LUNETTE: LUNAR GRAVITY MAPPING WITH A NANOSATELLITE

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ABSTRACT

Forty years after the first spacecraft entered lunar orbit, the gravitational field of the lunar farside remains poorly known, because spacecraft low over the farside cannot be tracked from Earth. Current farside gravity maps are based on indirect information; they are not very precise and their reliability is uncertain. A complete, dependable lunar gravity map would aid both lunar science and lunar mission engineering. The best way to achieve this is with an orbiter plus a subsatellite, doing continuous inter-spacecraft tracking, and recording data when out of touch with Earth.

Lunette is a 5 kg gravity-mapping payload, including a 3.5 kg subsatellite derived from the current CanX nanosatellites. It is planned to fly on the SSETI European Student Moon Orbiter (ESMO), now in Phase A development. The subsatellite includes attitude control, imaging, station-keeping and maneuvering propulsion, and a radio transponder for tracking by the electronics package on the parent spacecraft. Six months of formation flying will produce a reliable global gravity map with quality matching current nearside-only maps, and local measurements better than any current data of selected areas of interest.

1. INTRODUCTION

After several decades of neglect, interest in lunar exploration has revived considerably in the last few years. Most spectacularly, NASA's recent massive shift of emphasis has focused its attention on resuming lunar exploration, with unmanned missions as precursors to later manned flights. Many nations have either completed lunar missions (i.e., ESA's SMART-1) or are in the process of developing missions such as Japan's Lunar-A and SELENE, India's Chandrayaan-1, and China's lunar probe. Furthermore, the Student Space Exploration and Technology Initiative (SSETI) has also turned its attention to the moon with the European Student Moon Orbiter (ESMO) mission, currently in the Phase A preliminary design stage.

Despite the revival of interest, even unmanned lunar missions continue to have a reputation for being costly, with budgets typically of hundreds of millions of US$. For example, SMART-1, considered an unusually inexpensive project by ESA, is costing over US$120M, not including instrument development. While the "small-satellite revolution" of the past decade has started to produce space science missions in low Earth orbit with extraordinarily low costs (e.g., the MOST space astronomy microsat mission, the development of which was led by several of us [1]), it has not yet made itself visible in lunar exploration. However, recent microsatellite (mass < 100 kg) and nanosatellite (mass < 10 kg) technology developments can now enable well-chosen goals in lunar science and exploration to be met at much lower costs.

Most of the easy goals of lunar exploration and science have been met already, or are likely to be met soon by one of the several lunar orbiters now planned. Opportunities for small satellites to contribute useful results in obvious areas like imaging are now very limited. However, more specialized goals remain unmet, and some of them appear suitable for small spacecraft. Gravity mapping is one such goal, offering an opportunity for a lunar nanosatellite to do leading-edge work, contributing to lunar science, lunar exploration, and the engineering of future lunar missions.

1.1 Gravity Mapping

Many forms of remote sensing have been used to study the Moon, but few of them are practical for studying the lunar interior. Gravity mapping is a remote-sensing technique that has some unique advantages. Most notably, it is extremely penetrating (nothing blocks gravity), and is routinely used to study from near-surface depths right down to planetary cores. Gravity's view of internal structures is inherently blurred by distance, but even so, it reveals the interior of planetary bodies as few other techniques can.

The Moon's gravitational field is quite irregular when examined closely, much more so than Earth's, and carries considerable information about the interior. In particular, it is distorted by large mass concentrations, called "mascons", located below many of the major impact basins. Good-quality maps of the lunar gravitational field have major potential uses in science, exploration, and mission engineering.

Gravity data is one of the major potential sources of information for the study of lunar geophysics and geology, most notably the puzzling nature of the mascons, and the still-unsolved mystery of how much the lunar nearside and farside differ and why. Simple theories of the origin of mascons by magma flooding of impact basins have great difficulty explaining the farside's South Pole Aitken basin, which is unflooded (and shows no mascon) despite being the largest, deepest, and probably oldest impact basin on the Moon [2],[3].

Traditional theories attempting to explain why the mascons have not sunk deeper into the interior seem to require a very strong lunar crust forming very early [4], which is not easy to reconcile with models of the Moon's thermal evolution. Even such a simple question of lunar geology as whether the crust really is thicker on the farside than on the nearside—which has long been the accepted theory, but doubts have been raised about it recently [2]—could be definitively resolved by good gravity mapping. Fig. 1 shows Lunar crustal thickness inferred from Lunar Prospector gravity data, illustrating the putative nearside/farside dichotomy.

As discuss below, the single biggest problem of current lunar gravity maps is that the map quality is very much worse for the farside than for the nearside, and so there is considerable uncertainty about whether apparent nearside/farside differences seen in the maps are real. For scientific purposes, the highest priority for gravity mapping is a uniform global map free of artefacts introduced by data analysis.

