ASTEROID SURFACE GRAVIMETRY. Kieran A. Carroll, Gedex Inc., 407 Matheson Blvd. East, Mississauga, Ontario, Canada L4Z 2H2, kieran.carroll@gedex.com.

Abstract: Surface gravimetry is a standard terrestrial geophysics exploration technique. As nothing blocks gravity, this approach can detect subsurface structures with contrasting densities, both shallow and deep. In the exploration of other planetary bodies, two gravimeters have been used to make measurements on the Lunar surface, during Apollo 17 [1], [2]. Here we discuss near-term and longer-term asteroid exploration surface gravimetry applications. Requirements for a suitable asteroid surface gravimeter are derived.

Near-Term Application --- ARRM Target Scouting: NASA is contemplating an Asteroid Redirect Robotic Mission (ARRM) to capture and retrieve either a complete 100-1000 tonne asteroid (the "Get A Whole One" (GAWO) approach), or a boulder of mass as small as 10 tonnes from the surface of a larger asteroid (the "Pick Up A Rock" (PUAR) approach) [3]. The ARRM mission's planners must find a suitable asteroid target, a challenge made difficult by the very small size (~ 7m diameter) of GAWO targets, and by the somewhat higher ΔV needed for returning from PUAR target asteroids. They must also ensure that the total impulse capacity of the ARRM spacecraft's propulsion system is sufficient to return the target GAWO asteroid (or PUAR boulder) to Earth orbit.

GAWO Case. For a GAWO mission, knowing the upper limit on the mass of the target asteroid with a high degree of certainty before sending the ARRM spacecraft there would be highly desirable, to ensure that the asteroid will be found to be retrievable. Astronomical observations from Earth of a GAWO target can be used to constrain the target's mass, but with an uncertainty of a factor of 3 or 4 [4]. Relying on this approach to bound the target's mass drives target selection towards rather smaller targets, thinning out the already-small population of known candidate targets.

A mass determination technique used on asteroid 25134 Itokawa by the Hayabusa spacecraft determined its mass to within 5%, by using 90 minutes of LIDAR altimetry data taken while falling towards the asteroid's surface from an initial altitude of 1427 m to a final altitude of 825 m [5]. However, Itokawa's $3.6x10^{10}$ kg mass is about 50,000 times larger than the mass expected for GAWO targets; using this technique at such a smaller asteroid would require a much longer tracking measurement duration and/or a much closer initial altitude, to get a mass estimate with a similar relative accuracy. Another technique that has worked well for much larger asteroids, determining mass via radio tracking of a spacecraft during a close asteroid flyby, would require a similarly very close approach, at very slow flyby speed, and a very long tracking duration, to yield accurate results for a GAWO target. Also, uncertainties in perturbations from thruster firings and solar radiation pressure, noticeable for Hayabusa at Itokawa, would present a much larger problem in this case.

A novel, rapid means for determining the mass of an asteroid is to "weigh" it, by measuring its gravity at one point on the asteroid's surface with a gravimeter. If the gravimeter's location on the asteroid, and the asteroid's size (and shape, if that is irregular) and rotation rate are also determined --- *e.g.*, by taking photographs and range measurements prior to landing, or from an accompanying "mothership" --- then the asteroid's mass and density can be estimated by combining these data. (Non-principal-axis rotation would complicate this, but not insurmountably.) Accuracy can be increased by also measuring the lander's orientation on the surface, which can be done using a star tracker. For a fast-rotating asteroid, landing at or near one of its poles would be best to avoid being flung off (a capability for anchoring to the surface would further mitigate that risk); this would also minimize perturbing accelerations due to the asteroid's rotational dynamics.

The gravity on the surface of a GAWO target asteroid of mass 100 to 1000 tonnes could be as low as 100 nanoG. A gravimeter with an absolute accuracy (including effects of bias and bias drift) of 10 nanoG or better would be needed to estimate the asteroid's mass with an accuracy of 10%.

Precursor scout missions to GAWO candidate target asteroids, so equipped, could rapidly determine each asteroid's mass. Such missions could use a small, inexpensive microspacecraft; 6 or so such precursor scout missions to various ARRM candidate target asteroids could be accomplished for perhaps \$100M, a small fraction of the cost of a mission such as Dawn (> \$450M) or OSIRIS-Rex (~ \$1G).

