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Penetrator Science – Making an Impact On Planetary Compositional Science

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NASA's return to the Moon has a pressing need to understand whether usable concentrations of ice exist in permanently shadowed cold craters. This need is only one example of a number of high value scientific measurements that can be cost effectively made using penetrators. A significant body of penetrator data, software modeling tools, concepts, and history exist that provide a basis for penetrator missions to be defined, designed, developed and implemented. This paper examines the operational constraints for planetary missions, past and current penetrator missions, and, using lunar ice as an example mission, defines and explores the trade space for future penetrator missions.

I. Introduction

The utility of surface penetrators as science instruments has emerged in the recent planetary exploration missions. Penetrators are easy to launch due to their small size and mass; they are relatively cheap to develop and produce; they provide in situ measurements of surface or subsurface characteristics. Penetrators have had a long history with great success for many years on non-scientific Earth applications. Government labs such as Sandia have developed standard codes to calculate penetrator parameters that allows accurate modeling of penetrator performance.[1,2] These codes show good correlation with past test results and provide a solid basis from which to develop interplanetary penetrator designs, and the missions that implement them. This paper presents a short history of surface penetrators as science instruments, develops a candidate penetrator concept, examines that candidate mission, and makes recommendations about future possible penetrator missions and the development of penetrator technology. For our purposes, we define penetrators by their function: surface acquisition vehicles designed to reach and operate significantly below (one or more penetrator length) the surface of a planetary body.

Penetrator performance is influenced by penetrator mass and configuration, impact velocity and angles of attack and alignment, surface conditions, and the resulting g-loading. Penetrator mass is bounded by the need to control both penetration depth and g-loading. Penetration depth drives release trajectory and velocity which in turn place significant constraints on the overall mission design and carrier vehicle requirements and design. Primary penetrator mission trades include: the number of penetrators, capabilities of each penetrator, approach to slowing the penetrators down from entry or orbital velocity, penetrator orientation control approach, scientific sample assessment approach and communications concepts. A mission to assess the present or absence of usable amounts of water ice at the Moon's poles is used as a vehicle to show penetrator mission development and assessment.

II. The Need for Penetrators

In-situ resource utilization (ISRU) has become an increasingly important part of NASA's plans for the exploration of other planetary bodies. The primary material of interest is water, whose components can be broken down to oxygen and hydrogen, both of which can be used for fuel and life support. It has therefore become imperative for NASA to clearly demonstrate the existence of extra-terrestrial ground water, as the location of that water will be an enabling factor in future exploration activity. For example, NASA wants to create an outpost on the moon as a jumping off point to planetary bodies further afield. Having a plentiful source of water on the moon would greatly reduce the cost of missions both to the moon and to Mars. Orbiters around the moon and evidences from past missions such as Clementine have suggested the existence of underground water ice in permanently

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shadowed craters on the poles of the moon. The existence or non-existence of ice at the poles has a significant impact on the architecture of future lunar missions.

The difficulty in proving the existence of this ice is that it is thought to be part of the matrix of the lunar regolith. It would be difficult to remotely capture its signatures. Furthermore, the majority of the ice is thought to lie just below the lunar surface, starting at a depth of approximately 2 meters inside permanently shadowed regions of lunar craters. Therefore, the most definitive answer to the existence of lunar polar ice would be to "touch" the ice with by burrowing below the lunar surface. In fact, the Lunar Crater Observation and Sensing Satellite (LCROSS) is a NASA mission with a launch date of 2008 that hopes to accomplish the detection of subsurface ice. We briefly discuss LCROSS in Section V.

Access to these permanently shadowed craters is difficult. The lack of sunlight means precision soft landings inside these craters have to be done in the dark, requiring microwave or laser illumination systems. Alternatively, vehicles can traverse to the crater floors: a lander can land on the sunlit rims of craters, and a rover unit can be deployed to reach the bottom of these craters, but the rovers would have to first traverse down the crater sides and then operate in darkness, with power source becoming a large problem. The difficult terrain combined with a lack of site knowledge makes for difficult precision soft landings and ground vehicle operation. This is exactly the situation most ideally suited for penetrators. Penetrators do not need to negotiate horizontal terrain. They can be dropped at virtually desired location, efficiently depositing instruments to the correct depth.

The utility of penetrators is not just limited to water detection, or indeed any chemical detection, Penetrators should be thought of as delivery vehicle for any type of in-situ monitoring. Long-lived penetrators can monitor surface and subsurface activities such as temperatures, seismic activity, soil conductivity, and light level variability. The variety of measurements that can be taken with a penetrator is only limited by developing the properly shock hardened instruments. Miniaturization of detectors and elimination of moving parts go a long way towards surviving impact g-loading. Properly scoped, penetrators can be effectively used in place of landers and rovers.

Penetrators can also be complicated or simple. A large penetrator may carry its own navigation and propulsion system, as well as a variety of on board instruments, perhaps even a dedicated communications package. Fitted with large capacity batteries, these penetrators may be expected to act as a monitoring station for years, taking part in large and on-going planetary surface reconnaissance missions. A simple penetrator, on the other hand, may be a bullet shaped casing which allows a small scoop to deploy and collect a sample for simple testing. A small on board battery would only provide power for the short test, making it a very simple and cheap system to design and build, fitting in the cost structure of a small mission. Many of these small penetrators can be made and dispersed over a large area to gather statistically significant results on the distribution of chemical elements.

The coverage range of penetrators and the achievable science is rivaled only by rovers capable moving over many kilometers, with the main difference that penetrators are much more cost efficient. The immobility of penetrator significantly simplifies the operation, design, and risk of the vehicle. As an order of magnitude cost comparison, the Mars Exploration Rovers (MER), Spirit and Opportunity, were reported to cost 800 million dollars.[3] Out of this, $625 million were development costs. Building on MER heritage, a basic rover unit would still cost on the order of $100 million dollars, and, returning to the question of lunar ice, still have to be fitted with a drill that can reach 2 meters deep. In comparison, the Deep Space 2 penetrators only cost a total of $30 million, with $26 million in development and manufacturing.[4] Not included in the DS2 figures are the cost for a launch vehicle and operations. While DS2 ultimately failed in operation, the $26 million cost figure can be taken as the order of magnitude estimate for further penetrator development. For the same science return, a penetrator is a significant cost savings over a comparable capability rover.

