Near-Term Lunar Surface Gravimetry Science Opportunities

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2015 Lunar Exploration Analysis Group (LEAG) Annual Meeting

USRA HQ, Columbia, Maryland

October 20-22, 2015

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

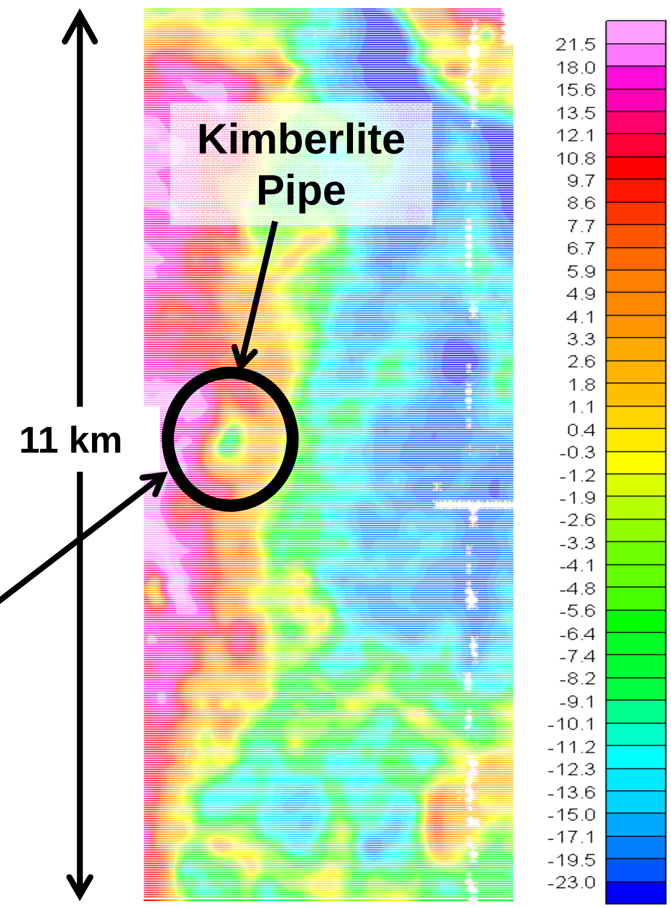
Lunar Surface Gravimetry

- 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

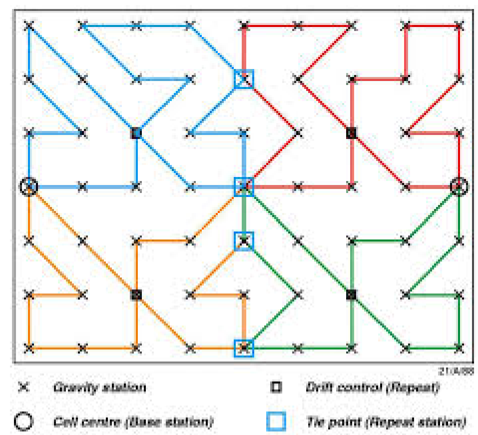


[Hatch et al., 2006]

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

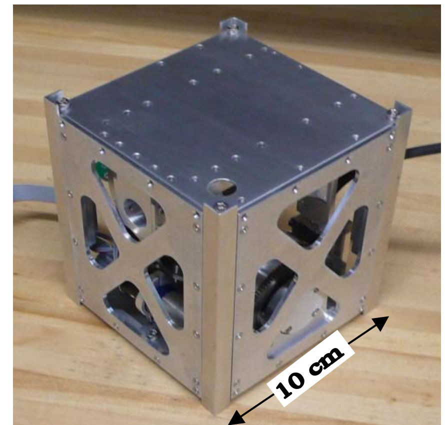
Scintrex CG-5 gravimeter



[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



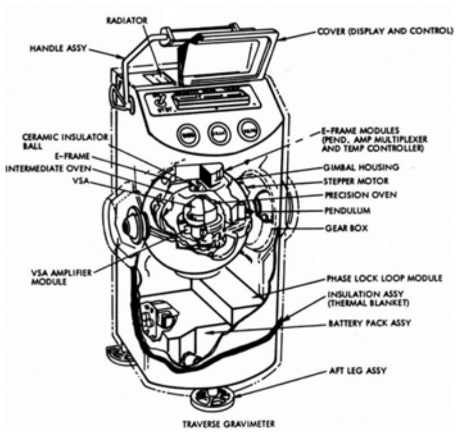
VEGA Mechanical Breadboard

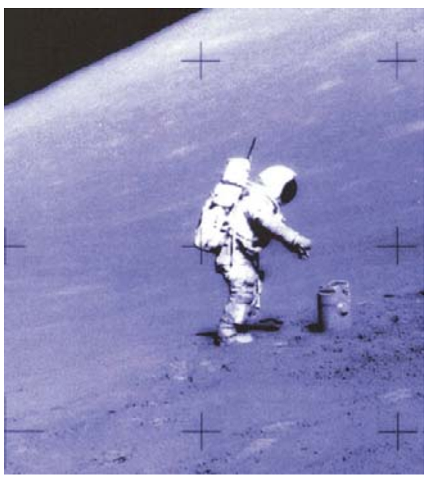
- **Size:** 10x10x15 cm
- **Mass:** < 1.5 kg
- **Status:**
  - ***Canadian Space Agency is co-funding development***
  - Preliminary design done, breadboard testing and detailed design underway
  - Test flight in LEO planned in 2017
  - Seeking lunar rover (and asteroid lander/rover) missions to fly on!