Lunar exploration would also benefit from good gravity maps, mostly high-resolution local maps of areas considered interesting for manned activities. Local gravity maps are extensively used on Earth for locating mineral resources, and should have similar uses on the Moon. They also have possible uses in locating subsurface physical features of interest, such as large lava tubes that might be good places for construction of naturally-sheltered bases.

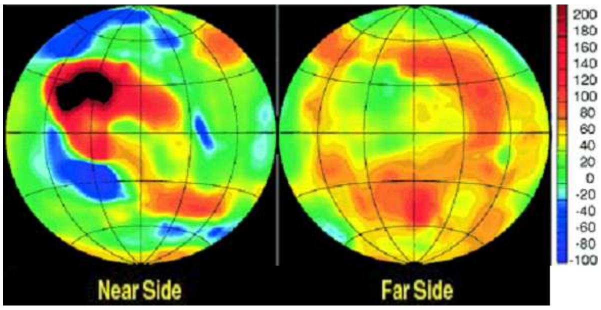

Figure 1. Inferred Lunar Crustal Thickness Maps (km) [7]

Finally, mission engineering for lunar spacecraft urgently wants good gravity maps of the Moon. Both mission planning and mission operations for lunar orbiters would benefit from accurate orbit prediction, which is extremely difficult in the Moon’s lumpy gravitational field. This is especially true for low Lunar orbits, which mascons perturb severely, and for which the difference between a well-chosen and poorly-chosen orbit can mean a large difference in orbit-maintenance propellant consumption, or a short orbital life before crashing. Even lunar landing missions need good gravity data to ensure a correctly targeted landing site; for example, poor orbit prediction contributed to Apollo 11 overshooting its intended landing site by 8 km. Long-term orbit stability predictions, and the finding of stable orbits, are particularly sensitive to data quality.

Odd though it may seem, despite extensive efforts by both early and recent lunar missions, the Moon’s gravity field is quite poorly mapped. There is an opportunity here for a very small spacecraft to improve the situation greatly.

1.2 Past Work

When spacecraft began orbiting the Moon, in the mid-1960s, it became obvious that the Moon’s gravitational field is quite “lumpy” compared to Earth’s. NASA’s Lunar Orbiter project discovered the lunar mascons [6], and the first attempts at lunar gravity maps used Lunar Orbiter tracking data. Even then, it was quickly obvious that the impossibility of ground tracking of spacecraft over the lunar farside was a problem for mapping. Using line-of-sight radio signals, radio tracking will not work when a Lunar satellite “sets” behind the Moon as seen from tracking stations on Earth; recalling that one side of the Moon always faces the Earth, it is the non-Earth-facing farside over which satellite’s cannot be tracked from Earth.

The Apollo manned missions supplied some further tracking data, as well as a clear indication of its practical importance: making pin-point landings at pre-selected points using pre-calculated orbits proved impossible, because of the uncertainties about the gravitational field over the farside. Apollo flight controllers found it necessary to do hasty last-minute tracking as the Lunar Module came into view, early in its landing approach, and insert a final correction to take out orbit errors introduced over the farside.

Unfortunately, gravity mapping from Lunar Orbiter and Apollo data was limited by poor data quality: both types of spacecraft frequently fired thrusters for attitude control, and the small orbit disturbances that resulted injected considerable noise into the gravity data. One attempt to deal with this was made by

Apollo 15 and 16: those two flights released small spin-stabilized “subsatellites” which did not have this problem. Unfortunately, tracking support for the subsatellites was rather sparse, as tracking was done periodically rather than continuously, and their orbits were not ideal for mapping. The Apollo 16 subsatellite, in particular, was released in a poor orbit due to spacecraft problems, and it crashed into the lunar surface after only 35 days, due to the irregularities of the lunar gravitational field. Even the subsatellites, however, could not be tracked over the lunar farside, as they were only tracked from the Earth.

One of this paper’s authors (J. A.-H.), together with W.L. Sjogren of JPL, investigated putting a pair of subsatellites on Apollo 18, with a tracking link between them; unfortunately, that proposal was stillborn when Apollo 18 was canceled in mid-1970.

Modern lunar gravity maps (see Fig. 2) are based almost entirely on data from the Lunar Prospector mission of 1998/99 [5], which spent a year in a 100 km circular polar orbit, and was progressively moved down to lower altitudes in its remaining six months. Lunar Prospector was spin-stabilized and rarely fired its thrusters, and tracking coverage was continuous. The resulting data quality was excellent, but only over the nearside. Once again, tracking over the farside was impossible.

