

## The Design of a Lunar Farside Gravity Mapping Nanosatellite for the European Student Moon Orbiter Mission

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### ABSTRACT

The construction of a high-resolution map of the lunar gravity field would be very useful for studies of the lunar interior, and would be invaluable for accurately planning future lunar orbiter missions. Previous gravity-mapping missions have tracked the gravitational perturbations of lunar satellite orbits from Earth to construct nearside gravity maps, but have only been able to provide extrapolated measurements of the far side gravity field due to the lack of tracking data while the satellite's orbit is occluded by the Moon. Gravity-mapping payloads utilizing satellite-to-satellite range-rate tracking between a pair of lunar orbiters have been proposed on previous lunar missions, but have not yet flown. The University of Toronto Space Flight Laboratory, using expertise and design heritage from the CanX nanosatellite program, is in the process of developing a payload for the European Student Moon Orbiter (ESMO) called "Lunette," a gravity-mapping nanosatellite that will separate from a parent spacecraft and fly along track in a 100 km altitude circular polar lunar orbit. The Lunette nanosatellite is based on SFL's Generic Nanosatellite Bus and includes a coherent S-band radio transponder, three-axis attitude determination and control, and a 100 m/s propulsion system, allowing it to maintain an along-track orbital formation and measure the range-rate between itself and the parent spacecraft using Doppler tracking. These range-rate measurements will be used to construct a full-sphere lunar gravity map with an accuracy of 20 mGal or better, comparable to the current best-accuracy nearside gravity map from the Lunar Prospector mission data. Lunette has been selected as a payload for the ESMO project under the Student Space Exploration and Technology Initiative (SSETI) program of the European Space Agency. ESMO is currently in Phase A study, and is targeting a launch in 2011.

### INTRODUCTION

After several decades of neglect following the first manned lunar explorations, interest in lunar exploration has once again increased. NASA is planning both unmanned and manned missions, and other nations have either recently completed or are currently planning unmanned lunar missions, such as ESA's SMART-1 which launched in 2003. Upcoming missions such as JAXA's Lunar-A and SELENE, India's Chandrayaan-1, China's Lunar Probe, and the student-designed European Student Moon Orbiter (ESMO) present the opportunity for new lunar science to be performed. Low-cost nano- and micro-satellites have not yet flown in a lunar mission, but are well-suited to accomplish some specialized lunar science and exploration goals. Gravity mapping is one such task that can be accomplished by adding a low-cost ejectable

subsatellite payload to an existing lunar mission with an appropriate planned orbit.

### GRAVITY MAPPING

The lunar gravity field is highly irregular and "lumpy" compared to that of the Earth, due to the presence of mass concentrations ("mascons") beneath the surface of many circular basins. Since these mascons affect the gravity field and are therefore measurable from orbit, lunar gravity mapping has emerged as an important source of geological information for use in science, exploration, and mission planning.

As a remote sensing technique, gravity mapping is particularly useful because it provides information about subsurface features, while other remote sensing methods (photography, altimetry, multispectral and radar imaging) only image a thin layer at the surface, or

potentially the first few meters of the surface using gamma-ray or neutron spectroscopy. Gravity mapping, on the other hand, is routinely used on Earth to study subsurface features ranging from shallow depths all the way down to the core-mantle boundary. Gravity measurements can be used to measure crust thickness, locate mineral deposits, and potentially resolve questions regarding the nature of the lunar mascons, their relationship to the lunar basins, and the differences between the near and far sides of the moon. Local gravity maps are also useful for manned exploration, and can be used to locate subsurface mineral deposits for mining operations, or other subsurface features of interest for further scientific investigation by a crew on the lunar surface.

Finally, a high-resolution gravity map has obvious benefits for mission planning purposes. Gravitationally-induced orbital perturbations can cause a spacecraft to waste precious fuel on orbital maintenance, and can also have detrimental effects on attempts at precision landing. Errors due to gravitational perturbations contributed to Apollo 11 overshooting its landing site, and were corrected on subsequent missions by measuring the position of the spacecraft after it emerged from the far side and entering the observed error into the flight computer.

