Air and Space this Week

Item of the Week

THE GRAIL MISSION

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Early explorations of the Moon from Space showed that the lunar gravity field is unusually "lumpy." Areas of slightly higher gravity were correctly assumed to be due to "mascons," mass concentrations within the interior of the Moon. One manifestation of mascons is the instability of orbiting the Moon; orbits decay more rapidly than they would if the Moon's mass was more uniformly distributed. But merely detecting lunar mascons could not reveal their geological causes in detail. If the gravity field of the Moon could be more precisely determined, it would reveal details as to the Moon's internal structure.

NASA planned and conducted the Gravity Recovery and Interior Laboratory *(*GRAIL*) mission to make those detailed measurements. Twin spacecraft were required, along with very precise tracking of both and imaginative trajectory design work. A similar mission, the* Gravity Recovery and Climate Experiment *(*GRACE*) had been flown in Earth orbit, and produced valuable data on the Earth's interior.* GRACE*'s success was the inspiration for GRAIL.*

GRAIL *was launched on September 13, 2011, thirteen years ago this Tuesday!*

GRAVITY AS A TOOL FOR GEOLOGISTS

The following are some pertinent quotes from "Applied Geophysics" published in 1977 by W.M Telford and others, a standard graduate-level textbook for exploration geologists:

"Since the great majority of mineral deposits are beneath the surface, their detection depends upon those characteristics which differentiate them from the surrounding media."

"Several of the devices now used by geophysicists were developed from methods used for locating guns, submarines, and aircraft during the two World Wars."

"Applied geophysics in the search for minerals, oil, and gas, may be divided into the following general methods of exploration: ***gravitational***, magnetic, electrical, elector-magnetic, seismic, radioactivity, well-logging, and other miscellaneous methods."

"Gravity prospecting involves the measurements of variations in the gravitational field of the Earth."

"Gravity prospecting is used as a reconnaissance tool in oil exploration; although expensive, it is still considerably cheaper than the seismic method."

The quotes are still true today. Exploration geologists used their less-expensive tools to find promising locations to examine in more detail with more-expensive tools before committing to test wells and other even-more expensive prospecting techniques.

The same tools and strategy are used by planetary scientists to determine internal structure/composition of planets and moons in the Solar System. They aren't looking for oil or mineral deposits, but they are looking to acquire data about the interiors of those bodies.

And gravity, first-listed by Telford et al., is one of them.

GRACE

The value of observing the details of Earth's magnetic field from Low Earth Orbit was determined before anyone had the technology to reach LEO! John O'Keefe of NASA's Goddard Space Flight Center realized that detailed tracking of the position and movement of an Earth satellite could provide accurate estimates of the Earth's gravity field and its variation. His idea was confirmed only a few years later, with tracking data from the *Vanguard 1* satellite in 1959.

One of the precursor set of missions that supported the Apollo Program was the Lunar Orbiter series in the mid-1960s. Five satellites were placed sequentially into lunar orbit to provide detailed reconnaissance of potential landing sites and other supporting data needed to land on the Moon safely. NASA found that the Moon's gravity field had a lot more variations than Earth's, a situation that makes lunar orbits less stable over time than Earth orbits. Areas of higher gravity tended to occur over lunar maria, because the basalt covering those surfaces is a bit denser than the rocks of the lunar highlands. Tracking in those days could detect such anomalous concentrations of mass (aka "mascons"), but the data were not detailed enough to provide much in the way of subsurface details.

A new gravity-measuring technique using detailed tracking of two co-orbiting satellites was proposed in 1969, and the necessary math and other details were worked out by the mid-1980s. NASA partnered with their German counterpart (DLR) to develop, launch, and operate the *Gravity Recovery and Climate Experiment* (*GRACE*) satellite, which became the second satellite in NASA's Earth System Science Pathfinder Program, selected in in 1997 and launched in 2002. *GRACE* was designed for a five-year mission, but it operated successfully until 2017.

