KINETIC PENETRATORS FOR EXPLORATION OF SOLAR SYSTEM BODIES

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ABSTRACT

We report on the potential usefulness of kinetic penetrators for the exploration of various types of Solar System bodies, including planets their satellites, and near Earth objects. We consider their potential scientific return, resource requirements and costs compared with soft landers, and outline their heritage and current state of development. Following the recent round of proposals for the European Space Agency Cosmic Visions, penetrators have been put forward for three missions: the Moon, Europa and Titan. Each situation involves a number of unique challenges which will be addressed in the presentation. The paper also includes technology roadmaps for various penetrator science instruments and key penetrator technologies (such as batteries and radioisotope heating units).

1. INTRODUCTION

The current rapid pace of technology advance combined with the expected change of emphasis from orbital to ground truth exploration of the Solar System is seen as an appropriate time to begin development of kinetic penetrators which potentially provide access to key science with pre-cursor missions for a great variety of planetary bodies. In fact, it is difficult to envisage any other method which allows widely spaced surface exploration of airless planetary bodies that is not prohibitively expensive.

We consider kinetic penetrators which are small probes around 2 to 13Kg that impact planetary bodies at high speed around 200-300m/s, and bury themselves a metre or so into the planetary surface. For such impact speeds it is necessary to employ technology able to withstand gee forces around 10kgee or higher. In addition, it will often be necessary to employ de-orbiting devices to slow down the probes prior to impact, together with attitude control to provide near vertical alignment to ensure both penetration and survival of internal components.

Their small size allows many probes to be deployed, which naturally provides redundancy so no mission is vulnerable to the loss of a single probe. Whilst their small size does not allow a full complement of the most capable scientific instruments, they are ideal to perform focused investigations across widely spaced surfaces of a planetary body not currently feasible with soft landers and rovers. For example:-

- For the Jovian satellite Europa and Saturnian satellites Titan and Enceladus, seismometers could determine the presence of an under-ice oceans and lakes, which could provide a possible habit for extraterrestrial life, and with chemical detectors the presence of associated local or upwelled organic material.
- For the Moon, a seismic network could provide information into the origin of the Earth-Moon system, and thermal and chemical detectors ground truth to the existence of water and other volatiles in permanently shaded areas in polar craters. The seismic suitability of sites for Lunar bases, and the potential presence and usefulness of in-situ resources could also be characterized.
- For NEOs (Near Earth Objects) accelerometers in particular would be of particular benefit to confirmation of whether they are rubble piles consisting of rather loose agglomerates of rock and dust, or hard rocky bodies as originally thought.

Whilst historically there has been no successful deployment of a high speed penetrator, and the only deployment, DS-2 (Deep Space-2) failed along with its companion lander, there is actually no evidence that these are inherently less reliable than soft landers. The only other mission to launch kinetic penetrators was the Russian Mars'96 mission which failed to leave Earth orbit due to a fault unrelated to the penetrators. Other penetrator missions include the Japanese Lunar-A which has now been cancelled but whose penetrators may be incorporated into the recently announced Russian Lunar-Glob mission [1,2].

Though the technology is challenging, it is to be noted that the above probes, together with the Japanese Lunar-A probe, have already been successfully constructed and space qualified [3,4,5]. This includes demonstration of survival at these impact speeds by ground tests of the full-up DS-2 and Japanese Lunar-A probes, and extensive military experience of firing instrumented shells into materials consisting of sand, concrete, steel and ice. Also, with major development costs no longer necessarily required, and the low mass of such probes which substantially reduce launch costs, this provides an excellent basis for future low cost missions.

In addition, it is likely that significant elements of technology developed for airless penetrators will also benefit exploration of planetary bodies having atmospheres, for which robustness and very low mass are always advantageous. The rapid pace of technology is also likely to lead to significant further improvements in miniaturization, which together with the challenge of high-gee survivability will stimulate technology innovation with potential spin-offs.