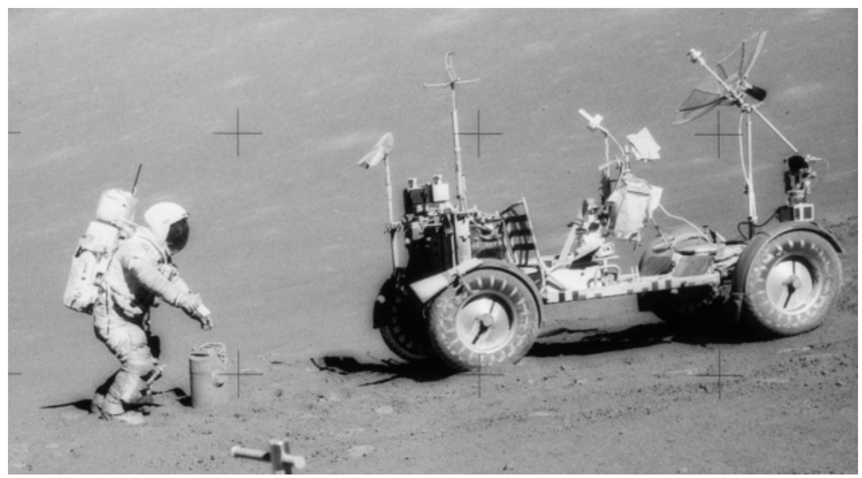
Past Lunar Surface Gravimetry

- 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)***

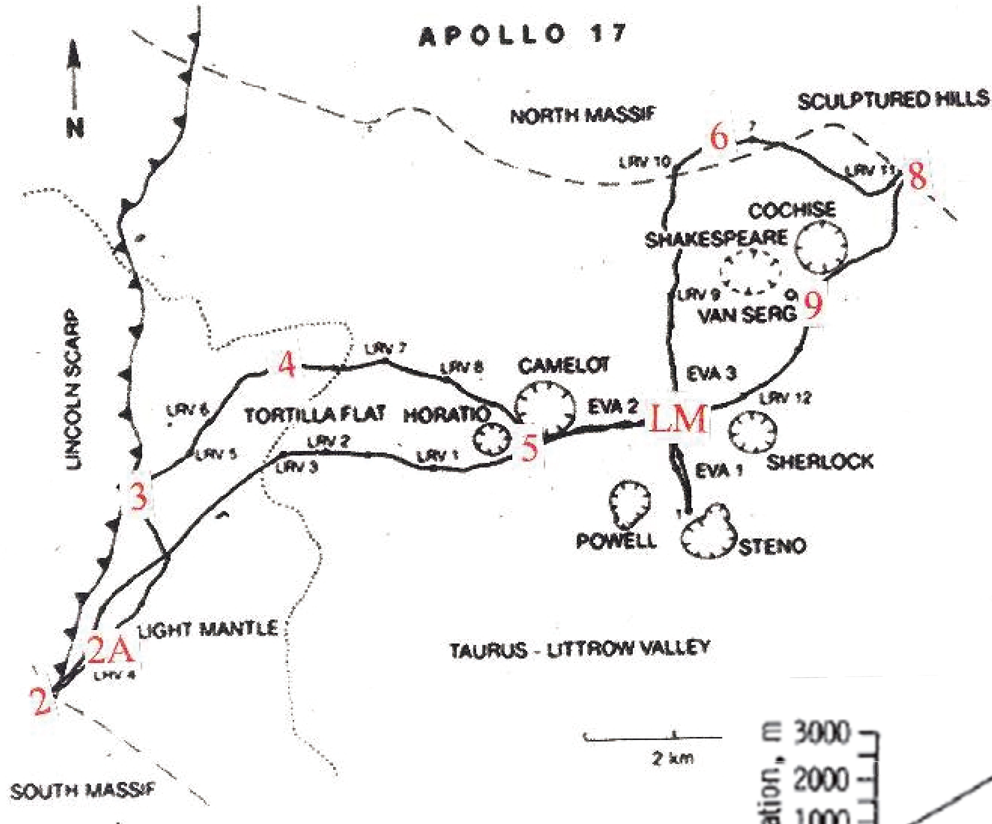
Traverse Gravimeter Experiment
Taurus-Littrow Valley Survey

