Near-Term Lunar Surface Gravimetry Science Opportunities

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Key Points

• We’re developing a (nearly) new type of geophysical instrument: the VEGA space gravimeter
• VEGA enables a (nearly) new type of Lunar exploration
• VEGA’s development is being supported by the Canadian Space Agency
• The instrument is a candidate for future CSA contribution to international planetary missions

• We are seeking exploration mission partners
  — Who can help arrange rides on Lunar rover missions
Relevance to This Meeting’s Themes

• **Lunar Resources:**
  – Lunar surface gravimetry surveying could help identify ISRU ore-bodies
  – E.g., water ice deposits
  – Just as gravimetry surveys do here on Earth

• **The Dynamic Moon:**
  – Lunar surface gravimetry surveying can help delineate near-surface geological structures
  – Some of which illustrate dynamic processes in the Moon’s formation and evolution history
  – E.g., lava tubes (volcanism)
Gedex, Terrestrial and Space Geophysics

• Located near Toronto, Canada
• Core business:
  – Airborne geophysics instrument development and exploration company
  – Developing world’s most sensitive airborne gravity gradiometer
• Senior technical staff led development of Canada’s first microsat missions
• Now also developing space geophysics instruments
• *Bridging between terrestrial and space exploration communities*
LSGG Study for Canadian Space Agency

- Lunar Surface Gravity Geophysics Science Definition Study
  - *Funded by CSA’s Exploration Core Program*
  - March 2014 to March 2016
- Motivated in part by Gedex’s development (underway) of a *new space gravimeter instrument, VEGA*
- Identify science that can be done on the Lunar surface with gravimeter and gravity gradiometer instruments
- Derive instrument requirements
- VEGA breadboard testing
LSGG Science Team Members / Co-authors

- David Hatch: Chief Geophysicist, Gedex
- Rebecca Ghent: Associate Professor, University of Toronto, Department of Earth Sciences
- Sabine Stanley: Professor, University of Toronto, Department of Physics
- Natasha Urbancic: Ph.D. candidate, University of British Columbia, Department of Earth, Ocean and Atmospheric Sciences
- Marie-Claude Williamson: Geological Survey of Canada
- W. Brent Garry: NASA Goddard Space Flight Center
- Manik Talwani: Schlumberger Chair, Rice University, Department of Earth Science
Lunar Surface Gravimetry

• Q: What could be detected by a gravimeter on the Moon’s surface?
• **A: The same sort of things as on Earth:**
  – *Subsurface density variations*
  – *Indicative of any local geology possessing anomalous density*
• Example interesting Lunar subsurface structures that could cause such signals:
  – Stratigraphy: layers of varying density and thickness
  – Megaregolith: variations in depth
  – Bedrock: “topography” of top surface
  – Faults
  – Buried craters
  – Magmatic intrusions
  – Lave tubes
  – etc.
Gravimetry 101

- A standard geophysical technique used in exploring for resources on Earth.
- Typically make measurements using a gravimeter at stations along a set of traverse lines covering a survey area.
- Gravimeters respond to subsurface density variations.
- Unlike with some other geophysical techniques, nothing blocks gravity.
- The data reflect some of the compositional and structural variations in geological formations.
- Hence some aspects of subsurface structure can be recovered from gravity maps.

[Ground Gravity Survey in Botswana Searching for Diamond Deposits]

[Hatch et al., 2006]
Existing Terrestrial Gravimeters

• The best field terrestrial gravimeters have drift-compensated repeatability within ~ 5-10 μGal (i.e., 5-10 milliG) over the course of a day
  – Relative gravimeters (not absolute)
  – Poor absolute accuracy
  – Arbitrary initial bias value
  – Bias drifts on the order of 1000 μGal/day
  – Bias drift rate varies significantly over 10-100 days
  – Very good relative accuracy achievable during surveys, but only by incorporating daily loop-closing in survey design

• Not suitable for the Lunar gravimetry application:
  – Can only function within +/- a few % of 1 G
    • Signal saturates outside that range
  – Daily loop-closing for a reasonably-sized survey would require a very fast rover

Scintrex CG-5 gravimeter

[Murray & Tracey, AGSO]
VEGA Instrument
(Vector Gravimeter for Asteroids)

- Developed by Gedex
  - Innovative (patented) design
  - Spun off from airborne gravity gradiometer system technology
- Measures absolute gravity vector
  - Vector: Allows arbitrary lander orientation
  - Absolute: Doesn’t require looping-back to calibrate out drift — compatible with slow rovers
- On the Moon:
  - Better than 1 mGal (1 μG) absolute accuracy
- Size: 10x10x15 cm
- Mass: < 1.5 kg
- Status:
  - Canadian Space Agency is co-funding development
  - Preliminary design done, breadboard testing and detailed design underway
  - Test flight in LEO planned in 2017
  - Seeking lunar rover (and asteroid lander/rover) missions to fly on!
Past Lunar Surface Gravimetry