Some limited information about the gravity field over the farside was obtained from Lunar Prospector by tracking its setting (disappearance) and rising (re-emergence) on each orbit. Unfortunately, disentangling nearly half an orbit of accumulated gravitational effects is difficult, and the resulting data analysis requires many questionable assumptions [8]. Moreover, Lunar Prospector’s orbit was not ideal for this; this technique would work much better in “crossover mode”, where later orbits cross earlier ones over the farside, but Lunar Prospector’s 90° orbit crossed itself only over the lunar poles.

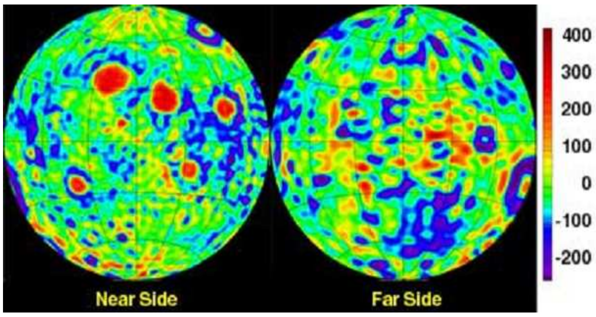

Figure 2. Lunar Gravity Map, Showing Anomalous Gravity Signal in mGal. The unit mGal, referred to in this figure, is 1/1000 of the CGS unit for acceleration, the Galileo unit, which in turn is 1 cm/s^2. So, 1 mGal is equal to 10^{-3} cm/s^2 or 10^{-5} m/s^2. This is the unit commonly used by geophysicists to measure local variations in the Earth’s gravitational field.

There have been many other proposals for lunar orbiters with gravity mapping as a primary or secondary mission, but none that has actually flown.

Spatial resolution is limited mostly by Lunar Prospector’s orbital altitude, which was down around 30 km (with perilune as low as 15 km) toward the end of its mission, resulting in excellent sensitivity to small gravity variations.

This level of map quality extends 10-15° into the lunar farside, because Lunar Prospector remained visible from Earth to around that point. Beyond that, unfortunately, the quality of the gravity maps is visibly poorer, with estimated errors 5-10 times those of the nearside areas. Worse, there is a distinct possibility of systematic errors. As noted above, the data analysis for set/rise tracking, especially without crossovers, is difficult and requires many assumptions, some of which are surely not exactly true. The large-scale features of current farside gravity maps are undoubtedly correct, but there is much uncertainty about the details. Attempts to derive quantitative data about issues like crust thickness are perilous, especially since data on the nearside cannot be used to constrain farside results, because some differences are expected.

Even for engineering purposes, the current maps are of limited use [8]. They do not appear to predict orbits reliably unless the orbits are very similar to those used in the mapping. Predictions of subtle orbit properties like long-term stability are hopeless: different models make very different predictions.

1.3 Gravity Measurement Approaches

Classical gravimetry, which amounts to a refined version of “hang a known weight on a spring and see how much the spring stretches,” does not work in orbit. Einstein’s Equivalence Principle posits that no local measurement, made at a single point, can on its own be used to distinguish between falling freely in a gravity field and sitting motionless in empty space. Since a spacecraft in orbit is indeed falling freely, it cannot directly measure the strength of the gravitational field. What can be done in orbit is to measure the difference in gravitational field between two separate points. There are currently two practical approaches to this:

1. An electromagnetic (radio or optical) tracking link can be used to measure the relative motion of two stations some distance apart—perhaps many kilometres apart, as in the case of measuring the relative motion between Lunar Prospector and a ground station on Earth.

2. A gravity gradiometer can apply extremely delicate measurement techniques to measure the difference in

the gravitational forces on two small masses a small distance (typically a fraction of a metre) apart [9]. (This small separation makes the measurement "non-local" in the sense meant in the Equivalence Principle, allowing gravity to be distinguished from acceleration.)

Both have their uses, especially since the lunar gravitational field is of interest on a wide range of scales. The "long-wavelength" components of the field, which must be measured over long distances, contain information about the overall structure of the Moon. The local, "short-wavelength" components reveal mascons and other local details. Gradiometers are inherently superior for measuring short-wavelength components, since a fast-moving spacecraft passes through a localized field irregularity too quickly for its orbital motion to be affected measurably. Tracking links are the only practical way to measure long-wavelength components and are generally the easier method for intermediate cases.

As the resolution of current maps has not yet reached the point where gradiometers are necessary to achieve the next level of improvement, a tracking link is the best choice for the next mission. Moreover, gravity gradiometers are complex, delicate instruments, and putting one in a spacecraft is currently a major technological challenge (i.e., very expensive).

Mapping the Moon's gravity to a reasonable resolution using a tracking link requires at least one spacecraft in low lunar orbit, the lower the better in order to measure with the finest spatial resolution. Lunar Prospector flew mostly at a relatively conservative altitude of 100 km. NASA's Lunar Reconnaissance Orbiter [10] is planning to use a 50 km orbit, based on Lunar Prospector's successful experiment with very low orbits late in its mission. The orbit of SSETI ESMO is still to be determined. The tradeoff here is that very low orbits require very careful navigation to avoid high points in the lunar terrain, and may need frequent orbit corrections (each of which adds noise to the gravity data) to maintain terrain clearance.

