EXPLORING SUBSURFACE LUNAR VOIDS USING SURFACE GRAVIMETRY. Kieran A. Carroll, David Hatch[2], R. Ghent[3], S. Stanley[3], N. Urbancic[3], Marie-Claude Williamson, W.B. Garry[4], Manik Talwani[5] [1]Gedex Inc., 407 Matheson Blvd. East, Mississauga, Ontario, Canada L4Z 2H2, kieran.carroll@gedex.com, [2]Gedex Inc., [3]University of Toronto, [4]NASA GSFC, [5]Rice University.

Introduction: 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. Recently-collected high-resolution imagery of the Moon has identified numerous pits, indicative of subsurface voids. Here we analyze the anomalous gravity signal expected at the Moon's surface due to both localized voids and more-extensive lava tubes, and find that the signal can be large enough to be measured with Lunar-compatible gravimeters. A potential near-term Lunar surface survey of a mare pit crater in Lacus Mortis is discussed.

Lunar Lava Tubes and Other Subsurface Voids: Lava tubes can form when an exposed magma flow cools at its top surface, forming a solid "lid" over the molten material flowing below it. When the source of the magma ceases to produce, gravity can cause the remaining molten material to flow away before it solidifies, leaving behind a hollow rock tube. Such structures would be of interest both scientifically, and for their potential as ore-forming sites; since at least as far back as 1985, they have also been considered as potentially "ready-made" excavations in which to emplace a Lunar base [1]. Those themes have been re-emphasized recently by other authors, e.g., [4].

Recent imagery from Kaguya and Lunar Reconaissance Orbiter have led to the detection of over 150 holes or pit features on the Lunar surface, with diameters ranging from 900 m down to <5 m, with more being detected on an on-going basis [2], [3], [4], [5]. These have mostly been found in maria or in impact melt deposits. Some of them are thought possibly to be skylights into lava tubes; e.g., Ashley *et al.* in [4] note that "the Marius Hills pit is located within a lunar rille and so currently represents the best candidate for a true skylight (collapsed lava tube ceiling) on the Moon.."

Regarding formation of these structures, Wagner and Robinson note in [5] that "the existence of collapse pits implies the existence of sublunarean voids, which leads to the question of the origin of the voids…a few mare and highland pits are near features that are suggestive of volcanic or tectonic origins…given their location within maria, it is at least reasonable that most mare pits could be collapses into lava tubes, melt chambers, or other volcanically-formed voids…other rilles or pit crater chains have been found to be linear but discontinuous…the space between such features likely represents uncollapsed tube."

The structure of these voids is currently unknown, being unobservable via imagery from orbit. Lava tube voids presumably might be like terrestrial lava tubes --- long, linear or sinuous tunnels. In [5], Wagner *et al.* speculate that "a complex plumbing system may form in some impact melt deposits," and that "where multiple pits were found in a single pond, the pits often occur in one or more small regions (~2-5 km square) within the melt deposit…occasionally, several pits occur within tens of meters of each other, indicating a possible subsurface connection." Presumably some other Lunar subsurface voids might instead be much more compact, resulting from the draining of a single small melt pond.

Mapping the details of subsurface voids on the Moon --- depth, size, extent, shape --- could provide otherwise-unobtainable information about volcanic and impact-melt processes over the course of the Moon's history.

Here we consider using surface gravimetric surveying to perform mapping of Lunar subsurface voids. Gravimetry is most sensitive to structures in the near-subsurface with distinct horizontal variations in density. Voids are ideal gravimetry targets, as their density --- zero, as they would be "full of vacuum" --- is much lower than the density of the surrounding rock --- typically 1,800 kg/m^3 for near-surface regolith, likely rather higher in bedrock formed of basalt flows. Also, they would exhibit considerable lateral variation in density, at every vertical wall between a void and the surrounding rock.

Lunar Surface Gravimetry: To carry out such surveys would require a stuiable instrument, and a means to move it around a survey area --- practically speaking, a rover-mounted gravimeter of suitable sensitivity.

To examine the question of required sensitivity, we consider an idelized model of a hypothetical Lunar lava tube. We assume this to be level, and cylindrical in cross-section, with a radius of 150 m, with its centre-line 200 m deep. We assume the surrounding rock to have a density of 1,800 kg/m^3. Figure 2 shows the vertical component of anomalous gravity generated by this feature at the surface, along a traverse line perpen-

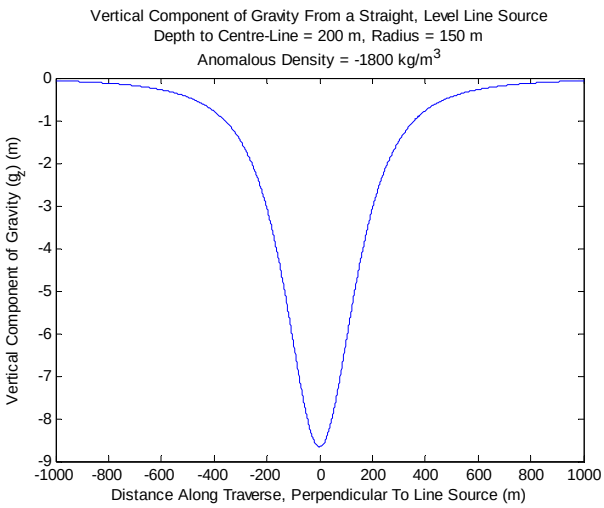

Figure 1

dicular to the direction of the lava tube. The peak signal is about 9 milliGal, dropping to about zero at a distance of 1000 m from the centre-line. Various other plausible values for the defining parameters produce peak signals in the range 2-10 milliGal, suggesting that a gravimeter with a sensitivity of 1 milliGal could sense at least the larger of these features.

