

Lunette: Lunar Farside Gravity Mapping by Nanosat

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ABSTRACT: One significant item of unfinished business in lunar exploration is the mapping of the Moon's notoriously-irregular gravitational field. This is of interest to science because it sheds light on the lunar interior, to exploration because it may help find useful resources, and to engineers because it is important for planning and operating missions in lunar orbit. Past mapping efforts have been severely hampered by the impossibility of Earth-based tracking of spacecraft over the lunar farside; the farside parts of the resulting maps are of questionable reliability. Many lunar-orbiter proposals have envisioned solving this with subsatellites, but none has yet flown.

Lunette is a 5-kilogram payload, designed to fly on one of the next generation of low-altitude lunar-polar-orbiter missions, such as ISRO's Chandrayaan-1 and NASA's Lunar Reconnaissance Orbiter, for lunar gravity mapping. It includes a 3.5-kg subsatellite derived from the current CanX series of nanosatellites. It will provide a trustworthy full-globe gravity map with resolution equaling that of current nearside maps, plus higher-resolution maps of selected areas. A follow-on microsatellite mission offers hope of global maps with resolution improved by a factor of ten or more, at costs that are still trivial by planetary-exploration standards.

INTRODUCTION

Return to the Moon

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. Less prominently, the European Space Agency's SMART-1 technology-demonstrator mission is currently in lunar orbit, and Japan is planning a pair of lunar missions (although their schedules unfortunately keep slipping). More interesting yet, India and China—two nations which have not previously shown an interest in planetary exploration—

have chosen lunar orbiters as their first projects beyond Earth orbit.

Despite the revival of interest, 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 has not yet made itself visible in lunar exploration, recent microsat and nanosat 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. We have identified one such goal, offering an opportunity for a lunar nanosatellite (!) and a follow-on microsatellite to do leading-edge work, contributing to lunar science, lunar exploration, and engineering of future lunar missions.

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*. Optical and near-optical techniques study roughly the top millimeter of the surface. Gamma-ray and neutron spectroscopy can work down to depth of a meter or two. The Moon is a particularly favorable target for penetrating radar, since its extremely dry regolith transmits radio waves quite well, but even so, a depth of a few kilometers is the most that can be expected.

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. Its only major competitor is seismology, but that requires instrument packages emplaced on the surface, and for the Moon in particular, seismology is badly hampered by the Moon's quiet interior: moonquakes are few and slight, and substantial impacts are rare, making it difficult to study the lunar interior by listening. Gravity does not have those problems.

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—"mascons"—located below many of the major impact basins. Good-quality maps of the lunar gravitational

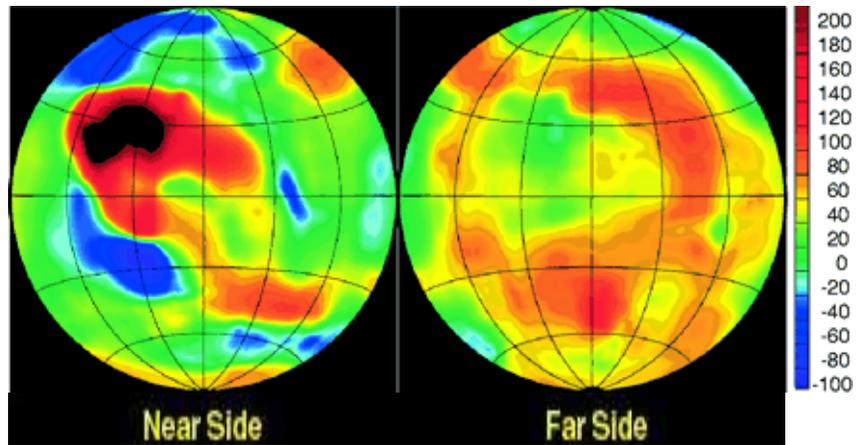


Figure 1: Inferred Lunar Crustal Thickness Maps (km)

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^{1,2}. 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 early³, 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 recently⁴—could be definitively resolved by good gravity mapping. (Figure 1 shows Lunar crustal thickness inferred from Lunar Prospector gravity data, illustrating the putative nearside/farside dichotomy.)

As we 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 "artifacts" introduced by data analysis. More detailed maps of important local areas, such as the South Pole Aitken basin and some of the more unusual farside mascons, would also be helpful.

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.