There are several possibilities for the other end of the tracking link. The main distinction is whether the other end is nearby ("low-low" satellite-to-satellite tracking) or far away ("high-low" satellite-to-satellite tracking). A low-low system requires another spacecraft in a similar orbit. A high-low system can be done with a spacecraft in high orbit, or a ground station either directly (for the nearside) or via a high-orbit relay satellite (for the farside). Which approach is preferable depends on various constraints, but a low-low system does have two specific advantages:

1. Since communications ranges are short, one of the spacecraft can be a small and simple "subsatellite" rather than a full-sized spacecraft.

2. For short-spatial-wavelength components of the gravitational field—with wavelength of the same order as the spacing between the satellites—a low-low system inherently makes differential measurements, measuring local gravity field changes directly [8]. A high-low system must derive them by numerical differentiation of a data series, which is inherently very sensitive to noise in the data. A low-low system is thus effectively a form of gravity gradiometer, where a high-low system is effectively a form of gravimeter.

Fig. 3 illustrates the results of simulating the use of a pair of satellites in a low-low configuration to measure the anomalous gravitational field due to a hypothetical (small) lunar mascon, which is assumed to due to a spherical deposit of anomalous density 20 km deep, with an excess mass relative to the surrounding Lunar material of 1.5×10^{16} kg (while real Lunar mascons results from deposits that are not spherical in shape, this simplified example serves to illustrate the principles involved).

The approach of the satellites, which are simulated here to fly directly over the mascon, is shown from a distance of 300 km before flyover to a distance of 360 km after flyover; the leading satellite is 90 km ahead of the trailing satellite. As the leading satellite

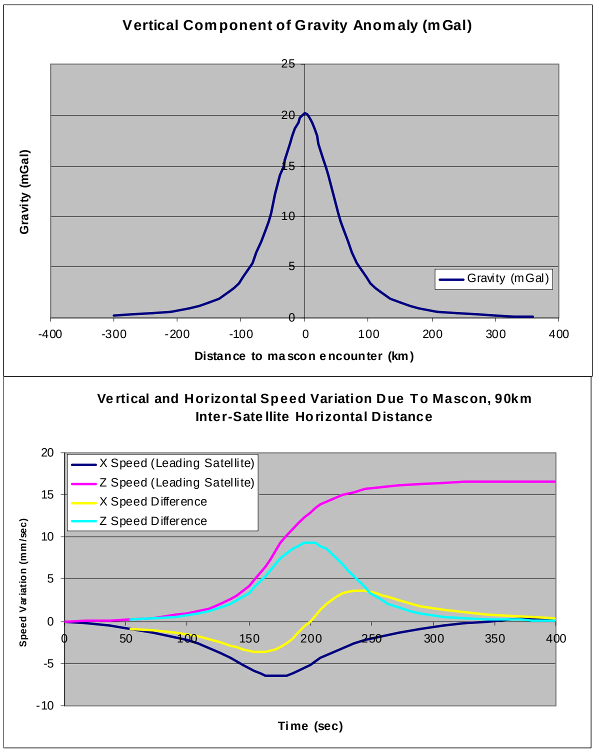

Figure 3. Low-Low Inter-Satellite Relative Speed Signals.

approaches the mascon's position, it accelerates forward (shown here as negative X speed) and downwards (shown here as positive Z speed); after it passes over the mascon, it accelerates downwards and backwards. The trailing satellite follows the same behavior, lagging 54 seconds behind the leading one. While significant relative velocity components are developed between the two satellites in both the horizontal (X) and vertical (Z) directions, radio tracking between the two satellite would measure only the component projected onto the line-of-sight between the two satellites; since negligible vertical motion results during the flyover, and since the satellites are here simulated to fly one following the other in the same orbit, this corresponds to the "X Speed Difference", which peaks at a relative line-of-sight speed of about 3.5 mm/s both before and after the mascon flyover.

The subsatellite option has been particularly attractive as an add-on to single-spacecraft orbiter missions, and so it has featured in many past proposals, including NASA's Lunar Observer [11] and ESA's MORO (Moon ORbiting Observatory [12]). Somewhat surprisingly, however, none of the currently-planned Lunar orbiter missions includes a (low-low) subsatellite or a (high-low) relay satellite, with one exception, that being Japan's SELENE [13], which includes two relay satellites.