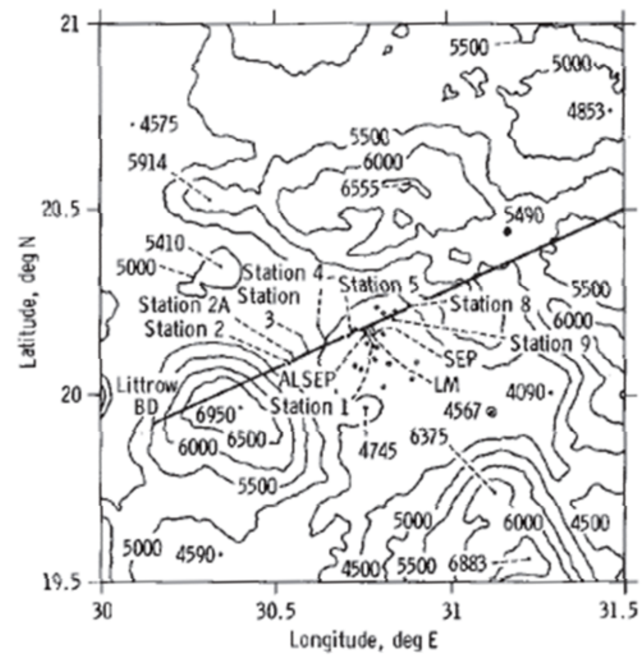


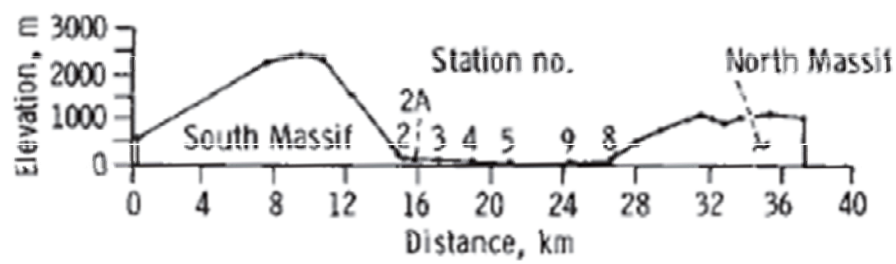




Taurus-Littrow Valley Survey
Traverse Geography and Topography

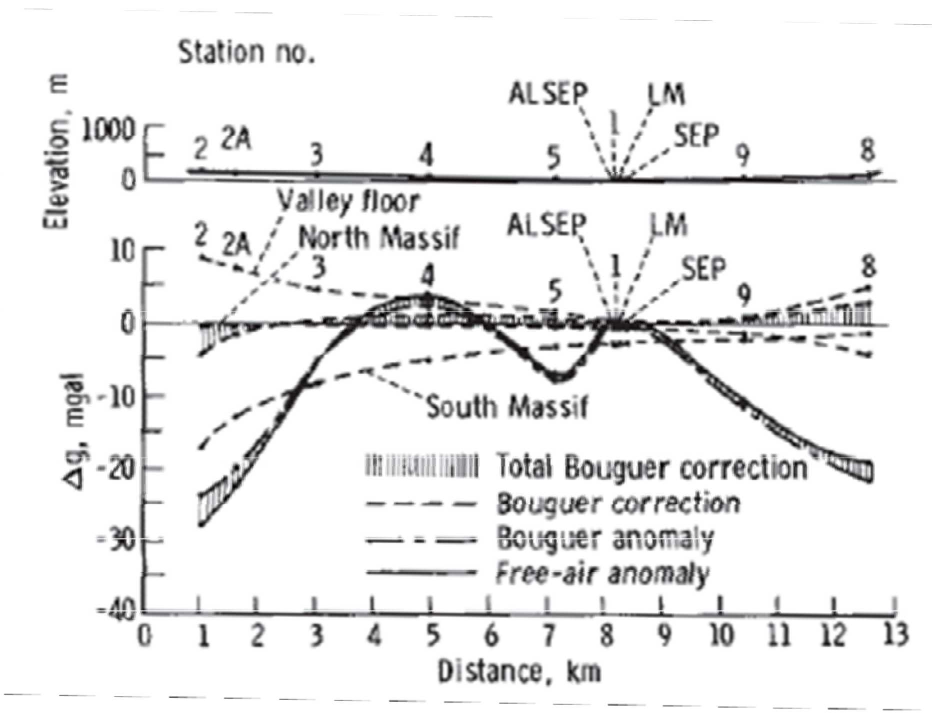


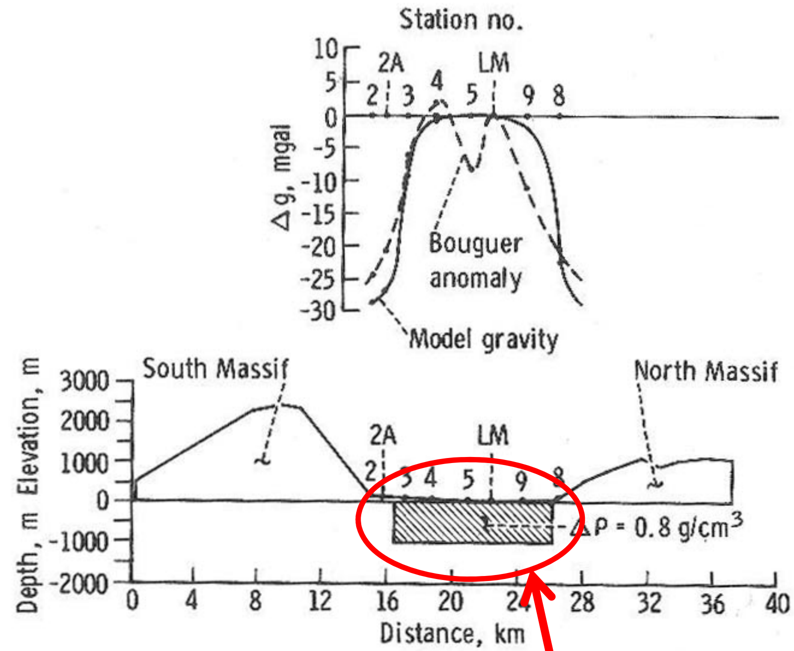




[Apollo 17 Preliminary Science Report, NASA-SP-330, ch. 13] & [Talwani, TLE, 2003]

Taurus-Littrow Valley Survey
Data Processing and Interpretation





Main Interpretation result

[Talwani *et al*., Apollo 17 Preliminary Science Report, NASA-SP-330, ch. 13] & [Talwani, TLE, 2003]