Finally, mission engineering for lunar spacecraft urgently wants good gravity maps of the Moon. Most notably, 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 (for a satellite without propulsive capability) a short orbital life before crashing. More subtly, even lunar landing missions need good gravity data: poor orbit prediction was the main reason why Apollo 11 overshot its intended landing site by 8 km. For mission engineering, like science, the main priority is high-quality uniform global maps. 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.

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 mascons⁵, 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. (The simplest way to insert the correction turned out to be lying to the guidance software, telling it not that there was an error in its spacecraft position estimate, but that the *landing site* had moved!) There were also one or two occasions during Apollo missions when unplanned orbit corrections were needed, because a low orbit was getting *too* low due to unexpected perturbations.

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 Apollos 15 and 16: those two flights released small spin-stabilized "subsattellites" which did not have this problem. Unfortunately, tracking support for the subsattellites was rather sparse—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—a graphic demonstration of the irregularities of the lunar gravitational field. (The Apollo 15 subsatellite lasted about two years before crashing.)

Even the subsattellites, however, could not be tracked over the lunar farside. Despite the suggestive name, they were not tracked from the main Apollo spacecraft, only from the Earth. One of this paper's authors (J. A.-H.), together with W.L. Sjogren of JPL, investigated putting a *pair* of subsattellites on Apollo 18, with a tracking link between them; unfortunately, that proposal was stillborn when Apollo 18 was canceled in mid-1970.

The ensuing long hiatus in lunar exploration was finally broken by the Clementine mission in 1994⁶. Clementine was tracked extensively during its three months in lunar orbit, but its relatively high orbit greatly reduced its sensitivity to local gravity irregularities. The Clementine data did improve lunar gravity models, but the improvements were modest. There was no farside tracking, although the high orbit reduced the significance of that.

Modern lunar gravity maps are based almost entirely on data from the Lunar Prospector mission of 1998/99⁷, 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 (see Figure 2) was spin-stabilized and rarely fired its thrusters, and tracking coverage was continuous. The resulting data quality was excellent... 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 assumptions⁸. 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.

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

As a result, existing lunar gravity maps (see Figure 3), mostly based on Lunar Prospector data, although incorporating available data from earlier missions, have excellent coverage of the lunar nearside. (The unit mGal referred to in that figure, is 1/1000 of the CGS unit for acceleration, the Galileo unit, which in turn is 1 cm/s². So, 1 mGal is equal to 10⁻³ cm/s², or 10⁻⁵ m/s².)



Figure 2: Lunar Prospector Orbiter (NASA)

This is the unit commonly used by geophysicists to measure local variations in the Earth's gravitational field.) 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, and sensitivity to small gravity variations was excellent.

