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Feature

Geophysics on the final frontier

Dr Jon Clarke
President Mars Society Australia
jon.clarke@bigpond.com

Introduction

Geophysics in the broad sense, the direct sensing physical properties in space, has been a key part of space exploration from the start. The first satellites were launched in the International Geophysical Year (IGY). Sputnik 1 provided data on the ionosphere, upper atmospheric drag, and micrometeorites. Sputnik 2 measured radiation intensities, although the significance of the readings was not realised until Explorer 1 mapped the Van Allen radiation belts. Sputnik 3 was an orbiting geophysical laboratory massing over 1.3 tonnes and carrying 12 different instruments. All these satellites, along with Explorer 3 and Explorer 4, and Vanguard 1, were launched during the IGY (Siddiqi 2003; McDonald 2008; McLaughlin Green and Milton 1970).

The first spacecraft to escape earth's gravity and enter solar orbit also had a strong geophysical focus. Luna 1, which flew past the Moon on 4 January 1959, refined understanding of the strength of the lunar gravitational field through its orbital perturbation, while its on-board magnetometer showed that the Moon lacked a magnetic field. The probe also measured cosmic radiation. A near duplicate probe, Luna 2, successfully impacted on the Moon's Mare Imbrium on 14 September 1959 (Harvey 2007*a*). Since then spacecraft have returned data from all of the nine 20th century planets of the Solar System, as well as many moons, asteroids, and comets. Most recently the New Horizons spacecraft has returned new data from Pluto during a flyby.

This article will not review all of these missions but will focus on missions that have investigated specific aspects of the surfaces and sub-surfaces of other bodies in the solar system; investigations that will be familiar to geophysicists exploring the earth.

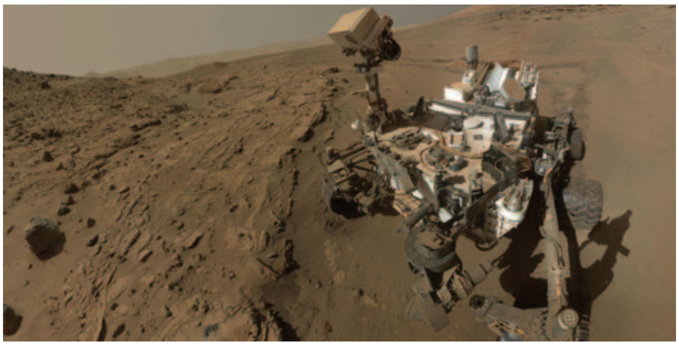
Challenges

There many constraints to geophysical exploration in the solar system. Instruments must perform in extreme environments, and few environments are more extreme than those encountered by the series of Venera landers on Venus. These landers had to deal with surface temperatures of 460°C, pressures of 92 bars, and an atmosphere of supercritical CO_2 laced with acid gasses. It is a great tribute to the mission engineers that they were not only able to meet these goals but to engineer landers that lasted well in excess of their designed operating life, not once, but eight times (Harvey 2007*b*).

All missions have to cope with noise and vibration during launch, cosmic rays, high accelerations during launch and, in some cases, entry and landing, micrometeorites, and erosion by ionised gases in orbit. Some missions have to deal with particular challenges such as the low temperatures on Titan, the high solar flux in orbit round Mercury, the intense radiation belts surrounding Jupiter, and the abrasive dust on the surface of the Moon and Mars. Engineers must build instruments to withstand these conditions with extreme mass, volume and power constraints. It is not surprisingly, therefore, that instrument design and scientific objectives are driven as much by what is possible as by what is desirable. Nor are budgetary and time constraints to be ignored. More than one instrument has been left off a mission because it was not ready in time, or because it cost too much to build. These constraints mean that instruments have limited ability to adapt to unexpected conditions or even to collect desirable data.

Instrument design is particularly challenging when the interaction between the instrument and the environment is complex. Passive sensors, such as a camera, are the easiest to design and operate. Active sensors, such as ground penetrating radar (GPR), are more difficult, those that require manipulation of the environment, such as inserting a probe, more difficult still. The instruments that require samples, especially of surface materials, to be taken on-board and processed are especially challenging, and prone to problems due to complexity of the sampling process and the likelihood of encountering situations outside the parameters to which they have been designed.

