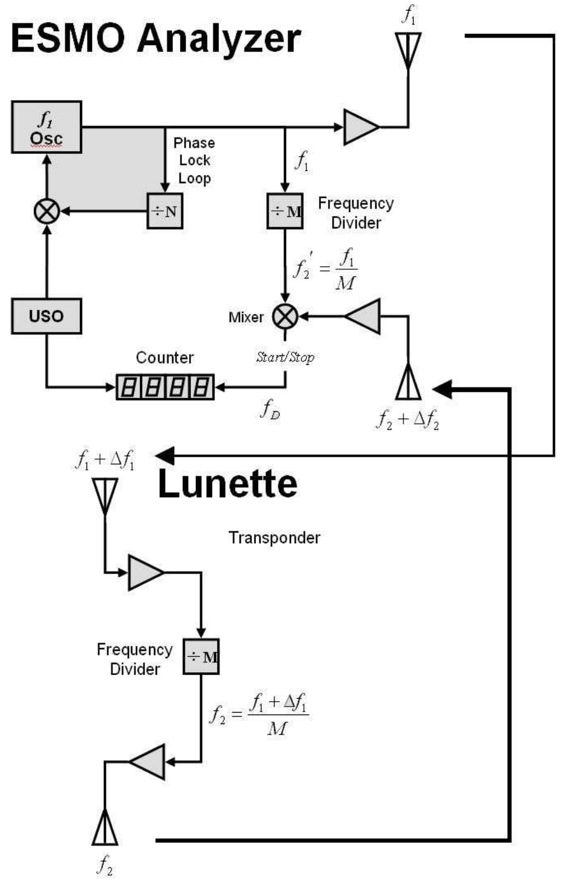

Figure 2: Range Rate Architecture

$$f_D = \frac{f_1 \Delta v}{Mc}\left[2 + \frac{\Delta v}{c}\right]$$

Equation 1: Range Rate Calculation

Where,

f_1 = Frequency of signal from ESMO to Lunette

f_2 = Frequency of signal from ESMO to Lunette

f_D = Total observed Doppler Shift

M = f_1/f_2 = Turn around ratio

Δv = Relative velocity of ESMO with respect to Lunette, in m/s

c = Speed of light = $2.998\text{x}10^8$ m/s

Once the relative range-rate is known, the gravity model can be inferred. A local sensitivity model can be used to illustrate the peak-to-peak range-rate signature observable using satellite-to-satellite radio tracking from a given peak surface anomaly. Assuming a 20 mGal peak surface anomaly caused by a subsurface mascon, a satellite ground track passing directly over the anomaly, a flat Moon (a reasonable rough assumption while the lunar radius is much larger than the separation distance between the satellites), an orbital altitude of 100km, and an along-track separation of 100km, the observable peak-to-peak range-rate signature is shown next.

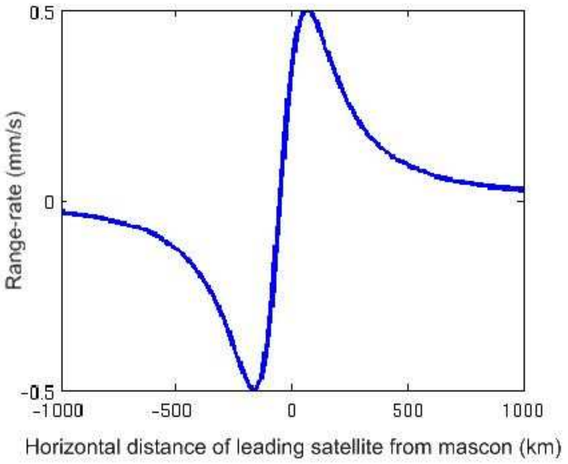

Figure 3: Range-rate signature of a 20 mGal peak surface anomaly, observed by two spacecraft at 100km altitude, with an along-track separation of 100km

THE LUNETTE PAYLOAD PACKAGE

The Structure

As was previously mentioned in the introduction, the Lunette satellite structure inherited a lot of its design from the Generic Nanosatellite Bus which was developed at Space Flight Laboratory. Some of the differences include the use of a central tray rather than a dual tray system. Additionally, the structure needed to be increased from 20cm to a 25cm cubic form factor to accommodate more solar cells. The components of the Lunette satellite were designed largely with mass minimization in mind when possible, as meeting our mass restrictions was a high priority in the early design stage. The exterior layout was in large part the result of power requirements which stemmed from the need to be in constant communication with ESMO using the S-band patch antennas.