2. POTENTIAL SCIENTIFIC RETURN & INSTRUMENTS

The potential scientific return from kinetic penetrators is very high, in particular for multi-site investigations spaced globally across planetary surfaces for which the cost of soft landers would be prohibitively expensive; pre-cursor single site investigations; and ground truth for orbiting investigations.

Global multi-point investigations allows single mission investigations into various surface geological features such as upland regions, frozen lakes, ices, plains and around fissures which could contain upwelled astrobiologically interesting material. Other important multi-point investigations include the setting up of a seismic network which allows characterization of the deep interiors of the bodies including the presence and nature of a core, and detection of potentially habitable subterranean oceans.

The potential scientific return from each individual site can include geological and chemical characterization of the sub-surface material and the detection of water and other volatiles. The penetration depth of a few metres can provide access to material which has been protected from cosmic ray or other surface transport affects. Penetrators allow such key science to be achieved cost effectively and for landing sites not suitable for soft landers.

Ground truth potential for penetrator measurements is high. Many orbital instruments provide global information for which a single or a few direct multi-point measurements can provide calibration or confirmation information. For example, interpretation of ground penetrating radar results can be greatly aided by direct determination of the permittivity of the soil from penetrator measurements [6]. Ground truth can be key in cases where remote observations have ambiguous interpretations, such as the case for the existence of ice in the lunar cold traps. Direct ground observations also allows orbital information (e.g. regarding inference of internal planetary cores and subterranean oceans) to be characterized as well as confirmed.

In particular, a modest payload of a few Kg can provide the following information:-

- **Accelerometers** provide information on the mechanical structure of the surface material and allow the penetration depth to be determined. For asteroids and NEO (Near Earth Objects) this could provide important information to distinguish whether the objects are conglomerates of loosely bonded rubble piles, or much more solid rock. The structural strength of the surface can also be important for later soft landers.
- **Seismometers** together with an associated tilt-meter can provide information on the internal structure and seismic activity levels of the planetary bodies. In particular, they allow probing for the existence of subcrustal oceans far below that which orbiting radar can penetrate; determine the existence and structure of a possible inner core to the planetary body; and characterize the seismic activity associated with tidal and possible volcanic activity. For the Moon they can also provide information on the geographical location and nature of the enigmatic shallow quakes of whose origin is not clear and which would be strong enough to cause concern for the siting of lunar bases. An alternative for detection of crustal movements could be the placement of beeping transmitters, with interferometric analysis of direct signal detection from Earth.

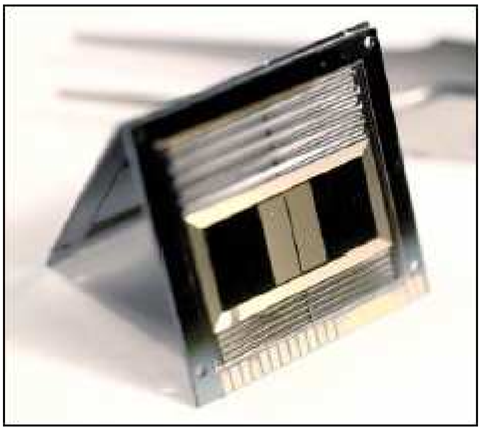

Figure 1. Microseismometer etched from single silicon wafer (20mm die) (Imperial College London).

- **Thermometers and thermal conductivity probes** positioned along the body of the penetrator and/or from the surface via a trailing aerial, allow sub-surface temperatures to be determined which can be important in determining the presence of water, and characterizing the internal body heat-flow which relates to the internal composition and structure of the planetary body. For the permanently cold traps on the Moon, the existence of sub-surface temperatures very close to those on the surface could provide strong indirect evidence for the existence of water, since even very low concentrations (e.g. 0.1%) would be expected to reduce the temperatures expected at around 20-30cm depth by around 50-60 degK [7]. Measurement of conductivity (via e.g. small heaters) can provide basic information on the sub-surface material, important to heat flow interpretation.
- Measurement of sub-surface material **permittivity** is important to interpretation of orbital measurements with ground penetrating radar which are suitable for detecting relatively shallow features down to a perhaps a few tens of Km.
- An internal **mineralogy/astrobiology** camera allied with led light sources (e.g. UV) via a lensed window can provide mineralogy information and the presence of material of an astrobiologic nature via UV fluorescence of (RNA/DNA) [8].
- A **geochemical package**, including mass spectrometers (fig.2), can provide information on the presence and concentration of water, volatiles, inorganic, organic and refactory materials. This can include strong indicators of the presence of astrobiologic material, and with sufficient resources could allow isotopic determination of the origin of any water (e.g. for the Moon could allow could allow differentiation between cometary and Earth origin.)

