Asteroid Mineral Prospecting via Surface Gravimetric Surveying

Kieran A. Carroll, Ph.D.
Gedex Inc.

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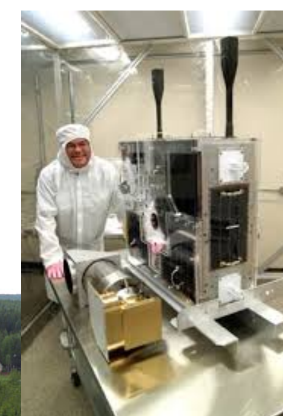
Main Points

- ***Assume that the presence of ore-bodies will be as important in asteroid-mining as it is in terrestrial mining***
- Gravimetry may be as powerful method for identifying potential ore-bodies on asteroids, as it is on Earth
- Most asteroids are small
- Traditional asteroid gravimetry techniques don't scale down well to small-size asteroids
- Surface gravimetric surveying is now an alternative, via VEGA instrument
- It does scale down to very small asteroids
- Gravimeter carried by an asteroid lander/rover vehicle supported by a "mothership"
- For small asteroids, could survey entire surface, invert to determine complete internal density distribution

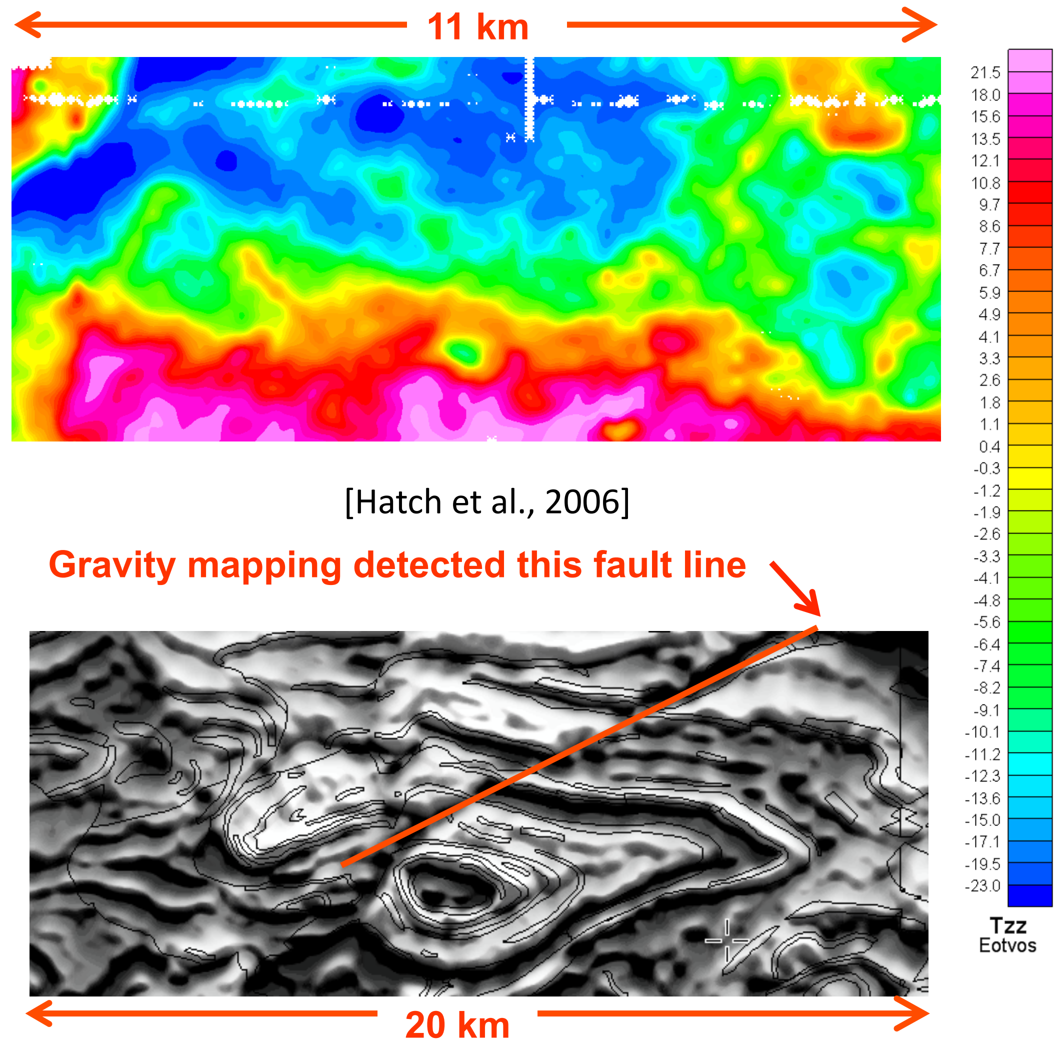
Gedex, Terrestrial and Space Geophysics

- 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
- Also developing space geophysics instruments
- Bridging between terrestrial and space exploration communities
- Working with Space Flight Laboratory at University of Toronto --- global leader in high-capability nanosats



Gravimetry for Resource Exploration on Earth

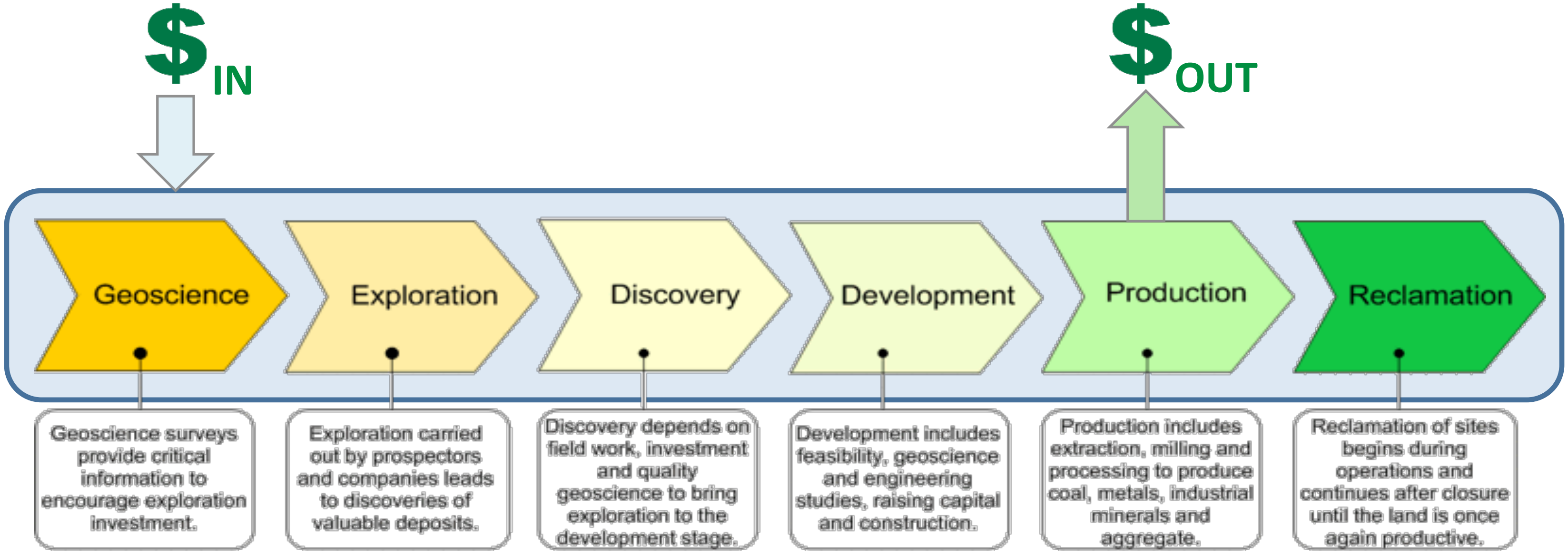
- A standard geophysical technique used in exploring for resources
- Gravimeters and gravity gradiometers ***respond to subsurface density variations***
- These reflect some of the compositional and structural variations in geological formations
- Hence some aspects of ***subsurface structure*** can be recovered from gravity maps
- Gravimetry survey data can be ***inverted*** to estimate subsurface density distribution



[Hatch et al., 2006]

Making Ore

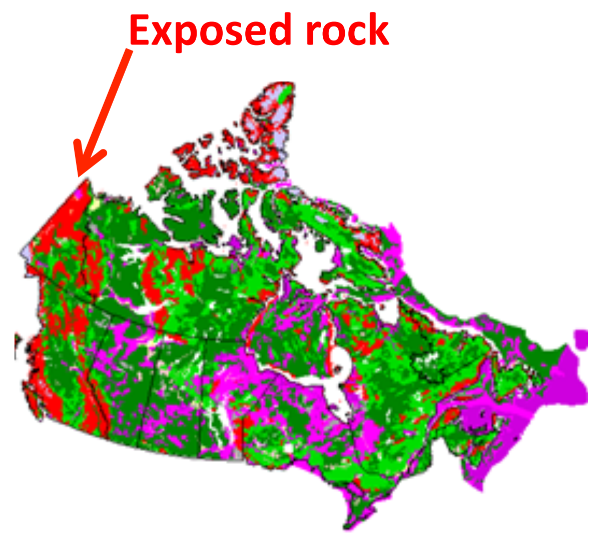
- If $\$_{OUT} > \$_{IN}$, it's ore.
- Otherwise it's dirt.
- Reducing costs at one or more stage can turn *dirt* into *ore*.
- (As can an upward fluctuation in a commodity price…)

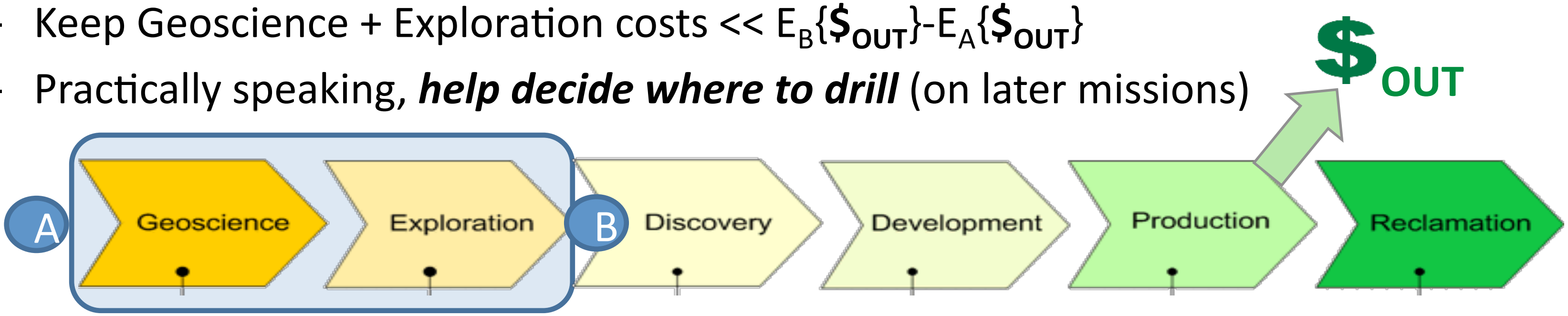


(Adapted from http://www.empr.gov.bc.ca/Mining/Pages/SixEssentialPhasesofMining.aspx)