In addition to these design constraints are the operational constraints of limited bandwidth, a narrow communications window, and communication latency. These factors reflect a combination of interplanetary distances and the limited spacecraft power resources. The Opportunity Mars rover, for example, has a direct-to-Earth transmission rate of 3.5–12 kbs. The data rate using orbiters, such as the Mars Reconnaissance Orbiter, as a link is higher; a constant 128 kbs. However, an orbiter passes over the rover for about eight minutes per sol (Martian day). About 60 megabits of data (about 1/100 of a CD) can be transmitted to an orbiter in that time. That same 60 Mb would take between 1.5 and 5 hours to transmit direct to Earth and the rover can only transmit direct-to-Earth for at best three hours a day (http://mars.nasa.gov/mer/mission/comm_data.html). Power is similarly limited. The triple junction gallium arsenide cells on Opportunity provide a typical 410 Wh per sol (http://mars.nasa.gov/mer/technology/bb_power.html). Power, bandwidth, and communications time, are all heavily rationed in consequence. Even if they were not, the time lag between Earth and other bodies (4.5 hours in the case of the New Horizons Pluto flyby) reduces direct control of unmanned operations except for the Moon. The robotic excavator arms on the Surveyor lunar landers were controlled directly from Earth, as were the Lunokhod rovers. Even with the Moon, however, the time lag is such that many operations, though commanded from Earth, have to be carried out autonomously. The Luna 16 spacecraft landed, drilled a core sample, loaded the sample into



Self-portrait of the Curiosity rover on Mars, the most complex unmanned mission to the surface of another solar system body. (Source: NASA).

the return capsule, and launched the sample back to Earth, all autonomously during the lunar night. Such operations are vulnerable if situations beyond the capability of the hardware and software arise.

Professional cultural differences among the teams of a score or hundreds of mission scientists and between scientists and engineers can pose additional challenges. For example, during the unmanned lunar missions leading to the Apollo landings, there was constant friction between the 'sky scientists' – interested in particles, fields, and global spectra – and 'earth scientists' – who wanted cameras and other instruments to characterise specific sites. The earth scientists had to fight very hard to include cameras on the missions because the data such instruments recover were seen to be qualitative rather than quantitative, and there was a systematic failure amongst the sky scientists to appreciate the importance of context and site specific data, the core of much geology and geophysics (Wilhelms 1993).

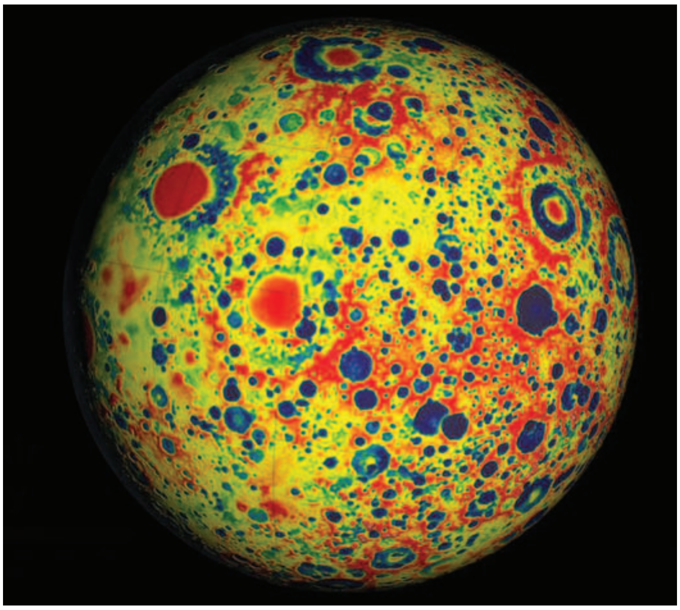
Lunar and planetary missions during the 60s and early 70s were generally sequential, each building on the technology of the previous missions, for example the, Mariner, Surveyor and Venera missions. More recent missions, particularly those from the US, have been unique, with missions and instruments selected by a competitive process, rather than as a result of an evolving program. This can make comparison between different datasets difficult, as they may have been collected by very different instruments with different design assumptions and technologies.