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

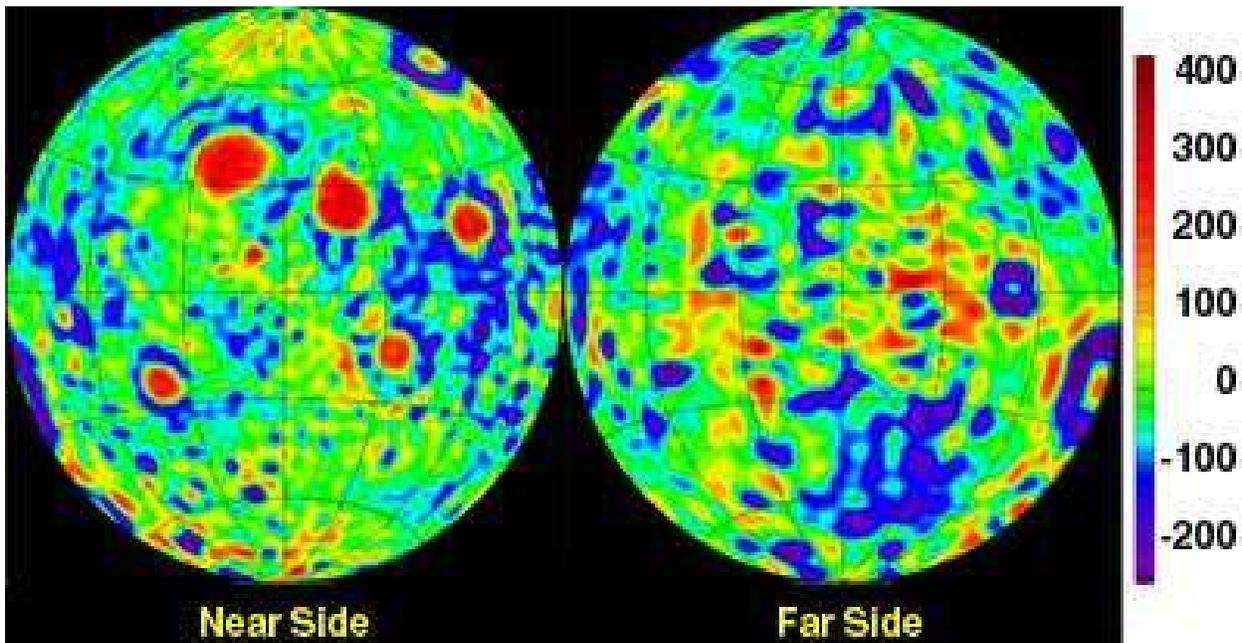


Figure 3: Lunar Gravity Map, Showing Anomalous Gravity Signal in mGal, Downward-Continued to the Lunar Surface

maps is visibly poorer, with estimated errors 5-10× 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 use⁸. They do not appear to predict orbits reliably unless the orbits are very similar to those used in the mapping (especially Lunar Prospector's). Predictions of subtle orbit properties like long-term stability are hopeless: different models make very different predictions.

GRAVITY MEASUREMENT APPROACHES

Classical gravimetry—which amounts to a very 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*, one of the foundations of his general Relativity theory, posits that no *local* measurement—made at a single point—can distinguish between falling freely in a gravity field and sitting motionless in empty space (and that no local measurement can distinguish between the force experienced when a body is supported at rest in a uniform gravitational field, and the pseudo-force experienced due to corresponding acceleration of the body by a non-gravitational force). Since a spacecraft in orbit is indeed falling freely, it can't *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. A radio tracking link can be used to measure the relative motion of two stations some distance apart—perhaps many kilometers 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 fraction of a meter apart⁹. (Even 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 much. Tracking links are the only practical way to measure long-wavelength components and are generally the easier method for intermediate cases.

At the moment, the choice is easy. The resolution of current maps has not yet reached the point where gradiometers are necessary for further improvement. Moreover, gravity gradiometers are complex, delicate instruments, and putting one in a spacecraft is currently a major technological challenge (i.e., very expensive). Gradiometer technology is improving—a point we will return to later—but isn't yet practical for economical space missions. Tracking links are relatively easy to build today.

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. Lunar Prospector flew mostly at 100 km altitude, and at least one of the new orbiter missions¹⁰ is planning to do likewise; that is a relatively conservative altitude. NASA's Lunar Reconnaissance Orbiter¹¹ is planning to use a 50 km orbit, based on Lunar Prospector's successful experiment with very low orbits late in its mission. 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”) or far away (“high-low”). 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 other 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 “subsattellite” rather than a full-sized spacecraft (whatever that means, in the context of the specific technology being used!).
2. For short-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 the field changes directly⁸. A high-low system must derive them by numerical differentiation of a data series, which is inherently very sensitive to noise in the data.

Figure 4 illustrates 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 be 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. The two satellites are assumed to be in a circular orbit around the Moon at an altitude of 50 km, and an orbital speed of 1.655 km/s. The magnitude of the gravity anomaly due to the mascon (at orbital altitude) is shown at the top of the figure.

The approach of the satellites, which 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 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 flying one after the other in the same orbit, this corresponds to the X component, which peaks at a relative line-of-sight speed of about 3.5 mm/s both before and after the mascon flyover.

The subsattellite 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 Observer¹² and ESA’s MORO (Moon Orbiting Observatory)¹³. Somewhat surprisingly, however, none of the currently-planned orbiter missions