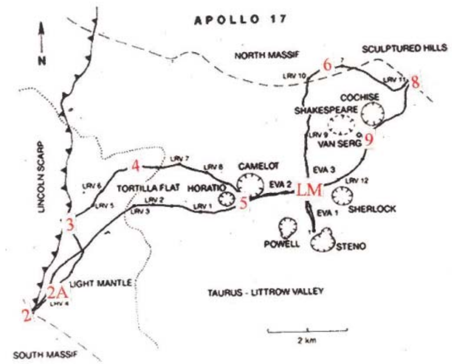
VEGA vis-à-vis TGE Gravimeter

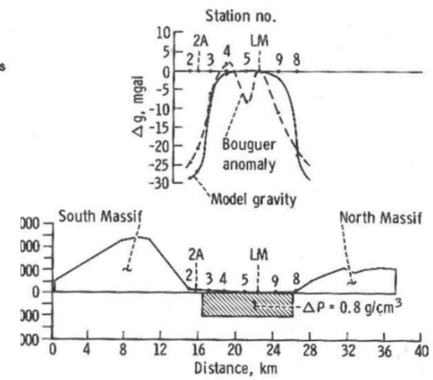
- ***In the current era of Lunar exploration, VEGA provides an essentially new capability for Lunar geophysical exploration***

- 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

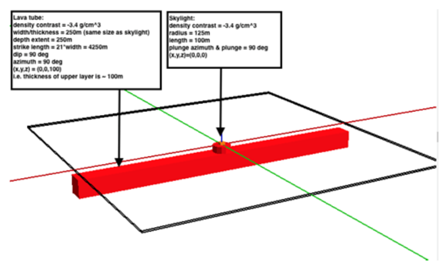
LSGG Science Applications Being Studied

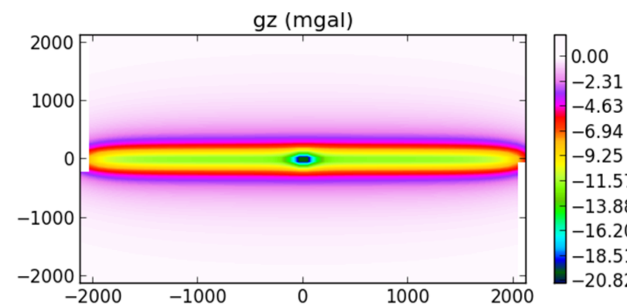
- ***(1) Follow up Apollo 17 Lunar Traverse Gravimeter survey***





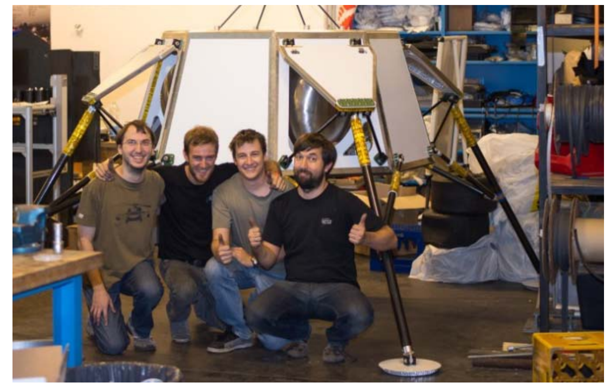
- ***(2) Survey potential lava tubes from the surface***





- ***(3) Survey for Lunar ice deposits in polar regions***

Mission Opportunity #1:
Part-Time Scientists GLXP Lunar Rover

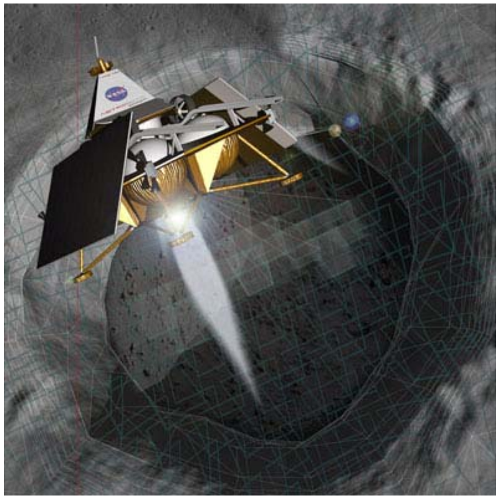


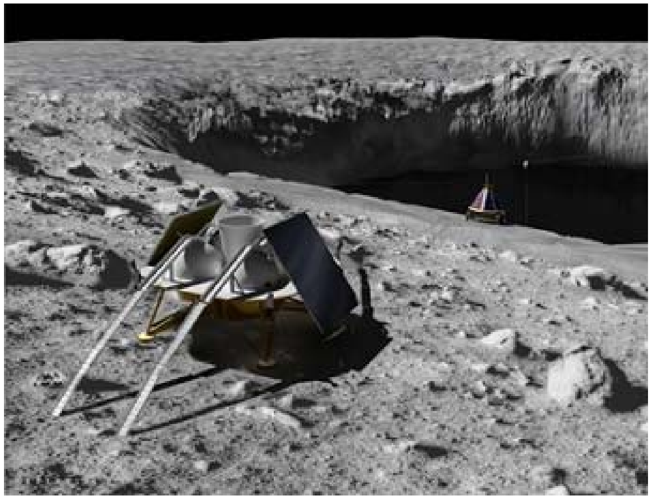
- German team, supported by Audi
- Planning to land 2 rovers near Apollo 17 landing site by end of 2017