Geophysics Value-Add

- Geophysics methods, including gravimetry, are most-used in the Geoscience and Exploration stages
- Use physics instruments (e.g., gravimeters, gravity gradiometers) to "see" beneath ***over-burden***:
  - Much of the Earth's land surface is covered by over-burden
  - E.g., more than half of Canada is covered by glacial till
  - If outcrop is not exposed, geologists must conduct expensive drilling to get to underlying rocks
- Prospectivity: $E\{\mathbf{\$}_{OUT}\}$
- Goals of geophysics exploration:
  - Increase $E_B\{\mathbf{\$}_{OUT}\}$
  - Keep Geoscience + Exploration costs << $E_B\{\mathbf{\$}_{OUT}\}-E_A\{\mathbf{\$}_{OUT}\}$
  - Practically speaking, ***help decide where to drill*** (on later missions)





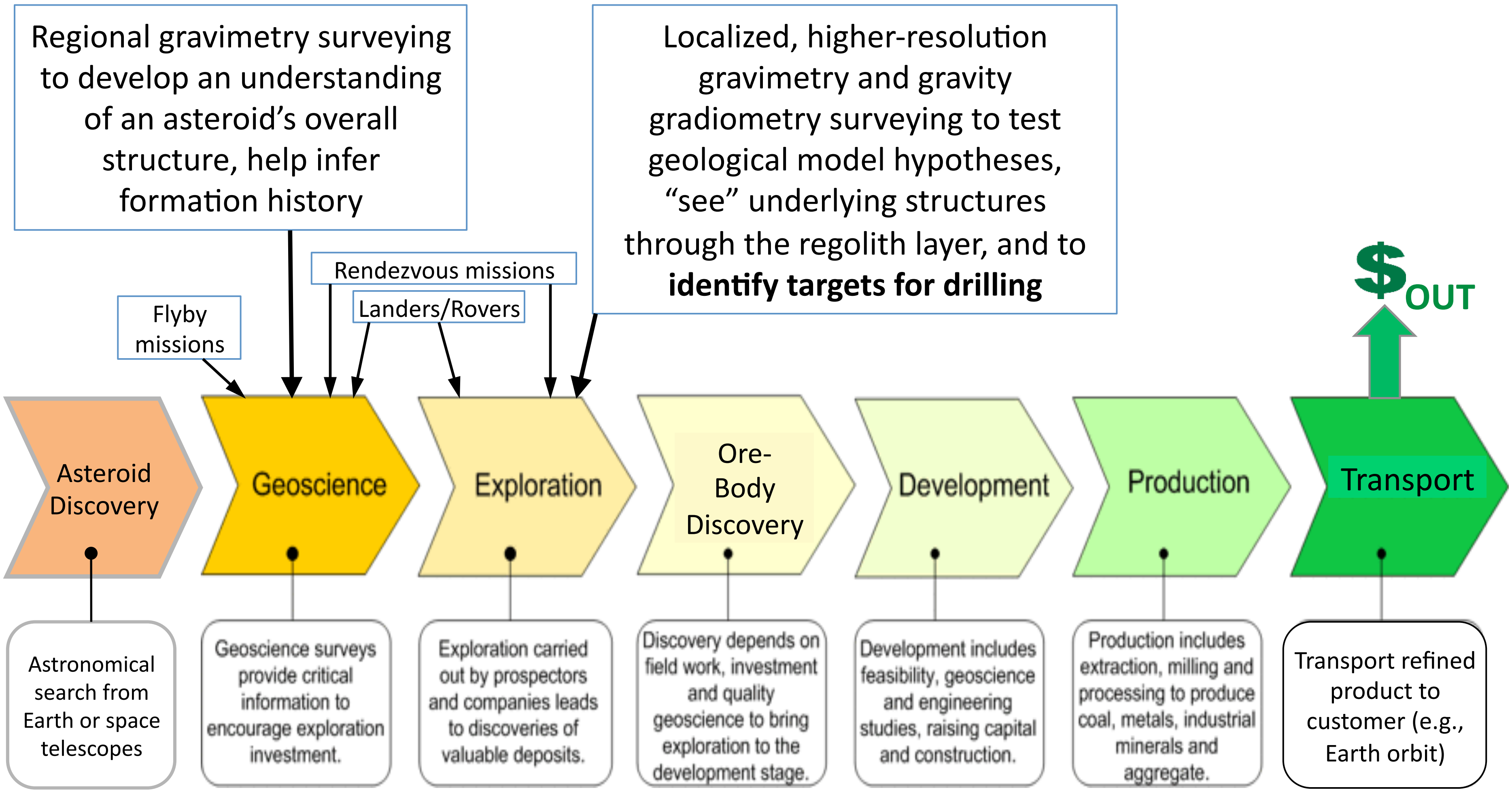
Ore-Bodies on Asteroids?

- Are asteroids typically of **homogeneous** composition?
  - If so, “there is no ore” — potentially valuable minerals too dilute
  - Or perhaps “it’s all ore” — maybe every patch of dirt on an asteroid can be profitable to mine (what are the odds of that?)
- Or are they **heterogeneous**?
  - In which case maybe *some* of the “dirt” is actually ore of some type
- Heterogeneity can produce **density contrasts** detectable by gravimetry:
  - Asteroid bulk density by type thought to be 1,400 kg/m^3 (C), 2,700 kg/m^3 (S), 5,300 kg/m^3 (M) [Krasinsky et al., Icarus 158 (1), 2002].
- Possibly-valuable minerals:
  - ***Water ice:*** density = 1,000 kg/m^3
  - ***Nickel-Iron containing PGMs:*** density as high as 8,000 kg/m^3

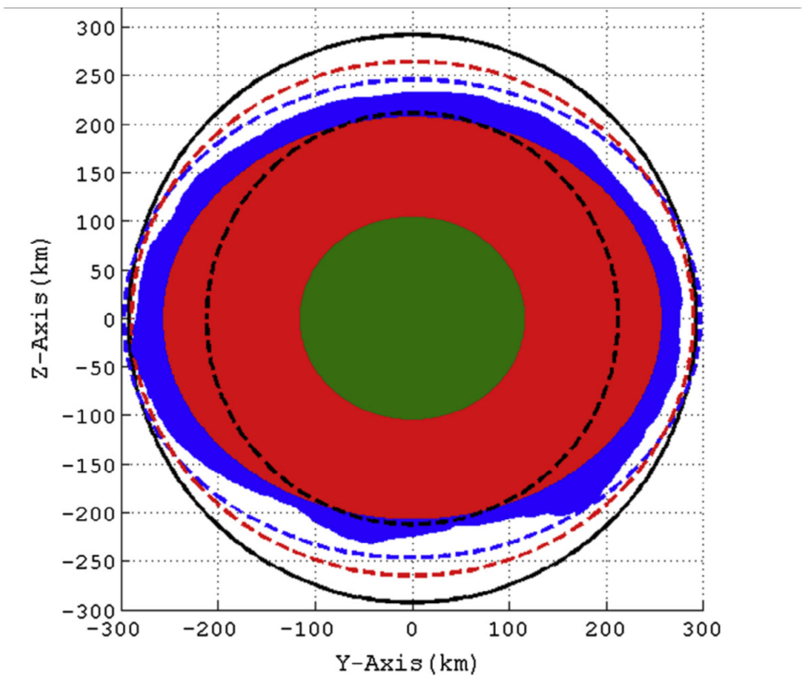
Over-Burden On Asteroids?

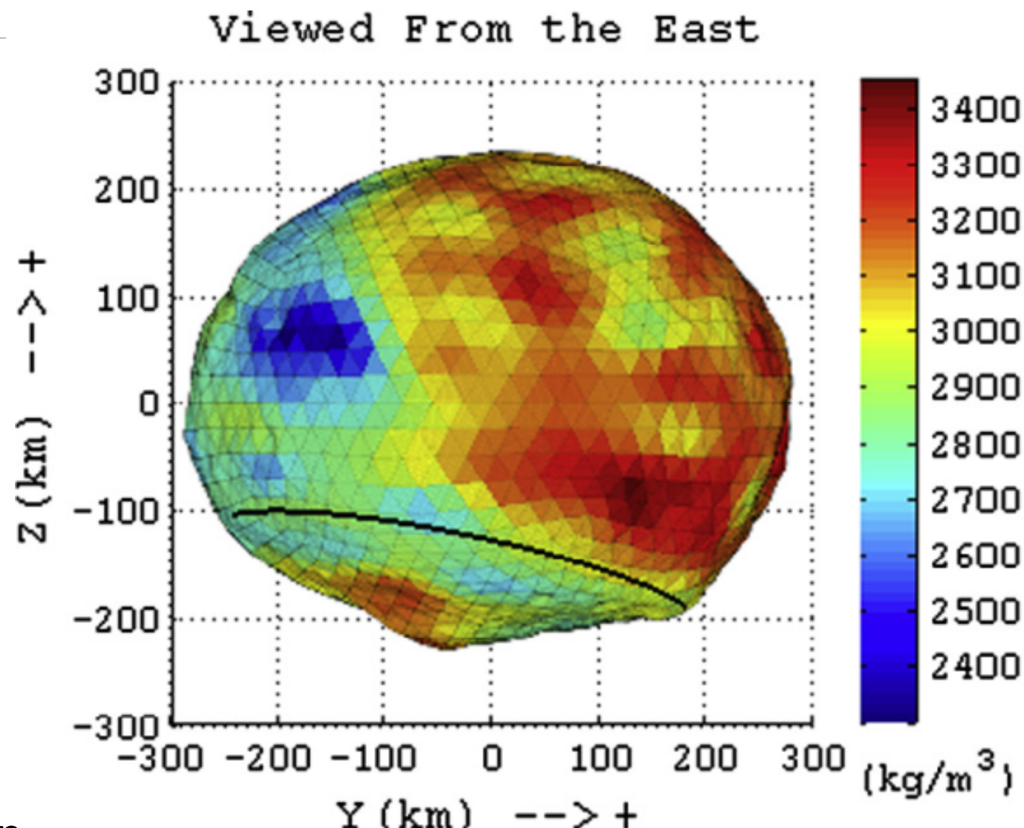
- Asteroids are thought to be largely covered by a layer of ***regolith***
  - Somewhat like that on the Moon's surface?
- Composition: fragments of the asteroid body, caused by high-speed meteoroid impacts over the course of billions of years
- Depth: unknown, perhaps on the order of metres
- Size range: boulder-sized down to microscopic particle-sized
- ***Local composition of regolith may not be representative of the composition of the underlying rock*** in any given location
  - Impacts eject debris, which travels
  - Small asteroids have very low surface gravity, so debris could travel globally
  - Local regolith likely a mix of debris from subsurface rock all over the asteroid
- Resource exploration issue:
  - Remotely-sensed imagery sees only the top surface of the regolith
  - "Mineral maps" produced by remote sensing imagery thus characterise mainly ***surface*** properties, which may not reflect composition of underlying rock
  - Mining decisions based only on this could find only a thin layer of the expected resource