### *Previous Work*

One method of constructing lunar gravity maps is to measure the orbital perturbations of lunar satellites. The first lunar gravity maps were constructed using radio tracking data from NASA's Lunar Orbiter project, which also yielded the discovery of the lunar mascons<sup>7</sup>. Since radio tracking from Earth requires a line of sight to the spacecraft, only near-side gravity mapping was possible using Lunar Orbiter data. The Apollo missions also yielded tracking data that was used for gravity map construction; however the need for frequent attitude control thruster firings added noise to the data, and only near-side tracking data was available. Apollo 15 and 16 attempted to solve the former problem by releasing small spin-stabilized subsatellites that could be independently tracked from Earth, but since there was no communication between the subsatellite and the Apollo spacecraft, again no tracking data from the far side was available.

More recently, the Clementine and Lunar Prospector missions yielded additional tracking data. The gravity maps constructed from the Lunar Prospector data are currently the best models to date<sup>4,5</sup>; the spacecraft spent a year in a 100km circular polar orbit, enabling high resolution mapping, and moved to a progressively lower orbit in the remaining six months before impacting the lunar surface<sup>1</sup>. A rough far side map was

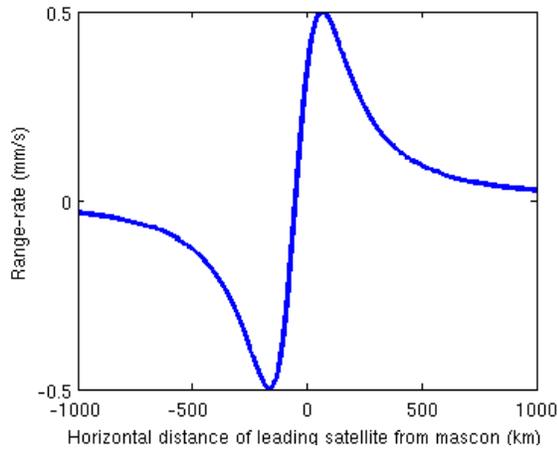
constructed using information inferred by comparing Lunar Prospector's orbit before losing contact with Earth and immediately after emerging from the far side. The near-side Lunar Prospector gravity map has a 10-20 mGal sensitivity, and a 50-100km 2-D spatial resolution, while the far-side map is estimated at five to ten times worse, and may contain systemic errors due to the assumptions necessary to extrapolate far side gravity information from limited data<sup>3</sup>.

### *Methods of Gravity Measurement*

Since a body in free-fall cannot directly measure a gravitational field, gravity maps must be constructed by measuring the difference in the gravity field between two separate points. Radio tracking can be used to measure the relative distance between two objects, such as a satellite in lunar orbit and a ground station on Earth. A gravity gradiometer can very precisely measure the difference in gravitational forces between two objects a short distance (less than a meter) apart<sup>10</sup>. However, gravity gradiometers have not yet flown in space (the first is planned for launch in late 2007 on GOCE, the ESA Earth gravity-mapping mission), and would add a great deal of complexity, and therefore cost, to a mission.

Radio tracking is the superior method of measuring long-wavelength fluctuations in the gravity field, which yield information about the structure of the moon. The current best-quality lunar gravity maps can be replicated using radio tracking in a low orbit, and performing range-rate measurements between two spacecraft (the main lunar orbiter and a low-cost subsatellite) would enable data collection on the far side of the moon. A full-sphere gravity map with the same sensitivity and resolution as the Lunar Prospector map would represent a significant improvement from the current state of lunar gravimetry.

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<sup>6</sup>. 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 spacecraft), an orbital altitude of 100km, and an along-track separation of 100km, the observable peak-to-peak range-rate signature is shown in Figure 1.