The quad rail system is a common design for nanosatellites. The rails fit into their counterpart in the deployment system and prevent the satellite from being destroyed by the forces during launch. The rails are directly connected to the central tray and the propulsion tank, allowing them to carry the majority of the loads due to acceleration at launch. The panels and the remaining components are mounted to the central tray and rails. The quad-canted monopole antennas will be pre-deployed which limits the risk inherent to deployment. The antennas will be oriented towards the door which will contain cut-outs to prevent the antennas from affecting the closing and opening motion of the door.

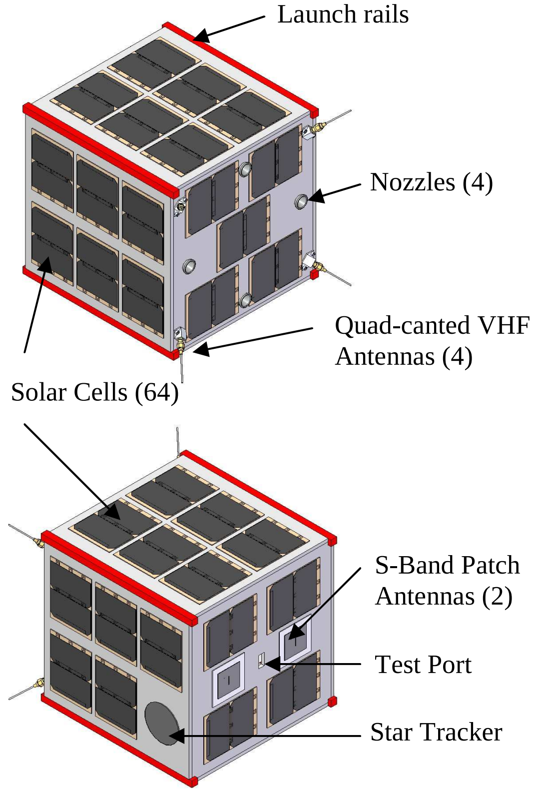

Figure 4: External Satellite Views

The S-Band patch antennas will be pointing towards ESMO in order to reduce the amount of power required to communicate. The star tracker needed to be placed on a face perpendicular to the antennas in order for Lunette to be able to rotate and see enough stars to obtain a lock. The quad-canted monopole antennas will provide near full-sphere coverage for the satellite to communicate with ESMO. The test port will not only be used for testing during assembly but will also serve as the link between Lunette and the stay-behind electronic package while Lunette is stored in ESMO.

The internal layout of the satellite began with the central tank design. In order to meet the 100m/s delta V requirement of the propulsion system, a large tank had to be selected. As the fuel is consumed during the course of the mission, the centre of mass of the entire satellite will also be modified which may cause an increase in inaccuracies for the attitude determination and control system. In order to minimize the effects, the tank is centrally located in the satellite. The satellite will also possess three reaction wheels, oriented in the three axes which will allow for pointing of the satellite during the data-gathering phases of the mission. The momentum dumping and orbital maneuvers will employ the four thrusters located on one face of the satellite. The computer boards were located on the face of the satellite which was accessible to the test port. Communications volume allotment was located in a corner which had reasonable access to the exterior antennas in the hopes of minimizing wiring difficulties. The propulsion volume allotment is rather large in order to accommodate all of the piping and secondary volumes and also to allow access to the nozzles.

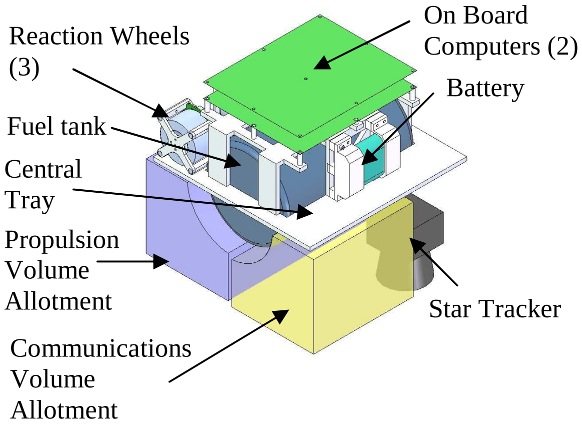

Figure 5: Internal Satellite View

The stay behind electronic package serves as a connection point between ESMO and Lunette. All of the power, communications and interfaces will pass through the stay-behind package. It will consist for the most part of a communications package that will make the gravity-mapping mission possible. The main component of this will be the Ultra Stable Oscillator (USO). The USO is an extreme version of a basic crystal oscillator providing a very precise frequency. This will allow for detailed measurements of the range-rate between the satellites which will in turn provide the gravity field data.