- Only one surface gravimetry survey has been conducted off-Earth, to date:

- **Apollo 17 Traverse Gravimeter Experiment**
  - Double-string accelerometer instrument
  - Built by Bosch-ARMA, then modified by MIT

- Measurements made at 9 stations during 3 EVAs by Eugene Cernan and Harrison Schmitt, spread across the 10 km width of the Taurus-Littrow valley floor

- Data analyzed and interpreted by Manik Talwani (P.I.)

- **Results:**
  - Valley floor composition determined to be basalt
  - Thickness of basalt layer determined (1 km)
Traverse Gravimeter Experiment
Taurus-Littrow Valley Survey

Taurus-Littrow Valley Survey
Traverse Geography and Topography

Taurus-Littrow Valley Survey
Data Processing and Interpretation


Main Interpretation result
VEGA vis-à-vis TGE Gravimeter

• In the current era of Lunar exploration, VEGA provides an essentially new capability for Lunar geophysical exploration

• New for this era --- TGE was Then, VEGA is Now
  – TGE was a “one-off” instrument, long out of production
  – VEGA currently in development, soon ready for use in missions

• VEGA accuracy expected to be better than TGE accuracy
  – Opens up more geophysics applications

• VEGA is small enough to be carried on almost all Lunar rovers
LSGG Science Applications Being Studied

• (1) Follow up Apollo 17 Lunar Traverse Gravimeter survey

• (2) Survey potential lava tubes from the surface

• (3) Survey for Lunar ice deposits in polar regions
Mission Opportunity #1: Part-Time Scientists GLXP Lunar Rover

- German team, supported by Audi
- Planning to land 2 rovers near Apollo 17 landing site by end of 2017
Gravimetry Survey Opportunity: 
Follow-Up Taurus-Littrow Gravimetry Survey

- Apollo 17 survey was quite limited in resolution
  - Due to EVA time limits
  - Only 9 gravimetry stations
  - Was able to “image” a large, deep geophysical target
- **A follow-up survey could discern smaller, shallower features**
- **Rationale:**
  - Extensive geological studies have been done of this area since 1972
  - Due in part to Harrison Schmitt’s role in the mission, and his subsequent engagement as a geologist in studying results from Apollo 17 and subsequent Lunar missions
  - Those geological studies could guide and target next round of geophysical surveying, aiming to investigate/test current geological understanding of the area
  - Apollo 17 gravimetry survey has some intriguing features that need further data to investigate
- Gedex discussing with PTS the possibility of one of their rovers carrying a VEGA instrument, conducting a gravimetry survey around central part of Apollo 17 survey area
- **Mission Concept:**
  - CSA funds the VEGA instrument
  - Some combination of CSA and NASA funds the ride
  - Joint Canadian/US science team, based on LSGG team
Mission Opportunity #2: Astrobotic GLXP Lunar Rover

- Pittsburgh company, led by CMU’s Red Whittaker
- Planning to land Griffin rover near a pit crater in Lacus Mortis by end of 2017
- Selling payload space commercially:
  - $1.8M/kg on lander
  - $2M/kg on rover
Gravimetry Survey Opportunity: 

Explore A Potential Lava Tube From Above

- Numerous pit craters have been found on the Moon
- Some Lunar pit craters appear to be skylights into subsurface void spaces
  - Localized voids, e.g., melt ponds?
  - Lava tubes?
- Lacus Mortis pit crater
  - Gravimetry survey around this could investigate presence/nature of subsurface void-space
  - Sooner/cheaper than other lava tube exploration concepts

Pit crater in the Rimae Burg region of Lacus Mortis (44.96° N, 25.62° E), from 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, via http://lunarnetworks.blogspot.ca]

~ 225 m

E.g., Spiral Survey Traverse

[Wagner & Robinson, (2014), NESF]
Possible Lava Tube Skylight?