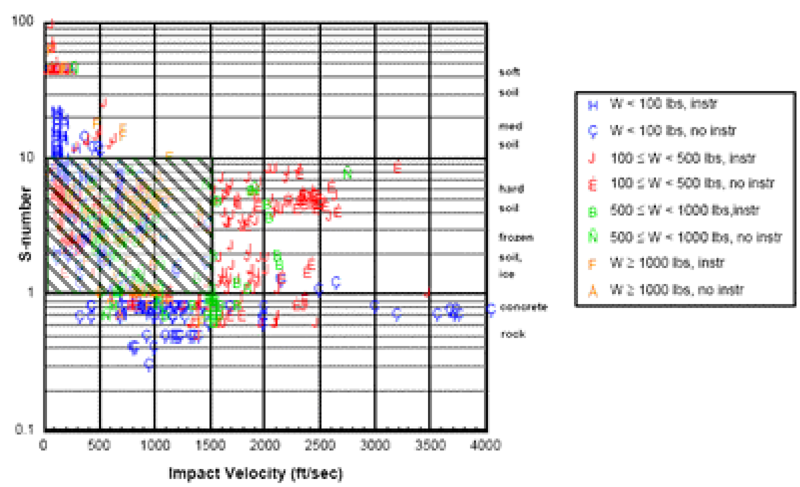

Figure 1. Sandia National Labs' penetrator test history as of 1998. The green hatched area indicates the range of penetrators for planetary bodies.

III. Penetrators Past

Penetrators originated at Sandia National Labs (SNL) in the early 1960's, where it was developed as part of the US government's nuclear weapons program. Much of Sandia's original research was declassified in the 1970's, when the penetrator equations were first published.[1] Since then, Sandia has gathered an impressive amount of empirical and theoretical data related to penetrators on all scales and various different types of surfaces. Figure 1 is a summary of SNL's penetrator testing, plotted in terms of impact velocity and S-number, which is an indication of surface characteristics. The dark green hatched area indicated the typical surface and impact velocity required for exploration of other planetary surfaces. While there has not yet been a successful penetrator mission returning science data, several penetrator concepts have been flown, and several more are proposed to fly in the near future. These penetrators are usually placed on board a carrier space craft which performs orbital insertion around the planetary body of interest. The penetrator is separated from the carrier spacecraft at the appropriate height, dependent on whether the penetrators carry their own propulsion system. We describe three recent penetrator missions to the Moon and Mars.

A. Deep Space 2[5]

Deep Space 2 penetrators were carried on the failed Mars Polar Landers (MPL) which were designed to penetrate high latitude regions on Mars and sample regolith two meters below the Martian surface. The penetrator consisted of a forebody and an aftbody, and was encased in an outer conical aeroshell. Figure 2 is a photo of a DS2 penetrator. The aeroshell was the DS2's only means of deceleration through the Martian atmosphere (obviously, aeroshells would not work on the lunar surface). The penetrator was launched from the main MPL spacecraft in orbit, and the aeroshell decelerated the penetrator through the atmosphere. On impact with the surface, the aeroshell would have broken up and the forebody would have plunged into the Martian surface, with a target velocity between 140 and 180 m/s. The aftbody was targeted to experience 60,000 g's, and the forebody 30,000 g's. The aftbody was to remain on the surface of the ice sheets and carried with it a basic communications package that sent information gathered in the forebody to Mars Global Surveyor, which acted as a communications satellite to beam the information back to Earth. The two bodies were connected by flexible wiring. Carried on the forebody was a drill, which was deployed to sample the Martian regolith. The sample would have been delivered back to the body where it was heated and water vapor tested by looking for absorption lines. In addition, the forebody carried a temperature sensor which measured the Martian soil conductivity. The aftbody carried the communications antenna, sun sensor, and transceiver, which enabled communication with MGS. The whole DS2 penetrator package was ~2.4 kg. The final reason for their failure is unknown, but the penetrators never established contact after impact.

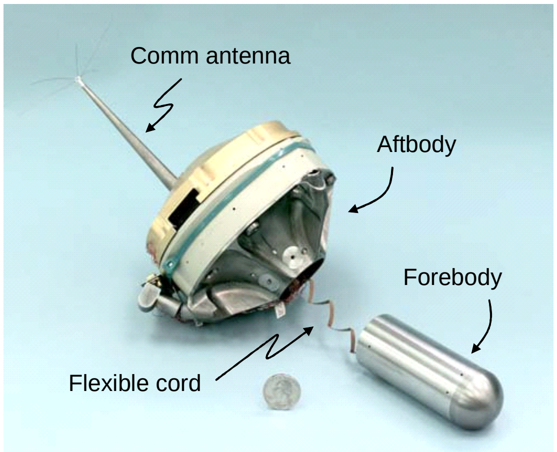

Figure 2. The DS2 penetrator compared to a US quarter coin. **Image Credit: JPL, NASA**

B. Mars 96[6]

The failed Russian mission Mars 96 also carried on board two penetrators. These were large payloads with masses of 45 kg each. The penetrators were to be ejected from the carrier spacecraft in orbit, and had autonomous flight capability, as well as dedicated deceleration propulsion. After separation, the penetrators were to orbit Mars, using aerobraking maneuvers to slow its velocity, and finally, use a gas filled aeroshell for the final vertical deceleration. The forebody was designed to penetrate to a depth of 5 to 6 meters, while the aftbody, containing the communications equipment, stayed on the surface. The expected impact velocity was 80 m/s, resulting in 500 g's of acceleration. An ambitious suite of instruments were carried on board, including an x-ray spectrometer, neutron spectrometer, seismometer, a gamma spectrometer, along with the usual suite of camera, magnetometer and accelerometer. These penetrators were designed to survive in the Martian regolith for 1 year, with a data rate of 8 kbits/s. Unfortunately, the Mars 96 spacecraft was not able to leave Earth orbit due to insufficient injection energy, and fell into the Pacific Ocean.