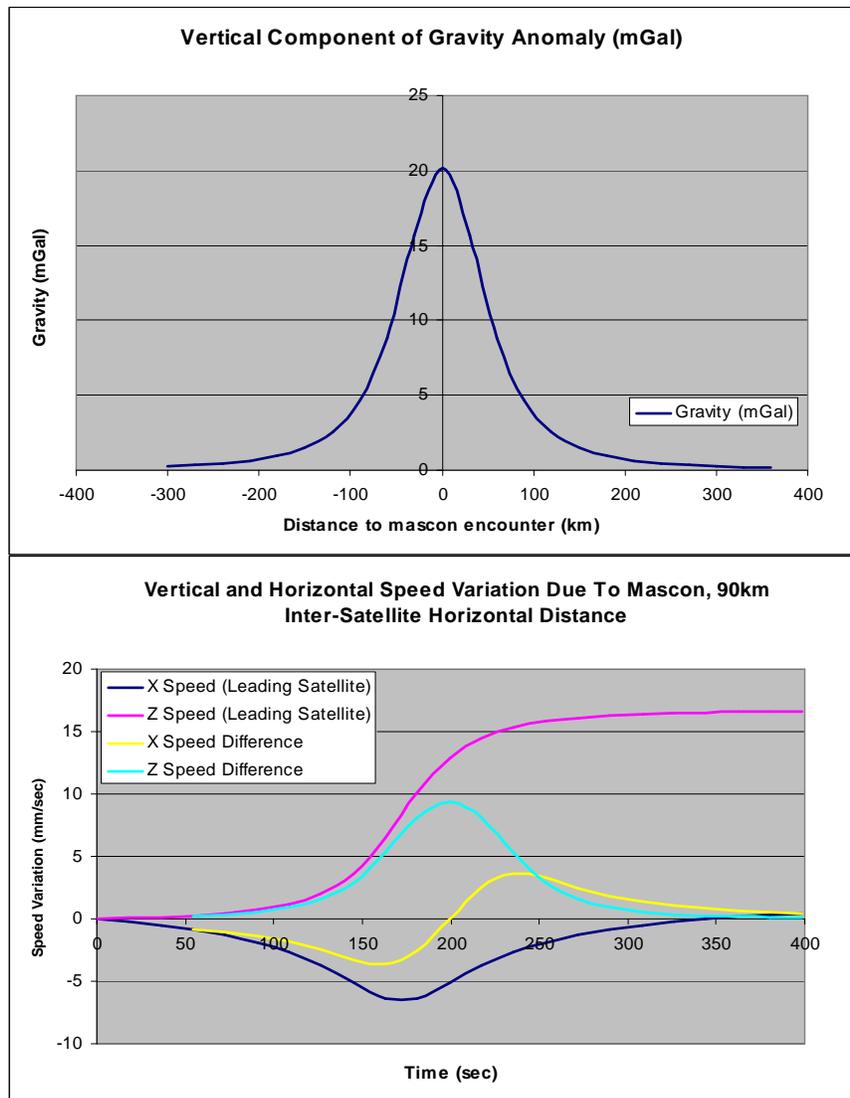


Figure 4: Low-Low Inter-Satellite Relative Speed Signals

includes a (low-low) subsatellite or a (high-low) relay satellite, with one exception, that being Japan's SELENE¹⁴, 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. The non-technical problem currently appears worse. SELENE is far behind schedule—it is a follow-on to the Lunar-A penetrator mission, which was originally supposed to launch eight years ago and reportedly is still not ready to go to the pad—and in the context of a space program which appears to be having serious budget and political problems, its future must be considered uncertain.

GRAVITY MAPPING BY NANOSAT: LUNETTE

Hardware

To fill this persistent gap, we propose Lunette: a very small subsatellite to fly as an “ejectable instrument” on a bigger orbiter. 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 the parent 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 University of Toronto's Space Flight

Laboratory¹⁵ for the BRITE¹⁶ mission. 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 Figure 5) is approximately a 15-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 Prospector⁸), and will offer the option of pointing a medium-gain antenna at the parent if an improved link margin is necessary. (Current indications are that low-gain antennas should suffice.)

Past subsatellite proposals typically have not had propulsion systems, but the Lunette subsatellite does. The attitude-control system will normally maintain attitude without thrusting, using its reaction wheels, to