A gravimeter of close to this sensitivity has been used on the Moon: the Lunar Traverse Gravimeter (LTG), which was used in Apollo 17 [6], was carried by astronauts Gene Cernan and Jack Schmitt on their lunar rover, making 22 measurements at 9 stations along a ~ 10 km traverse. Numerous measurements were made at the first station, demonstrating a repeatability within +/- about 2 milliGal. The data fron this survey, once reduced, were interpreted by one of us to be consistent with a 1 km thick basalt slab underlying

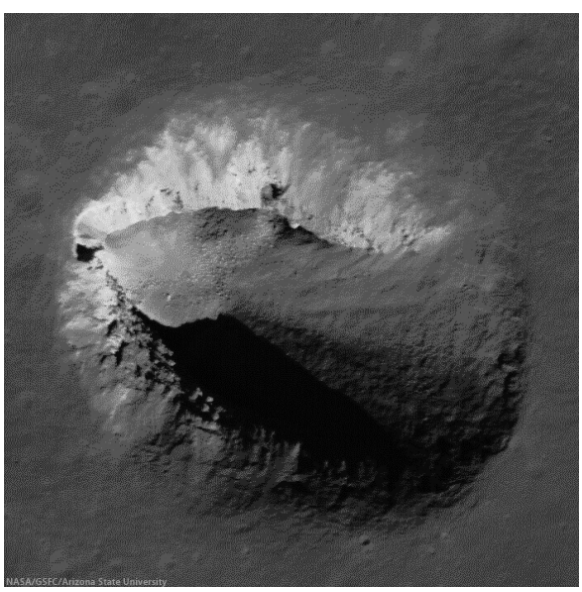

Figure 2: LROC Narrow Angle Camera (NAC) observation M126759036L, orbit 3814, April 24, 2010; 49.4° angle of incidence, resolution 0.5 meters from 45.56 km [NASA/GSFC/Arizona State University].

the Taurus Littorow valley site. The instrument used in that survey, custom-developed for that application, is no longer in production.

Gedex is developing a new gravimeter for use in space, with funding support from the Canadian Space Agency. The VEGA (VEctor Gravimeter for Asteroids) instrument makes measurements of the magnitude and direction of the local gravity vector. In an asteroid's gravity field, it is expected to be accurate to within 1-10 microGal. In the Moon's higher gravity field, a repeatability of 1 milliGal is targeted. The instrument is compatible with the smallest of asteroid and Lunar surface landers and rovers, with a size of 10x10x15 cm, a mass of 1.5 kg and a power consumption a few W. A flight-test of this instrument aboard a satellite in Earth orbit is planned by the end of 2016.

This instrument, mounted on a suitable Lunar rover, should be able to conduct surveys that would be able to map subsurface Lunar voids from the surface.

A Near-Term Survey Mission Opportunity: A target of particular interest is the partially-collapsed pit crater in Lacus Mortis, at 44.96°N, 25.62°E, shown in Figure 1, which is the target for CMU's "Andy" Lunar rover, which the company Astrobotic plans to send to the Moon in 2016 [7] to compete for the Google Lunar X-Prize. Intriguingly, the collapsed eastern side of the crater provides a ramp down to its bottom, perhaps making it feasible for a rover to descend that ramp to explore the floor of the pit, and any associated void. This feature could be a skylight into a lava tube, or a collapse into a subsurface void from cooling of a melt pond. A local surface gravimetric survey, say within a 1 km radius around this crater, could distinguish between these possibilities, mapping the shape, extent and size of any void underlying this feature. For example, the lava tube analyzed in Figure 1, which has a size and depth commensurate with this pit crater's 230 m diameter, produces a signal easily within the expected detection capability of the VEGA gravimeter currently in development.

References: [1] Horz, F. (1985), in **Lunar bases and space activities of the 21st century** (A86-30113 13-14), Houston, pp. 405-412, Bibcode 1985lbsa.conf..405H. [2] Haruyama J. et al (2010) LPSC Abstract #1285. [3] Wagner R.V. et al. (2012) LPSC Abstract #2266. [4] Ashley J.W. et al. (2013) LEAG Abstract #7040. [5] Wagner R.V. & Robinson M.S. (2014) NASA Exploration Science Forum poster. [6] Talwani M. (2003) *The Leading Edge v.22 no.8*, 786-789, doi: 10.1190/1.1605083. [7] http://lunar.xprize.org/ content/lunar-destination-lacus-mortis.