Gravimetry's Role in the Asteroid Mining Process



Gravimetry Can Be Used To Infer Asteroid Internal Structures



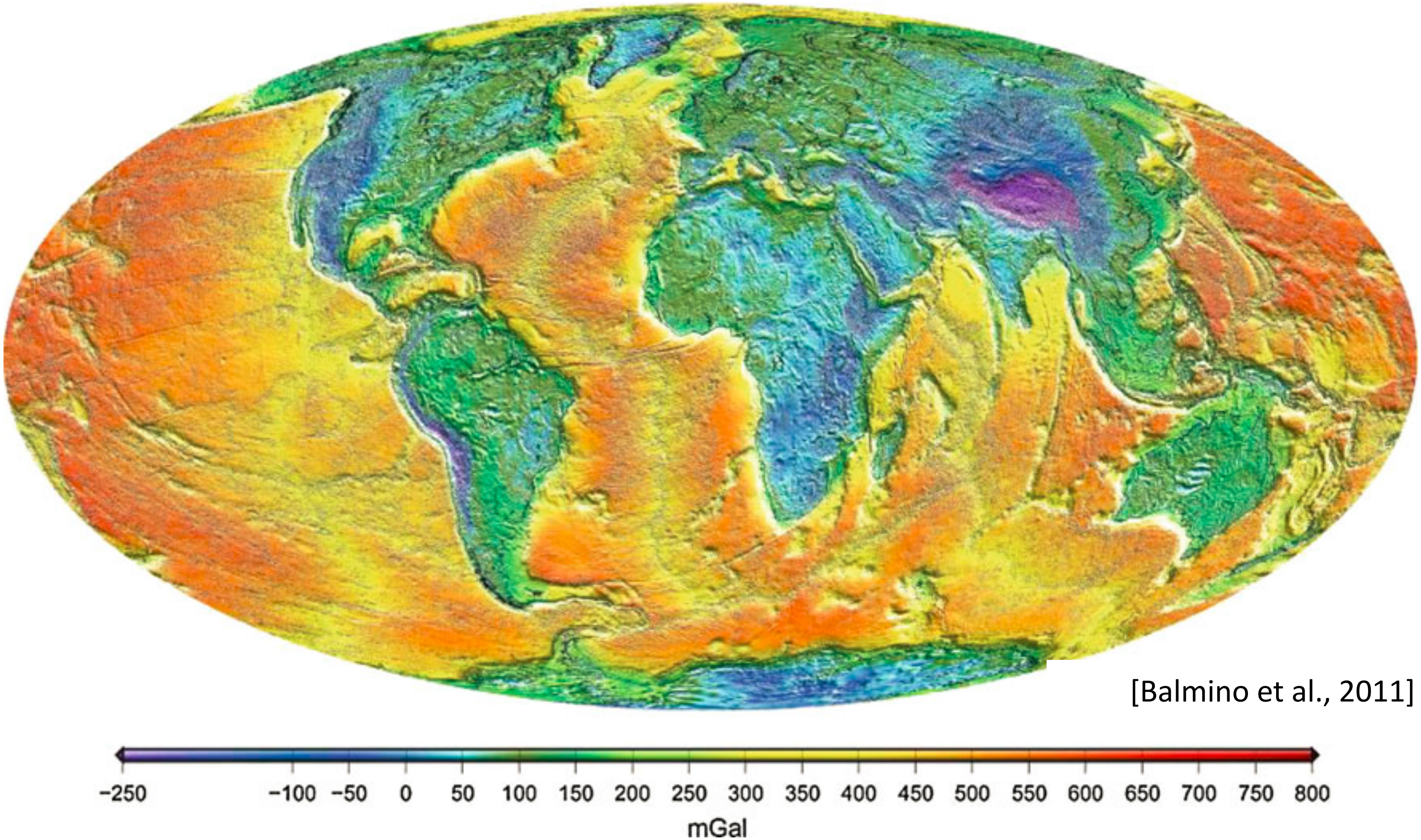


- Data from RF tracking of Dawn
- [Park et al., 2014] derived a 3-layer internal structure for Vesta, as well as lateral crustal variations via ***inversion to equivalent surface sources***

So, Can't Gravimetry Be Done From Orbit?

- ***Yes…***
  - Using radio tracking of a spacecraft, measure range and range-rate, and from these estimate the trajectory
  - Infer gravity field from trajectory perturbations
  - Used successfully for many spacecraft in Earth orbit, Lunar orbit, asteroid flybys, in orbit around asteroids, …
- ***But…***
  - Works very well (produces high resolution gravity maps) for large bodies (planets, moons, big asteroids)
  - Performance deteriorates for smaller bodies
  - Most asteroids are *very* small, and this technique barely works for these

Earth Global Bouguer Anomaly Map



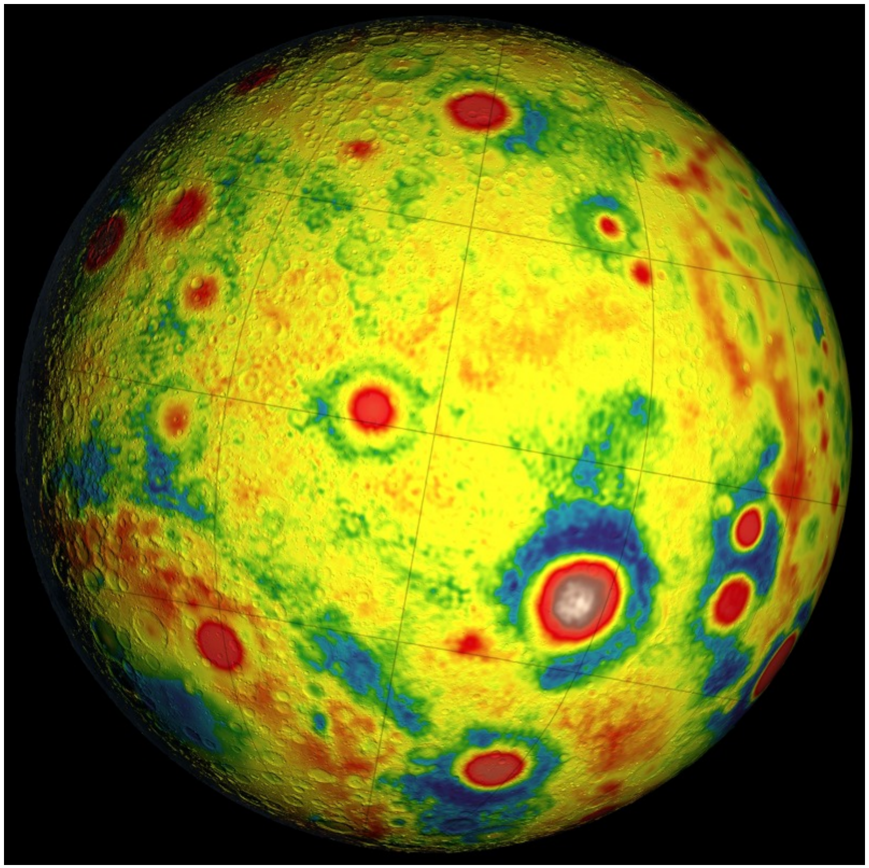
[Balmino et al., 2011]

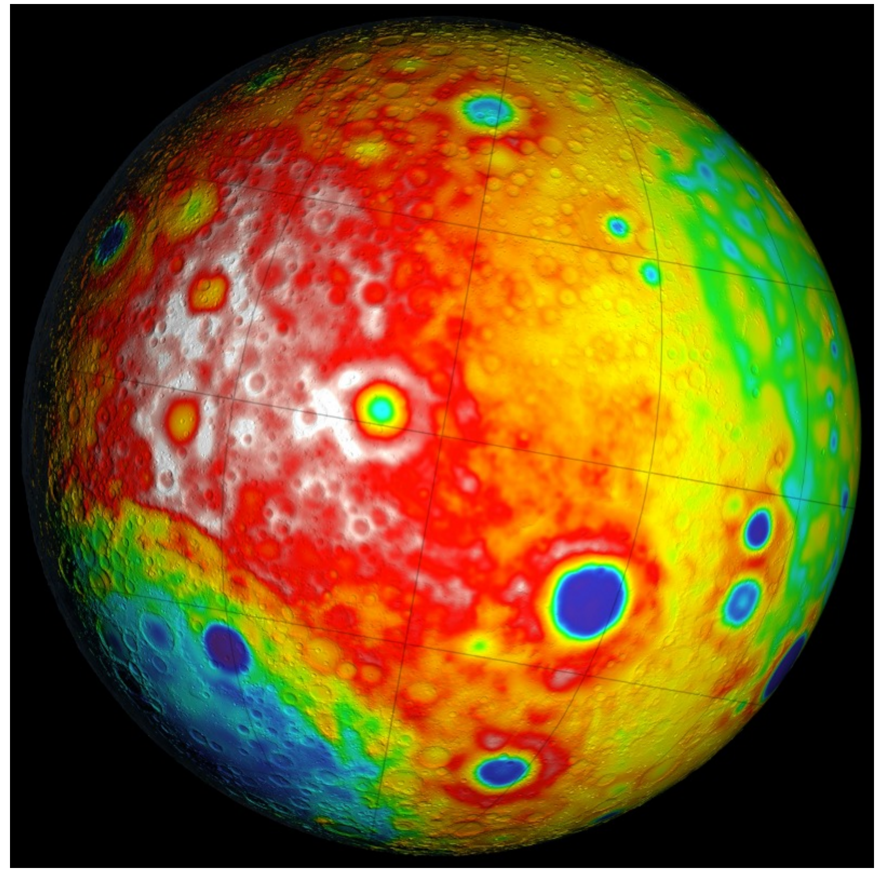
12,742 km

Bouguer Anomaly

- **The residual that's left after measuring a gravity signal, then subtracting off the effects of all known gravity sources**
- First, the effect of the overall mass of the planet (zeroth order term in gravity model), given the location of the measurement station
- Next, the effects of planetary rotation
  - Centrifugal force
- Then, the gravity due to the non-spherical shape of the planet
  - Gross effects such as Earth's ellipsoidal shape
  - Fine effects such as local topography
  - Assuming a constant density for the body
- **This residue is due to variations in density in the body**
  - Indicative of internal variations in composition, structure