70mm

Figure 2. Prototype ruggedized ion trap mass spectrometer. (Open University, UK)

- A **magnetometer** could provide information on the internal structure of the body, and e.g. on the Moon a measurement of the remanent magnetization.
- A **radiation detector** could provide important information about planetary differentiation as well as characterize sites for later manned exploration, and to provide an astrobiological context.
- A **descent camera** can provide geological context information of the impact site.

3. PROS AND CONS COMPARED WITH SOFT LANDERS

Pros of kinetic penetrators include :-

- Provide a good stable base under surface for investigating material not modified by local surface effects such as high radiation and cosmic rays. This includes solid implantation for seismometers, without requiring extra mechanisms and resources, and naturally protected from perturbing winds.
- Low mass allows multiple probes to investigate a wide variety of geological features and provide a seismic network not possible with single soft lander.
- Inexpensive compared with soft landers. Lower mass because requires less deceleration fuel, and mechanisms for landing, access to undersurface material and provide solid implantation, are either eliminated or greatly reduced. Low mass reduces launch costs, increases ability to launch multiple probes on a single mission, and multiple probes provide natural redundancy. Reduced complexity leads to lower development costs (c.f. Mars polar lander and DS2). Largely autonomous operation greatly reduces operation costs.

- Ruggedisation and multiple probes allows targeting of landing sites not possible with soft lander (e.g. highlands, icy terrains, lakes, deserts, fissures)
- Able to support future soft landings by providing surface characteristic measurements, seismic appraisal of landing sites (e.g. Lunar bases), and low cost determination of in-situ resources (e.g. water on Moon).
- Less temperature variation.

Cons of kinetic penetrators include :-
- The scientific capabilities of penetrators are more restricted due to ruggedisation needed.
- No solar power available for single body penetrators.
- No above surface view/science.
- It is more difficult to ensure communications because of the buried nature of the penetrators. Though some materials, such as the lunar regolith, are expected to be no significant barrier to communications, others may require deployment of a trailing aerial.

In general, kinetic penetrators are ideally suited to pre-cursor investigations of planetary bodies, including multiple diverse geophysical sites and provision of seismic networks, to provide key science at low cost. Soft landers can provide additional important scientific capability, including roving ability, at specific localized regions but with more restricted landing site constraints and much greater cost.

4. ARCHITECTURE & KEY TECHNOLOGIES

A penetrator archictecture may consist of the following 3 major elements:-

1. Spacecraft support and ejection system.
2. Descent Module
3. Penetrator

The Spacecraft Support and Ejection System provides a mounting for the descent module on the spacecraft, and an ejection system to deploy the module. In addition, the spacecraft may also have to provide power and communication facilities to enable checkout of the descent module prior to deployment; and most likely communications to the descent module during deployment to provide confirmation of deployment maneouvres. Communications may also be required to accept images taken with a descent camera, though, considered likely that such images will be stored within the penetrator for later transmission. Finally, support may be required to provide communications with the penetrator after impact.

The Descent Module consists of the penetrator and the necessary PDS (Penetrator Delivery System) which is designed to ensure impact of the penetrator on the planetary surface at an acceptable velocity and orientation (See Fig.3). Sufficient mis-orientation of the long axis of the penetrator with its velocity vector (attack angle) can set up harsh vibrational gee forces internally in the penetrator which could cause serious damage. The PDS system may consist of a de-orbiting system (e.g. motor), ACS (attitude control system), a penetrator separation system, and a descent camera. A penetrator separation system is designed to eject the de-orbit motor, ACS system, and any camera prior to impact so that it lands sufficiently far from the penetrator to avoid contaminating the impact site. The descent camera is designed to take images of the impact site prior to landing to provide geological context to the later penetrometer measurements, and also provide good public outreach.