SELENE, unfortunately, has two problems for gravity mapping:

The technical problem is that it will do many thruster firings, at least during its primary mission, and the quality of the resulting gravity data is uncertain. This is because gravity models are extracted from radio tracking data by fitting the latter to simulated tracking data, based on candidate gravity-model parameters, and this type of parameter-fitting gives better results when operating on long sequences of uninterrupted tracking data, than on numerous much-shorter tracking sequences. Every firing of SELENE's thrusters will likely necessitate starting a new tracking sequence, unless the thruster's force model is calibrated extremely well.

The non-technical problem currently appears worse. SELENE is far behind schedule. In the context of a space program which appears to be having serious budget and political problems, its future must be considered uncertain.

2. GRAVITY MAPPING BY NANOSATELLITE: LUNETTE

2.1 Hardware

To fill this persistent gap, the Lunette mission is proposed. It is a very small subsatellite to fly as an "ejectable instrument" from the SSETI ESMO lunar satellite. Gravity mapping will be done with a low-low tracking link between the subsatellite itself and a small electronics package left on the parent spacecraft. With SSETI ESMO supplying transportation to lunar orbit, and handling most routine communication with Earth, Lunette can be both small and inexpensive: a nanosatellite for lunar exploration.

Our current concept is a nanosatellite of about 3.5 kg, derived from the CanX-3 design currently in development at the University of Toronto Space Flight Laboratory (UTIAS/SFL) [14] for the BRITE mission [15],[16]. 1.5 kg is budgeted for the base unit that remains behind on the parent, giving a total of 5 kg for the Lunette mission.

CanX-3 (see Fig. 4 an Fig. 5) is a 20 cm cube, with solar arrays on all six faces. It has arcminute-level three-axis attitude control with miniature reaction wheels, a miniature star tracker, and a capable onboard computer. For Lunette, the star tracker will be used occasionally as an imager, to return images of the Moon or (shortly after separation) the parent spacecraft. The BRITE photometer payload will not be carried.

The payload of the Lunette subsatellite will be a radio transponder (currently baselined to use S-band), replacing CanX-3's radios with a system that can do phase-locked coherent "bent-pipe" retransmission of an incoming signal, for precision range-rate measurement. Superimposed on the tracking signal will be a low-precision ranging system for navigation relative to the parent, and a low-speed two-way data link so that command and telemetry can be done via the parent. Precise three-axis attitude control will eliminate spin modulation of the range-rate signal (very visible in tracking data from Lunar Prospector, as discussed in [8]), and will offer the option of pointing a medium-gain antenna at the parent if an improved link margin is necessary. Current design analysis, however, indicates that low-gain antennas should suffice.

Lunar subsatellites proposed in the past typically have not included propulsion, but Lunette's does. Its attitude-control system will normally maintain attitude without thrusting, using its reaction wheels, to permit long undisturbed tracking runs; however, wheel desaturation will occasionally be necessary, and since the Moon has no useful magnetic field the standard low-Earth-orbit approach of using magnetorquers for desaturation will not work, so occasional attitude control thrusting will be needed.

Orbit corrections will also be needed occasionally, both to avoid terrain and to fly formation accurately with the parent spacecraft for an extended period of time, despite differential gravity perturbations and parent satellite maneuvering, which should result in a much improved gravity model. Finally, the Lunette mission

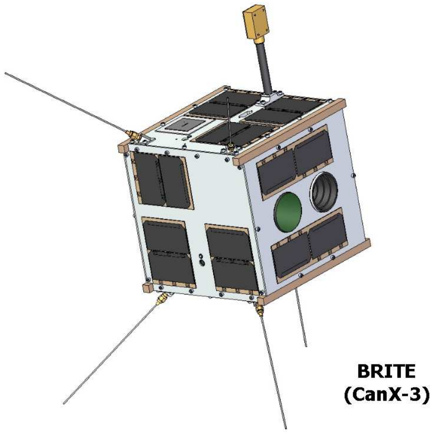

Figure 4. Solid Model of the BRITE (CanX-3) Nanosatellite. Each face is 20x20 cm.

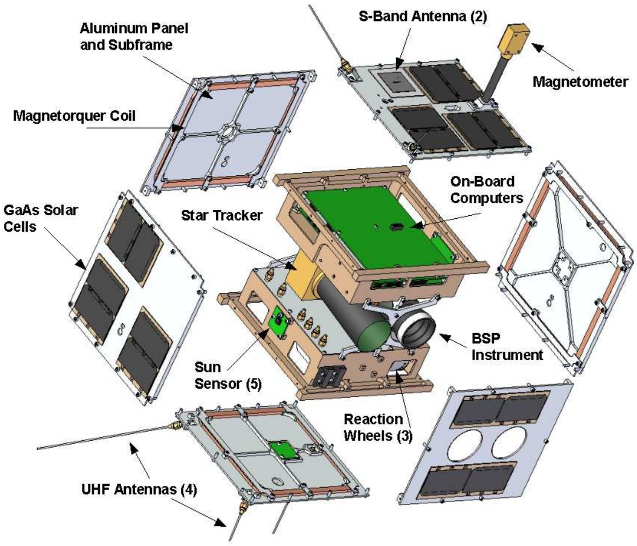

Figure 5. Exploded-view of CanX-3.

