# OFF-NADIR LIDAR TO DETECT BOUGUER ANOMALY ON AIRLESS WORLDS.

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**Introduction:** One of the few ways to probe the subsurface of a planet is by the identification of density fluctuations, or mass concentrations (hereafter “mascons”). Mascons manifest themselves as gravity (Bouguer) anomalies, and can arise from buried impact craters, visually unidentifiable crustal phenomena such as volcanoes, and other geologic formations not apparent through visual and spectroscopic techniques. A goal of most outer planetary missions usually involves identifying these gravity features. On a future Europa mission, probing the physical environment under the ice will be vital in the search for future landing sites.

The concept discussed here (see also [1]) will allow for the detection of mascons using only one spacecraft, and in only one pass. On a mission such as the proposed Europa Orbiter flyby mission, where the useful lifetime could be short due to the intense radiation environment, this method may be the only method to identify mascons within and under the ice sheet.

There have been no identifiable anomalies associated with Europa, but given the nature of the ice sheet covering a subsurface ocean, obvious fresh surface features, and the lack of impact craters, the likelihood of convection in the subsurface of the planet seems high. Identification of gravity anomalies can tell us a tremendous amount about the subsurface environment, including identification of new surface geologic factors, ocean depth and the most likely place to send a probe to melt through the ice. The subsurface liquid environment may be the most important astrobiological target in the solar system for the search for extant life given the combination of a robust tidal energy source, presence of liquid water over geologic time scales and the presence of organic material [2]. One of the likely objectives of any upcoming Europa-focused mission will be to pave the way for a future lander, and identification of negative and positive anomalies in the sub-surface will be a key to identifying landing sites.

We present a novel method to characterize Bouguer anomalies using a modified laser altimeter method. The modification consists of the addition of two new beams to the traditional nadir-pointed one. One of the beams points into the direction of spacecraft motion (the “leading” beam); the other points away from the direction of spacecraft motion (the “trailing” beam). These beams point at large angles with respect to the nadir beam: in the modeling to follow, we use an angle of 45 degrees for both beams. This architecture can determine mass anomalies to <10 mgal. Here we discuss the methodology.

**Off-Nadir Pointing:** Consider a simple example: a single mascon embedded in a planet that is otherwise perfectly spherical, smooth and of uniform density. This example can be reduced to a simple two-dimensional model, where the planet and mascon are each represented by a point mass. If a spacecraft is in a circular orbit about the planet, that orbit will be perturbed as the spacecraft passes over the mascon. The effect of a positive gravity anomaly is to increase the eccentricity of the spacecraft’s orbit, turning it toward the surface. This is graphically represented in Figure 1, which shows a spacecraft at three places along the perturbed orbit over a mascon of mass Δm.

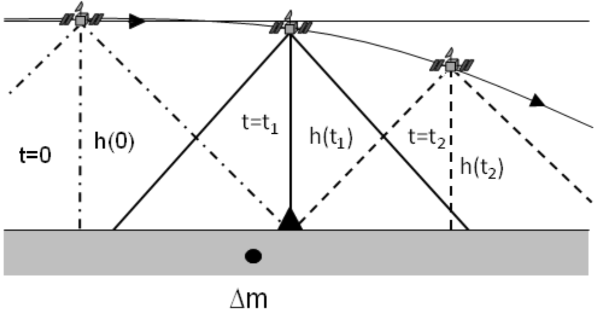

**Figure 1. Schematic of the off-nadir pointing technique**

Previous instruments, such as MOLA [3], used nadir-pointing beams to gather topography data. The effects of gravity anomalies are separated out from topographical variations by spacecraft tracking and multiple passes over the same location at different altitudes [4]. The technique discussed here introduces two more beams, pointed at a large angle φ from the nadir direction, into and out of the direction of motion of the spacecraft. These, then, are called the leading and trailing beams. The three beams (nadir, leading, trailing) are represented as dashed lines in Figure 1 at each of three spacecraft positions.

As the spacecraft travels along its orbit, each of the beams measures a distance to the surface. The leading and trailing beams will measure a slant range, but effectively measure the spacecraft altitude at a point some distance d away, which is given by:

$$d = r_p \sin^{-1}\left(h \tan(\varphi) / r_p\right).$$

Here, $r_p$ is the radius of the planet, $\varphi$ is the off-nadir pointing angle, and $h$ is the orbital altitude. As the spacecraft passes over some spot on the surface (shown in Figure 1 as a black triangle), its orbit is perturbed by the gravity anomaly. As the spacecraft altitude decreases, the three beams will each record a different altitude over the spot on the surface. In Figure 1, the situation is shown for three different times: at time $t = 0$ when the leading beam measures an altitude $h(0)$ for the marked spot (the red triangle), a time $t_1$ where the nadir beam measures $h(t_1)$, and a time $t_2$ when the trailing measures beam measures $h(t_2)$.