Lunar Bouguer Gravity Map and Derived Crustal Thickness Map

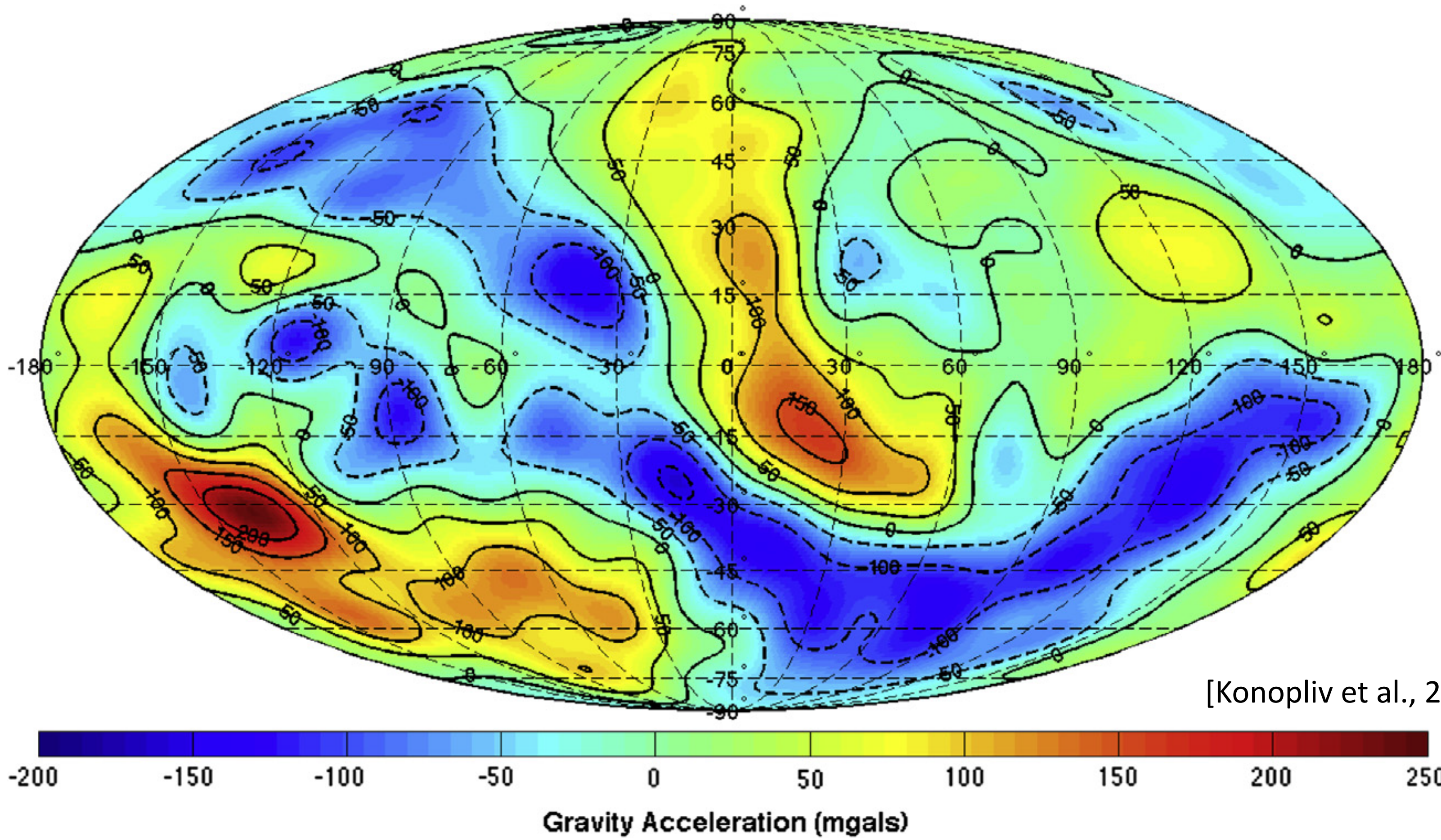




3,476 km

[From GSFC GRAIL website]

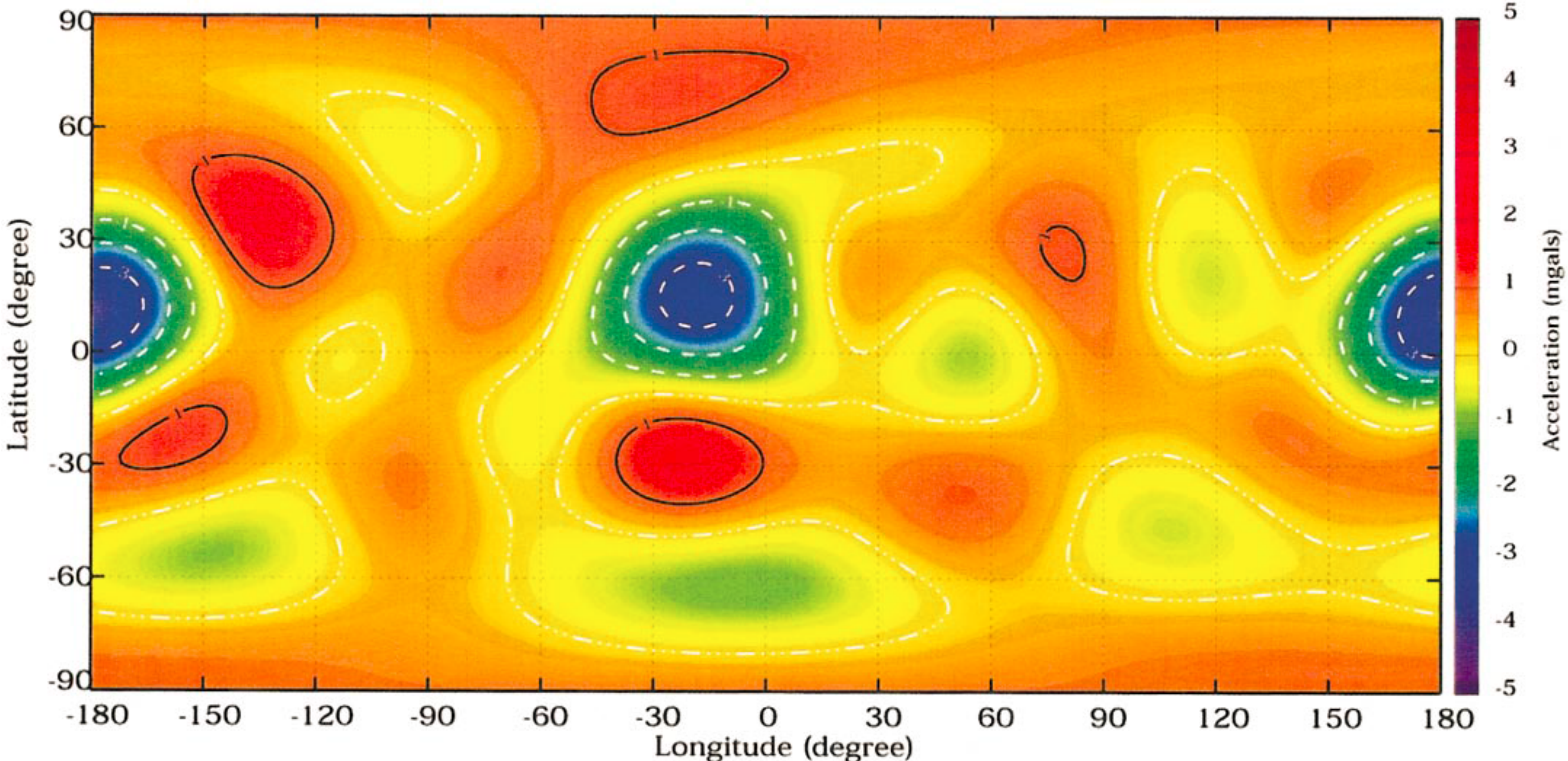
Vesta Bouguer anomaly from Dawn



[Konopliv et al., 2014]

525 km

Eros Bouguer anomaly from NEAR Shoemaker [Miller et al., 2002]

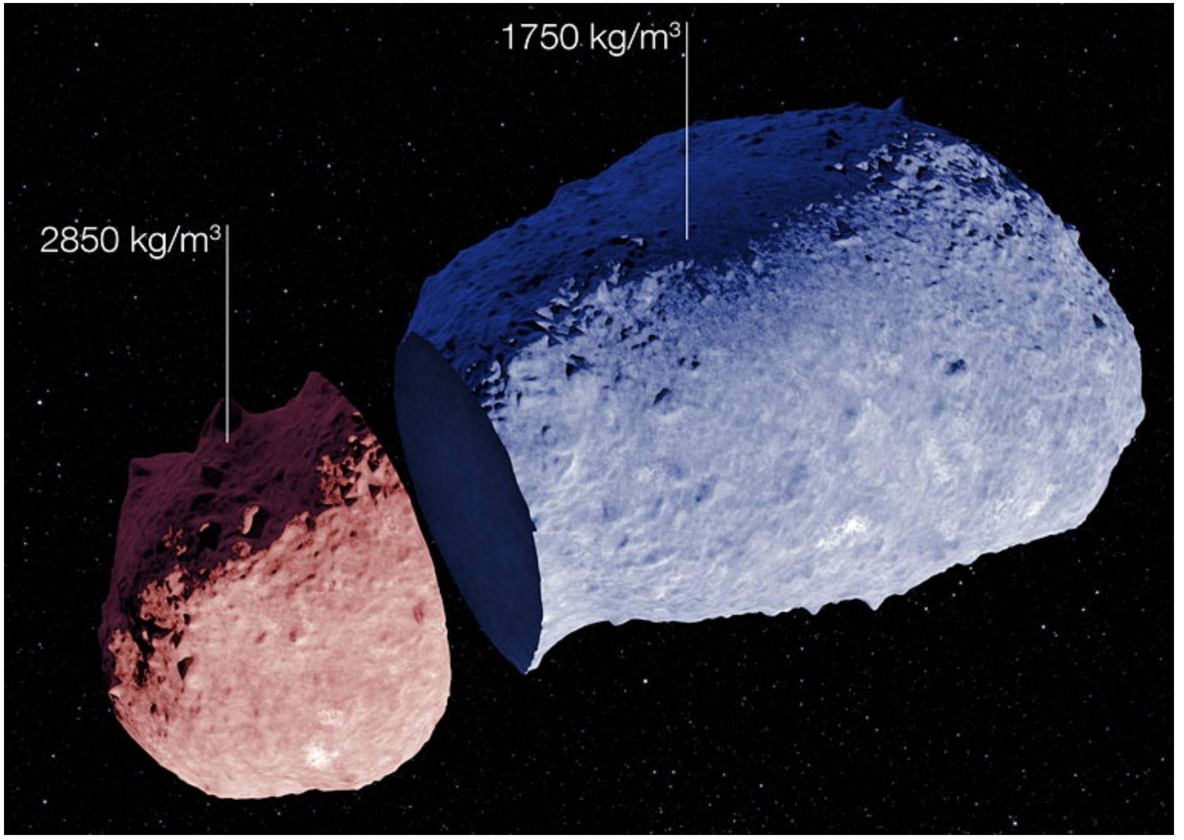


[Miller et al., 2002]