Some examples

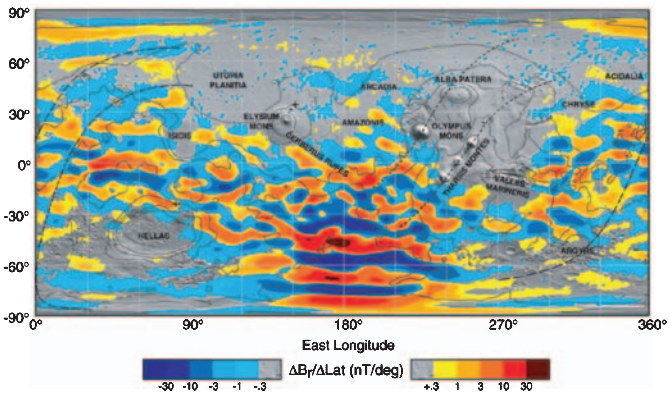
Despite these issues a great diversity of geophysical instruments have been flown on space missions. Some examples of past and present unmanned missions follow. Gravity and magnetic fields have been mapped from orbit, for example the GRAIL mission for the Moon (Zuber et al. 2013) or the Mars Global Surveyor (MGS) mission for Mars (Acuna et al. 1998). These surveys are much lower resolution than airborne surveys on earth, being flown at much higher altitudes (50 km for GRAIL, 171 km for MGS). Despite such limitations, these missions have revealed much about the nature of the crust and evolution of these bodies. The GRAIL, similar in concept and operation to the terrestrial GRACE mission, used gravity gradiometry to show a population of linear gravity anomalies with lengths of hundreds of km associated with early expansion of the lunar lithosphere (Andrews-Hanna et al. 2013), and mapped in unprecedented detail the distribution of lunar mascons, positive gravity anomalies mostly associated very large impact basins (Zuber et al. 2013). One of the major geophysical discoveries of the MGS mission (Connerney et al. 1999) was that crustal magnetisation, mainly confined to the most ancient, heavily cratered Martian highlands of the southern hemisphere, frequently was an east-west–trending pattern of linear features, the longest extending over 2000 km. Crustal remanent magnetisation exceeds that of terrestrial crust by more than an order of magnitude. These formed groups of quasi-parallel patterns of alternating magnetic anomalies. They are reminiscent of similar magnetic features associated with terrestrial sea floor spreading but on a much larger spatial scale. They may be a relic of an era of plate tectonics on Mars.

Seismology has been attempted on two planets, Mars and Venus. The Viking 1 and 2 landers in 1976 both carried seismometers, but both failed to yield useful data. The Viking 1 seismometer failed to uncage after landing, so no data were collected. The Viking 2 seismometer did uncage, but engineering constrains meant that the instrument had to be mounted on the deck of the lander. As a result any potential seismic signals were generally lost in the noise generated by Martian winds blowing over the lander (Ezell and Ezell 1984). No seismic events were recorded during the still periods, but the usefulness of these data must be questioned given the poor mounting of the instrument. More successful were the seismometers set to Venus on Veneras 13 and 14 (Ksanfomaliti et al. 1982) as part of the Gronza 2 instrument. These instruments, which included a kilohertz radio sensor and a uniaxial seismometer, also collected signals from lightning, the probes' drills and the wind, as well as several microseismic events. The microseismic events may be due to the location of the landing sites on the flanks of a possibly volcanic edifice called Phoebe Regio.

The surface properties of the moons and planets in the solar system are important data for engineers designing future missions and for providing ground truth for other data. Much can be determined from engineering performance data, for example comparing the distance travelled against the number of revolutions of the wheels of a vehicle provides data on the mechanical properties, as does the depth to which the landing pads sink into the surface.



Gravity globe of the Moon, projected from data collected by the GRAIL mission. Source: NASA.