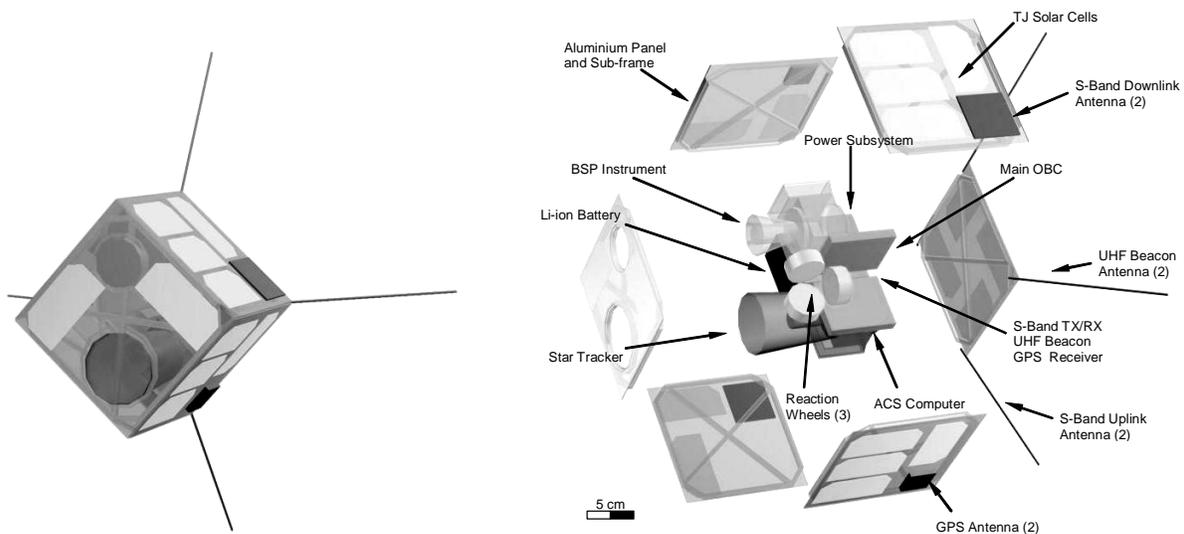


Figure 5: CanX-3/BRITE Nanosatellite Layout

permit long undisturbed tracking runs, but wheel desaturation will occasionally be necessary and the Moon has no useful magnetic field. Orbit corrections will be needed occasionally, both to avoid terrain and to fly formation accurately with the parent spacecraft. Finally, the Lunette mission plan (see 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 beginning to become available from multiple suppliers.

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, a USO (Ultra-Stable Oscillator) as a precision reference for the transmitter frequency, 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 tracking (over the nearside) of one spacecraft or the other. The basic low-low tracking link is expected to be sensitive to inter-satellite speed variations of 1 mm/s, averaged over 10 seconds.

Our plan is that the subsatellite and base unit will be built primarily by UTIAS/SFL, who have an active nanosatellite program built on the foundation of their bus-building experience for the MOST astronomy satellite^{17,18}, which is currently in its third highly-successful year of operation in Earth orbit. (An update on SFL’s CanX nanosat program is presented as one of the student papers¹⁹ at this conference.)

Mission Plan

The following is the preliminary mission plan for Lunette; details are rather subject to change, depending on the level of spacecraft performance achieved as the design matures. 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 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, 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 the parent—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

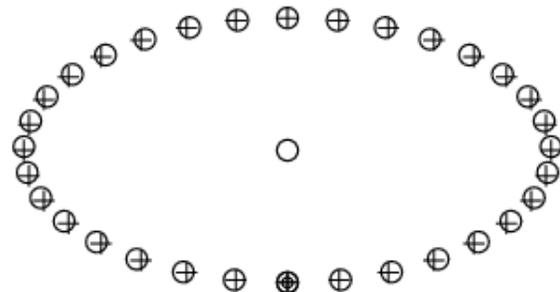


Figure 6: Elliptical Trajectory of Follower Sub-Satellite Relative To Leader Satellite

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 within their mutual orbital plane, with long axis along the parent's orbit, as shown in Figure 6 (the subsatellite crosses the parent's orbit roughly 100 km ahead of and behind the parent). The point of this orbit change is to take the subsatellite down to 50 km over specific points of interest, such as farside 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, Figure 4 shows that Lunette should be capable of measuring 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 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.

Mission-level coordination, 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 (third author of this paper), whose expertise in lunar gravity mapping and geophysics began with Apollo and has continued through over 20 refereed papers on lunar geophysics (plus roughly 100 on the other terrestrial planets).

History and Status

Lunette was originally proposed for India's Chandrayaan-1¹⁰ mission, in response to ISRO's Announcement of Opportunity for international payloads. The proposal was well received and was included on ISRO's initial "short list", but the extremely tight proposal schedule ultimately made it impossible to arrange firm funding quickly enough. (The cost of the Lunette payload should be able to come in well under \$10M.)

The Canadian Space Agency's Space Exploration Advisory Committee has since strongly endorsed Lunette, and we are pursuing flight opportunities for Lunette on later lunar orbiters. Any sizable orbiter in a low polar orbit would be suitable, although 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.

We continue to investigate options for further improvements to the Lunette mission. There are several possibilities for achieving higher tracking-link performance, and improved propulsion would permit a wider range of orbits and more ambitious extended missions. Finally, it's conceivable to do the mission with a *pair* of nanosatellites, relying on a parent spacecraft only for transportation to lunar orbit and thus eliminating constraints on parent operations; the main technical difficulties this add are getting the nanosats into Lunar orbit, and communications to and from Earth.