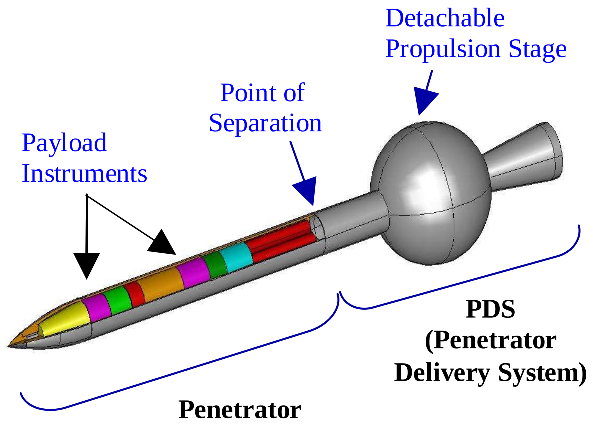

Figure 3. Penetrator Descent Module Schematic

The Penetrator is the only body which has to survive impact, and consists of the protective shell, subsystems and scientific instruments. The protective shell is designed to survive without deformation in order to prevent mechanical damage to internal components, though all internal subsystems will feel the deceleration, but could be protected from some high frequency deceleration spikes. The support subsystems will consist of power and thermal control, communications (for telemetry and commands), and data handling.

All technologies for the penetrator system are ‘key’ though particular aspects may be seen as more critical than others.

‘Key’ aspects of the above technologies include:-
- **Ruggedness:** The penetrator and all its subsystem have to survive gee forces of the order of 10kgee or more. Though many subsystems such as accelerometers, data handling systems and scientific instruments have been shown to survive these forces we propose some lower mass technologies such as

seismometers and geochemical instruments which require development and qualification at these levels.

- **Lifetime (power, thermal):** The ability to provide sufficient power to operate the penetrator long enough for in particular seismic observations is a challenge for such small penetrator masses, and in particular to operate in sites where the local temperature may be very low around 50-100K. Power options include solar cells, fuel cells, batteries and micro RPS (Radio-isotope Power Supplies). However, solar cells require an aft body to remain on the surface such as for DS-2 [5], which is thought to introduce a large element of risk into the penetrator design. Also, for outer solar system bodies such as Europa and Enceladus, the solar emission is extremely weak, and for lunar cold traps there would not be any sunlight at all. We have not yet evaluated fuel cells in detail though these could be promising. We propose batteries which have previous ruggedness and space heritage, though do not operate well in low temperature environments. To counter this, comprehensive thermal insulation allied to using some of battery power, or RHUs (Radioisotope Heating Units) which are very robust and low mass, could be used to keep the batteries warm. Micro-RPS's (Radioisotope Power Supplies) could probably provide the best solution with the longest lifetime when they become an available choice.
- **Mass:** To achieve a system which is low mass, capable, and rugged is a particular challenge. This is thought to be particularly applicable to the ACS system (which has to achieve acceptable impact and attack angles). Seismometers are also receiving particular attention regarding mass to achieve ruggedness without seriously compromising performance, and low mass power (batteries) of sufficient capacity.
- **Data Handling:** In particular, seismometers can generate a great deal of data that requires compression and careful selection of events if not to exceed expected telemetry rates. One approach for the Lunar case is to heavily wavelet compress the initial data which is then telemetered to Earth where particular events can be selected by hand and then re-transmission requested at fuller resolution. For more distant planets, selection could be performed autonomously on an orbiter. For the happy situation where many events are recorded, it may be that there is insufficient telemetry to transmit all events.
- **Long Cruise Phases:** For outer solar system bodies where cruise phases from earth to the selected bodies can be around 6-10 years it may be that consideration to stability of materials such as solid fuel propellant needs to be considered, whether by thermal or radiation induced chemical degradation.
- **Communications:** Communications from a few metres beneath planetary surfaces could be subject to considerable degradation depending on the material. Though signal attenuation this is not thought to be significant for dry lunar regolith, or icy regolith at the expected concentrations expected, further studies are planned, including the possibility to leave a trailing aerial on the surface. Such an aerial would be deployed from the rear of the penetrator to limit stresses on the wire during deployment; a technique which has extensive heritage in the defense sector.