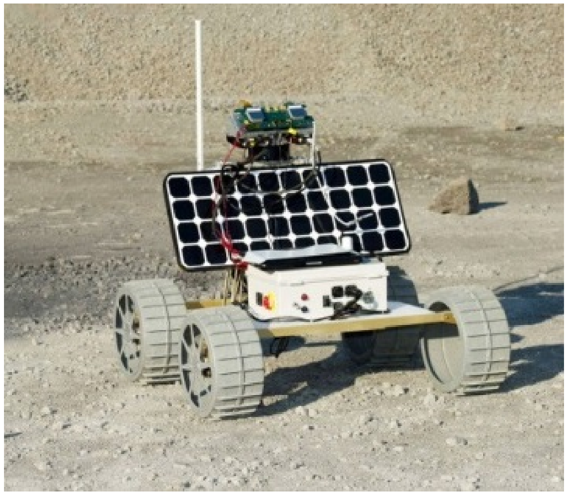
Gravimetry Survey Opportunity:
Follow-Up Taurus-Littrow Gravimetry Survey

- 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

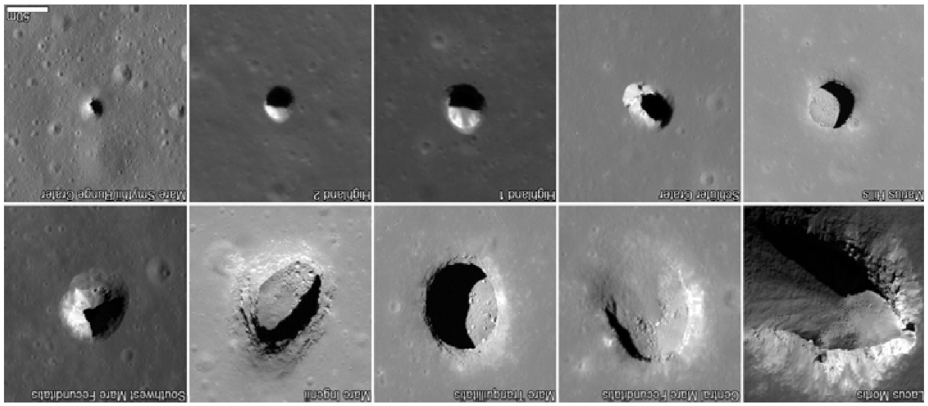






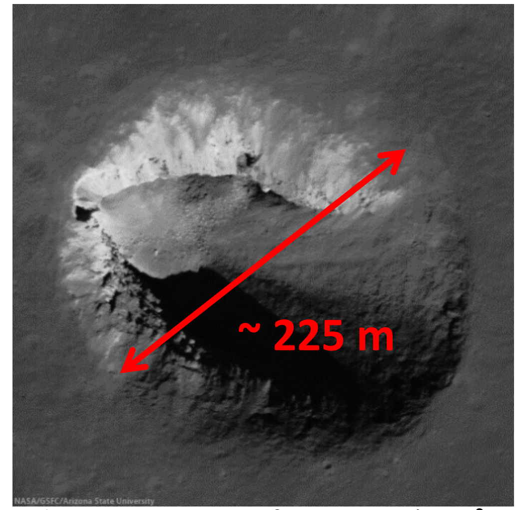
- Pittsburgh company, led by CMU's Red Whittaker
- Planning to land Griffin rover near a pit crater in Lacus Mortis by end of 2017
- Selling payload space commercially:
  - $1.8M/kg on lander
  - $2M/kg on rover

Gravimetry Survey Opportunity:
Explore A Potential Lava Tube From Above



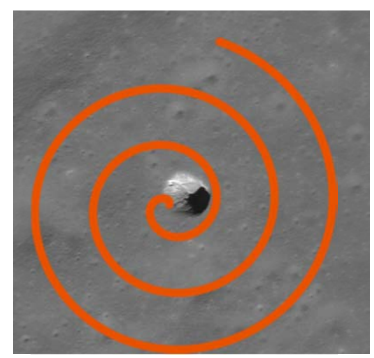
[Wagner & Robinson, (2014), NESF]

- 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

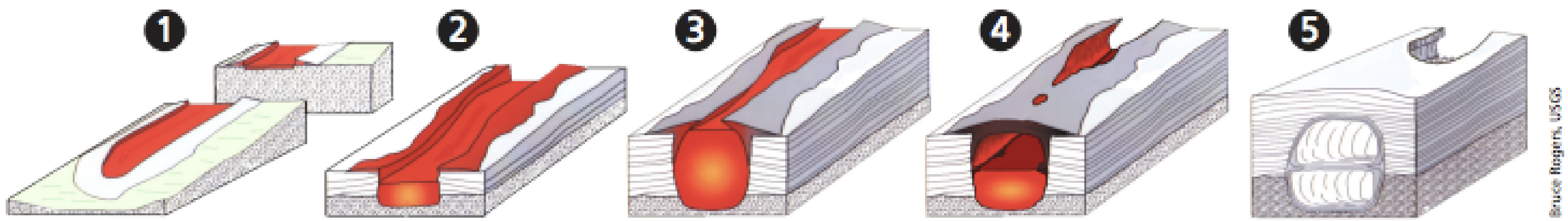


Pit crater in the Rimae Burg region of Lacus Mortis (44.96° N, 25.62° E), from LROC Narrow Angle Camera (NAC) observation M126759036L, orbit 3814, April 24, 2010; 49.4 angle of incidence, resolution 0.5 meters from 45.56 km [NASA/GSFC/Arizona State University, via http://lunarnetworks.blogspot.ca]

E.g., Spiral Survey Traverse



Possible Lava Tube Skylight?