C. Lunar-A[7,8]

An upcoming penetrator mission is the Japanese Lunar-A, currently scheduled for a 2007 launch. This is a lunar seismology experiment aimed at launching two penetrators, one on the near side of the moon and one at the far side. The penetrators are approximately 10-15 kg in mass, with the additional mass over the DS2 probes mainly accounted for by the on board propulsion system. The penetrator release scenario is to have the two penetrators launched from 40 km above the lunar surface while the carrier spacecraft is in an elliptical orbit. The onboard thrusters fire to correct for the horizontal velocity of the penetrators and acquire the precise landing location. Anti-nutation devices are on board to ensure the penetrator is pointed correctly. Just prior to impact, the propulsion unit separates from the main body of the penetrator. Impact with the lunar surface is estimated to be less than 300 m/s, sustaining 8000 to 9000 g's. The penetrator will burrow 1 to 3 meters into the lunar regolith. In this mission, the penetrators are not measuring subsurface properties, but the burrowing is done to insulate the seismometers from the lunar surface temperature fluctuations (from ±280 k to ±3 k). This eliminate temperature control mechanisms on the penetrators which greatly reduces the energy requirements and battery size. Overhead flyby of the carrier spacecraft (orbiter) every 15 days allows information transmission. The latest set of prototype penetrators were tested at Sandia National Labs in May of 2006, with initial reports indicating test success. This penetrator is a single body design, with the top of the penetrator carrying the communications equipment, requiring line of sight connection to the orbiter for transmission.

IV. Penetrator basics

The desired depth of penetration is the main factor determining penetrator design. The deeper the penetrator needs to travel, the faster the necessary impact velocity, which results in larger g-loading. The mass of the penetrator is the second most important factor affecting the penetration depth. Obviously, the more massive penetrators will be able to travel deeper for the same impact velocity. Substrate hardness and structural configuration is roughly the third most important factor; moist soil allows further penetration than frozen tundra. Other factors that affect penetration depth include impact velocity angle, tilt of the penetrator along the velocity axis, and the shape or geometry of the impactor, particularly the front head, known as the nose.

A. Penetrator Equation

The Young penetration equations were developed at Sandia National Labs; these equations determine the depth a penetrator will reach for a given velocity. Penetration equations for soil, rock, and concrete targets is given by,[2]

$$V = D / 0.000178 SN (m / A)^{-0.7} - 30.5 \tag{1}$$

where *V* is the velocity of the penetrator given in m/s, *D* is the penetration distance traveled in meters, *S* is the substrate penetrability (dimensionless), *N* is also a dimensionless nose performance coefficient, and *m/A* is the mass to area ratio of the penetrator. This equation allows a first order determination of the necessary impact velocity to reach a certain depth. A similar equation for frozen soil and ice is given by,

$$V = D / 0.000234 SN \ln(50 + 0.06m)(m / A)^{-0.6} - 30.5 \tag{2}$$

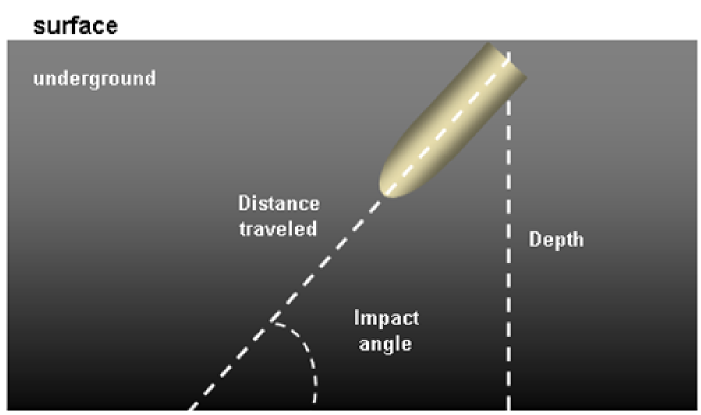

Figure 3. Penetrator geometry.

As shown in Figure 3, the actual distance traveled may not represent the depth of penetration, if the penetration occurred with a significant impact angle.

The penetration equations have a lower mass limit of 2.2 kg in soil and 4.4 kg in frozen surfaces. In real applications, penetrators are seldom designed to be less than 2.5 kg. The left plot of Figure 4 shows the surface velocity vs. the penetration depth for different penetrator masses, where the S number used is 3; this is slightly softer than frozen soil. S number is a dimensionless penetrability index that hitherto has applications only in penetrator equations. The larger the S number, the more "penetrable" a surface. Realistic S numbers range from 0.4 to 60. Outside of this range, the penetrator equations break down and should not be used. For example, S = 60 describes marine clay sediments, which are very soft. S = 0.4 describes highly strengthened concrete. A 5 kg penetrator with a good nose performance coefficient (N = 0.9), will only need 40 m/s impact velocity to penetrate the marine clay sediment; the same penetrator will need to travel 5740 m/s to penetrate the concrete. Intermediate S numbers include S = 2 – 4, describing dense cemented sand, and S = 4.5, described frozen seawater.

Heavier penetrators are able to achieve deeper penetration for a given velocity. In fact, the main challenge of designing penetrators for planetary surface characterization is to slow the penetrator down to reach the desired depth. For example, in order to reach a depth of 2 meters, a 10 kg penetrator only needs a surface velocity of 148 m/s. For the Russian Mars 96 penetrators, which were 45 kg, the surface velocity to penetrate 2 meters is only ~60 m/s, with modifications depending on the exact shape of the penetrators (nose coefficient *N*).

B. Penetrator g-loading

The limitation to the maximum sustainable impact velocity is the g-loading limits of the penetrator, both in terms of the structural integrity, whether the housing disintegrates on impact, and also the shock tolerances of the instruments and any movable parts. In general, g-loading should be kept to a minimum, and therefore the slowest impact velocity to reach penetration depth is desired. The instantaneous impact g-load can be estimated by tripling

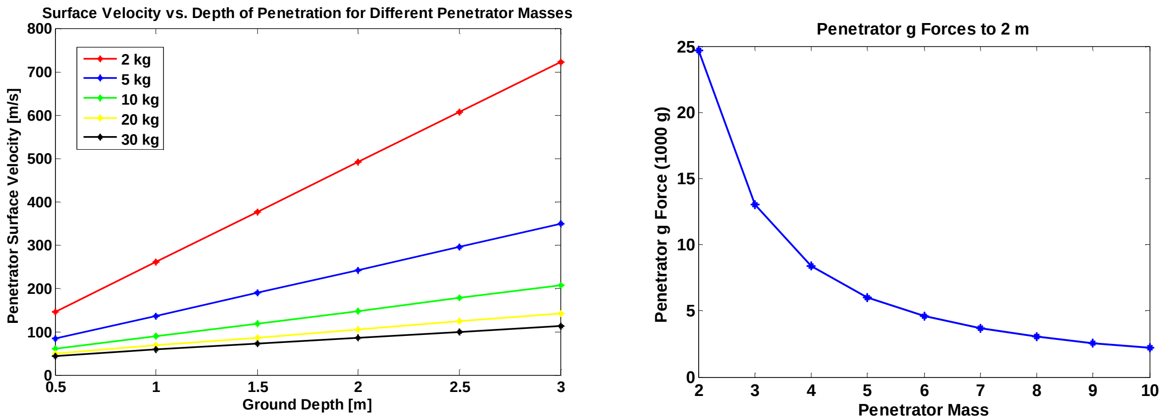

Figure 4. Left: Penetrator ground depth vs. surface velocity for several different masses of penetrators. The S number of these values is ~3, slightly softer than frozen soil to approximate the fluffy lunar regolith. Right: The g-loading for various penetrator masses for 2 m final depth.