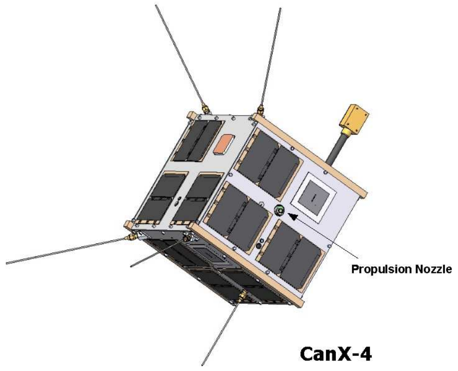

Figure 6. CanX-4 Nanosatellite under development for Formation Flying experiments in 2008/09. This 5 kg satellite also contains a propulsion system [18].

plan (described below) requires several maneuvers to set up the correct orbits for various mission phases. The propulsion system is currently baselined as a low-thrust warm-gas system with a nominal total delta-V of 100 m/s. Nanosatellite-sized propulsion systems with this level of performance are being developed at UTIAS/SFL [16].

The base unit, left behind on the parent spacecraft when the subsatellite separates, comprises a mount and separation system for the subsatellite, the rest of the tracking link, and an interface to the parent. The base-unit half of the tracking link includes antennas, transmitter and receiver, an ultra-stable oscillator as a precision reference for the transmitter/receiver frequencies, and electronics for Doppler measurement of range rate. The base unit also has its own on-board computer and data storage, to control the Lunette equipment and minimize demands on the parent.

The tracking link will primarily function between the parent and the subsatellite, but there will also be some “three-way” tracking, in which a ground station listens to the signals from both spacecraft, when visibility and ground-station availability permit. An interesting further possibility is to use VLBI techniques to do ultra-precise cross-range tracking (from ground stations, over the nearside) of one spacecraft or the other. The basic low-low tracking link is designed to be sensitive to inter-satellite speed variations of 1 mm/s, averaged over 10 seconds.

Data quality will be improved if the parent can minimize thruster firings during Lunette’s primary mission. That aside, Lunette puts minimal demands on the parent spacecraft, adds little risk to its mission, and uses only 5 kg of payload mass and 6-8 W of parent-spacecraft power.

The subsatellite and base unit will be built primarily by UTIAS/SFL, which has an active nanosatellite program [18] built on the foundation of their bus-building experience for the MOST astronomy microsatellite [1],[17], currently in its third highly-successful year of operation in Earth orbit.

2.2 Mission Plan

The following is the preliminary mission plan for Lunette; details are subject to change, depending on the level of spacecraft performance achieved as the design matures in the Phase A study, and on the details of the SSETI ESMO mission. The working lifetime of the subsatellite will be limited by either propellant exhaustion (followed by drifting too far away from the parent spacecraft and/or crashing on the lunar surface) or lunar eclipses.

Roughly every six months, the Moon passes through Earth’s shadow, producing a lunar eclipse. The depth of these eclipses varies considerably, but in the worst

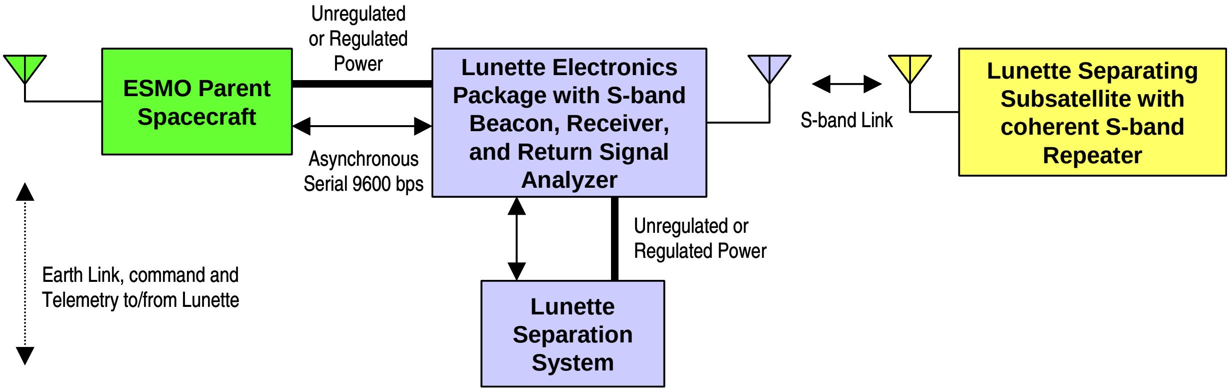

Figure 7. Functional Block Diagram for Lunette.

case, a spacecraft in lunar orbit can be in total darkness for 2-3 hours. This is a severe strain on the power subsystem and on thermal control, especially for a very small spacecraft which has little thermal mass and can spare little battery power for heating.