[Bruce Rogers, USGS]

Lava tube skylight on Kilauea, Hawaii, from http://commons.wikimedia.org/wiki/Kilauea

Valentine Cave in Lava Beds National Monument, California, from http://en.wikipedia.org/wiki/Lava_tube
Surface Gravimetric Surveying Above a Lunar Lava Tube

- Gedex discussing with Astrobotic the possibility of their rover carrying a VEGA instrument, conducting a gravimetry survey around the pit crater --- could determine presence/size/shape of any associated subsurface void
- Mission Concept:
  - CSA funds the VEGA instrument
  - Some combination of CSA and NASA funds the ride
  - Joint Canadian/US science team, based on LSGG team
Traverse Results Indicative of Tube Diameter, Depth

Vertical Component of Gravity From a Straight, Level Lava Tube of Circular Cross-Section
Depth to Centre-Line of Lava Tube = 200m
Lava Tube Radius From 20m to 200m in 20m increments
Anomalous Density = -1800 kg/m$^3$

Vertical Component of Gravity From a Straight, Level Lava Tube of Circular Cross-Section
Lava Tube Radius = 150m
Depth to Centre-Line From 150m to 300m in 25m increments
Anomalous Density = -1800 kg/m$^3$

[Carroll et al., LPSC, 2015]
Mission Opportunity #3: NASA Resource Prospector Mission Rover

• 2020 launch, NASA
• Rover to Lunar polar region, to search for ice
• *Ice deposits could cause density anomalies, make a signal detectable by VEGA*
  – Solid ice specific gravity = 1
  – Dry regolith s.g. perhaps 2.5
  – Regolith with ice in voids s.g. > 2.5, perhaps 3.0
• Could be an *affordable* Canadian contribution to RPM (<< $10M)
Nature of Lunar Ice Deposits Not Yet Known

- We don’t know the nature of Lunar ice deposits --- depth, concentration, etc.
- Instruments used to date can only “see” down to ~ 1 m depth
- Nothing blocks gravity --- a gravimetry survey could detect signatures from deeper deposits
Gravimetric Detectability of Ice Deposits

- Assume large, horizontal deposit of uniform thickness \( t \)
- Anomalous gravity signal upper-bounded by Bouguer correction:
  - \( \Delta g_B = 2\pi G \Delta \rho \cdot t = 0.042 \Delta \rho \cdot t \) [\( \mu \text{Gal} \)]
  - Finite extent of deposit can reduce the peak signal
  - If there are defined edges they will also produce “edge effects” which can enhance detectability over a traverse
  - Sharpness of edge depends on the deposit’s mean depth

- Two examples:
  - *Solid ice slab*: \( \Delta \rho = 1000-2500 = -1500 \) kg/m\(^3\)
  - *Regolith with ice in voids*: \( \Delta \rho \) might be as high as 500 kg/m\(^3\) (assuming 50% porosity)
Gravimetric Detectability of Ice Slab

- For **solid ice**, $\Delta \rho = 1000-2500 = -1500 \text{ kg/m}^3$
  - *Gravity low over the deposit*
  - For $t = 1 \text{ m}$, $\Delta g_B = -62 \mu\text{Gal}$
  - To reach $\Delta g_B = -0.25 \text{ mGal}$, $t = 4 \text{ m}$
  - Plot (below) assumes 1 m depth to top of ice, 4 m ice slab thickness, 200 m traverse

![Diagram](image)

- Dry Regolith
  - $\rho = 2500$

- Ice Slab
  - $\rho = 1000$
Gravimetric Detectability of Ice In Regolith

- For *regolith with ice in voids*, $\Delta \rho$ might be as high as 500 kg/m$^3$ (assuming 50% porosity)
  - *Gravity high over the deposit*
  - For $t = 1$ m, $\Delta g_B = +21$ $\mu$Gal
  - To reach $\Delta g_B = +0.25$ mGal, $t = 12$ m
  - Plot (below) assumes 1 m depth to top of ice-bearing deposit, 12 m deposit thickness, 200 m traverse

![Diagram showing anomalous gravity signal and traverse distance.](image-url)
Gravimetry Survey Opportunity:
Look for Gravity Signature of Ice on RPM

• Mission Concept:
  – CSA funds the VEGA instrument
  – CSA provides this as a Canadian contribution to the Resource Prospector Mission
  – Joint Canadian/US science team, based on LSGG team
  – RPM adds gravimetry measurements to its mission operations
    • Make a gravity measurement whenever the rover is stopped
    • Preferably (but not necessarily) when other rover payloads are quiescent
    • Baseline: analyze gravity data post-mission
    • Opportunistically: analyze data during RPM’s traverse, use that to help guide drilling decisions
Conclusion

- VEGA gravimeter will soon be ready for use on Lunar rover missions
- VEGA is small enough to fit on even quite-small Lunar rovers
- Any Lunar rover planning to traverse much more than 10 m could potentially detect the signature of subsurface density variations
- There are numerous scientifically interesting subsurface structures to “look” for
- Including for three potential near-term Lunar rover missions
SEEKING EXPLORATION MISSION PARTNERS