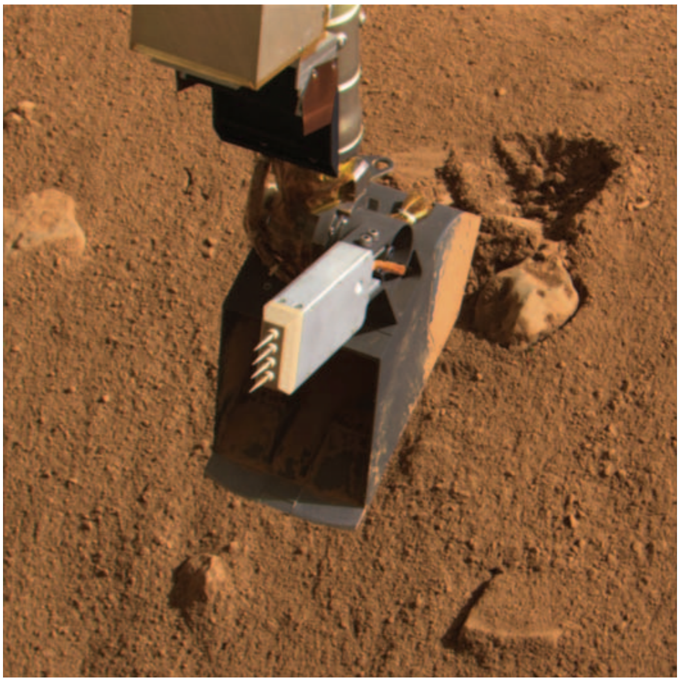


Linear magnetic anomalies in the southern highlands of Mars, mapped by the Mars Global Surveyor spacecraft. Source: NASA.

Physical properties have been measured almost from the first mission. Luna 13 in December 1966 was the third spacecraft to safely land on the Moon and it carried a gamma densitometer to measure regolith density (Harvey 2007*a*). Advances in instrumentation over the past 40 years mean that modern spacecraft are able to carry out many more and more sophisticated measurements of surface properties. The Phoenix Mars lander touched down in the north polar regions of Mars in 2008. Among its many mission objectives was the characterisation of the physical properties of the Martian regolith using the thermal and electrical conductivity probe or TECP (Zent et al. 2010). The TECP, which consisted of a series of probes that could be pushed into the Martian regolith, measured thermal conductivity, heat capacity, temperature, electrical conductivity, and dielectric permittivity throughout the mission.

The December 2013 landing of Chang'e 3 on the Moon was the first mission to the lunar surface since 1976. This large, complex mission deployed a rover, Yutu, while the lander itself carried out astronomical observations. Yutu carried a GPR, the first to be deployed beyond Earth, that operated at two frequencies, 60 Ghz and 500 Ghz. Yutu was damaged and immobilised on its third lunar day of operation, but while mobile it collected data on the stratigraphy of the Moon's Mare Imbrium (Xiao et al. 2015). After landing near the rim of a young crater Yutu drove 114 m across the ejecta blanket. In addition to imaging the surface and scattered rocks and collecting geochemical data, the GPR probed through the subsurface stratigraphy to a depth of over 360 m. More than nine subsurface layers were identified in the returns, indicating that this region has experienced a complex geological history of flow events separated by periods of development of impact regolith.

A different technique of exploring the subsurface has been used by the Curiosity Mars rover. This mission landed in Gale Crater in August 2012 and carried a pulse neutron generator (DAN) to map the distribution of water in the shallow subsurface. Operational and planetary protection constraints precluded the mission from being sent to areas with shallow, subsurface ice at latitudes poleward of 45 degrees in each hemisphere. However, DAN has been mapping the distribution of water of hydration and elements responsive to the neutron pulse such as chlorine. DAN operates in active and passive modes and is able to differentiate between shallow and deep water contents (Litvak et al. 2014). One DAN observation campaign consisted of active measurements every 0.75–1.0 m to search for the variations of subsurface hydrogen content along a 15 m traverse across geologic contacts on the floor of Gale Crater. The results



The Phoenix thermal and electrical conductivity probe mounted on the sampler arm and used to measure the physical properties of Martian regolith. Source: NASA.

showed that several subunits within each identified formation could be characterised by different depth distributions of water-equivalent hydrogen (WEH) and chlorine-equivalent abundances. The top 60 cm of the subsurface contained up to 2–3% WEH. Chlorine-equivalent neutron absorption abundances ranged within 0.8–1.5%. These results reflect variations in content of water-bearing minerals including sulphates and clays, known from XRD data collected by Curiosity, and of salts.

The future

Several forthcoming missions may be of interest to geophysicists. These include the 2016 InSight mission, the Chang'e 4 and ExoMars Rover missions, both in 2018, and the 2020 Mars rover.

InSight will be the first dedicated geophysical mission sent to the surface of Mars. The lander, based on the 2008 Phoenix design, carries a range of instruments, mostly of European origin, to study the interior of Mars. The instruments will measure heatflow, record seismic events (this time using an instrument lowered onto the Martian surface and isolated from wind interference), and the planet's rotation using the X-band radio. The mission is scheduled to launch in March 2016 and land on the plains of Elysium (https://en.wikipedia.org/wiki/InSight#Landing_site).