the average g-load on the penetrator. The right plot of Figure 4 shows the penetrator g-loading as a function of penetrator mass, with impact velocities high enough to reach a 2 meter depth. It can be seen that larger penetrators suffer less g-load shocks than small penetrators.

The amount of g-load a penetrator can take is usually limited by the on-board instrumentation. According to Sandia, penetrators designed for g-loads of less than 3,000 are routine. More work is needed, but g-loads of up to 9,000 are possible. Beyond 9,000 g's, it becomes difficult to manufacture instruments that will survive. For most low S number surfaces, the g-loading increases with penetration distance, due to the higher velocity necessary for penetration. For very soft materials, the reverse is true, where a slight increase in velocity enables a lot of penetration. In these rare circumstances, the g-loading decreases with depth.

Pulling penetrator design towards smaller penetrators and higher impact velocity is the penetrator delivery method. Generally, penetrators are dropped from an orbiting carrier spacecraft. Stable orbits are high above planetary surfaces, with high horizontal (parallel to ground) velocities. There is no atmosphere on the moon to aerobrake the penetrator, so deceleration must be performed by either a propulsion module on board the penetrator, or the carrier spacecraft. By placing propulsion on the penetrator, the mass of the penetrator is increased, and so the penetrator needs to be slowed down even more to reach the desired depth, which in turn requires more fuel. If the carrier spacecraft breaks orbit, it consumes a lot of fuel to descend to the desired height. The smaller the carrier spacecraft, the less fuel it takes to reach that height. The smaller the penetrator, the smaller the change in carrier spacecraft altitude. Given the limiting amount of mass a spacecraft can carry, this usually drives the design to smaller penetrators. The mass of the carrier spacecraft is now also a critical consideration in the trade space. The penetrator size and descent method must be carefully chosen by considering all the relevant mass systems.

C. Penetrator Mission Trade Space

Most of a penetrator mission architecture can derived from the penetrator depth required, which is guided by the science requirements. Whether the penetrator needs to obtain a depth of 1 or 10 meters should depends on its purpose. The primary constraint, as we mentioned, is the upper limit g-loading the penetrator can withstand. Working with these two factors, it is possible to sketch out the development of a penetrator mission architecture. Figure 5 shows the top level trades of a penetrator mission design.

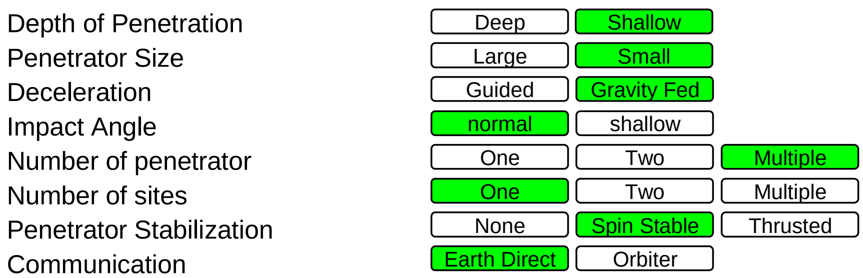

Figure 5. Top level penetrator trade space. Green indicates the option chosen for the example lunar ice penetrator mission discussed in detail in Section IV.

There is a tight coupling between the penetrator architecture and the penetrator science. Small concessions in the science requirements can mean the difference between a viable penetrator mission and a dead one. Carrier spacecraft design can also have a significant impact on the penetrator mission. As a general rule, the penetrator size should be determined by the science instruments needed. A long-lived, multi-tasking penetrator like those on board Mars 96 may be large. Since the science has driven the penetrators to be large, we know that it will need less impact velocity. This means it is more economical to give each penetrator a propulsion system, rather than slowing down the whole carrier spacecraft for the following reasons:

- the increase in mass due to the added propulsion is a smaller fraction of the total penetrator mass,
- each penetrator is already a large investment of the total budget, so a guided propulsion in this case reduces the risk of impact and failure to reach the destination

In the case where the science does not clearly dictate the size, the drive is generally towards smaller penetrators, with the trade that much of the mass resides in the de-orbiting fuel needed by the carrier spacecraft. While this philosophy is not necessarily mass efficient, it is usually cost efficient, as the risk is reduced on each penetrator by

- having more penetrators per unit mass to increase likelihood of penetrator survival,
- fewer number of systems on each penetrator means less integration, test, and qualification,
- de-orbiting a carrier spacecraft is a lower risk operation, since most of the subsystems needed for de-orbit are already on board, and has been tested and proven repeatedly.

The economy of carrier spacecraft de-orbit is somewhat eroded by the fact that a penetrator ejection mechanism must be devised for the carrier spacecraft. Ideally, the carrier spacecraft should be lightweight so that the extra de-orbiting mass is not a hindrance. The pros and cons of the four major penetrator considerations mentioned are summarized in the table below.