**Figure 1: Range-rate signature of a 20 mGal peak surface anomaly, observed by two spacecraft at 100km altitude, with an along-track separation of 100km**

**LUNETTE**

Lunette is a low-cost gravity-mapping payload that has been designed by UTIAS/SFL to create full-sphere lunar gravity maps with the same quality as the Lunar Prospector data. The payload consists of a subsatellite, “Lunette,” that separates from a parent spacecraft, a separation system that encloses Lunette during the transfer to lunar orbit, and an electronics package that remains on the parent spacecraft to measure the range and range-rate between the two spacecraft. Lunette has been selected as a primary payload on the European Student Moon Orbiter (ESMO), a project under the Student Space Exploration and Technology Initiative (SSETI) program of the European Space Agency, and managed by the ESA Education Office. ESMO is currently in a Phase A study, and is planned for launch in 2011. ESMO will carry a narrow-angle camera for

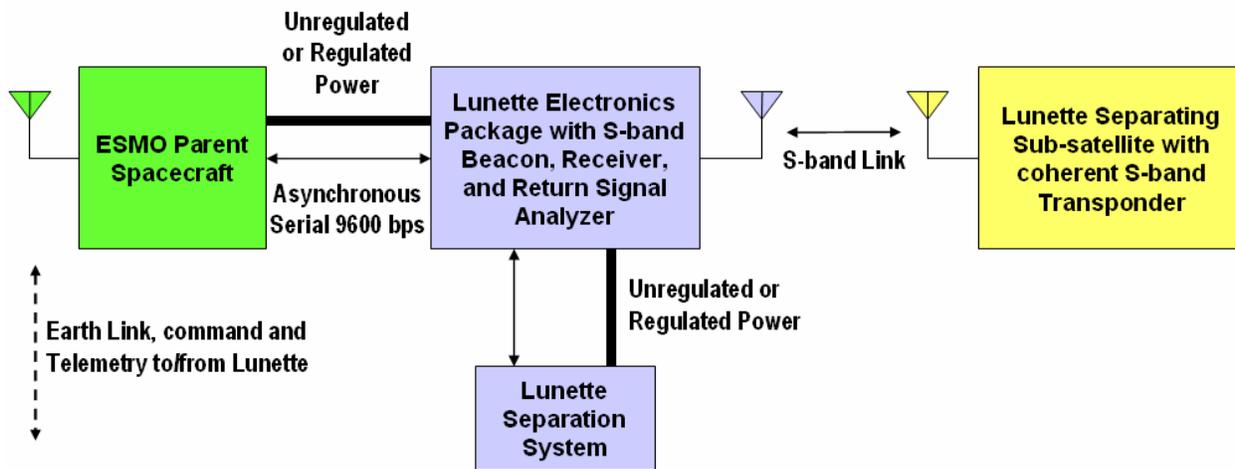
photography of the lunar surface, and will release the Lunette subsatellite into a low orbit for gravity mapping operations.

**Requirements**

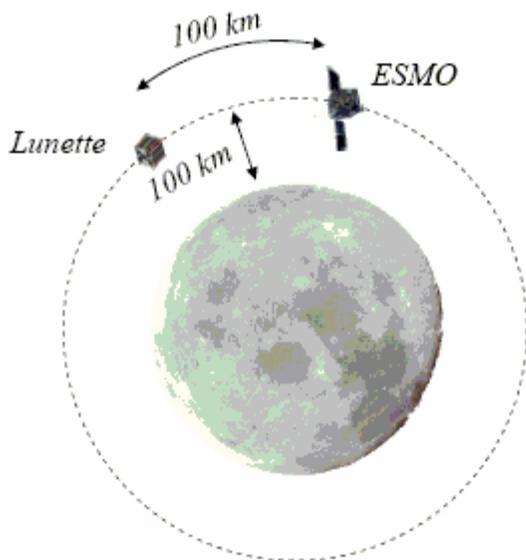
Lunette’s science objective is to replicate the quality of the Lunar Prospector gravity maps, which translates into design and operational requirements on both Lunette and ESMO.

In order to construct gravity maps with a 10-20 mGal sensitivity and a 100km spatial resolution, Lunette must operate in a low 100km-altitude orbit (similar to that of Lunar Prospector), that is circular (to ensure consistent sensitivity to gravitational fluctuations) and polar (to ensure full-sphere coverage). Lunette must be capable of maintaining its orbital altitude to within  $\pm 10$ km of the nominal altitude, and maintaining a 100km along-track distance from ESMO.

The attitude determination and control system must be capable of 3-axis control to ensure that Lunette’s main antennas are continuously pointed toward ESMO, and must be capable of restricting Lunette’s angular motion to less than  $0.015^\circ/s$  to ensure that any antenna motion is not significant enough to add unacceptable errors into the range-rate measurements. Finally, Lunette must be capable of measuring the peak-to-peak range-rate between the analyzer and Lunette to an accuracy of 1 mm/s over a 10 second integration period.