Gravitational observation/prospecting techniques have to make accurate measurements of slight variations in a larger gravitational field. The GRACE program managed to do that by using two satellites, in the same 450-km high near-polar orbit, but ~220 km apart. Their positions could be determined by tracking from the ground, and each satellite ("GRACE-1" and "GRACE-2" – but more whimsically nick-named "Tom" and "Jerry") had its own GPS system, laser ranging system (to accurately determine the distance between the two), star cameras (to determine the satellite's attitude), and accelerometers (to measure non-gravitational forces whose effect on the satellite had to be accurately subtracted).

"During their mission, the twin GRACE satellites have provided unprecedented insights into how our planet is changing by tracking the continuous movement of liquid water, ice and the solid Earth." [source]

The initial GRACE mission was so successful that a second set of satellites was launched in 2018, collectively called GRACE-FO (FO for "Follow On"). They are even more capable than the initial pair, and their data has yielded "… insights into how Earth's water, ice, and land masses are shifting by measuring monthly changes in the planet's gravity field. Tracking large-scale mass changes – showing when and where water moves within and between the atmosphere, oceans, underground aquifers, and ice sheets – provides a view into Earth's water cycle, including changes in response to drivers like climate change." (source)

The success of the initial GRACE pair and ongoing success of the GRACE-FO, and the need for a continuous, long-duration, gravity record has led NASA and the DLR to design and build a third pair of satellites for launch no later than 2028, to be called the "GRACE-C" mission ("C" for "Continuity").

GRAIL

The concept behind the GRACE satellites worked very well in helping terrestrial scientists understand "how water, ice and solid Earth mass move on or near Earth's surface due to Earth's changing seasons, weather and climate processes, earthquakes and even human activities, such as from the depletion of large aquifers. It did this by sensing minute changes in the gravitational pull caused by local changes in Earth's mass, which are due mostly to changes in how water is constantly being redistributed around our planet." (source)

If the GRACE concept worked well for Earth, it could also work well for the Moon. Lunar scientists weren't going to look for how water and ice move, of course, but detailed gravity data for the Moon could help scientists "determine the structure of the lunar interior from crust to core and to advance understanding of the thermal history of the Moon." (source)

The two GRAIL satellites were launched on September 10, 2011, on a Delta II rocket. The two weighed just under 900 pounds, but the Delta II is a rather small rocket, so a round-about trajectory was used to get them to lunar orbit. That took almost five months. Data were acquired for the 88 days that followed lunar orbit insertion. The primary mission was to make very detailed observations of the lunar gravity field in order to:

- Map the structure of the lunar crust and lithosphere
- Understand the asymmetric thermal evolution of the Moon
- Determine the subsurface structure of impact basins and the origin of lunar mascons
- Ascertain the temporal evolution of crustal brecciation and magmatism
- Constrain the deep interior structure of the Moon
- Place limits on the size of the Moon's inner core

All of the mission objectives were fully met, but the GRAIL satellites were not quite finished yet!

Engineers used computer models of the propulsion system to determine fuel supply and consumption. Since the science part of the mission had been successfully concluded, NASA OK'd a test to support the models. The main engines were fired one more time, and run until their fuel was expended. The fuel flow rate and firing time helped calibrate those models with "Space Truth," which helped planning and design for future missions.

The two GRAIL satellites impacted the Moon on December 17, 1972. Planetary geologists really wanted to observe the impact process, but the spacecraft were so small that the craters they would form and the ejecta plume they would create would be very small. The *Lunar Reconnaissance Orbiter* spacecraft would be only 100 miles away, but the impacts would occur on the wrong side of the day/night line for it to see the impact site in daylight. However, *LRO* would be able to see the ejecta plume when it got high enough above the surface to be in the sunlight. Its sensors detected hydrogen and mercury in the plume, but deconvolving how much was Moon and how much was ex-spacecraft was very difficult.

The two impact sites are less than 1.5 miles apart. The craters formed are less than 20 feet across, and, oddly, the ejecta is darker than expected, perhaps caused by material from the spacecraft.