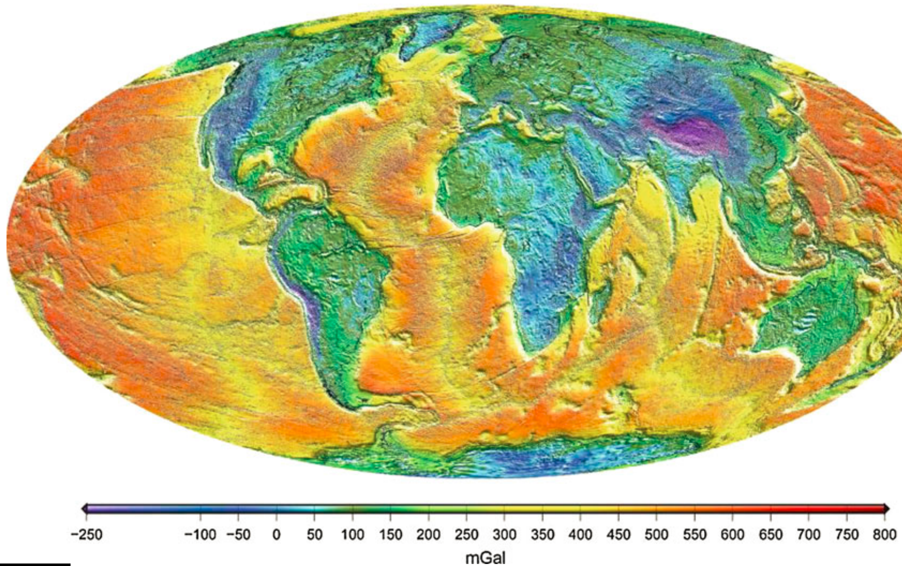
33 km (long axis)

Itokawa Quadrupole Gravity Model

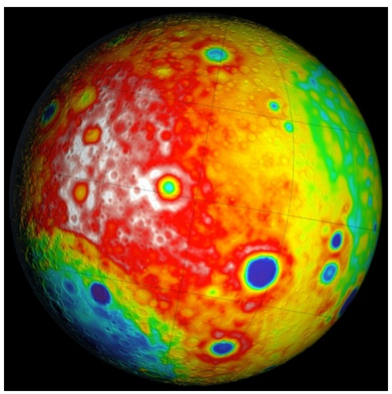
- Hayabusa was (just) able to measure Itokawa's mass
- I.e., zero-th order gravity model, no spatial distribution information
- [Lowry, 2014] inferred a mass quadrupole from light-curves measured from Earth, plus a YORP model



← 0.535 km (long axis) →



12,742 km



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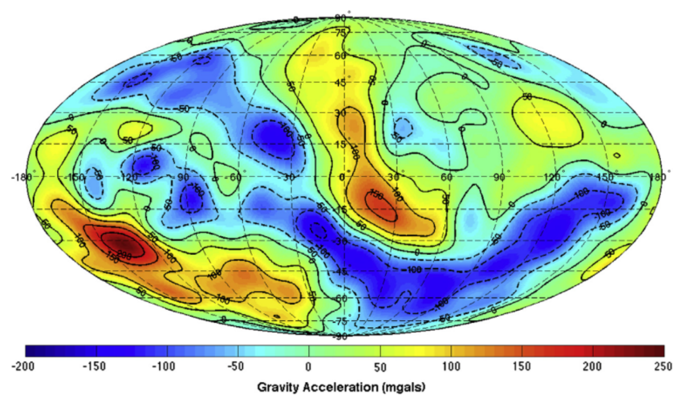
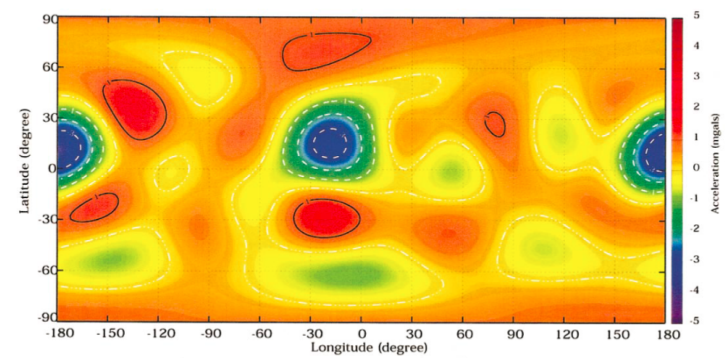
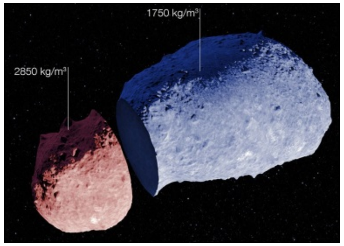


525 km



33 km

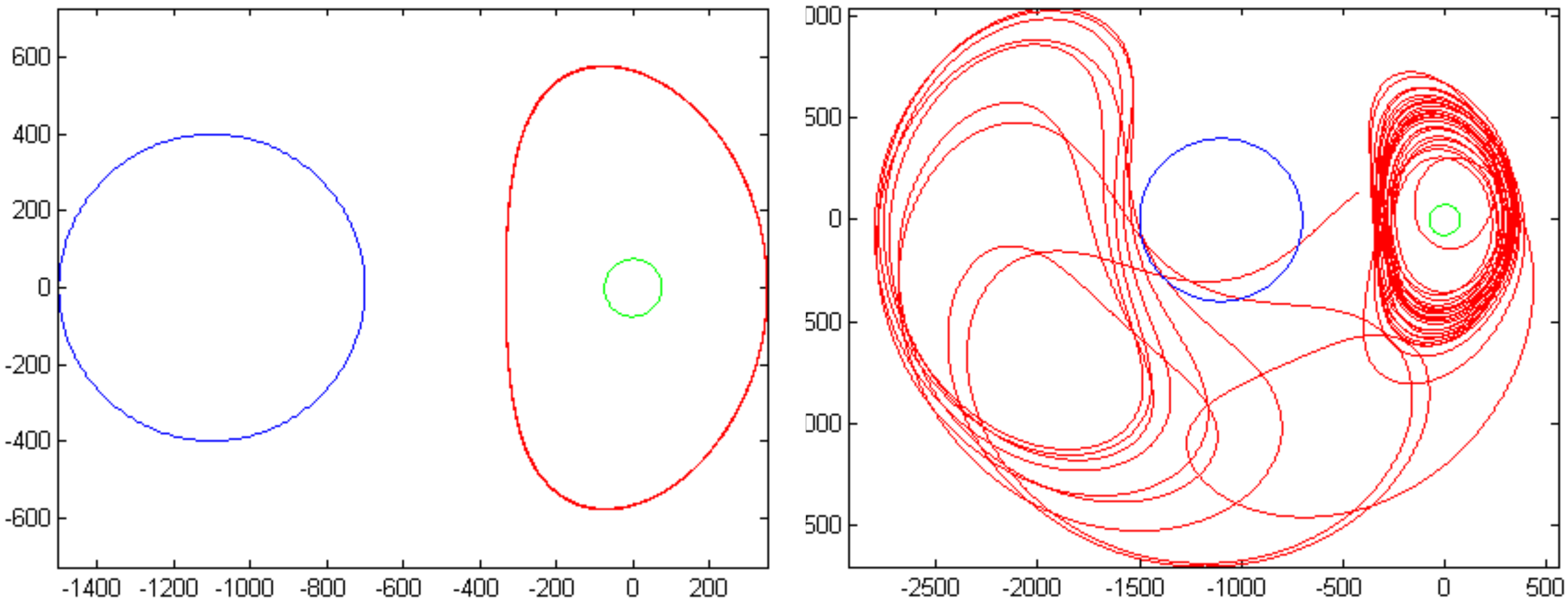
0.535 km



Gravity Model Resolution Is Worse For Smaller Bodies

- **The smaller the body, the lower the mass:**
  - Gravity signal becomes smaller
  - Signal/noise ratio gets worse
  - As S/N drops, higher-order terms of the gravity signal drop below the noise floor
  - Loss of *relative* spatial resolution
  - Even though *absolute* spatial resolution is actually higher!
- **Irregular shape effect:**
  - Gravity signal drops with $1/r^2$
  - The closer you can get to the surface, the stronger the signal
  - When orbiting an irregular body, can only get as close as r_{MAX}
  - The spacecraft never gets very close to much of the surface
  - Thus S/N drops for the signal over much of the surface
- **Errors From Other Sources:**
  - E.g., force due to ***solar radiation pressure*** acts on orbiting spacecraft
  - Magnitude of this is not perfectly known
  - Thus an error remains when this error is estimated and subtracted off in post-processing
  - This error becomes relatively larger for smaller asteroids