NEXT, IMPROVING THE GLOBAL LUNAR GRAVITY MODEL RESOLUTION: *GLOBE*

Lunette aims to correct the main deficiency of the current-best Lunar gravity model, by 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, about 10-20 mGals, via a very low-cost mission. It is possible to improve significantly on this level of accuracy, and there are numerous scientific, exploration and engineering reasons to want to do so. The two main methods for doing this are:

- To fly a more-elaborate low-low radio tracking mission. For example, the past ESA MORO proposal¹³ 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, with MORO aiming for a budget of 345 million “European Accounting Units” (the precursor of the Euro) in 1993, about 50 times the estimated cost of Lunette.

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

The latter concept has some striking fundamental advantages over the former one:

- Only a single satellite is flown, not two, reducing the mission complexity substantially.
- This mission does not need highly-precise, continuous radio tracking from the ground (needed by the other mission in order to achieve good orbit estimates); a relatively coarse orbit estimate (to within a few km at any given time) will suffice to register to gradiometer data-set. This will greatly reduce the mission operations cost.
- In this case, the instrument data post-processing is fairly simple and straight-forward, in comparison to the extremely challenging job of gravity-model fitting to tracking data that is needed for the other type of mission. This will enormously reduce the science data post-processing effort and cost.

The Lunar-orbiting gravity gradiometer mission concept was first proposed, as far as we can tell, by Robert L. Forward²⁰ in the mid-1970s, based on a concept he had developed in the mid-1960s for a rotating cruciform gravity gradiometer²¹. As originally conceived, this was a room-temperature instrument whose performance would have been somewhat limited by the technology available at that time. Gedex is developing an evolved version of that design for airborne geophysical exploration operations. This version was invented by van Kann²², and has been dubbed by him the Orthogonal Quadropole Responder (OQR). It achieves significantly better performance via various improvements, including operating at cryogenic (liquid helium) temperature.

Gedex’s target OQR performance level, in an airborne environment, is a error+noise intensity of 1 Eo²/Hz, implying that gravity gradient signals larger than about 3 Eo (a SNR of 3) should be visible to this instrument on a time-scale of 1 second. (The Eo is another CGS unit commonly used by geophysicists to measure local variations in the Earth’s gravitational field, in this case the gradient of the gravity field with respect to distance; 1 Eotvos units is equal to a change of 10⁻⁹ Gal over a

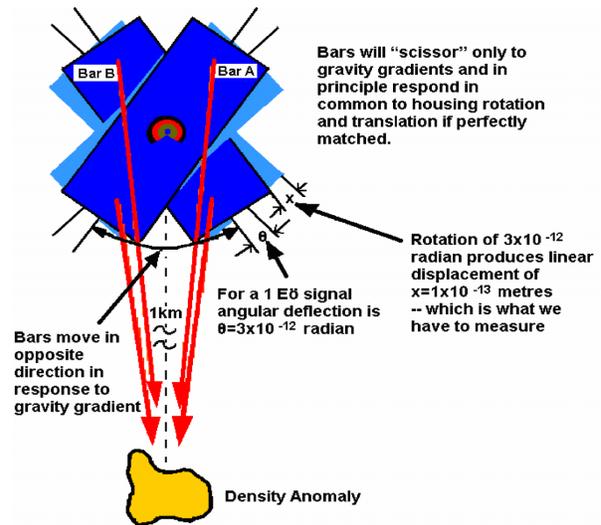


Figure 7: An OQR Responding To A Gravity Gradient

distance of 1 cm. In SI units, the equivalent is 10⁻⁹ s⁻².) Figure 7 illustrates the operation of a Gedex OQR in response to the gravity gradient signal arising from a density anomaly (e.g., a buried mineral deposit).

Gedex is developing a mission concept for a Lunar orbiting OQR gravity gradiometer named GLOBE (“Gradiometer in Lunar Orbit for Better Exploration”), as the natural follow-on to the Lunette mission. Assuming that the same 1 Eo²/Hz instrument performance level can be achieved in Lunar orbit, Figure 8 illustrates the performance achievable in detecting gravity anomalies. The mass of anomaly shown here is 1.5x10¹⁵ kg, or 1/10 the size of the one shown in Figure 4, and is assumed to be at a depth of 20 km. For a single satellite flying at an orbit altitude of 50 km, the peak gravity anomaly intensity is 2 mGal, 1/10 that of the previous example. The bottom plot in the figure shows several components of the gravity gradient tensor’s signal in the orbit plane (the tensor components to which such a gradiometer would tend to be most sensitive); their values peak at 0.3 to 0.6 Eo. Given an orbit speed of 1.655 km/s, and an effective dwell-time over the target of about 20 s, that level of instrument noise would filter to about 0.05 Eo (RMS), resulting in an excellent signal/noise ratio of about 10 for this target.