Thermal Design and Control

In keeping with common practice for nanosatellites, the thermal controls were to be kept mostly passive. This reduces the possibility of a malfunction and therefore reduces risks, and additionally reduces complexity and power consumption. However, the thermal design of the Lunette satellite still provided numerous challenges even for a phase-A study.

The requirements imposed on the satellite design from the subsystems required a large amount of power to be generated in numerous operational scenarios. Therefore, a large percentage of the faces of the satellite were covered in solar cells to meet the requirements. In the hopes of keeping the thermal controls passive, the first step in the design was to select appropriate coatings and tapes for the portions of the exterior surface of the satellite which were not covered in solar cells. A simple thermal model was created and it was realized early on that the satellite would not be able to survive a worst-case eclipse scenario. However, these eclipses only occur once every six months, and while Lunette stays within ESMO there would be no survival problems. Therefore, an additional mission requirement was placed that Lunette was to separate from ESMO only at an eclipse-friendly time which would ensure enough time for commissioning of Lunette and the completion of the mission.

Following the selection of passive controls for the mission, the addition of trim heaters was found to be necessary in order to keep the battery temperatures within the operational specifications. Furthermore, the battery was thermally decoupled from the surrounding panels of the satellite as the temperature changes proved unfavourable.

The Separation System

The design of the separation system for the Lunette mission is based largely on the XPOD (eXperimental Push Out Deployer) systems currently being used by SFL and other small satellite builders. The deployer is in essence a jack-in-the-box system which uses a large spring to eject the satellite. While contained within, the satellite is shielded from radiation by a 5 mm thick aluminum door and supported on all rails. The door and push plate allow the structure to exert a preload to the satellite if desired in order to help minimize the possibility of impact loads during launch.

Additionally, the Lunette separation system will serve as a thermal control measure for the satellite while it is inside ESMO. The inside of the separation system will thermally connect Lunette and ESMO with the use of coatings, while the door will isolate the satellite from the cold of space.

The dimensioning of the rails and the satellite structure is a highly toleranced system as slight manufacturing defaults could result in a satellite that does not fit within the deployer or in a deployer that does not support the structure sufficiently.

The Communications Subsystem

The communications system is essentially the mission payload for Lunette. The architecture of the system employs an S-band link between the two satellites after they have separated. During the voyage to the Moon, the satellites communicate via the stay-behind electronics package. All communications to Earth will be relayed through ESMO although there is a possibility in case of emergencies to directly contact Lunette.

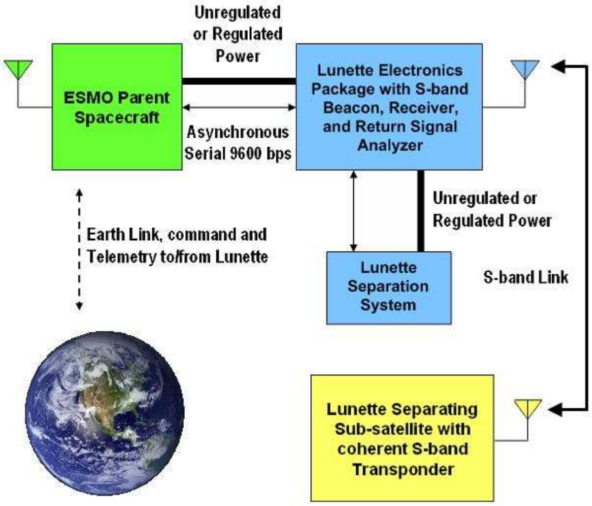

Figure 6: Communications Architecture

The communications system also proved to be the largest power consumer of the satellite. In operational modes, the communications system will draw over 3.7 W of power. In comparison, the remainder of the satellite (computer, ADCS, thermal) requires only 1.2 W of power.

The S-band patch antennas selected for this mission were developed within SFL and will be flown on the demonstration mission CanX-2 in late 2007.

The Computer Subsystem

A large part of the computer system and architecture will be derived from the current CanX mission being developed at SFL. The computer system on the Lunette satellite will be a centralized architecture. This is chosen in order to increase the reliability of the system. Should one interface fail, other interfaces and systems will not be affected.

The onboard computer (OBC) will require EPROM for storage of the bootloader software which will be the default software that runs on Lunette. This will be highly simplified and thoroughly tested software in order to ensure a bug-free environment in which Lunette will be able to operate. Data transfer will be routed through ESMO's high gain transmission system and is expected to see no more than 73.125 kByte/orbit.