Example of the Perturbing Effect of Solar Radiation Pressure: Orbiting Didymos-B

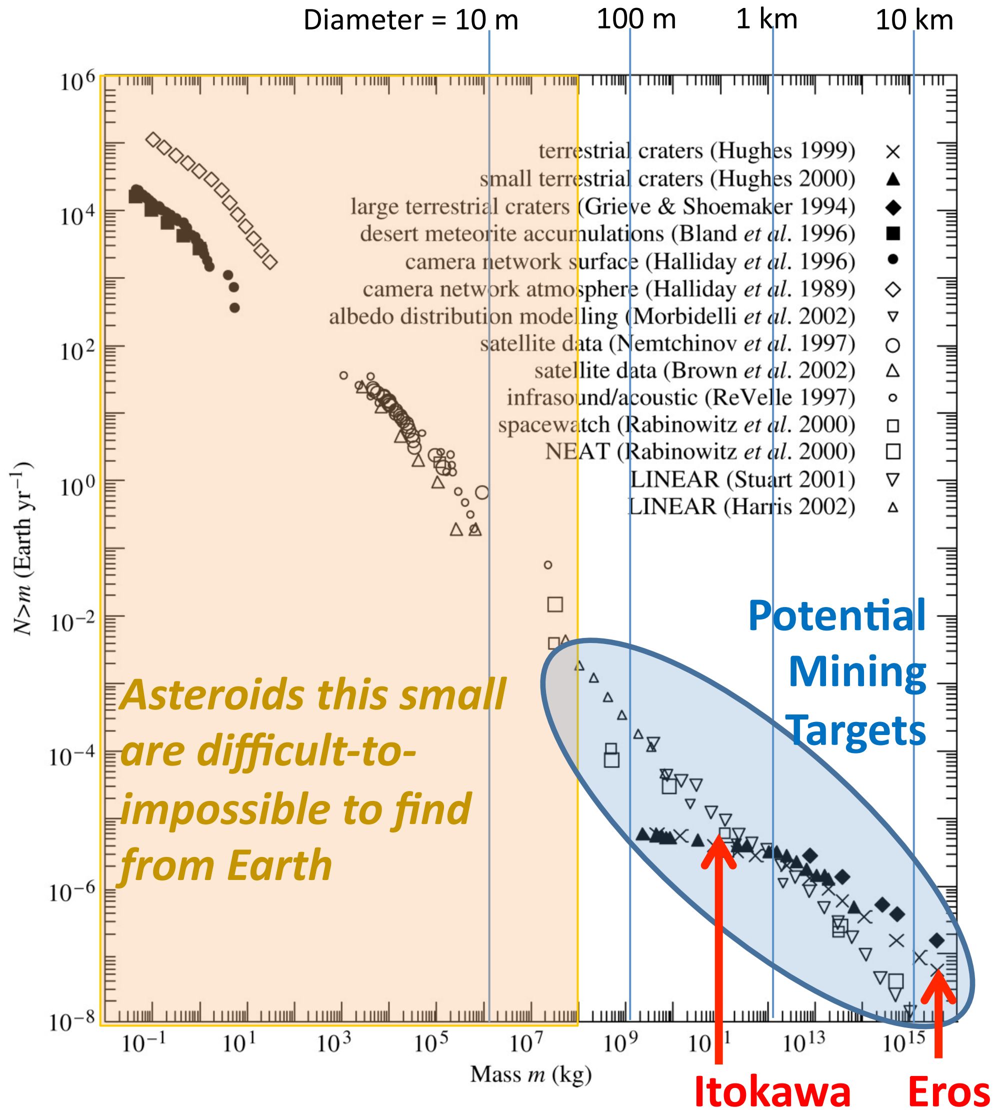


- Both plots show the trajectory (red) of a spacecraft orbiting a small (180 m diameter) asteroid — Didymos-B (“Didymoon”), in green
- That asteroid in turn is orbiting a larger (800 m diameter) asteroid — Didymos-A (“Didymain”), in blue — in a circular orbit with a 12 hour period

- Plotted in synodic (rotating) reference frame
- Left: Spacecraft trajectory ***without*** solar radiation pressure
- Right: Spacecraft trajectory ***with*** solar radiation pressure acting on spacecraft (1 AU from the Sun)

Most Potentially-Mineable Asteroids are Small

- ***There are perhaps 100x as many asteroids in 100 m – 1 km size range as there are > 1 km in diameter***
- ***Much more frequent and accessible exploration mission opportunities in this size range***
- This dataset is from [Philip A Bland, Phil. Trans. R. Soc. A 2005;363:2793-2810]
- Plots measured/estimated impact rate per year with Earth versus asteroid size
- Indicative of Near-Earth Asteroid size distribution, hence of NEA potential mining target distribution



How To Overcome This Problem For Small Asteroids

- Make gravity measurements ***on the surface*** of an asteroid
  - As close to the sources of the gravity signal as possible
  - Hence signal is as large as possible
- Similarly to ground gravity surveys on Earth
  - Make a large number of measurements, more or les evenly distributed
  - On smaller asteroids, it could be feasible to conduct a ***global*** ground gravity survey!
  - Individual measurements can have long duration, improving S/N
- ***Requires a suitable gravimeter***
  - Able to perform in an asteroid's surface gravity field: typically 1-100 microG
  - Accuracy requirement better than 10 nanoG (10 microGal)

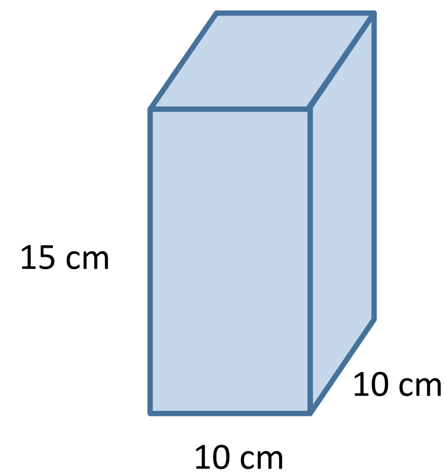
Existing Terrestrial Gravimeters

- Best field gravimeters have ***repeatability*** within ~ 5-10 microGal over the course of a day
  - Very poor absolute accuracy, though
  - Rely on loop-closing to control for day-to-day bias drift
- ***Not suitable for the asteroid gravimetry application:***
  - Can only function within +/- a few % of 1 G
  - Signal saturates outside that range
  - Massive: 8 kg (incl. batteries)
  - Large: 30x20x20 cm

[Scintrex]

VEGA Instrument (Vector Gravimeter for Asteroids)

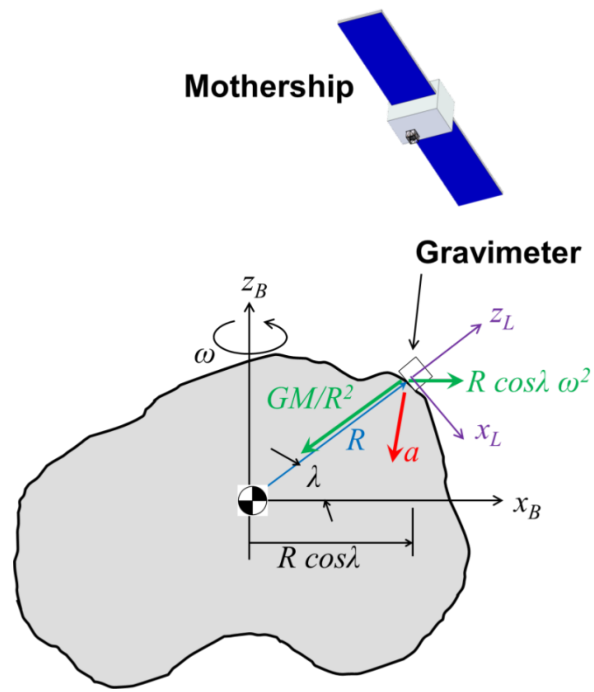
- Developed by Gedex
  - Innovative (patented) design
  - Spun off from airborne gravity gradiometer system technology
- Measures complete gravity vector
  - Allows arbitrary lander orientation
- 1-10 microGal (1-10 nanoG) ***absolute accuracy***
- Size: 1.5U
- Mass < 1.5 kg
- **Status:**
  - Canadian Space Agency is co-funding development
  - Preliminary design done, breadboard testing and detailed design underway
  - Test flight in LEO planned in 2016
  - Seeking asteroid lander/rover missions to fly on!



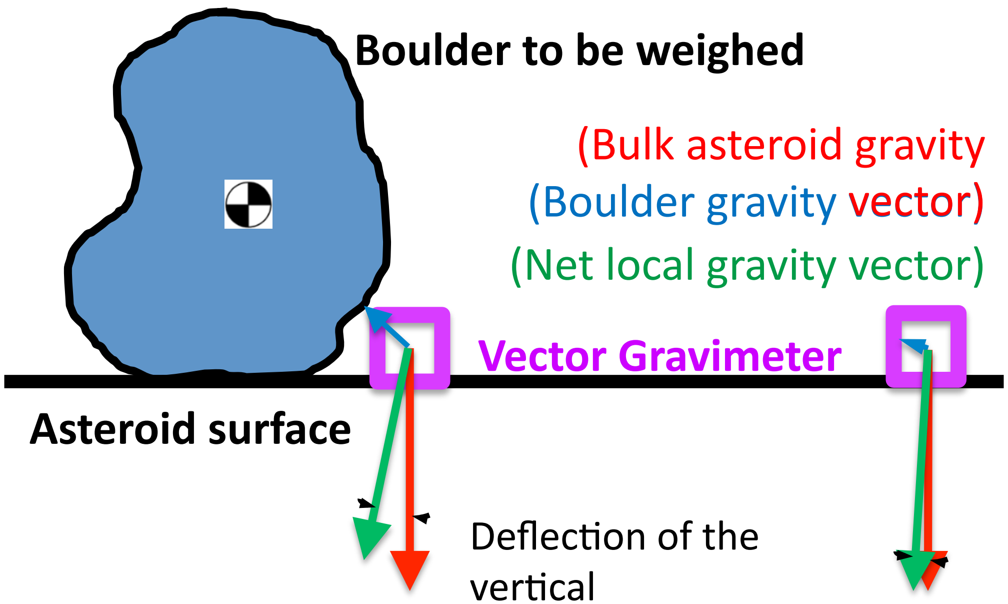
Prospecting Specifics

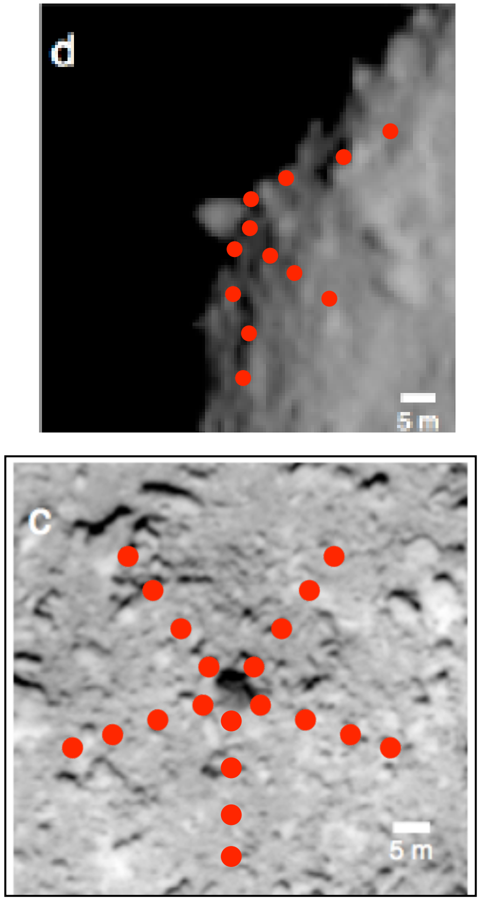
E.g., “Weighing” An Asteroid Gravimetrically Using VEGA

- Mothership arrives at asteroid.
- Mothership takes imagery to determine asteroid size, shape, spin rate and direction, tumbling state.
- Lander carrying VEGA is released, makes its way to some point on the surface.
- Make gravimetric measurement.
- Imagery from Mothership used to determine location of that station in asteroid-fixed reference frame.
- In post-processing, compensate out centrifugal component of measurement (plus components due to asteroid wobble, if significant).
- Fit compensated measurement to asteroid shape model to estimate average density.