With this in mind, in the baseline plan Lunette's primary mission is five months long. Exact scheduling will depend on just when the parent spacecraft arrives in lunar orbit, but the subsatellite will remain on SSETI ESMO, partially protected against temperature extremes and able to draw on the parent's power system, until just after a lunar eclipse. The primary mission will be completed before the next eclipse, on the assumption that the eclipse will kill the subsatellite. This is a conservative assumption: the spacecraft has a reasonable chance of surviving a single exposure to extreme cold accompanied by deep battery discharge, and an extended mission is possible if it does.

Separation from the parent will be done in an attitude chosen so that the separation impulse will produce a slow drift back along the parent's orbit. The drift will be slowed and then stopped by subsatellite maneuvers, leaving the subsatellite flying formation 100 km behind the parent (assuming a parent orbital altitude of 100 km). Subsatellite checkout and commissioning will be done over the first two weeks, but formation flying will be continued for another six weeks with continuous tracking. The six weeks will give three complete passes over the entire lunar surface, providing the data needed for a uniform global gravity map.

At this point there are several options for Lunette mission continuation, but the baseline is to expend about 25 m/s of delta-V, over several days of maneuvering, to move the subsatellite into an elliptical orbit. The orbit's period will be the same as that of the parent's circular orbit, but it will (nominally) drop down to 50 km altitude at perilune, and rise to 150 km at apolune. Viewed from the parent, the subsatellite will appear to move in an ellipse centered on the parent and lying within their within their mutual orbital plane, with its long axis along the parent's orbit, as shown in Fig. 8. The point of this orbit change is to take the subsatellite down to 50 km over specific points of interest, such as farside or polar mascons, for higher-resolution local mapping. Orbit-maintenance requirements in the elliptical orbit are quite uncertain, and the situation will be reassessed after the first few weeks in that orbit. Preliminary estimates suggest that it will be possible to remain in the elliptical orbit for the remainder of the five-month primary mission, at the cost of possibly using up most of the remaining propellant.

Using relatively inexpensive radio equipment to achieve a range-rate tracking resolution of 1 mm/s over a 10-second integration period, Fig. 3 shows that Lunette should be capable of detecting mascons with anomalous gravity fields as low as 10-20 mGal. Thus the data from the six-week global-mapping phase should yield a global map with resolution and quality roughly equal to that of the nearside portion of the Lunar Prospector maps. This map will cover the full globe based on direct measurements, with a straightforward data analysis requiring no

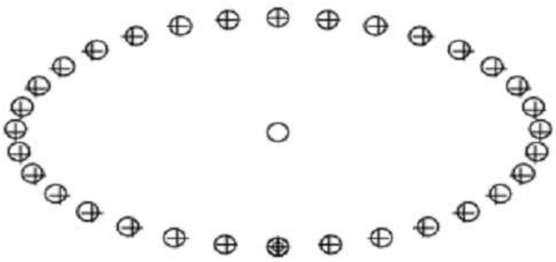

Figure 8. Elliptical Trajectory of Follower Sub-Satellite Relative To Leader Satellite. Here, down is towards the center of the Moon, and the subsatellite crosses the parent's orbit roughly 100 km ahead of and behind the parent.

questionable assumptions, and will provide, at last, a trustworthy basic reference for science, exploration, and mission engineering. Lower-altitude data from the elliptical-orbit phase will provide local maps of some interesting areas at substantially higher resolution, depending on altitude. If subsatellite propellant consumption is low and an extended mission is possible, a sizable fraction of the Moon could be mapped at this resolution.

Coordination of the Lunette Payload, planning and operations will be by Gedex Inc., a Canadian company whose main business is terrestrial gravity mapping for mineral exploration, and SP Systems, software architect for the MOST astronomy satellite and primary developer of the Lunette mission concept. The Lunette science team is led by Dr. Jafar Arkani-Hamed, whose expertise in lunar gravity mapping and geophysics began with Apollo and has continued through over 20 refereed papers on lunar geophysics.

2.3 Design Constraints

As single subsatellite deployed from a parent lunar orbiter, the Lunette mission does have some disadvantages. Most seriously, it puts two constraints on the parent spacecraft, which might complicate parent operations:

Experience with Lunar Prospector [8] indicates that it is essentially impossible to model thruster firings precisely enough to take them completely out of the tracking data. So each thruster firing puts a discontinuity into the data. The parent must therefore do thruster firings relatively infrequently, because the complexity of analyzing the tracking data rises greatly as the runs of continuous data get shorter. At the very least, thruster firings must typically be several orbits apart. A spacing of days would be highly desirable, and weeks would be preferable. A parent spacecraft that uses thrusters, rather than reaction wheels (etc.), for primary attitude control probably cannot do this at all. Even when the spacecraft design permits it, this constraint will be unpopular with the spacecraft's operators, especially for operations in very low orbits where frequent orbit corrections are desirable.