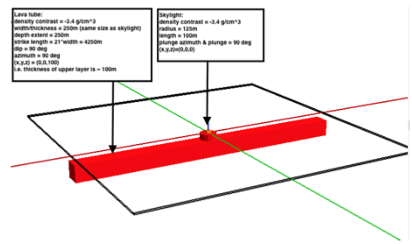
[Bruce Rogers, USGS]

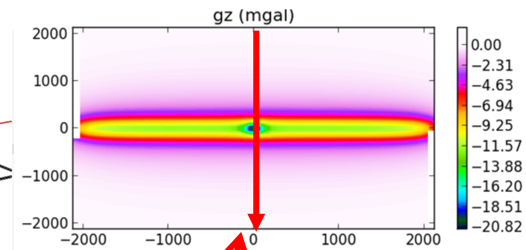
Lava tube skylight on Kīlauea, Hawaii, from
http://commons.wikimedia.org/wiki/Kilauea

Valentine Cave in Lava Beds National Monument,
California, from . http://en.wikipedia.org/wiki/Lava_tube

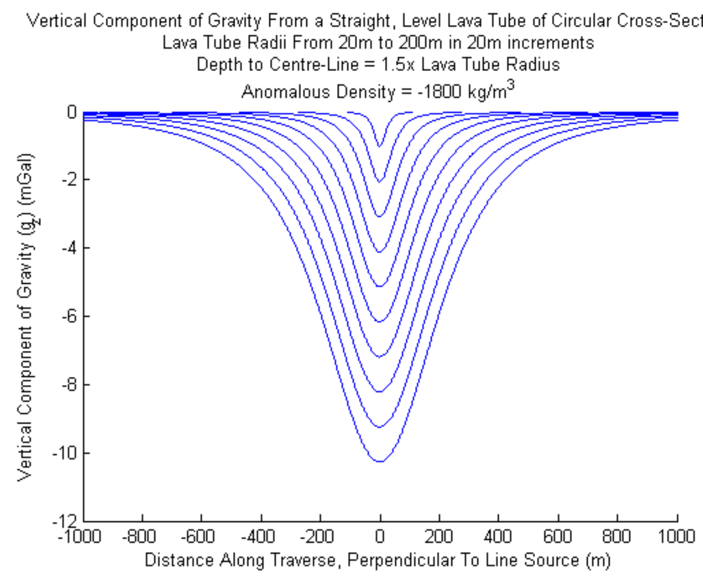
Surface Gravimetric Surveying Above a Lunar Lava Tube