The ExoMars Rover mission is phase 2 of a series of missions planned by the European Space Agency in its ExoMars program. The first is a 2016 Mars orbiter. The 2018 mission will consist of a mid-sized rover with the capability to drill to depths of up to 2 m. The mission is essentially focussed on the search for past and/or present life in the Martian subsurface. Supporting these goals are two geophysical instruments, the WISDOM GPR and the ADRON neutron probe. WISDOM will operate across a range of frequencies (0.5–3 GHz0), which will allow penetration to depths of 2–3 m and provide cm scale resolution of shallow radar reflectors. ADRON is an improved version of DAN, like the earlier instrument it will map the presence of water and chlorine to a depth of approximately 1 m (https://en.wikipedia.org/wiki/ExoMars_rover).

Also scheduled to fly in late 2018 or 2019 is the Chang'e 4 mission. Like Chang'e 3, this mission is targeted for the lunar farside, the first lander to do so. This will require a relay satellite, probably in an L-2 halo orbit, to communicate with earth. The lander and rover are largely complete and the final experiment package is in the process of being finalised. The rover will, once again, carry a GPR to study shallow structure. The mission is also planned to study the particle radiation environment and the deep interior. This suggests some type of magnetic and plasma observatory and a seismometer, perhaps carried on the main lander (CNSA 2015).

The 2020 Mars rover will be based on the current Curiosity mission, although hopefully with more robust wheels. The mission's objectives are to document, collect, and cache samples for future return to Earth by an as yet unfunded mission. Once again a GPR will be carried. The instrument, the Radar Imager for Mars' Subsurface Experiment or RIMFAX, is being supplied by the Norwegian Defence Research Establishment (https://www.nasa.gov/press/2014/july/nasa-announces-mars-2020-rover-payload-to-explore-the-red-planet-as-never-before). No landing site or formal name has yet been assigned for this mission.

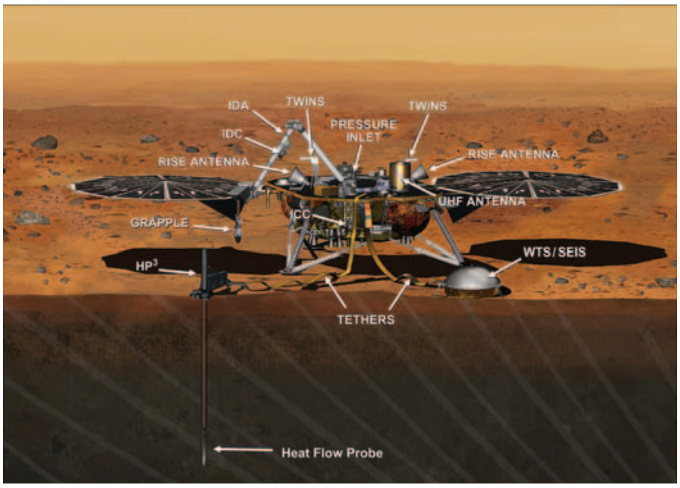
Geophysicists in space

All the missions that have been described are unmanned. Despite media anthropomorphism and Twitter accounts, these missions can do no more than they are instructed, with the previously outlined limitations. More sophisticated geophysical techniques, for example those requiring complex surface installation, deployment of large sensor arrays on planetary surfaces and rapid or large amounts of power, are beyond the capability of any unmanned mission for many decades to come, despite the hype about future planetary robotics technologies.