PUAR Case. For a PUAR mission, knowing the mass of the target asteroid in advance of ARRM spacecraft launch is much less critical. Based on imagery from asteroid rendezvous missions such as Hayabusa at Itokawa [6], it seems plausible that boulders of various sizes will be found on the surface of many asteroids, and that a boulder of suitable size for retrieval will be found on any PUAR target asteroid. The special challenge here is to select a suitable boulder once an ARRM spacecraft arrives at the asteroid.

The obvious selection technique uses imaging and assumptions about density, perhaps informed by spectral data. However, meteorites are often heterogeneous, and if asteroid boulders are too, then even spectra may not be a reliable guide to density; *e.g.*, note that some of Itokawa's boulders appear distinctly different from each other, with differing spectra [7]. Discovering after pick-up that the chosen boulder is unexpectedly dense could be an acceptable approach to follow, if the ARRM spacecraft is designed to be able to "try again" with other boulders until its finds one whose mass is not too high. However, if the ARRM boulder grappling system is a one-shot device, then another approach would be needed to determine boulder mass.

An asteroid surface gravimeter can be used to "weigh" a boulder on the surface of an asteroid, by carrying out a local gravimetry survey near the boulder. The basic technique is to make a gravimetry measurement at a survey station on the asteroid surface adjacent to the boulder, and at least one other measurement at a station located farther enough away that the gravitational effect of the boulder's mass is much smaller. As the ratio of boulder mass to asteroid mass will be very small, the change in the *magnitude* of the measured gravity between the two stations will be insensibly low. However, changes in the *direction of the gravity vector* may be detected. To do so requires that the instrument measure the entire gravity vector. It also requires that the orientation of the gravimeter with respect to the asteroid be known at both stations, to allow the two measured gravity vectors to be compared in the same reference frame; a star tracker collocated with the gravimeter will certainly be needed for this.

Candidate PUAR asteroids are far enough away from Earth in terms of ΔV that retrievable boulders may be as small as 10 tonnes [8]. For such a boulder on Itokawa, 1.5 arc-min accuracy in the knowledge of the orientation of the gravity vector would enable estimation of its mass to within 10%. For this application, the gravimeter would need to be mounted in a lander with surface-mobility capability. Measurement stations need not be much more than 10m from the boulder.

A complicating factor is the asteroid's lumpy shape, compensation for which can be done by developing an asteroid shape model based on photographs and LIDAR measurements from orbit, with which to forward-model estimated asteroid gravity at survey stations based on an assumed uniform density. The location of each measurement station relative to the boulder must also be known with fairly high accuracy, which can be determined using photography on the surface, in conjunction with photos from orbit, and possibly some active navigation aids. Measurements at additional stations (perhaps as many as 10 or 20) would provide data with which to distinguish local subsurface density variations from the mass of the boulder on the surface.

Gravimeter Requirements. A gravimeter suitable for the above applications should have an absolute accuracy of 10 nanoG, and be a vector gravimeter, able to measure the gravity vector direction to within 1 arc-min. Preferably it should be very small and low in mass, to enable carriage by a low-cost asteroid scout mission, *e.g*., a microsat-class mothership and nanosat-class lander. Gedex is pursuing the development of such an asteroid gravimeter, with a size of 10x10x15 cm and a mass less than 1 kg.

Longer-Term Application --- Asteroid Surface Gravimetry Surveying: Many asteroids are known to have a bulk density significantly lower than the densities of related meteorites [9], [10]. This could be due to some combination of inherent mineral microporosity, and macroporosity (large-scale voids and fractures) arising from impacts. Compositional inhomogeneity (*e.g.*, from ice deposits [11]) could also contribute. The PUAR surveying approach can be extended to a gravimetric survey that covers the entire surface of a small to medium-sized (*e.g.*, Itokawa-sized) asteroid, allowing its internal density distribution to be mapped, potentially to a much higher resolution than can be achieved using current radio-tracking techniques. This in turn could provide asteroid structural and compositional information which would be difficult or impossible to obtain by other means, which could aid in understanding an asteroid's formation history.

This type of whole-asteroid gravimetry survey could also produce valuable prospecting information for future asteroid mining activities, helping to delineate ore bodies. *E.g.*, gravimetry could detect subsurface concentrations of frozen volatile materials within a rocky matrix, as these would have a low density as compared to their surrounding rock. Similarly, gravimetry could detect deposits of high-density materials, such as nickel-iron ore, which could be high in platinum-group metals.

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