However, key technologies also differ depending upon the solar system body targeted, and some of the major differences are listed below:-

- **Moon:** A very short cruise phase and communication links together with world class science make it an ideal target for a first mission. In addition, the similarities in gravity and very low temperatures at the polar cold traps provide considerable common ground for the technologies to meet the needs of the bodies below.
- **Europa:** This moon of Jupiter has a surface material believed to consist mostly ice of uncertain consistency but could be very hard requiring qualification at higher gee forces, reduced impact velocity, or introduction of shock load reduction methods. Also, the radiation environment for a Europa mission is very high around several Mrads, though penetrators, being constructed of thick, dense, material implanted below the surface are much less vulnerable than orbital instruments.
- **Enceladus:** This is a small moon of Saturn with very low gravity, but very difficult to access requiring a very large delta-V of around 3.8Km/s [9]. This implies a large mass to provide the deceleration of the order of 5 times the dry delivered mass. However, since penetrators are very low mass compared with orbiters, they become an attractive proposition for this world, providing in-situ science in combination with flyby spacecraft.
- **Titan:** This is a moon of Saturn which is similar to Earths' Moon in size but has a very thick atmosphere with a surface pressure greater than that of the Earth at its surface [9]. This could result in significant perturbing and braking forces for a penetrator which could affect its terminal velocity and attitude control. A detailed study is yet to be performed to assess these affects, but could lead to a quite different descent system. (E.g. a motor might instead be required to apply forward thrust to access sufficient penetration, and fins for orientation, though this technology would actually have considerably more heritage with existing Earth based systems. A particular advantage for the use of

motor descent compared with balloon based system is the ability to ensure specific targets.)

5. RESOURCE REQUIREMENTS

Most of the science return can be achieved with a relatively modest payload of around 2Kg as shown by the mass estimates given in Table 1 which are based on existing space instruments, except for the ground camera system which is based on relatively simple adaptations of working Earth based instruments. However, the total mass of the impacting penetrator should also include the structure, power data handling and communication systems, which is heavily dominated by the power/lifetime requirements and the power/thermal insulation technology. Both DS-2 and Lunar-A penetrators were designed for the ~200-300m/s impact speeds considered here and were 3.6Kg and 13.5Kg respectively. In addition to this is the mass of any required de-orbiting motor, attitude control system, and spacecraft attachment and ejection system. This mass is heavily dominated by the de-orbiting requirements, and for deployment from lunar orbit the mass of these extra elements is around 2x that of the penetrator.

Table 1. Possible Penetrator Science Payload

Penetrator Payload Instrument	**Mass (g)**	**Power* (Whr)**	**Heritage**
Descent Camera	10	0.01	Beagle2, ExoMars
Accelerometer and Tiltmeter	66	0.002	DS2, Lunar-A
Geochemistry package	260	12.0	Beagle-2 XRS
Water-Volatile Experiment	750	4.1	DS2, Ptolemy (Rosetta)
Seismometer	300	464.0	ExoMars
Thermal/Heat Flow	300	1.0	Lunar-A
Permittivity	~100	-	IWF (Graz)
Mineralogy/astrobiology camera	~200	-	Ground based (USA)
Magnetometer	60	-	Various space missions
Total Penetrator Payload Mass	**~2Kg**	**~480**	

Note: * Integrated power usage over 1 year Lunar mission.

Power estimates have been provided for the 1-year duration ESA Cosmic Visions LunarEX proposed mission to illustrate the dominance by the seismometers which is the only instruments requiring extended continuous operation, and estimated to require ~96% of the total power budget of 481Whr. The other dominant power requirement may be to counter heat losses on very cold sites, if extended lifetimes are required. For these situations, additional power sources may be required together with extra mass.