**Figure 2: Functional block diagram for the Lunette payload**



**Figure 3: Along-track formation, 100km orbital altitude, 100km separation**

Besides providing the required structure, power, and data transfer, Lunette's science objective necessitates some operational requirements on ESMO. ESMO must release Lunette into a 100km circular polar orbit in an along-track direction, and remain in that orbit for the duration of Lunette's mission. Once gravity mapping begins, ESMO must coordinate any orbit corrections with Lunette such that each two-week mapping period is uninterrupted by thrusting, and must maintain a stable, constant attitude so that antenna motion does not contaminate the range-rate measurements.

### ***Mission Profile***

Optimally, once ESMO reaches its science orbit, Lunette should be released immediately following a Lunar eclipse. Lunar eclipses occur approximately once every six months, and Lunette most likely will not be able to survive an eclipse outside of ESMO, so this restriction will place an upper bound of six months on Lunette's mission. Once Lunette is released, it will drift to a separation distance of 100km, and perform detumbling and commissioning operations. Up to four weeks has been allocated for the commissioning phase of the mission. Following commissioning, six weeks are allocated for gravity-mapping in the along-track formation with ESMO. In a 100km circular polar orbit, Lunette will be able to collect data for one full-sphere map every 14 days, resulting in three full-sphere maps from the along-track phase. 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. A small amount of time will be allocated every 7 days for

orbital correction maneuvers, to ensure that Lunette remains within  $\pm 10$  km of the nominal altitude.

Following the along-track phase, Lunette will fire its thrusters to implement a 1-degree plane change, which will improve measurement of east-west gravity gradients. It will then continue gravity mapping operations for the remainder of its lifetime. Once all fuel has been expended, Lunette's orbit will gradually become more elliptical, causing it to intermittently lose contact with ESMO and eventually crash into the lunar surface. It is expected that Lunette will have enough fuel to maintain a 100km altitude orbit for at least four weeks after the plane change maneuver, yielding at least two additional full-sphere gravity maps.

### **DESIGN**

The Lunette subsatellite uses design heritage from current planned missions at the University of Toronto Institute for Aerospace Studies (UTIAS) Space Flight Laboratory (SFL). Lunette is based on the Generic Nanosatellite Bus that supports the BRITE Constellation and the CanX-4&5 missions currently under development. The Lunette Separation System is derived from the XPOD family of nanosatellite ejection systems. Subsystem designs for communications, propulsion, and attitude determination and control that were tailored to Lunette's mission requirements have been added.

### ***Generic Nanosatellite Bus***

The Canadian Advanced Nanospace eXperiment (CanX) program at UTIAS/SFL provides the opportunity to develop low cost nanosatellites for cost-effective access to space for the research and development communities. Recent missions have led to the development of a Generic Nanosatellite Bus (GNB) to provide low cost access to space for small payloads using a versatile high-performance platform. The GNB results from designing a common satellite bus to support two missions with very different requirements. The first, CanX-3 (or "BRITE," short for BRiGht-star Target Explorer), is a four-nanosatellite mission planned to make photometric observations of several of the brightest stars in the sky in order to understand the structure of these stars. Each BRITE spacecraft consists of a GNB carrying an optical photometer. The second mission, CanX-4 and CanX-5, consists of a pair of identical nanosatellites whose objective is to demonstrate precise and autonomous formation flying in space. For the purpose of CanX-4 and CanX-5, the GNB will carry a propulsion system payload<sup>2</sup>.

The Lunette subsatellite has been designed using heritage from the GNB. Specifically, elements of the structure, attitude control equipment, power, and the

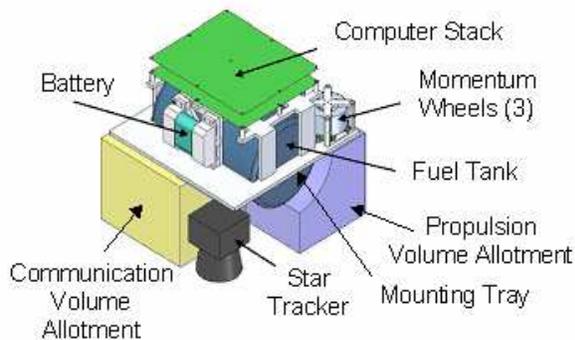
main on-board computer are derived from the GNB design and modified slightly to meet Lunette mission requirements.