The combined site of the two craters has been officially for Sally Ride, who played a key role in the mission, especially:

MOONKAM

NASA has always been aware of, and interested in support of, the engaging value of its Space exploration efforts, a point particularly brought home by the first Internet- supported mission, *Mars Pathfinder* and its *Sojourner* rover, back in 1997.

NASA was particularly interested in the promotion of STEM education, one of the reasons I was asked to detail over to NASA HQ for the best two years of my career. Rather than call the two GRAIL spacecraft "GRAIL-1" and "GRAIL-2" and cause folks to have a "Cat in the Hat" flashback, NASA decided to hold a contest for school kids to come up with cooler names for the GRAIL satellites. A middle school class in Montana won with "Ebb" and "Flow!"

Even better for generating interest, NASA outfitted *Ebb* and *Flow* with a small camera called "MoonKAM" for "Moon Knowledge Acquired by Middle school students." Students in middle schools all over the U.S.A. could request MoonKAM images be acquired of areas of *their choosing*; over 115,000 images were selected and distributed. This was the first time that school students could actively interact with an ongoing NASA mission. The idea was so engaging and inspiring that other missions would follow suit, notably the Hi-RISE camera mission aboard the *Mars Reconnaissance Orbiter*.

First American Woman-in-Space, Sally K. Ride, was in charge of the MoonKAM program. Her organization at UCSD, Sally Ride Science, is still in operation, providing K-12 students and teachers with a variety of inspiring educational materials and opportunities. Find out more about it at: https://sallyridescience.ucsd.edu!

PERSONAL NOTE

The GRAIL mission was the first launch I worked after I detailed over to NASA HQ from NASM in 2011. It was a difficult mission concept to get across to the public, and my new boss and I were brainstorming about how we could engage a large audience. The original launch date for *GRAIL* (9/9) happened to be the 45th anniversary of the premiere of the original *Star Trek* series, an odd fact I knew from the A+StW installment I distributed just before moving over to NASA HQ. When I told my new boss of the date coincidence, she smiled oddly; I was sure I had committed a NASA *faux pas*. But no, what I didn't know was that KSC's Visitor Center already had a *Star Trek* exhibit in place; my new boss arranged for it to remain there through the *GRAIL* launch and for a personal appearance by Nichelle Nichols, the original Lt. Uhura. The *Star Trek* tie-in was the "hook" we were looking for! When her attendance was announced, media attention hextupled, and when the launch was postponed due to high-altitude winds, the folks who came with their kids to see it had their disappointment replaced by *Star Trek*/Space learning fun and a Uhura photo op. And in the post-mortem meeting, my new boss asked me how I knew about the date coincidence, and after learning about A+StW, she tasked me with the creation of NASA's SPACE365 app, using the A+StW database as a starting point! For more on this part of the story, see: https://www.airandspacethisweek.com/astwhistory.

The *GRAIL* launch was the first I witnessed personally. The outreach work was done the day before, the original launch date, so I headed out to the more southern part of the KSC launch area to get a good view. I had NASA's only travelling, touchable Moon rock in my possession, used to great effect the day before, and would leave directly for the airport after seeing the launch. The viewing spot I chose had once been a park for NASA employees but was now public facility. There were a number of picnic tables there, along with 200-300 people, mostly families.

I realized that everyone there might actually want to see, and touch, "my" Moon rock, so I sauntered up to the end-most picnic table and gave the family there a "Hi, NASA is glad you took the effort today to come out and see us launch something to the Moon. I think it's only appropriate that NASA bring something from the Moon for you to see" as I opened the Moon rock's carrying case with a flourish. The rock, more than my repartee, made quite an impression! I worked my way from table to table, and when the very last person at the very last table touched the Moon rock, the Delta II ignited and lifted skyward as though they had pressed the launch button. Best. Outreach. Event. I. Ever. Did!

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GRACE

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MoonKAM

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