The estimated cost to produce the DS2 probes was ~$28M and for the Lunar-A penetrators ~$135M [4,5]. However, we feel there is now considerable scope for much lower cost developments. Firstly, by utilizing extensive UK defense experience of military instrument shells including highly predictive modeling (including hydrocode techniques) to greatly reduce the need for extensive trials. Secondly, by taking advantage of the previous penetrator developments, including reduction of the number of option studies to the most promising. Finally, the developments required for a technical demonstrator lunar mission will greatly reduce the developments needed for e.g. a Europa or Enceladus program. This is especially applicable for the case of the cold polar traps which closely resemble the temperatures expected on these outer Solar System bodies.

The cost of the corresponding Mars Polar lander development was estimated at £110M which is almost 4x that of the DS-2 microprobes. In addition, $10M was estimated for Mars Polar Lander operations. Also, because of the largely autonomous operation of penetrators, operational costs would be expected to be considerably lower.

6. CURRENT STATE OF DEVELOPMENT & HERITAGE

We lead a largely UK penetrator consortium which is gradually being internationalized, and is currently funded for a 3 year development period. The consortium is currently engaged in developing a baseline penetrator design verified by modeling, leading to a full scale ground impact demonstration currently scheduled for 2008. These developments are based around a U.K. lunar (MoonLITE) mission initiative and LunarEX Cosmic Visions proposal [10] which provide very strong science as well as a technical demonstrator mission. Such developments will additionally provide a good and timely foundation for further delta developments necessary for either of the other Cosmic Visions proposals LAPLACE to Europa [11], or TANDEM to Titan and Enceladus [9], that we are involved in.

A **technology roadmap** has been developed consisting of 5 phased elements to build up capability and confidence in the technology:-

a) Modeling: Development of a baseline penetrator design in accordance with a Lunar technology demonstrator mission, using sophisticated modeling including hydrocode. This modeling will be highly predictive, allowing cost savings by reducing the number of expensive ground based trials. During this phase relatively cheap gas gun trials will be performed for small elements.

- **b) Ground based trials:** will be performed at full impact velocities for whole penetrator. Initially, this will qualify the penetrator structure, and later the platform and scientific instruments. Additional trials will be undertaken at unit level.
- **c) Full scale qualification programme:** will be performed with a complete penetrator a system.
- **d) Lunar Mission:** A Lunar mission is envisaged as the cruise phase and the communications links are very short, and the potential science return is very high, making this a very attractive target. It also will qualify many of the systems prior to high profile science missions to more distant solar system bodies.
- **e) Follow-on Science Missions:** These will require only the delta developments needed for the specific targets which differ from the Moon as discussed earlier, thereby providing significant cost savings.

This also includes significant parallel activity to forward the mission definitions to allow feedback into the technical developments, and because of the long lead times for such mission opportunities.

Though most of the instruments have space heritage, significant ruggedization will generally be required, and the technology program is currently focused on bringing all instruments and subsystems up to ESA (Technology Readiness Level) TRL 5, which is appropriate for entry into a phase-B for a specific mission development. It is also aimed at refining the instrument performance levels and required resources, in particular mass, power, and telemetry.

The current development program is funded to achieve the penetrator structure developments, together with associated thermal and data handling system studies. Bids to develop the instruments and other systems are currently being prepared.

We are also exploring potential science return from such penetrator missions, leading to additional or improved measurement performances. This recently resulted in a conceptual instrument capable of investigating both mineralogy and astrobiologic material; how simple temperature measurements could be very sensitive to the presence of even small amounts of water [7]; and how our seismic view of the Moons farside interior may change [12]. We have also identified how penetrator measurements can support orbiting instruments, with soil permittivity measurements to help interpret orbiting ground penetrating radar observations; and seismic observations to aid orbiting magnetometer and gravimetric observations relating to the celestial body interiors.

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