**Figure 4: Lunette subsatellite**

Lunette is a 25-cm cube with eight to twelve solar panels on every face for power generation, as shown in Figure 4. Four “launch rails” on four parallel sides of the cube allow Lunette to be constrained within its deployment system. A set of quad-canted S-band antennas for omni-directional communications are pre-deployed to reduce the risk inherent in deployable systems. Other components mounted on the faces of the satellite are the S-band directional patch antennas for communications during range and range rate measurements, the star tracker for attitude determination, and the four thruster nozzles for orbital and attitude control. Thermal control of the satellite is achieved passively by applying coatings and thermal tapes to the remaining area on the exterior panels of Lunette.

The internal layout of Lunette consists of a propellant tank mounted centrally to reduce variations in the location of the center of mass as fuel is depleted, and a central structural mounting tray built around the propellant tank, where the remaining components are attached as shown in Figure 5. The total wet mass of Lunette is 6.2 kg.



**Figure 5: Internal layout of the Lunette subsatellite**

### Communication

The primary function of the communications system is to perform the high precision range-rate (1 mm/s) measurements and the lower precision range (1 km) measurements between ESMO and Lunette, which are required to construct the lunar gravity map. In addition, the communications system provides a low-speed two-way data link between Lunette and ESMO which serves to relay data, commands and telemetry to and from the ground.

The communications system is composed of two separate modules: the analyzer package on ESMO, and the communications system on Lunette.

The module on board Lunette consists of a directional antenna system, a near omni-directional antenna system, and a radio transponder. Communication is in S-band and allows for coherent retransmission of a modified incoming signal for precision range-rate measurements, direct retransmission of a modified incoming signal for lower precision range measurement, as well as the exchange of telemetry and commands between Lunette and the parent spacecraft.

The analyzer package, which is left behind on the parent spacecraft after the separation of Lunette, includes a pair of monopole antennas, a radio transponder and an ultra stable oscillator as a precision reference for the high accuracy range-rate measurements.

Some of the technologies being re-employed from the CanX program are the quad-canted monopole antenna system designed for CanX-2, the patch antennas designed for CanX-2, and the CanX-4 & CanX-5 inter-satellite link (ISL), which provided the base model for the Lunette design.

### Modes of operation

There are four communications system operation modes that dictate the specific available functionalities and hardware components being employed at any given time. These modes include High Gain, High Transmission, Low Gain and Emergency Mode.

High Gain Mode is utilized during range-rate data collection. This mode employs the high gain patch antennas and provides directional communication, which requires some pointing restrictions. It uses a minimum information data rate in order to reduce noise during range-rate data collection, meaning that no telemetry data is transferred simultaneously.

High Transmission Mode is used during tracking, telemetry and command transmission. During this mode

range measurements are taken while commands, software and telemetry data are being relayed between the two spacecraft. This is accomplished using a high information data rate in order to maximize the amount of data transfer while using the same hardware configuration as in the high gain mode. This mode occurs once every six orbits over alternating poles (where there is a large amount of overlap in data collection) for short durations to minimize the interruptions to the range rate data collection.

Low Gain Mode is used during safe-hold mode, commissioning, and any other situation when the high gain antennas are not pointed towards the parent spacecraft. This mode provides near omni-directional coverage using the lower gain quad-canted monopole antenna system. The data rate in this mode is minimized in order to reduce the power requirements.

The Emergency Mode is used for direct communication between Lunette and Earth, in the event that Lunette is not able to communicate with the analyzer package on the parent spacecraft, or if the parent spacecraft loses communication with its ground station on Earth. This mode employs the omni-directional low gain quad-canted monopole antennas, a low data rate and a different modulation technique that is more suitable for communications over long distances.