Trade Area	PRO	CON
Small Mass	• higher hover altitude, less fuel • more penetrators for given mass	• large NRE to withstand higher g's
Large Mass	• less NRE for lower g-loading	• fewer penetrator for given mass • lower hover altitude, more fuel
Guided Penetrator Descent	• need to decelerate only penetrators, less SC fuel needed, more room for penetrators	• more NRE to develop • more risk
Gravity Fed Descent	• known method, no NRE	• whole SC need to be decelerated, need to carry more fuel

As an example, consider the following scenario for a lunar penetrator mission. The total spacecraft is allotted 1000 kg wet mass, and a penetrator experiment is desired. The minimum carrier spacecraft mass is 380 kg. The ΔV

for lunar orbit insertion is ~850 m/s. If the mission uses small, 2.5 kg penetrators, there is the addition of another ~1200 m/s for the de-orbit and hover to roughly 10 km above the surface to deliver the penetrators. Most of the allotted mass for this mission will go to carrier spacecraft fuel, so that this mission can carry ~20 penetrators. If, on the other hand, we fitted each penetrator with its own propulsion, the mass per penetrator would be ~35 kg. Within the allotted mass, we would be able to carry ~10 of these large penetrators. Usually, more penetrators means higher mission success probabilities, but the larger penetrators would have more accuracy. The benefits of more penetrators versus more precise penetrators are unique to each mission. For example, a lunar seismic monitoring program only needs one penetrator per site, perhaps two for failure tolerance. In this case it is better to have two precise, large penetrator to ensure proper insertion and survival, like the Lunar-A mission. In other circumstances where a large number of penetrators is needed at multiple locations, construction of a carrier craft capable of de-orbit and hover is desirable. Careful examination of mission requirements and analysis of performance return per penetrator usually can disentangle any degeneracy. We describe in the next section, a sample lunar mission that goes into more details the pros and cons of large vs. small penetrators, and illustrate a case where small penetrators are more desirable.

D. Penetrator Alignment and Comm

A penetrator must be well aligned with the direction of motion; even slight mis-alignments can lead to penetrator failure. An aligned and a mis-aligned penetrator are shown as the top and bottom pictures in Figure 6. The mis-alignment angle is the angle between the center of inertia line of the penetrator and its velocity vector. Mis-alignments of 1º results in a lateral load equal to half of the front impact g-load. A mis-alignment of 5º results in the same amount of lateral g-loading as the front will experience. In general, penetrators are not designed for high lateral g-loads, and the penetrator will shatter if mis-aligned. Proper pointing can be maintained by on board propulsion, or by spin stabilization.

A final major hurdle for penetrators is communication. Most modern penetrators solve this problem by having two bodies: an aftbody carrying communications equipment that stays on the surface and is linked by flexible cording to a forebody which goes underground and performs the experiment(s). An orbiting spacecraft is generally necessary to relay the results back to Earth. In most cases, this function is performed by the carrier spacecraft. In limited cases, it is possible for penetrators to talk directly to Earth. If the required bit rate is low, and the penetrator is within line of sight of Earth, direct communication is a possibility. This eliminates the cost of an orbiting space craft, reduces the necessary lifetime of the penetrator (which no longer needs to stay alive until the orbiter returns), and simplifies the penetrator subsystems, since storage and dump capabilities can be eliminated. Our Lunar H2O verification mission describes such a concept.

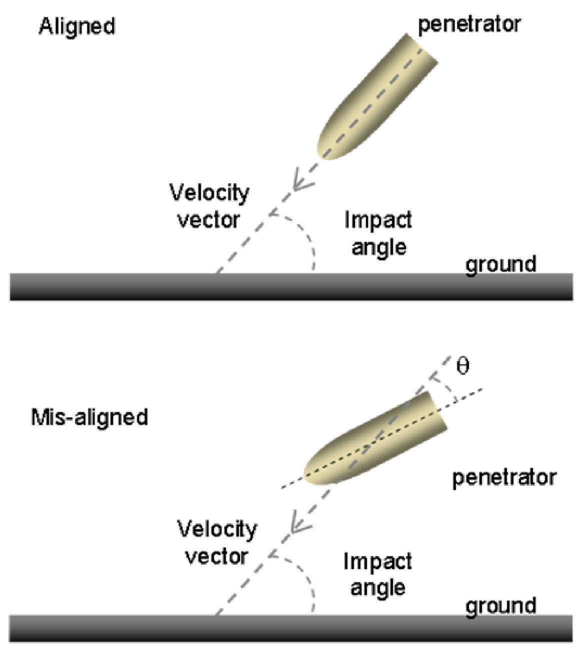

Figure 6. Penetrator alignment.

V. Lunar H2O Verification Mission

As an illustration of trading penetrator requirements and science return, and a demonstration of the advantage of the penetrator architecture, we now detail a hypothetical mission to the lunar South Pole to verify the existence of ground ice. A very similar mission to explore the existence of water at the lunar South Pole is the Lunar Crater Observation and Sensing Satellite (LCROSS). LCROSS is a value-added companion to mission LRO. Due to the cost, mass, and schedule constraints of LRO, LCROSS will achieve measuring water by observing an impact plume generated by sending the upper stage that carried both LRO and LCROSS to the moon into the lunar surface. Our sample mission assumes no such constraints and consequently is very different from LCROSS while performing similar goals. The budget for LCROSS is approximately half of a penetrator mission, due to its collaboration with LRO.

A. Mission Background

The primary goal of this mission is to verify the existence ground ice in the permanently shadowed regions of impact craters in the lunar South Pole and assess the distribution of water. Water ice brought onto the lunar surface from impacting bodies is proposed to collect in these craters, where they cannot be sublimated by sunlight. The location of accessible ground water will determine the site of future ISRU lunar outposts, and is therefore of great interest. The body of ground ice is presumed to start at a depth of 1.5 to 2 meters below the surface. The penetrator would have to burrow 2 meters, take a sample of lunar regolith, and measure the existence of water. The signal then has to be communicated back to earth.

The target location is one of the permanently shadowed craters in the South Pole; we chose the Shackleton crater. Shackleton is entirely within the South Pole-Aitken basin, which means its crater floors remain within the permanently shadowed zone. Shackleton is 12 km across and 2 km deep, located at 89.9ºS and 0.0ºE. The overall mission scenario is to drop enough penetrators to return a statistically valid yes or no result for lunar ice inside this crater.

