Lunar Surface Gravimetry Surveying Through the Lunar Night

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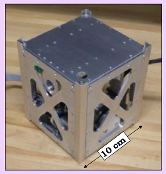
Introduction
VEGA Instrument

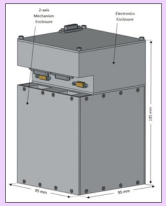
- Gedex has developed a low cost compact space gravimeter instrument , **VEGA** (Vector Gravimeter/Accelerometer)
- This instrument could be used in various lunar surface science investigations, see below
- Currently this is the **only** available gravimeter that is suitable for use in space
- (Ca. 1972 MIT developed a space gravimeter instrument for use on the Moon, for Apollo 17. That instrument is long-ago out of production and obsolete.)

<u>***VEGA Space Gravimeter Information***</u>

- Measures ***absolute gravity vector,*** with no bias
- ***Accuracy:*** 0.1-1 microG on the Moon
- ***Bandwidth:*** 1-10 mHz
- ***Size:*** 9.5 x 9.5 x 18.5 cm, 2.1 kg
- ***Power consumption:*** 4-12.5 W (depending on spacecraft temperature)
- ***Current Technology Status:*** TRL 5



VEGA mechanical breadboard



The VEGA Instrument

Lunar Surface Gravimetry
Science Team

A growing number of planetary scientists are science team members for several recent Lunar Surface Gravimetry proposals based on the VEGA instrument:

- Alexander Braun, Queen's University, Kingston, Ontario
- Anthony Colaprete, NASA Ames Research Center
- W. Brent Garry, NASA Goddard Space Flight Center
- Carle Pieters, Brown University
- Claire Samson, École de technologie supérieure, Montreal
- Clive Neal, University of Notre Dame
- Dan Britt, University of Central Florida
- David Blewett, Johns Hopkins University Applied Physics Lab
- David Hatch, Gedex
- Ed Cloutis, University of Winnipeg
- Georgia Fotopoulos, Queen's University, Kingston, Ontario
- Gordon Osinski, University of Western Ontario
- Harriet Lau, Harvard University/University of California at Berkeley
- Harrison Schmitt, University of Wisconsin-Madison
- John Crowley, Canadian Geodetic Survey, Natural Resources Canada
- Junichi Haruyama, JAXA
- Manik Talwani, Rice University
- Maria Annecchione, Gedex
- Noah Petro, NASA Goddard Space Flight Center

Benefits of Surveying Through the Lunar Night

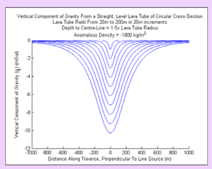
- **Net VEGA measurement error is a zero-mean, stationary random process:**
  - RMS measurement error decreases with larger sampling time, with 1/sqrt(T) — more time to make measurements produces better results
  - E.g., for 10-minute measurement, expect ~ 0.3 micro-g RMS error — about 10x better than the Apollo 17 Traverse Gravimeter Experiment instrument
  - For 1-day measurement, RMS error should drop to ~ 10 nano-g — as good as the best terrestrial survey gravimeters
- **Impact on Static Lunar surface gravimetry investigation:**
  - Measures time-varying signal, due to Earth and Sun tides
  - Post-processing involves fitting measurements to a parameterized Lunar interior structure model (e.g., modeling Lunar mantle horizontal thickness variation)
  - The longer the data-set, the better the fit, and the more accurate the parameter estimates
  - Natural periods for the tidal time-variations range from 1 month to several years; measurements spanning multiple cycles will allow for better fits and parameter estimates
- **Impact on Lunar-Rover-Mounted gravimetry surveys:**
  - More time available to carry out surveys results in more line-length covered, with enough time at each station to make accurate-enough measurements
  - E.g., For a 0.2 km/hr Lunar rover (Yutu), could cover ~ 40 line-kms in one Lunar day-time (14 days), or 2x2 km survey area at 100 m line spacing
  - If survival through the Lunar night is possible, then e.g., a 2-year (24 Lunar day) survey could cover perhaps 1000 line-kms, or a 10x10 km survey area

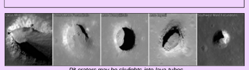
Potential Near-Term Lunar Surface Gravimetry Science Investigations

Rover-Mounted Investigations — Lunar Surface Gravimetric Surveys

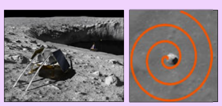
Explore Lava Tubes

- Astrobotic lander mission to a pit crater in Lacus Mortis
  - Potential rover payloads from iSpace and CubeRover
- Possible iSpace lander/rover mission to pit crater in Marius Hills
- Gravimetry could "see" and map subsurface voids from the surface
- Forward modelling of model lava tubes indicates 100 m diameter voids should be easily detectable