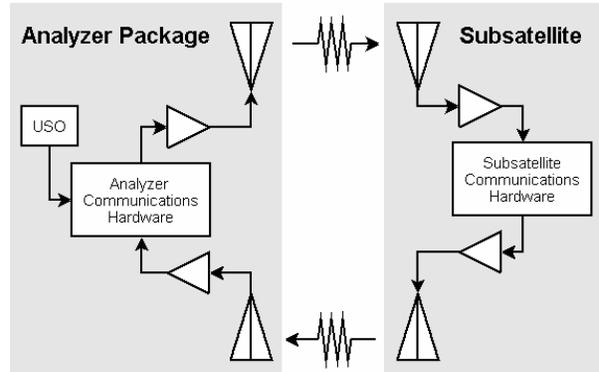
**Range and range-rate measurements**

The range tracking between Lunette and the parent spacecraft is performed by a low precision ranging system. The range information is utilized for navigation, and to determine Lunette’s absolute position, ensuring accurate placement of the measured gravity map on the lunar globe.

In order to perform the ranging measurements, the analyzer package sends a ranging bit sequence, which is repeated by Lunette. The signal return time is used as a measure of distance, with hardware delays taken into account. The range-rate tracking between Lunette and the parent spacecraft is performed by measuring the Doppler frequency shift induced by the relative motion of the two satellites. An ultra-stable oscillator on board the analyzer provides the timing precision necessary for Lunette to meet the required peak-to-peak range-rate measurement accuracy.

Orbital determination of Lunette will be performed using an initial orbital determination scheme and will be propagated in order to have uninterrupted position data for science and navigation. The initial orbital determination will be performed at discrete points in time using absolute position and velocity information for ESMO and relative position and velocity

information between the two satellites. The absolute position and velocity vectors of the parent spacecraft will be obtained on the near side of the moon using Earth ground station radio tracking. The relative position and velocity of Lunette with respect to ESMO will be determined using range-rate, which is already available from the science measurements, and angular data obtained by using an imager on board Lunette to take a picture of the parent spacecraft. Lunette’s orbit can then be determined from the absolute position and velocity of the parent spacecraft, and the relative data.



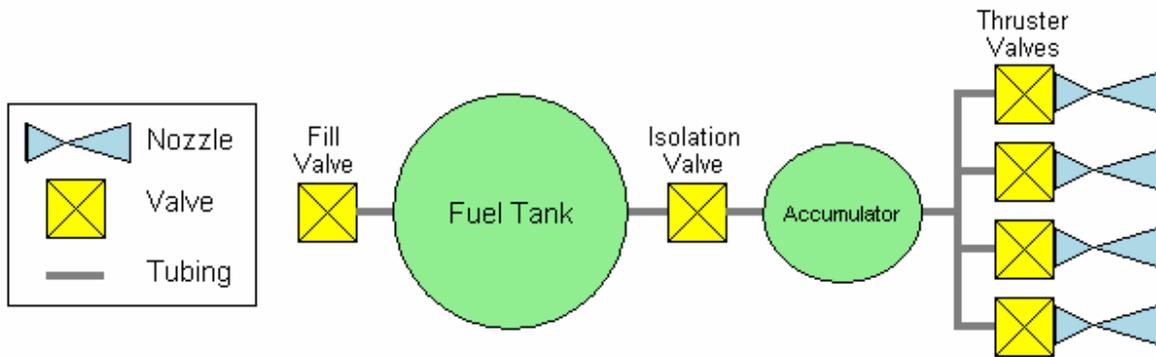
**Figure 6: Functional block diagram of the Lunette communication system**

**Propulsion**

In order to maintain the required science orbit without risk of the orbital periapsis becoming dangerously low, the spacecraft is equipped with a 100 m/s propulsion system with attitude control capabilities. This propulsion system allows the spacecraft to maintain an along-track orbital formation with the parent satellite while trimming the stored angular momentum on the attitude control reaction wheels that arises from the secular disturbances of the space environment.

The propulsion system was selected to be a cold gas system due to its relative simplicity compared to other systems such as a bi-propellant system, and also for its low power requirements and compactness. The configuration of the gas system, shown in Figure 7, includes an accumulator or secondary volume where the propellant coming from the fuel tank is allowed to vaporize completely. The pressure in this secondary chamber is regulated to a lower level than the propellant tank pressure using an active control system. This ensures constant thrust magnitudes of each propulsion nozzle and avoids the issues arising from operating above the critical point of the propellant fluid, where the performance is significantly degraded.