This analysis suggests that a 1 Eo²/Hz gravity gradiometer in low Lunar orbit should be capable of making gravity measurements with a sensitivity about 10 times that of Lunette, which make it able to produce a complete global Lunar gravity model about 10 times as accurate as the current Lunar nearside gravity model. This is about the performance level targeted by the MORO mission. Also, note that the gravity-gradient

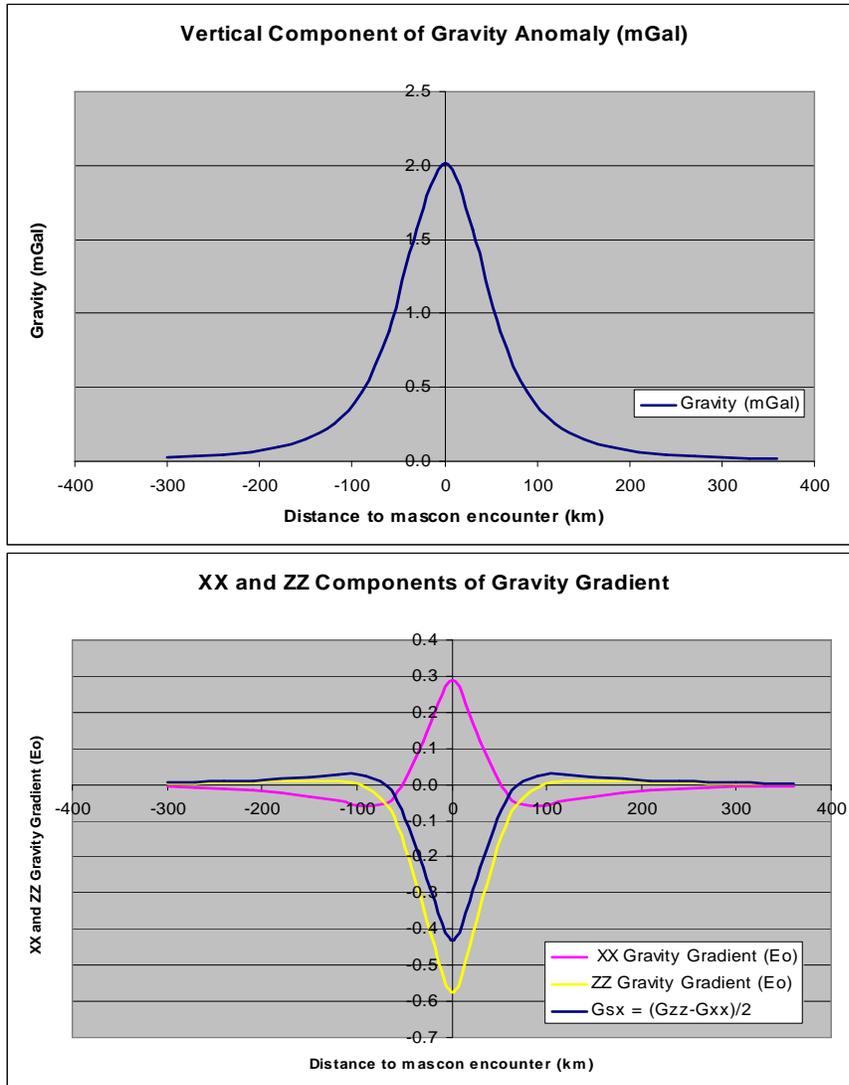


Figure 8: Low Lunar Orbit Gravity Gradiometer Signals

plot (bottom) in Figure 8 shows a sharper rise and drop-off than the corresponding gravity-signal plot (top); this reflects the facts that the gravity gradient signal varies with the inverse-cube of the distance to a density anomaly, versus the inverse-square variation of the gravity signal. Even at the same raw signal sensitivity level, GLOBE should be more capable than MORO would have been at discerning short-wavelength variations in the Moon's gravity field (i.e., it should have higher spatial resolution).