In order to mitigate errors cause by single even upsets (SEU) the error detection and correction (EDAC) scheme implemented will be 'triple voting', a system in which the code is stored in three separate locations in memory. When instructions are read, the EDAC chip will compare the three locations and the majority wins.

Attitude Determination and Control System

The attitude determination and control system (or ADCS) is the navigation hub of the Lunette satellite. In order to determine Lunette's location in space as well as control its orientation, the system will possess the following sensor and controller suite:

Lunette Sensor Suite	Error
6 Sun Sensors	0.7º
3 Rate Sensors	0.01º/s
1 Star Tracker	0.0194º
Lunette Attitude Controller Suite	
3 Reaction Wheels	
4 Nozzle Thruster System	

Table 2: ADCS Suite

The six sun sensors will be located on each of the panels of the satellite, affording nearly spherical coverage of the sun's location. Combined with the knowledge of the sun's position will be the star tracker's information. The duty cycle of the star tracker had to be greatly limited due to the lack of available power. Therefore, the rate sensors will be extremely useful in propagating the satellite's position that will be updated with absolute knowledge from the star tracker whenever possible.

The reaction wheels used to control the satellite's position are designed and built in-house at SFL. They will be flown in the demonstration mission CanX-2 late in 2007 and will also be included in the GNB missions CanX-3 (also known as BRITE) and in the CanX-4/-5 formation flying mission. The 4 nozzle design of the propulsion system will be used to dump built-up momentum from the reaction wheels whenever possible. This will be performed by negative pulsing of the quad thruster system. In order to minimize the contamination of the data with propulsion inputs, the thrusts will be performed only once a week. This will coincide with the orbital maintenance maneuvers and will occur over the poles of the Moon, where there is the most overlap in data.

Typical Earth-based ADCS missions often include the use of a magnetometer and magnetorquers. These instruments make use of Earth's strong magnetic field to provide additional position information (in the case of the magnetometer) and torques to the satellite allowing for momentum dumping of the momentum wheels (in the case of the magnetorquers). However, the magnetic field of the Moon is not strong enough to be detected with a typical magnetometer or used by magnetorquers to any level of efficiency.

Figure 7: Sinclair-SFL Reaction Wheel

A preliminary controller was designed and simulated for the Lunette mission in order to prove the controllability of the mission. It was concluded that the Lunette goals would be achievable with the current suite of controls. However, a complicated controller would need to be designed, and this was outside the scope of the current Phase A study.

The ADCS system will be required at different stages of the mission. During the measurement mode of the Lunette mission, it will be imperative to point the S-band antennas towards ESMO, while keeping the satellites attitude stable and ensuring favourable power generation.

The Power System

The power system for the Lunette mission provided some interesting challenges during the initial design stages of the Lunette mission. It was quickly realized that the 20cm cubic form factor would not provide enough power for the mission. Many alternatives were examined at this point including deployable panels, different form factors and pre-deployed solar cells. The simplest solution, which also accommodated the request for more fuel storage space, was to grow the entire satellite structure to a 25cm cubic form factor.

The surface of the Lunette satellite is covered with 64 solar cells. They help generate between 3.57 and 7.25 W depending on the orbit and the mode of operation. The lowest power margin, 14.94%, occurs when the satellite is inertially locked with the lowest power-generating side facing the sun. The remainder of the scenarios sees the power margin climb to well above 25%.

The battery selected for the mission provides power when the satellite enters an eclipse scenario. Based on the mission requirements which necessitate flight over the full sphere of the Moon, this will most likely occur quite often. However, due to the fact that the Moon precesses under the satellite, Lunette may never experience the full possible eclipse time.

The Propulsion System

In order to achieve the full-sphere gravity map of the Moon, the Lunette satellite will be required to fly in formation with the ESMO satellite for a minimum of three months. Therefore, a propulsion system will be required to detumble the satellite, perform orbital maintenance maneuvers and an orbital plane change. The goal of the plane change is to increase the quality of the data by varying the path taken by Lunette behind ESMO. With a one degree plane change, the data acquired will help improve the quality and precision of the lunar gravity map.

The Delta-V requirement for the propulsion system was derived from orbital simulations using the LP75G map generated from the Lunar Prospector mission. A summary of the budget has been included in the following table. Non-impulsive propulsion penalties were included as well as a margin of 30% in order to accommodate any unknown orbital perturbations that may be encountered.