Attitude control during thrusting is achieved through a four-nozzle configuration, where nozzles are placed near the corners of one of Lunette’s faces. By using a



**Figure 7: Subsatellite propulsion system design**

‘negative pulsing’ control scheme (turning one or more thrusters off momentarily during a four-thruster burn), any pitch and yaw torques caused by individual thruster misalignment can be compensated. Moreover, momentum accumulated in pitch and yaw reaction wheels can be dumped using the same method. In addition, the thrusters are canted to provide the coupling necessary to be able to control roll about the thrust axis using an active control scheme.

After extensively analyzing the characteristics of many different fuels, Nitrous Oxide was selected for its high density and other convenient properties, including relatively easy and safe handling.

The total wet mass of the micro-propulsion system is below 2 kg, of which almost half is propellant mass. The performance that the system can achieve is in excess of 60 s of specific impulse, with a thrust magnitude of 0.3 N per thruster and a minimum impulse bit of less than 10 mN-s.

***Attitude Determination and Control***

The attitude determination and control system in Lunette is employed at different stages in the mission for various purposes. During range and range-rate measurements it is imperative to point the directional communication antennas toward ESMO with a required level of stability, while keeping an attitude favorable for power generation using the body mounted solar panels. Also, the star tracker must be able to acquire an attitude solution, implying that it is not pointing toward the Moon, Sun or Earth. In addition, an attitude solution is required for analysis of the range-rate data, to remove any errors induced by the motion of the antenna. During orbital correction maneuvers, the attitude determination and control system must be able to point the thrusters in the required direction and maintain this attitude throughout the duration of the thrusting period.

The characteristics of the lunar environment are significantly different from the Earth environment, and therefore some methods of attitude determination and control traditionally used in an Earth orbit are not available in the lunar environment. Specifically, the Earth’s moon lacks a strong enough magnetic field that can be measured with magnetometers for attitude determination, and whose dipole can be harnessed with magnetorquers to provide some level of attitude control. For this reason, the attitude determination and control system for the Lunette subsatellite required some innovative re-design deviating from that of the GNB. Nevertheless, some GNB heritage, such as the reaction wheel hardware and the attitude determination software scheme and architecture, was employed in the design of this system.

Attitude determination for Lunette is achieved at different instances using different combinations of data from sun sensors, rate sensors and a star tracker. Fine attitude determination is achieved using the star tracker. However, due to power constraints the star tracker must be powercycled while propagating the attitude solution. The propagated attitude solution is re-initialized using the star tracker at the beginning of each cycle. Coarse attitude solutions are employed during thrusting since a high update rate is required for the automatic attitude corrections performed by thruster pulsing. This high update rate cannot be achieved using the star tracker, and therefore attitude determination during thrusting is achieved by using the sun and rate sensors with periodic corrections from the star tracker.

Attitude control is achieved using three orthogonally-mounted reaction wheels and negative pulsing of the quad thruster system. Fine attitude control and slewing maneuvers are performed using the reaction wheels, while attitude control during thrusting is achieved by pulsing the thrusters. In addition, the reaction wheels are employed to suppress the environmental disturbance

torques arising from elements such as solar pressure and gravity gradients. Any secular disturbances on the attitude of the spacecraft will store momentum in the wheels, which needs to be dumped periodically to prevent wheel saturation. Momentum dumping is performed during thrusting maneuvers, employing the pulsed thruster system to provide the torques necessary to dump the momentum of the wheels.

## CONCLUSIONS

The technology developed in the CanX program at UTIAS/SFL has enabled the development of a low-cost ejectable subsatellite payload that will accomplish significant niche lunar science. Lunette combines an adapted CanX Generic Nanosatellite Bus, a 100 m/s propulsion system capable of attitude control and orbital maintenance, an attitude determination and control system capable of the precise attitude knowledge necessary for the processing of range-rate data, and a communications system capable of measuring the range and range-rate between Lunette and the main spacecraft to a high degree of accuracy. The result of this design process is a payload capable of advancing the current state of lunar science by constructing high-resolution full-sphere gravity maps, gaining important geologic, exploration, and mission planning knowledge at a low cost.

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