Gravity gradients manifest themselves as relative motion of the centres of gravity of the two spacecraft, but what is measured is relative motion between the two tracking-link antennas. Lunette's parent-spacecraft antenna will presumably be located wherever convenient on the parent, and its electrical centre ("phase centre") is most unlikely to coincide with the parent spacecraft's centre of gravity. As a result, parent-spacecraft attitude motion will cause spurious changes in measured range rate, because the attitude motion will move the antenna. Data analysis can remove this spurious signal only if the parent's attitude history is known quite precisely. This may or may not be feasible, especially if the parent's own mission does not require precise attitude sensing.

Lunette's own mission design is constrained by having the parent's orbit essentially predetermined. For example, moving one spacecraft into an elliptical orbit that dips down lower is not nearly as satisfactory as moving both spacecraft into a lower orbit, but the latter is impractical unless the parent is going to do it anyway.

Finally, operation as a subsatellite inevitably involves Lunette with the parent's data handling, operations, etc. This is good in that some tasks will be dealt with by the parent's operations team, bad in that others will be joint operations requiring careful coordination.

There is an alternative mission design which avoids most of this: fly Lunette as a pair of nanosatellites, accompanying the parent for part of the way (ideally, into a low lunar orbit), but then separating from it to perform an independent mission. A two-spacecraft Lunette project can schedule its own manoeuvres and attitude changes, put antennas in the best places for Lunette operations, gather attitude data as required, plan its own orbits (within limits), and handle its own operations and data. However, this may exceed the payload mass limit and volume envelope allocated on SSETI ESMO. Furthermore, Lunette must then handle its own communications.

3. CURRENT STATUS

In September 2006, Lunette was selected as a primary science payload for the SSETI ESMO mission, currently in Phase A and planned for a 2011 launch. A team of seven Masters students at UTIAS/SFL is focused on the Lunette preliminary design, and they have begun refining the design described in this paper.

4. FUTURE POSSIBILITIES

It is possible to improve significantly on the 10-20 mGal accuracy obtainable with the ESMO Lunette mission, and there are numerous scientific, exploration and engineering reasons to want to do so. The two main methods available for doing this are:

1. To fly a more-elaborate low-low radio tracking mission. For example, the past ESA MORO proposal [12] aimed to fly a pair of satellites in low Lunar orbit, equipped with a radio tracking payload with an accuracy about 10 times better than that of Lunette (achieving an accuracy of about 0.1 mm/s, making the system sensitive to anomalous gravity down to 1-2 mGal). However, achieving this higher level of performance would come at a steep price [19].

2. To fly a single satellite carrying a gravity-gradiometer instrument.

For any gravity instrument, the spatial resolution is limited by geometry to be not much lower than the distance between the instrument and the anomaly being measured. Thus, the lower the gravity gradiometer flies, the higher its spatial resolution can be. It may be possible for a gravity gradiometer to generate higher-resolution maps of a selected spot of interest on the Lunar surface (e.g., a candidate site for a Lunar base), by arranging its orbit to have a low perilune over that spot. If the gravity gradiometer spacecraft has sufficient propulsion capability, this could be repeated for some other sites as well.

Lunette would lead naturally into a lunar-orbiting microsatellite carrying a gravity gradiometer for dramatic further improvements in gravity mapping, including local maps of potential lunar-base regions. The technology for a spaceborne gravity gradiometer capable of fitting within microsatellite resources is not yet in hand but is not far off.

The utility of gravity data could also be enhanced when combined with LIDAR measurements. Topographic models derived from satellite-borne LIDAR data have reduced accuracy if accurate gravity modelling data is not available, because the LIDAR measures only height relative to the surface, which is a combined effect of surface terrain variations and satellite instantaneous height variations due to gravity variations. By carrying both a gravity gradiometer and a LIDAR, the synergies between the two instruments will significantly improve the accuracy of the final data product from both.

5. CONCLUSION

The time is ripe to demonstrate that small satellites can play a useful role in planetary exploration in general and the exploration of the Moon in particular. One interesting niche for small satellites in lunar exploration is mapping the Moon's gravity field. The persistent absence of direct data from the lunar farside makes current lunar gravity maps uncertain and untrustworthy.

Lunette aims to correct this deficiency by flying as a SSETI ESMO payload and filling in the farside model using direct measurements. This will bring the accuracy of the farside model up to about that of the current nearside model and provide more detailed maps of selected areas.

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