E.g., "Weighing" a Boulder on an Asteroid



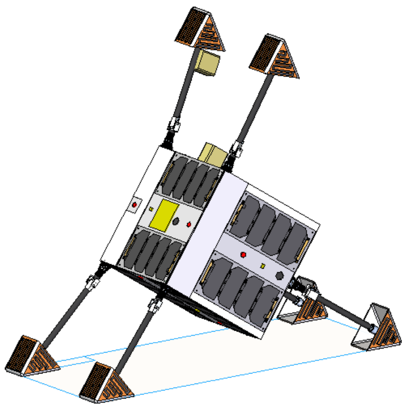


[Hirata & Ishiguro, 2011]

- Make measurements at multiple stations
- Requires a lander capable of roving about the asteroid's surface in a controlled manner

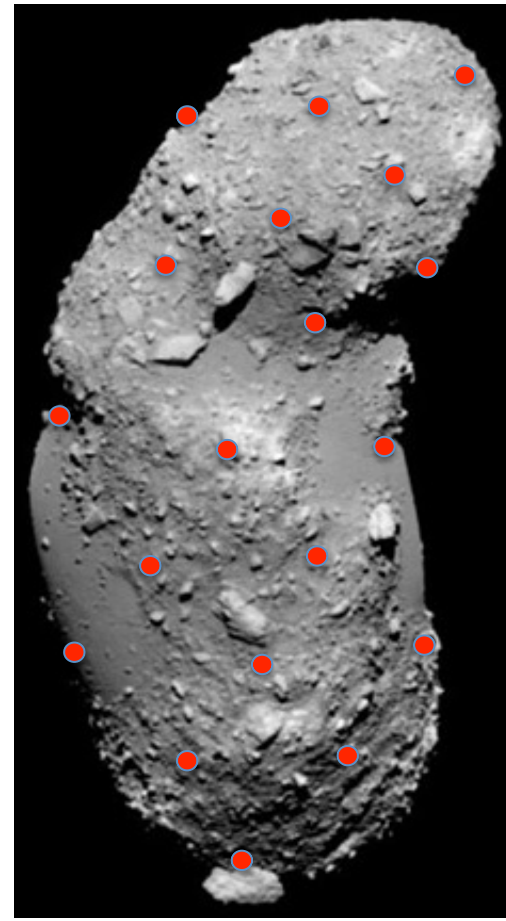
E.g., GRASP Asteroid Lander/Rover

- “GRavitational Asteroid Surface Probe”
- Initial preliminary design done by SFL & Gedex (2013/14)
- Objective: scope out a minimal-cost surface scout for geophysical prospecting of small asteroids
- Build on SFL’s experience in low-cost, high-capability LEO nanosats, and Gedex’s geophysics instrumentation experience
- Payloads: VEGA gravimeter, magnetometers, cameras
- 15 kg spacecraft, 30” cube, full 3-axis ACS
- Propulsion system: 13 m/s, for landing, hopping
- Mobility on asteroid surface: propulsively & by tumbling
- “Mothership” provides support:
  - Transport to the target asteroid
  - Comms relay to Earth
  - Navigation support during landing, localization post-landing



Whole-Asteroid Gravimetry Survey

- Assuming a roving lander is used to carry VEGA instrument
- For a small asteroid, could conceivably survey at stations distributed over the entire body
- Use the resulting measurements to estimate a whole-body internal density distribution
- With enough measurement stations, can produce much higher-resolution gravity model than from orbit



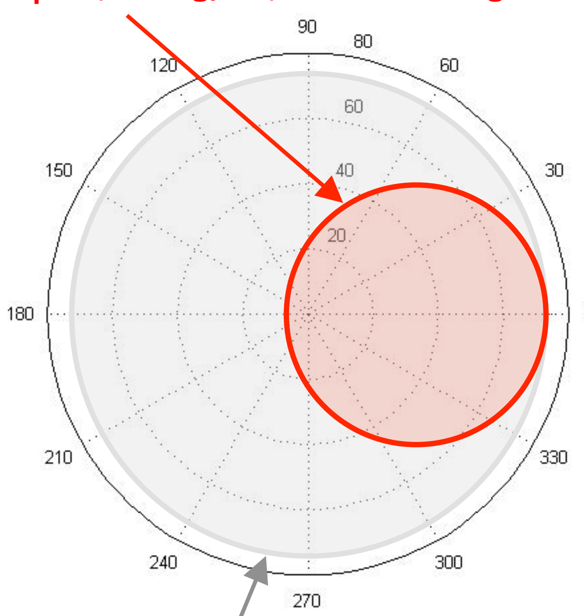
[Saito et al., 2006]

E.g., Anomalous Gravity Signal at Surface of Didymos-B [nG]

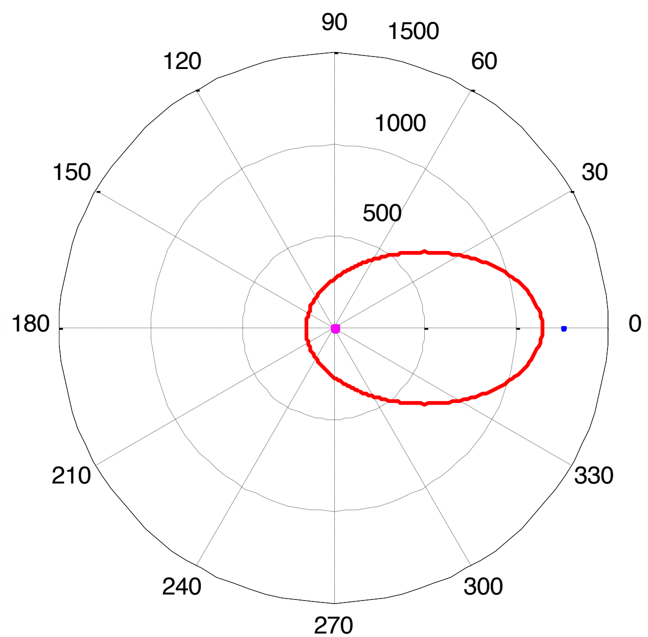
E.g., from a large (15% of total Didymos-B volume) medium-density anomaly just below the surface

VEGA accuracy: 1-10 [ng]

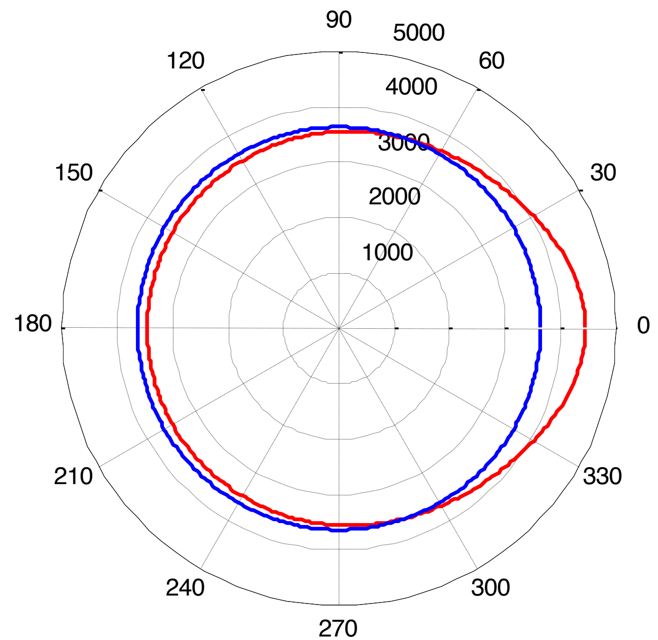
Density anomaly, radius = depth to centre = 40 m, $\Delta\rho$= 1,000 kg/m^3, m=2.7x10^8 kg



Didymos-B, r=75 m, Average ρ= 1,700 kg/m^3, m=3x10^9 kg, f_g=3635 ng, assumed spherical

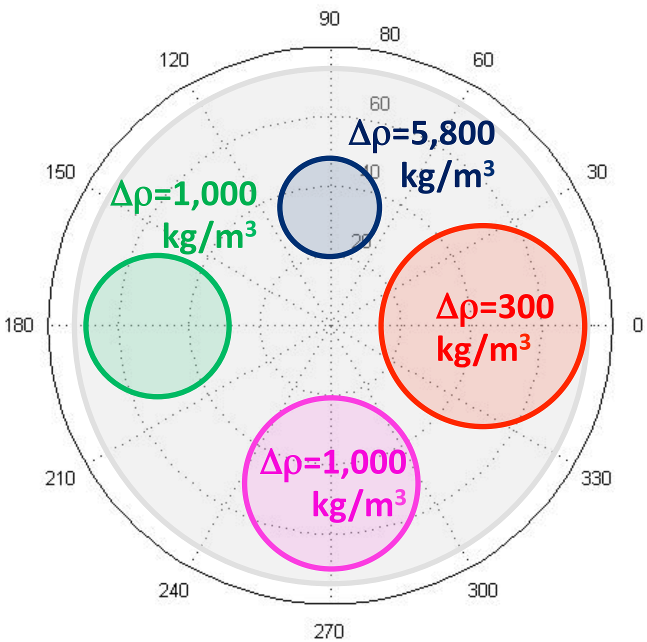


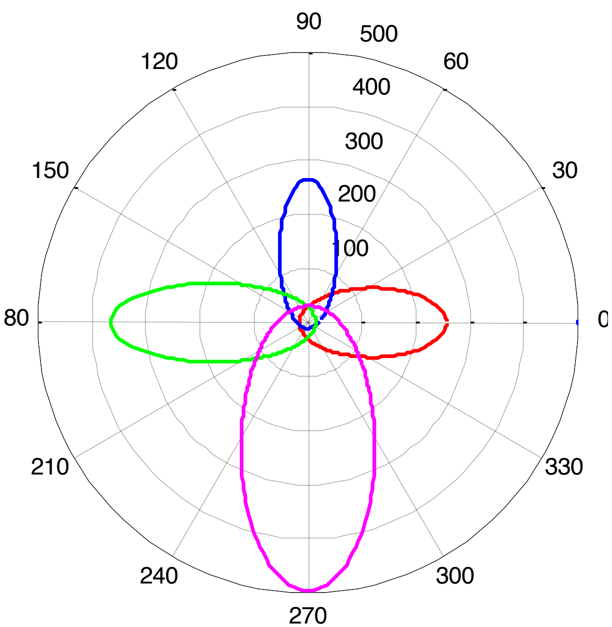
Gravity signature of the anomaly at the surface versus longitude