- 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

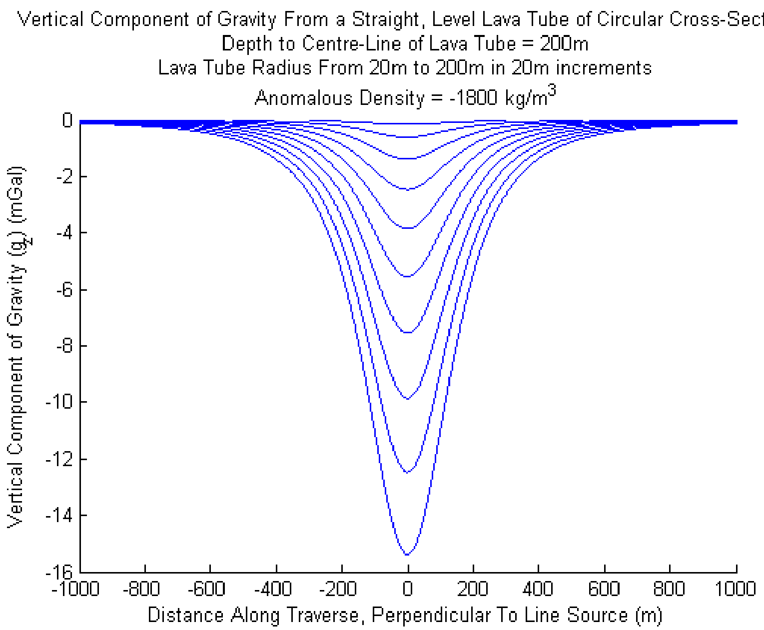


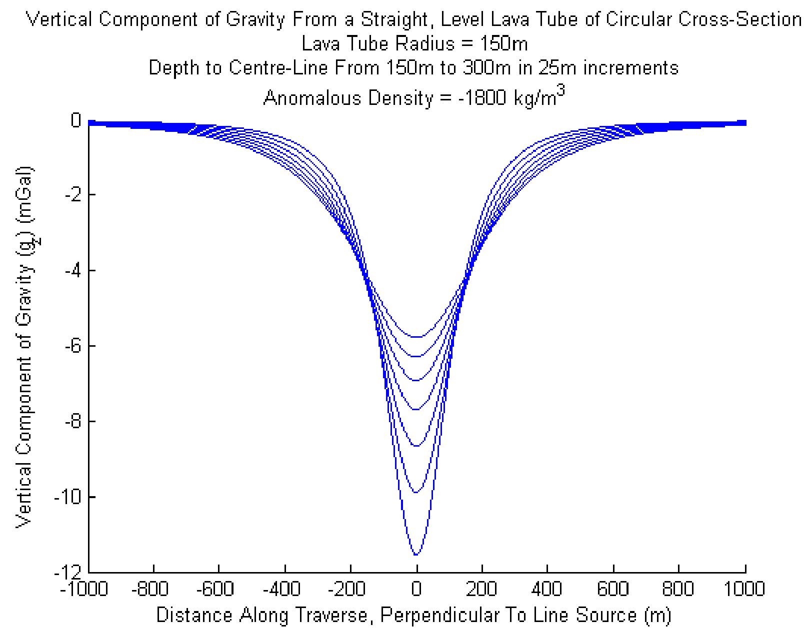


E.g., Linear Survey Traverse



Traverse Results Indicative of Tube Diameter, Depth

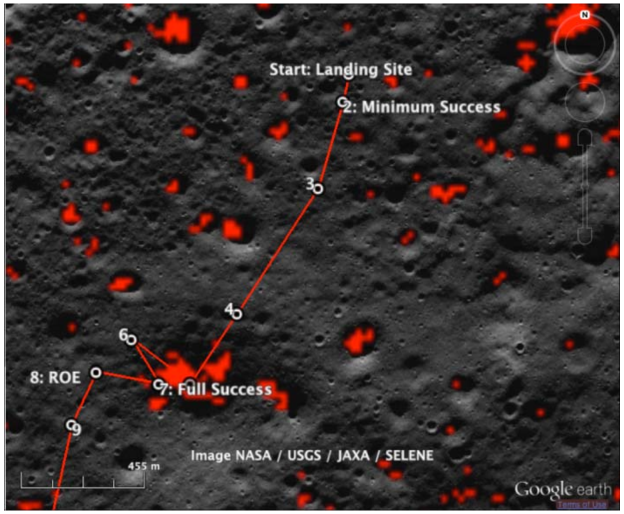




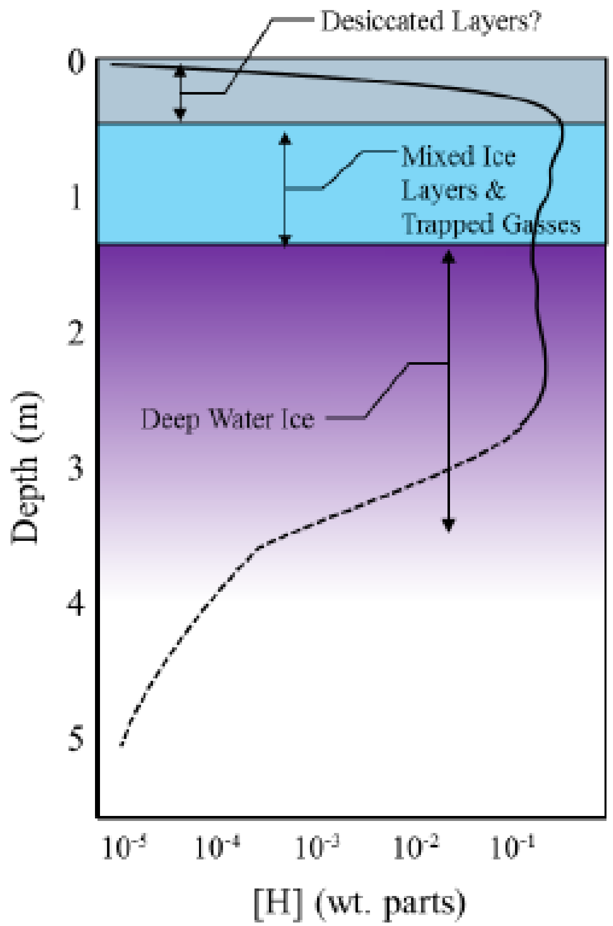
[Carroll *et al.*, LPSC, 2015]

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*



[Colaprete et al., LEAG 2013]

[David Hollister, http://hop41.deviantart.com/art/Lunar-Ice-174785137]

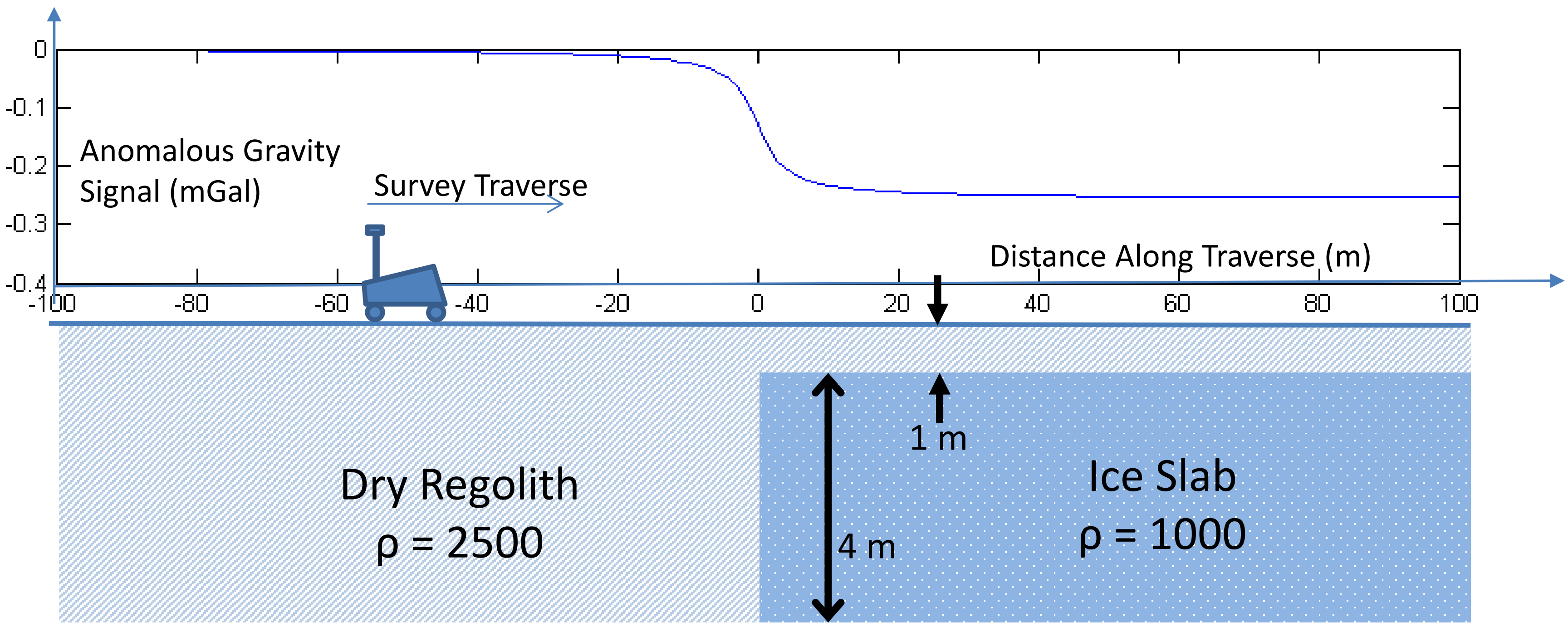
- We don't *know* the nature of Lunar ice deposits --- depth, concentration, etc.
- Instruments used to date can only "see" down to ~ 1 m depth
- **Nothing blocks gravity --- *a gravimetry survey could detect signatures from deeper deposits***