B. Mission Development

Following the rules outlines in Section IV, the first task is to determine the penetration depth. This is easy: the science dictates that we want the penetrators to go between 1.5 m and 2 m. The second task is to determine the complexity of the science. Again, this is easy: we want a simple yes or no answer to the existence of water. The

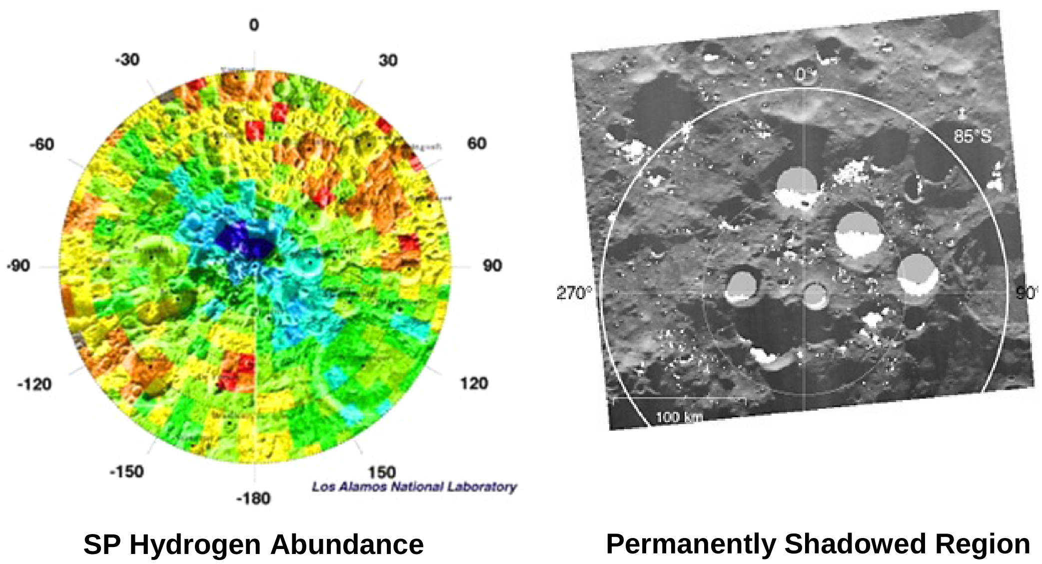

Figure 7. Left, Lunar Prospector data on the South Pole hydrogen abundance.[9] Right: Clementine data showing permanently shadowed regions in the lunar south pole.

instrument would involve a simple extendable scoop which can sample the regolith around the penetrator. An oven and a water sensor would do the actual water verification. In this case, the science has determined that the penetrators can be small and very simple.

This mission calls for carrying numerous small penetrators. The reason has to do with the uncertainties of the impact surface. There are two major uncertainties: the first is the penetrability of the target surface, and second is the uncertainty of the existence of water. We address surface penetrability first. The fluffy lunar regolith is thought to be a relatively hard substance, but whether the lunar regolith inside an impact crater is more like rock or soil is unknown. If we assume a rock like structure, the S number can be estimated from the following equation,

$$S = 2.7(f_c Q)^{-0.3} \tag{3}$$

where f_c is the unconfined compressive strength of the material, and Q the rock quality. The maximum compressive strength of lunar regolith is given as 3.5 Mpa, and Q is 0.2, similar to frost shattered rock. This gives lunar regolith an S number = 3.1, with the caveat that degree of cementation of the local regolith may preclude the use of Eq. (3). If the local regolith is very loose, it may be more appropriate to treat it as dry sand, whose S number is ~5. Radar imaging data indicate that the lunar surface have insufficient water content to reflect ice-like signature, so we do not expect the regolith to be frozen solid like an ice sheet, but it will be still be very cold (being permanently shadowed), and therefore hard but probably brittle. The real S number of lunar regolith inside Shackleton is difficult to estimate beyond a factor of 2. Sandia, for example, have used powdered concrete as a lunar regolith stimulant (solid concrete has a mean S-number of 0.9, and in powdered form, that number increases significantly, but is variable with compactification). Penetration velocity needs to almost double (from 235 km/s to 440 km/s) for a 2.5 kg mass to penetrate 2 m in a surface with S = 5 to a surface with S = 2.5.

A second uncertainty associated with surface penetrability has to do with unknown terrain features. From the various Apollo missions, we know that the surface of the moon is highly irregular. Some fields are flat and smooth, and some are strewn with boulders and rocks. A measure of surface roughness can be given by topographic undulations of the vertical relief per unit length, shown in Figure 7. The smoothest areas on the Moon do not have any features larger than 1 m in vertical relief, which means a very small chance of penetrator impact with a vertical surface. The roughest surfaces, however, have features with 1 m or greater vertical relief less than 10 meters apart, which enhances the destruction of the penetrators.[10] A penetrator grazing the edge of a boulder would shatter from the excess lateral impact. Lunar rocks are thought to be significantly harder than the regolith, and a direct impact with a boulder may expose the penetrator to excess g forces. Shakelton crater is a relatively small crater by lunar standards, and is not expected to have a smooth and featureless interior. However, it is also not expected to be as littered as the rough mare regions. A factor of 10 difference in terrain relief between the two extremes presents a high uncertainty in penetrator survival rate.

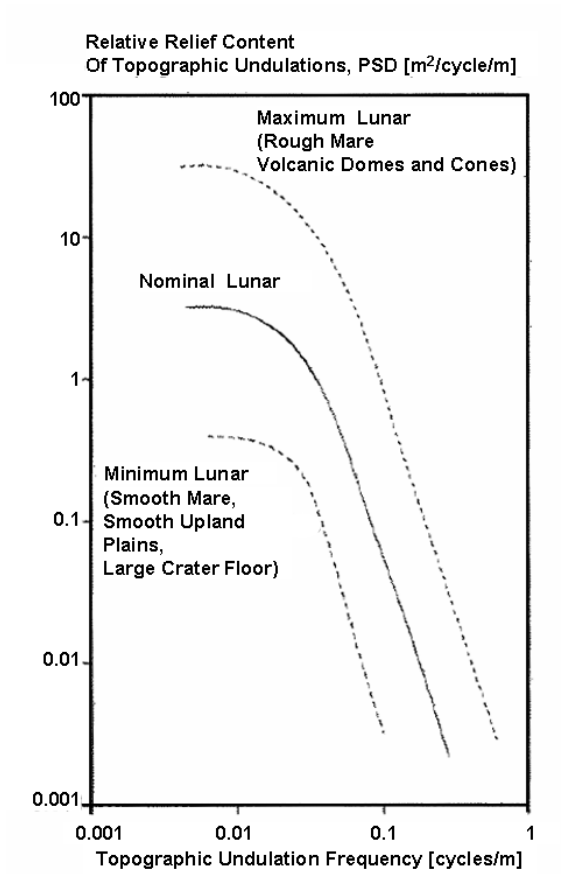

Figure 8. Relative relief of the lunar surface.[10]

The last uncertainty resides in the distribution of underground ice. Data from reflected radar measurements indicate that sample South Pole lunar crater interiors are not filled with ice sheets.[11] The interpretation is that the ice may be patchily distributed, or reside in thin layers beneath the surface. A more extreme interpretation is the there is no ice at all. Therefore, a single penetrator may be unlucky and land in a location, for whatever reason, lacks ice at the penetrated depth, or that the ice density is below the detection threshold. The risk of missing significant portions of ice must be mitigated by having first a spread in the penetrator locations, and also having a statistically significant number of penetrators at each location.