By measuring altitude variations over the course of a single pass, a single spacecraft is able to measure gravity anomalies without needing tracking from Earth. A positive mascon will tend to increase the spacecraft's orbital eccentricity, with the result that the altitude downrange of the mascon as measured by the nadir and trailing beams should be lower than that measured by the leading beam. Comparison of the vertical distance from the spacecraft to the surface for each of the three beams provides enough information to detect the Bouguer anomaly and characterize the mascon responsible for it. This technique enables high-resolution gravity measurements on missions that might not otherwise have this capability. In particular, a spacecraft performing multiple flybys at Europa, which promises to have a comparatively short mission lifetime, should be able to use this technique. The cross-over technique would not be feasible due to the shorter mission lifetime.

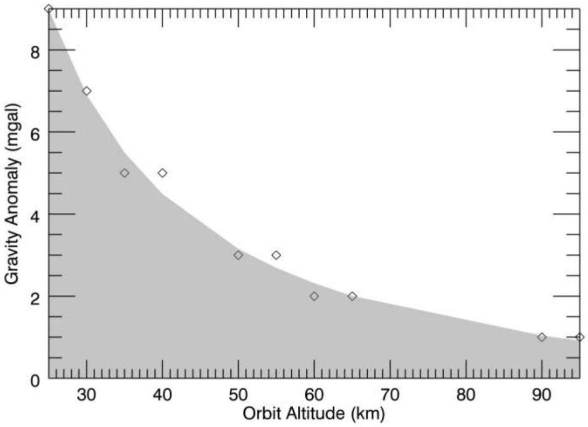

**Figure 2. Threshold detectable anomaly**

**The simulation:** In our simple simulation, a spacecraft orbits a perfectly smooth, spherical planet of uniform density, upon the surface of which a single mascon has been embedded. The simulation is two-dimensional, with the spacecraft passing directly over the mascon. The planet is modeled as a sphere the size and mass of Europa; the spacecraft is assumed to begin in a circular orbit at a given altitude. The mascon is at a distance d=100 km downrange from the spacecraft. The trajectory is computed numerically with a timestep of 0.02 seconds. The simulation consists of 15000 steps, resulting in a simulated trajectory that starts 100 km before the mascon and ends about 300 km after.

The spacecraft trajectory about the mascon thus obtained, the next step is to find the altitudes at the points where the three beams hit the surface. For an off-nadir angle of $\varphi=45°$, the distance $d$ is approximately the orbital altitude $h$.

A detection is deemed to have been made when the altitudes for a given spot seen by the leading and trailing beams diverge by more than the range resolution of a typical LIDAR instrument. We assume 10 cm for our range resolution.

**Results and Conclusions:** A series of simulations were performed for orbit altitudes between 25 km and 100 km, and for Bouguer anomalies under 15 mgal. Simulation runs of interest were those that generated a difference between the leading and trailing beams of at least 10 cm. An orbit altitude of 25 km seems a realistic minimum for any Europa mission.

Figure 2 shows the minimum anomalies at each orbit altitude in the simulations for which one finds a maximum altitude difference of over 10 cm. The altitude difference is that between the leading and trailing beams. The boundary between the shaded area and the unshaded area represents a rough estimate of the limits for minimum detectable Bouguer anomalies.

The simple calculations done here suggest that this technique would be a viable method to detect gravitational anomalies on airless worlds to thresholds as yet unseen, using a single spacecraft in a single pass, without tracking through the DSN. As such, a LIDAR instrument making use of this technique could be a valuable component on any mission to an airless world whose gravitational field is not well understood. It might be the best method for identifying the best possible landing site for in situ investigations. Examples include Europa and the other Galilean satellites of Jupiter, as well as large asteroids, Enceladus, and Triton. The ability to obtain anomaly data on a single pass without tracking makes this a viable technique on short-duration missions where cross-over analysis might not be feasible. The need for only a single spacecraft opens up the possibility for gaining high-resolution gravity data for missions to planets that are otherwise technically challenging, such as the Galilean satellites of Jupiter. In particular, this technique may make possible high-resolution gravity measurements of Europa with even the limited mission currently under consideration.

**References:**

[1] Sollitt, L.S., Beegle, L. W. and Arenberg, J. W., ASR (submitted). [2] McKay, C. P., Space Science Reviews 135(1-4): 49-54, 2008. [3] Zuber, M. T., et al., Science 266(5192): 1839-1843, 1994. [4] Neumann, G. A., et al., JGR-Planets 106(E10): 23753-23768, 2001.