Gravimetric Detectability of Ice Deposits

- Assume large, horizontal deposit of uniform thickness *t*
- Anomalous gravity signal upper-bounded by Bouguer correction:
  - $\Delta g_B = 2\pi G * \Delta\rho * t = 0.042 * \Delta\rho * t$ [μGal]
  - 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)

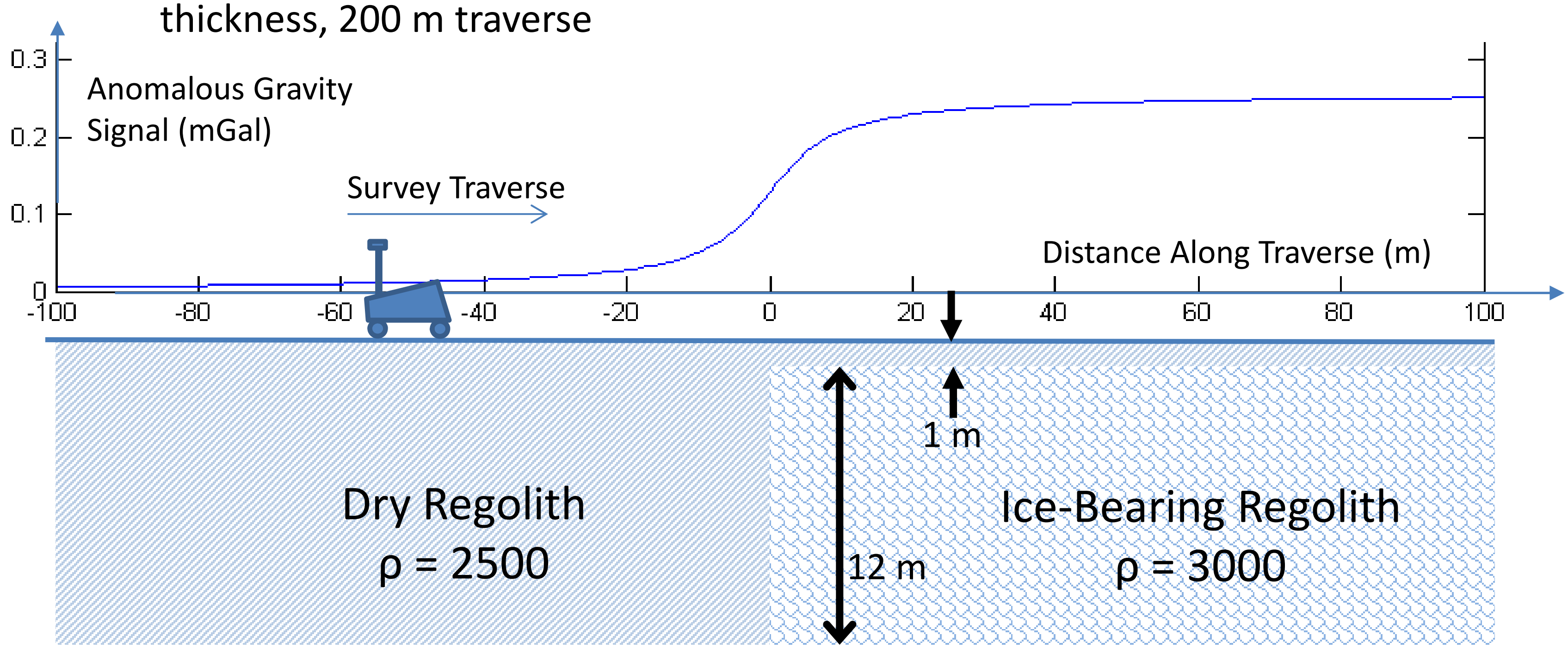
Gravimetric Detectability of Ice Slab

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



Gravimetric Detectability of Ice In Regolith

- For ***regolith with ice in voids***, *Δρ* might be as high as 500 kg/m³ (assuming 50% porosity)
  - ***Gravity high over the deposit***
  - For t = 1 m, Δg_B = +21 μGal
  - To reach Δg_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



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