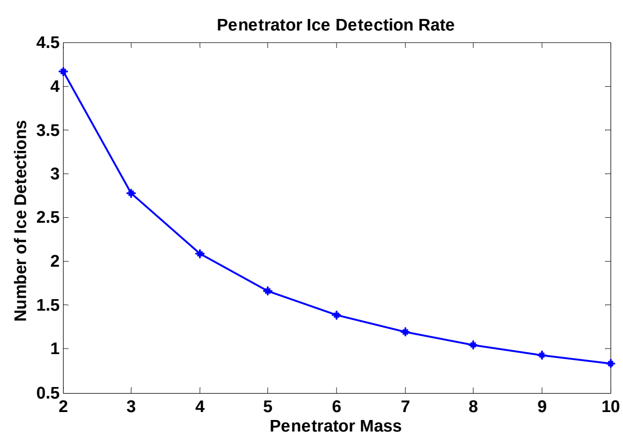

Figure 9. Probability of success. Assume 50% of penetrators fail, and 1 in 3 surviving penetrators detect water. Calculations assumes a total penetrator mass budget of 50 kg.

Taken together, we estimate that the survivability of penetrators is 50% due to surface uncertainty. Of the penetrators that do survive, 1 in 3 may return signatures of water. The details of the probability numbers can be modified, but the general message remains the same: water detection is a very strong function of the number of penetrators. For a space mission with fixed payload mass, this drives us to smaller penetrators. Shown in Figure 8 is the theoretical number of ice detections as a function of penetrator mass. For this graph, we assume that the carrier spacecraft is capable of lifting and inserting 50 kg of penetrators.

The uncertainty in the soil condition may be partially mitigated by having a range of penetrator masses. The penetrators can be loaded with dummy weights to produce, for example, two, three, and four kg penetrators. The different mass penetrators combined with similar impact velocities cover the uncertainty in the soil conditions to ensure that some penetrators will succeed. This concept also provides valuable ancillary science results regarding crater floor substrate conditions. The knowledge of penetrated depth, penetrator mass, and penetration time is a valuable indicator of surface hardness, boulder distribution, and may even give soil hardness profile. For example, if all the light penetrators fail on impact and only a few heavy ones penetrate, we know that the crater floor is much harder than we expected. If all of the penetrators survive and achieve the desired depth, we know that the surface is relatively free of rocks and now have a suite of instruments to measure the vertical ice content profile. If the light penetrators all achieve expected depth, but the heavy ones are shallower than calculated, then we know there is probably a hard layer of regolith right under the surface. Different mass loading on a suite of penetrators can provide a host of valuable information.

A fourth argument calls also for small penetrators. Due to the relative tilt of the Earth and the Moon, the monthly lunar nutation enables the Arecibo observatory in Puerto Rico to obtain line of sight with portions of permanently shadowed regions of the South Pole. This simplifies the communications process. This mission has a very low communications requirement, as the penetrator simply needs to provide a yes or no answer, and a percentage or concentration number. This low bit rate combined with the powerful receivers at Arecibo means we can eliminate the need for an orbiting communications platform. Our penetrator design has a 3 cm dish transmitting at 12 cm. This communications system is sufficient to be picked up by Arecibo at a low data rate (e.g. total data consisting of around 100 bits), which is sufficient to return simple mission status. If more information is desired, for example, transmission of a mass spectrum, the total data rate would be more consistent with 100 kbits. Each penetrator will have its own unique tone for each mission milestone: power on, deployment, impact, data collection. Upon impact, the scoop in the penetrator element will deploy, and collect the sample. The sample will be boiled in the oven, and the instruments will collect the data. At the end of data collection, the data collection tone will cease and the data will be transmitted. The complete data stream for each penetrator will be repeatedly transmitted until the batteries fail. This will allow the observatory to build up a signal over time. From impact to end of communication should be no longer than several hours.

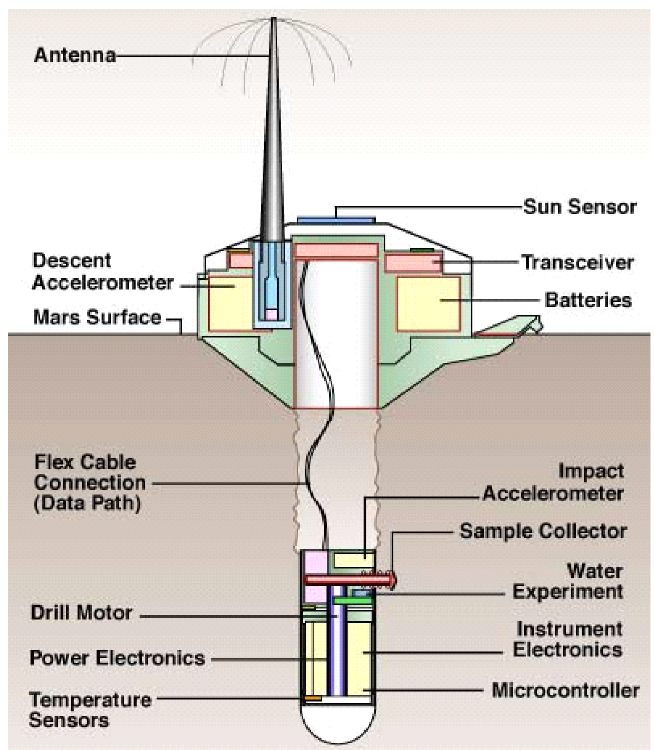

Figure 10. Details of the JPL DS2 penetrator.
Image credit: JPL/NASA.

The cost of developing this penetrator should be similar to the DS2 penetrators. In fact, the DS2 penetrators serve as very good first generation models on which the following engineering questions must be addressed to convert it to a lunar penetrator:

- **Adaptation to the lower temperatures**: the original DS2 microprobes were designed to operate at typical Mars temperatures. The cold traps on the Moon are much colder. The electronics and drill mechanism will have to be tested for operations in the much colder environment; the system may have to be adapted. It may happen to be that heating on board the carrier spacecraft might be sufficient; after all, they will not operate for very long. DS2 carried Two lithium-thionyl chloride batteries providing 600 mA-hr each to survive 1-2 days in Mars.