The list of necessary propulsion maneuvers are as follows. Following separation, the Lunette satellite will need to stop drifting (LOA #1). The orbital maintenance maneuvers required to keep the satellite in a 100km circular orbit will be performed once every week (LOM #1). The plane change maneuver (LOA#2) is the single largest delta-v maneuver in the Lunette mission. The remaining maneuvers are performed for attitude control and consist of momentum dumping (ACM #1) and de-tumbling momentum dumping (ACM #2).

Delta-V Budget for Lunette Mission

Maneuver	# of Executions	Non-Impulsive Penalty [m/s]	Total Delta V [m/s]
LOA #1	1	7.20E-06	0.67
LOM #1	9	2.45E-03	32.32
LOA #2	1	5.18E-01	29.03
LOM #2	4	1.09E-03	14.36
ACM #1	14	5.77E-09	0.36
ACM #2	1	5.87E-12	0.01
Total Delta V [m/s]			76.75
Margin (30%)			23.03
Total w/ Margin [m/s]			99.78

LOA - Lunar Orbit Alteration
LOM - Lunar Orbit Maintenance
ACM - Attitude Control Maneuver

Table 3: Delta V Budget for Lunette Mission

After examining several commercially available propulsion systems, it was concluded that none met the requirements needed for this mission. Therefore, a custom system was designed. The propulsion system was inherited in large parts from the CanX propulsion systems, NANOPS and CNAPS, which are both cold gas propulsion systems. However, in comparison to the two other systems, the Lunette propulsion system has a much larger Delta-V capability.

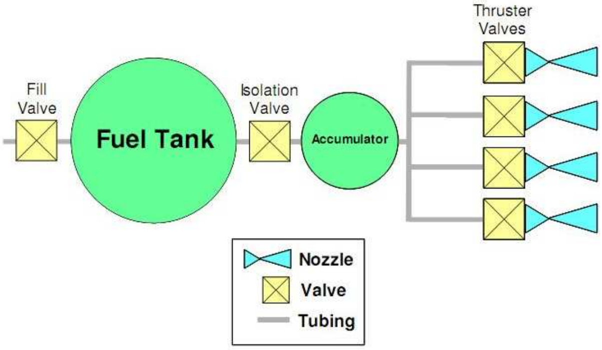

Figure 8: Propulsion System Architecture

The architecture of the system follows a simple layout containing a large fuel tank which is contained between an isolation valve and a fill valve which is accessible from the exterior of the fully assembled satellite. This allows the satellite to be transported without a full fuel tank and to be charged immediately before launch. On the other side of the isolation valve is an accumulator, the role of which is to ensure that the gas expelled is in vapour form and at the correct pressure. Tubing will then link the accumulator with the four thruster valves allowing the system to be fined-tuned in order to compensate for any thrust or alignment variations from the nozzles. The fill valve will also contain a burst valve to ensure that the valve will release gas to prevent an explosion should the system come under higher pressure than it was designed for.

The selection of the propellant proved to be a study in tradeoffs. The required Delta-V directly translated into a total necessary impulse of 540 Ns. The mass restriction kept the overall system mass, including propellant, to 2.4 kg. Once the components mass is estimated, the remaining mass for the propellant (1.2 kg) results in a specific impulse requirement of greater than 50 s. Considerations had to be given to the nature of the propellant as well. Some chemicals require permits to purchase, store, and transport not to mention the danger it would pose when stored in a working laboratory. The possibility of explosive propellant would also make the primary payload nervous and might have prevented the mission from being launched. The culmination of this search yielded the best choice for the Lunette mission: Nitrous Oxide in an aluminum tank.

CONCLUSION

The nanosatellite technology developed at the Space Flight Laboratory is versatile and can be used for a wide range of high performance missions. The Lunette concept is a significant step towards enabling scientific missions using affordable nanosatellites that can be designed, constructed, and launched in a short timeframe.

The proof of concept from the completion of the Phase A study demonstrates that Lunette is feasible based on existing SFL technology and would be a valuable addition to the ESMO mission. The creation of a full-sphere gravity map for any future Moon missions would make an important contribution to the scientific community and Moon mission planners. Furthermore, the Lunette concept can be expanded to other planetary missions as a first-step in exploration. The generation of accurate gravity maps facilitates orbital navigation and landing precision while also helping to determine the geological make-up of the planet. The data can potentially be combined with a magnetic survey to help locate specific materials.

The potential of nanosatellites is constantly being expanded and Lunette will be the next step in providing access to space for science.

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