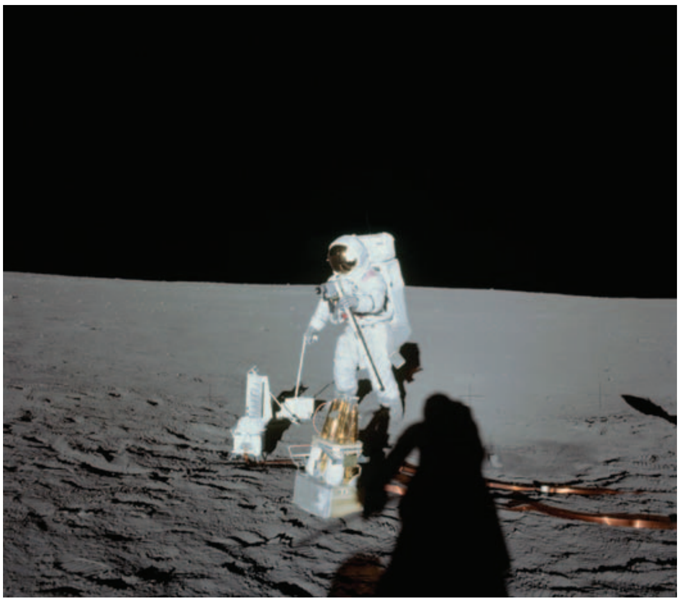
The Apollo missions are our only guide to the potential of direct human geophysical exploration of other solar system bodies. Despite the primitiveness of the technology, the achievements of Apollo in this respect were enormous. The largest unmanned mission to date, the Curiosity Mars rover, had a science payload of 75 kg. In contrast, five of the six successful Apollo Moon landings carried an Apollo Lunar Science Experiment Package (ALSEP), each one of which massed up 90 kg (Bates et al. 1979). Fifteen different experiments were carried, mostly of a geophysical nature, and these included the deployment of active seismic arrays, seismometers, plasma and magnetic recorders, heat flow probes, gravity meters, solar wind collectors, dust collectors, and laser ranging reflectors. The observations that were made, in many cases still not duplicated by later unmanned missions, were a small part of a much more comprehensive exploration of the lunar surface over the course of six landings. In less than 14 days of operations not only were almost half a tonne of instruments deployed across the lunar surface, but cores were drilled to depths of 3 m, almost half a tonne of samples collected and over 90 km of the lunar surface traversed (Wilhelms 1993).

Crawford (2012) carefully compared the returns on the Apollo program compared with the returns on the unmanned exploration of the Moon and Mars, focussing on sample return and rover missions. He showed that per day of field work, as measured by output of peer reviewed science papers, Apollo was three orders of magnitude more productive than the Spirit and Opportunity rovers on Mars. This is in line with the qualitative assessment made by Squyres (2005), based on his experience as principal investigator of the Mars rover missions, and the empirical study of Snook et al. (2007). While the cost of human exploration is often used as a justification for not sending people into space, Crawford (2012) pointed out that the cost of the Apollo program as a whole, allowing for inflation, was only 12 times that of the Curiosity Mars mission, and has proved to be much more productive, based on scientific publications. Crawford (2012) also showed that that science component of the Apollo missions was only 1.2% of the overall mission costs, making the science expenditure of the program extremely cost effective.

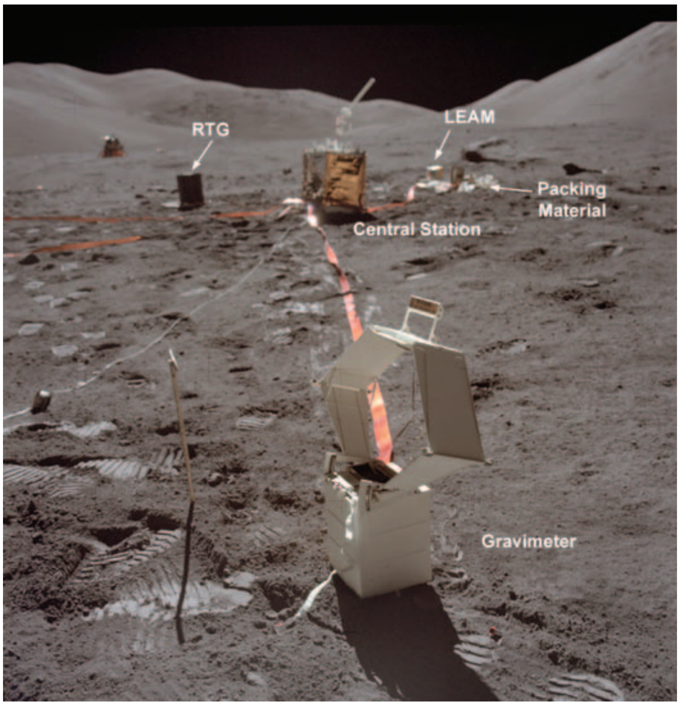
At present there are no funded programs by any space faring organisation to return people to the Moon or to go beyond to Mars or asteroids. However, such missions are within the capability of our technology. If we wish to develop a better



Labelled diagram of the forthcoming 2016 Insight mission to Mars, which will place a geophysical observatory on the surface. Source: NASA.



Astronaut Al Bean deploying the ALSEP during the Apollo 12 mission. Source: NASA.



Components of the Apollo 17 ALSEP on the lunar surface. Source: NASA.

understanding of the character of the solar system then, sooner or later, geophysicists will need to travel to that final frontier.

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