- **A new communications system**: the communications system will have to be built from scratch or adapted from existing systems. It will be very low power. Which radio observatory or observatories are used will have to be determined; it may even be that the 70-m DSN dishes could be sufficient to pick up the signal.
- **The battery system**: the battery system will have to be reviewed – in the original DS2 mission, the batteries only were used post-landing. We will want to turn on the microprobes prior to release, and transmit all the way to data return. This is likely to be a longer period of time than was planned on the DS2 mission. The DS2 batteries were 40 grams each, so we could achieve this by adding more batteries without significantly increasing the penetrator mass, but the batteries were designed to operate in -80ºC, whereas the lunar night has an average temperature of -150 ºC. One simple alternative is to restrict penetration to be performed during the lunar day.

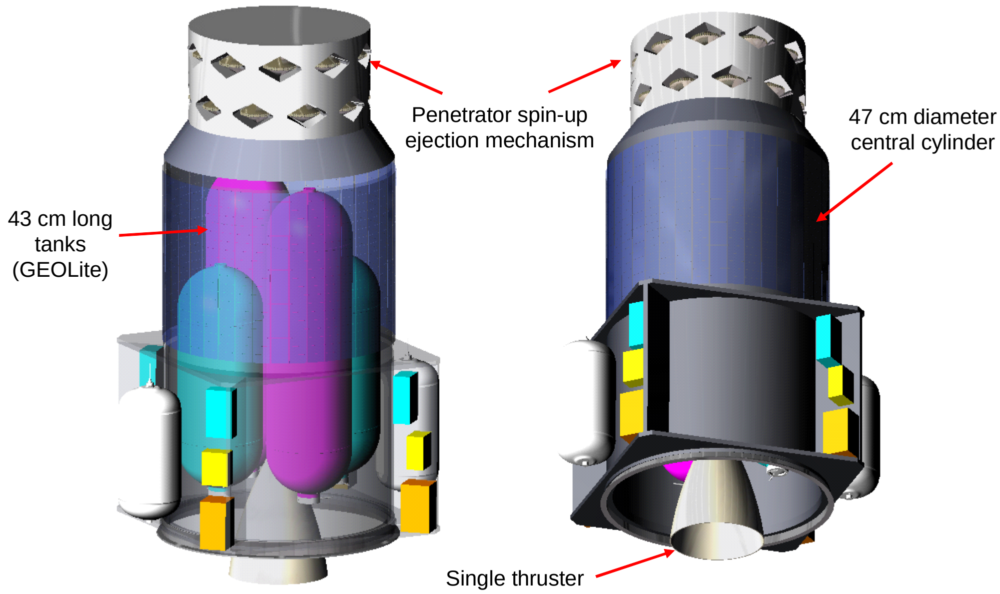

Figure 11. The Lunar H2O concept mission penetrator carrier spacecraft.

- **Instrumentation**: The easiest thing to do would be to use the existing DS2 water sensors. However, we may want to put a GCMS on a chip or similar instrument on board instead. We would have higher science return, though we would also have a higher data return, and we would certainly have a lower TRL. We might consider is whether to add other instrumentation. It is possible that an impact-resistant CCD camera could be used to do site survey, or that corner cube reflectors could be used for ranging.

The delivery mechanism is also an area that needs new development. Without an atmosphere to perform aerobraking, the lunar probes will have to be ejected from the carrier spacecraft with very little lateral velocity, at the appropriate height so that free fall will give the penetrators the proper impact velocity. An ejection mechanism that spins up the penetrators is the simplest stabilization concept. Our current concept uses a spring loaded, circular ejection housing to push out penetrators in a circle around the carrier spacecraft, shown in Figure 11. The horizontal velocity of the penetrators will determine the spread area, and impact angle. The exact height above the lunar surface at release will determine the final horizontal velocity to penetrate to the required depth. In fact, this is an added layer of control that enables better precision in penetrator depth control.

The carrier spacecraft needs to perform a deorbit to within approximately 10 km of the surface. This should not be a very intensive task, as this is very similar to executing a soft landing, without the impact and touch-down hazards of a soft landing. The precise landing location can be quite flexible, since the penetrators are to be spread out, and Shackleton has a diameter of 12 km. A spread zone of 3 to 5 km for the penetrators easily gives good statistical coverage. Moreover, if different penetration depth is desired, the carrier spacecraft can eject penetrators at different heights to achieve different impact velocities, or impart larger horizontal velocity for the same. The carrier spacecraft may also sweep in at an angle and eject penetrators along a horizontal trajectory. This will ensure that penetrators are distributed along the floor of the entire crater, increasing the certainty of the result by covering a larger percentage of the crater.

The main events of our sample mission is summarized in the following table.

Sequence of Lunar H2O Mission	
1	Launch
2	Lunar trajectory control maneuvers
3	Lunar orbit insertion to 100 km orbit
4	Lunar orbit corrections to 40 km orbit
5	De-orbit burn at 40 km
6	Descent maneuvers to 10 km
7	hover maneuvers at 10 km
8	penetrators turned on
9	penetrators ejection
10	penetrator free-fall and impact
11	penetrator experiment conduction
12	penetrator transmission until battery death

VI. Conclusion

Penetrators are emerging as a cost effective tool to sample planetary surfaces. In this paper, we have summarized the advantages of using penetrators, namely simplified mission development, operation, and cost. We have outlined the trade space for penetrator missions, and developed some guidelines for trade space selection. The main trades involve penetrator size, the number of penetrators, and the delivery mechanism. The carrier spacecraft is also an important piece of the overall architecture.

Penetrators are ideally suited for high risk ground truth verification. They are currently limited primarily by their maximum sustainable g-loading. Increasing the g-load capabilities will increase the utility of penetrators. Miniaturization and improving the shock tolerance of instruments will also broaden the utility of penetrators. At the heart of penetrator science is a better understanding of planetary surfaces. Having more penetrator missions will also improve the data regarding the penetrability of other planetary surfaces, and therefore decrease the risk of successive missions. Penetrator technology is becoming a precision science capable of increasing our knowledge of other planetary surfaces exponentially, and should be included as an essential part of plans to explore other worlds.

Acknowledgments

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