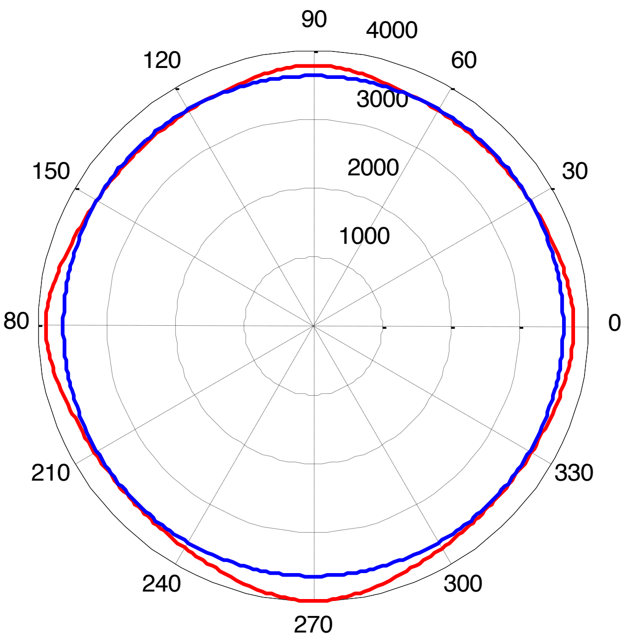
Nominal Didymos-B Surface Gravity
Surface Gravity Including Anomaly

Several Sample Anomalous Masses and the Resulting Anomalous and Total Gravity Signal [ng]



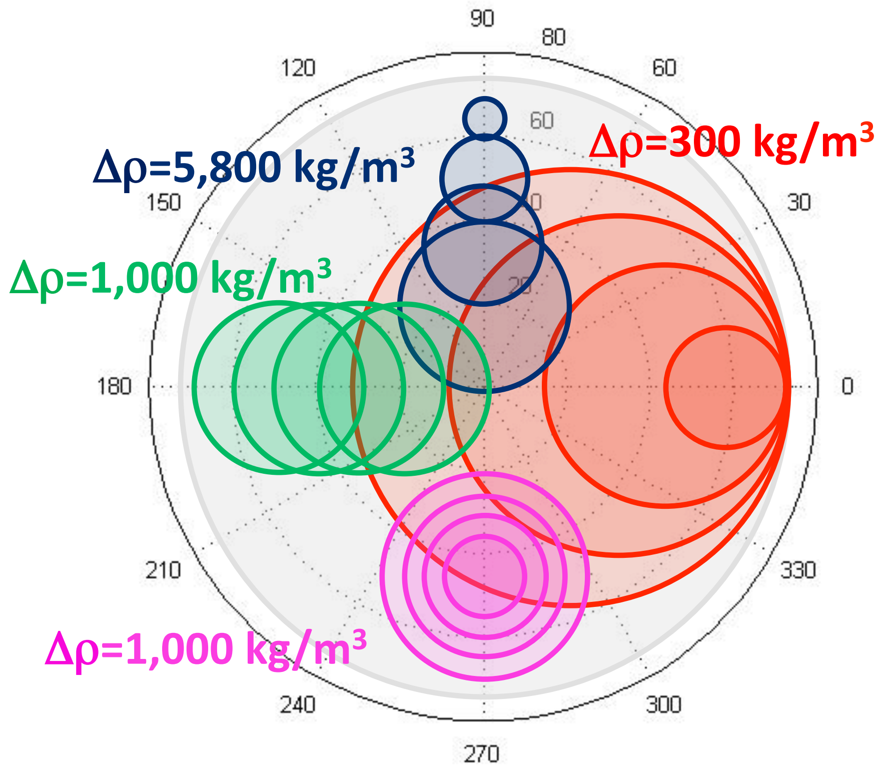


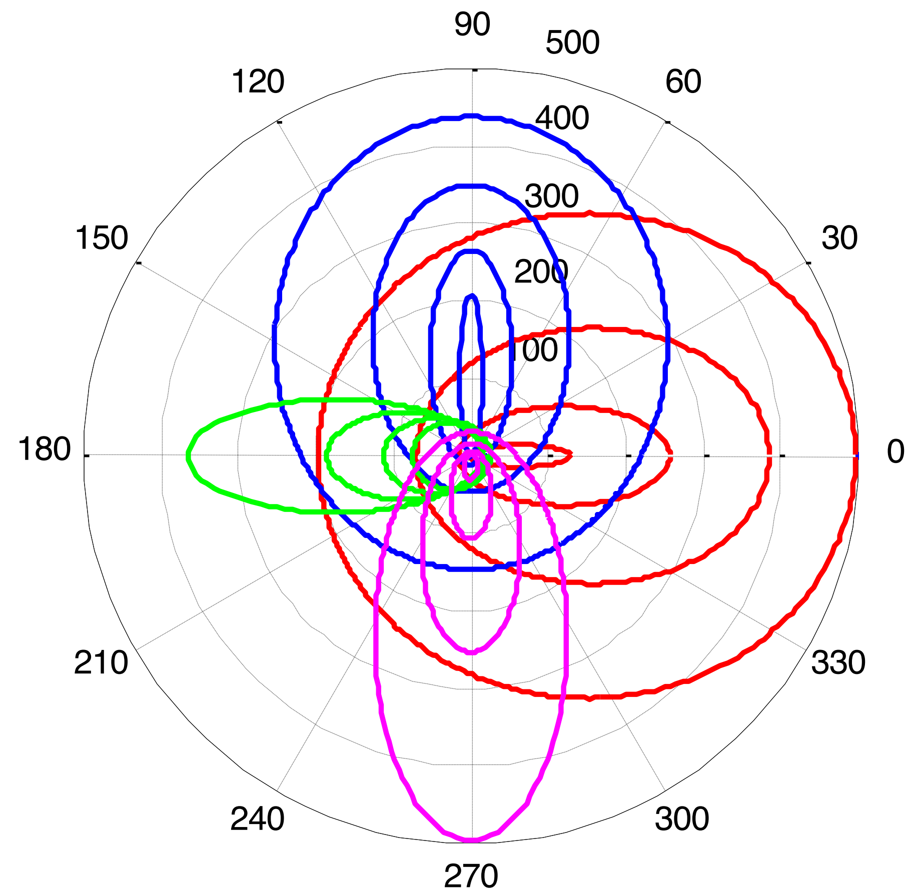
Gravity signatures of the anomalies at the surface versus longitude



Nominal Didymos-B Surface Gravity
Surface Gravity Including Anomaly

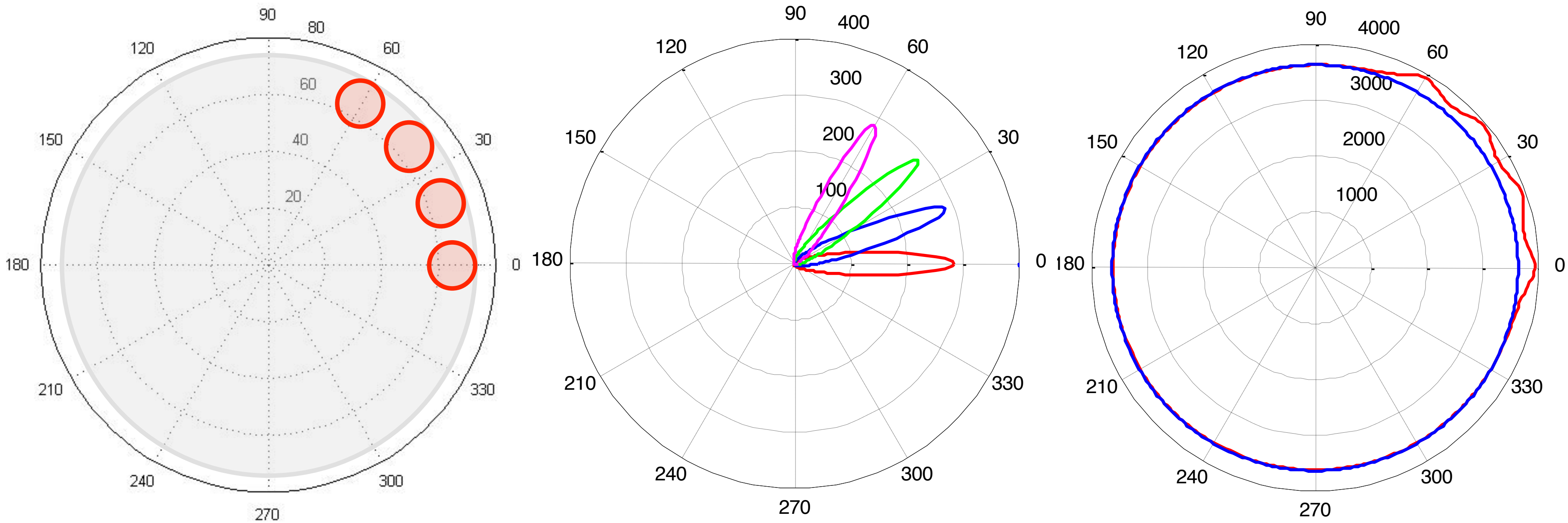
Various Volumes, Depths and Density Contrasts of Mass Anomalies Planted Within Didymos-B





Anomalous gravity signal at the surface vs. longitude for each source [ng]

High-Order Gravity Field Resolution Achievable by Surface Gravimetric Surveying



Plantation of 4 targets in the near-subsurface at 0°, 20°, 40°, 60°
$\Delta\rho$=1,000 kg/m^3, radius = 10 m, depth to centres = 10 m

In Conclusion

- Asteroid surface gravimetry is a new method for exploration of interior of asteroids
- Potentially capable of discovering ore-bodies within an asteroid, based on density variations.
- Just now becoming feasible:
  - Due to recent instrumentation advances
  - Also due to the advent of asteroid lander/rover mission capabilities

Backup Slides

Auxiliary Measurements Needed to Compensate Gravimetry Measurements

- Asteroid's size, shape
- Asteroid's rotation state: spin speed, pole orientation, tumbling characteristics (if any)
- Location of measurement stations on the asteroid
- Orientation of lander when taking each gravimetry measurement

Cf. the Schiehallion Experiment

- Mountain in Scotland
- 1774 experiment by Maskelyne
- Measured ratio of densities of Schiehallion and Earth
- In effect, first determination of G
- Via measuring deflection of plumb-bod vertical versus astronomical vertical
- Ever since then, a standard geodetic technique