While it is *conceivable* to fly the superconducting version of the Gedex OQR gravity gradiometer in Lunar orbit, the resulting satellite would need to carry its instrument in a dewar containing many months' worth of liquid helium. Based on other satellites that have been flown with the same requirement (e.g., IRAS), that would likely be a very large and expensive

satellite; it is hard to see such a satellite costing any less than MORO would have.

In parallel with development of the superconducting version of the OQR, Gedex is also developing new technology to enable development of a room-temperature version of the OQR design, which may be able to achieve performance levels similar to those of the superconducting version. This next-generation instrument would significantly improve the logistics of conducting airborne gravity gradiometry surveys at locations throughout the world. Preliminary indications are that such an instrument may also be suitable for packaging on a microsatellite platform, for Lunar orbit operations. This could bring the cost of the GLOBE mission down to a very reasonable level.

Other points of note regarding GLOBE:

- When data is collected by a high-resolution gravity instrument, estimation of high-resolution subsurface density distributions becomes possible (this is done routinely in terrestrial geophysical exploration). However, to achieve good results the gravitational effects of local terrain height variations must be accurately estimated and filtered out. Because of the inverse-cube sensitivity of a gradiometer, terrain variations (which are at surface height) have a much stronger effect on the instrument's signal than equivalent density variations below the surface. We are planning for GLOBE to carry a LIDAR altimeter instrument, to allow collection of accurate terrain height models, in order to enable the best possible corrections for the GLOBE gradiometer data.
- Conversely, topographic models derived from satellite-borne LIDAR data have reduced accuracy if accurate gravity modeling 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.

- For any gravity instrument, the spatial resolution is limited to be not much better than the distance between the instrument and the anomaly being measured. Thus, the lower GLOBE flies, the higher its spatial resolution can be. It may be possible for GLOBE 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 GLOBE has sufficient propulsion capability, this could be repeated for some other sites as well.
- Like Lunette, GLOBE will need to be able to reach Lunar orbit. Unlike Lunette, it does not easily fit the idea of being an “ejectable payload” of some other Lunar orbiter mission. GLOBE will either need to be delivered directly into Lunar orbit by some launch system, or will need serious on-board propulsion of its own, to make its own way to low Lunar orbit from Earth orbit.

FUTURE POSSIBILITIES

In terrestrial geophysical exploration, mapping is done at different scales for different reasons. Large scale “sovereignty mapping” is often undertaken by national or provincial geological survey ministries, to define the geological context of a broad territory, largely in order to attract mining companies to explore in their territory. Mining companies will carry out medium-scale surveys of large staked claims, in order to narrow down the areas for which they wish to renew their claims. Both of these are typically done using airborne instruments on fixed-wing platforms, the most economical means for wide-scale mapping. Local fine-scale surveys may then be done via helicopter-borne instruments (a more expensive but higher-resolution and more-accurate approach), to identify target areas for the most expensive form of exploration: ground-based surveys, followed by drilling.

A similar progression seems reasonable for Lunar exploration:

- Current mapping is being done at a regional level, from sensors in Lunar orbit, to develop an overall understanding of the Moon’s structure

and geological history. This will provide the context for later, more-focused exploration. Radio tracking gravity measurements in the past have been in this category; Lunette and GLOBE are concepts to improve on these in a step-by-step manner.

- Higher resolution and accuracy can be achieved, at least in some localized areas, via instruments on satellites in specialized orbits (e.g., with very low perilune altitude over a target area). GLOBE’s gravity gradiometer and LIDAR altimeter would be suitable for this.
- The next natural step is Lunar-surface-based surveying with various instruments, to decide the most interesting spots to drill, and then dig. On the surface itself, gravimeters become an option (as the Equivalence Principle no longer hinders them once they’re not in free-fall), and indeed have already been used there (the Apollo 17 Traverse Gravimeter); gravity gradiometers continue to be very valuable, as they are more sensitive to near-surface density variations (i.e., possible mineral deposits, or voids beneath the surface) than are gravimeters.

In either case (and also in the case of various other types of geophysical surveying instruments), placing the instruments on some sort of mobility platform—e.g., a rover vehicle—will greatly improve their productivity.

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, and the problem can be addressed well by quite small spacecraft.

We specifically propose Lunette: a nanosatellite intended to fly as an auxiliary to a main lunar-orbiter spacecraft. At the cost of 5 kg of payload mass, it would provide a trustworthy global gravity map with resolution and quality at least equal to that of current *nearside* maps, plus more detailed maps of selected areas.

Lunette would lead naturally into GLOBE, 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 (not least being budget!) is not yet in hand but is not far off.

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