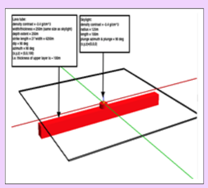




Pit craters may be skylights into lava tubes

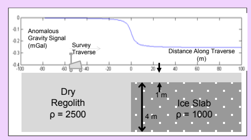


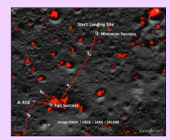
Spiral survey path is suggested around pit crater

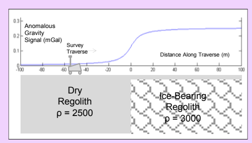


Lava tube gravity forward model

Detect Lunar Ice Deposits

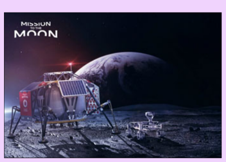






- Future rover missions are expected to explore Permanently-Shadowed Regions near a Lunar pole, looking for signs of ice
- Certain types of plausible ice deposits would produce measurable gravimetry signals

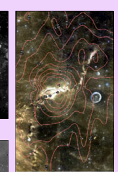
Taurus-Littrow Follow-up Gravimetry Survey

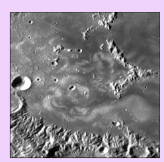


- PT Scientists is planning a lander/rover mission to the Apollo 17 landing site in Taurus-Littrow Valley
- A rover equipped with a VEGA gravimeter could do a follow-up to the initial, low-resolution (1 km between stations) Apollo 17 Traverse Gravimeter Experiment survey
- Survey with increased spatial resolution — 100 m between stations
- E.g., try to resolve details of the Station 5 10 mGal anomalous gravity low

Explore Lunar Swirls

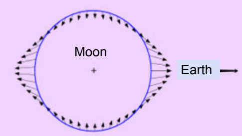
- High-albedo, optically immature, sinuous features on the Lunar surface
- E.g., Reiner Gamma, Mare Ingenii
- These are coincident with relatively strong magnetic anomalies.
- Possible cause: an intrusion of iron-rich material near the surface
- This could cause a mass anomaly large enough to detect with a surface gravimetry survey
- Blewett et al. of JHU/APL have proposed a Lunar rover mission (Lunar Compass) to study lunar swirls. A VEGA instrument could help investigate the source of the Reiner Gamma magnetic field

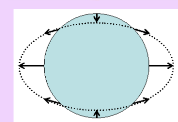




Static Investigation

Probe Lunar Mantle Structure





GLIMPSE:
Gravimetry of the Lunar Interior through the Moon's PulSE

- Just as the Moon and the Sun exert tidal forces on the Earth, the Earth and the Sun exert tidal forces on the Moon.
- Tidal stresses in the Moon are proportional to the gravity gradient tensor field at the Moon's centre, multiplies by the distance from the Moon's centre.
  - The gravity gradient at the Moon due to the Earth is 81x larger than the gravity gradient at the Earth due to the Moon.
  - But the Moon is smaller than the Earth, so the maximum tidal force on the Moon's surface due to the Earth, is ¼ of that, or about 20x larger than the maximum tidal force on the Earth's surface due to the Moon.
- While the Moon is tide-locked to the Earth, and so the ***direction*** of the tidal force vector is (roughly) constant in the Moon-fixed frame…
- …the Moon's orbit around Earth is elliptical (e=0.0549), and so the Moon's distance from Earth varies between about 357,000 km and 406,000 km, a variation of about +/- 7%, or a total of 14%.
- Gravity gradient varies with $1/d^3$, and so the ***magnitude*** of tidal forces on the Moon vary by 1.07^3 = 1.23, or +/-23%, or a total of 46%.
- A gravimeter on the Moon's equator will see a variation in apparent gravity of about 1 micro-g due to this effect.
- The effect is magnified somewhat due to the Moon deforming elastically due to the tidal stresses.
- The amount of Lunar deformation, and hence of the variation in gravity measurement at a static location, depends on details of the deep Lunar interior structure.
- Sufficiently accurate measurements of variations in gravity at one or more points on the Lunar surface, over several orbits, can be used to constrain models of Lunar elasticity.
- **Specific testable hypothesis :** that the Lunar nearside/farside dichotomy extends to heterogeneity of the Lunar mantle.

Acknowledgments: Some figures sourced from Astrobotic, PT Scientists, NASA,, and various geology web-sites.