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Penetrators for in situ subsurface investigations of Europa

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Abstract

We present the scientific case for inclusion of penetrators into the Europan surface, and the candidate instruments which could significantly enhance the scientific return of the joint ESA/NASA Europa-Jupiter System Mission (EJSM). Moreover, a surface element would provide an exciting and inspirational mission highlight which would encourage public and political support for the mission.

Whilst many of the EJSM science goals can be achieved from the proposed orbital platform, only surface elements can provide key exploration capabilities including direct chemical sampling and associated astrobiological material detection, and sensitive habitability determination. A targeted landing site of upwelled material could provide access to potential biological material originating from deep beneath the ice.

Penetrators can also enable more capable geophysical investigations of Europa (and Ganymede) interior body structures, mineralogy, mechanical, magnetic, electrical and thermal properties. They would provide ground truth, not just for the orbital observations of Europa, but could also improve confidence of interpretation of observations of the other Jovian moons. Additionally, penetrators on both Europa and Ganymede, would allow valuable comparison of these worlds, and gather significant information relevant to future landed missions. The advocated low mass penetrators also offer a comparatively low cost method of achieving these important science goals.

A payload of two penetrators is proposed to provide redundancy, and improve scientific return, including enhanced networked seismometer performance and diversity of sampled regions.

We also describe the associated candidate instruments, penetrator system architecture, and technical challenges for such penetrators, and include their current status and future development plans.

Keywords: Penetrators; Europa; Astrobiology; EJSM

1. Introduction

1.1. History and motivation

Europa, the smallest of the four Galilean moons of Jupiter, has been investigated remotely both by flyby missions passing through the Jovian system, Voyagers 1 and 2 (both in 1979), Cassini-Huygens (2000, en route to Saturn), and New Horizons (2006, en route to Pluto), and by the Jovian Orbital mission Galileo between 1995 and 2003. The latter made a series of close targeted flybys of Europa during the mission, acquiring the highest spatial resolution data thus far. However, there has been no in situ investigation of the surface or subsurface materials and environment. Recent proposals by both NASA and ESA (Blanc et al., 2009), have been united to form the 'Europa Jupiter System Mission' (EJSM, 2009) proposal, within which there will be orbital platforms targeted to both Europa (JEO, 2009) and Ganymede (JGO, 2009). The payloads of these orbiters provide scope for provision of lightweight surface elements which could be in the form of penetrators, that are the focus of this paper.

As summarized in Gehrels (1976), through Greenberg (2005) to Bagenal et al. (2007) and Pappalardo et al. (2009), Europa has long been an object of particular fascination. Its high albedo at both visible and radio wavelengths indicate that it is a body with an icy surface, despite its comparatively high density. Images from the Voyager spacecraft revealed an extraordinarily smooth body, virtually free of both significant topography and of impact craters, suggesting a geologically young surface – perhaps resurfaced by the eruption of liquid water through the many reddish-brown lineaments that criss-cross the surface.

The Galileo mission transformed our view of Europa again, providing remote data which has been used to infer the satellite's internal structure, and to determine the composition (in particular the spatial heterogeneity) of non-ice substances on the surface. It now seems that parts of Europa's surface are very rough, and that some significant topography exists, for example at Castalia Macula there are mountainous features with elevations approaching 1 km (Prockter and Schenk, 2005). Furthermore, the lack of impact craters also implies a lack of significant regolith (Moore et al., 1999).

Nonetheless, it is clear that Europa is an extremely attractive target for closer scientific investigation, arguably more so than any other object in our solar system. Whilst several large icy satellites appear to have vast global oceans of liquid water deep underground, it is only on Europa that this ocean seems likely to be in direct contact with the warm rocky interior, perhaps 150 km beneath the surface. Inside all of the other icy bodies, the oceans are thought to be sandwiched between shells of low pressure ice (above) and high-pressure ice polymorphs (below). Moreover, the outermost icy crust of Europa appears to be comparatively thin (of order 10 km). These two factors make Europa's ocean, protected from the harsh radiation trapped in the Jovian magnetosphere, an environment of very high astrobiological interest (Kargel et al., 2000; Marion et al., 2003; Lipps and Rieboldt, 2005; Greenberg, 2005; Raulin, 2005). On the ocean floor, high-temperature water–rock interactions may synthesize complex organic chemicals and produce energetic compounds that can drive the electron transport chain we call 'life' – in other words, food (Lowell and DuBose, 2005; Abbas and Schulze-Makuch, 2008). Such hydrothermal systems are known to occur on the

Earth's ocean floors, and these are frequently hotspots of biological activity. Similarly, photolysis and radiolysis of surface ices also produce organic chemicals and energy-rich compounds, such as ozone, hydrogen peroxide, and acetylene. These substances may be mixed downwards to the top of the subsurface ocean through tectonic cracks, or during periodic penetrations of the crust by impactors (cf. Cox et al., 2008; Hand et al., 2007; Shapiro and Schulze-Makuch, 2009).

The exchange of matter between ocean and surface is not uni-directional. The reddish-brown stains on the surface are closely related to geological features that are indicative of endogenic activity, and hence suggest a contaminant transported from beneath the surface, possibly from the subsurface ocean. Were this material to be exogenic in origin, we would expect a more uniform distribution, on a hemispheric scale, than is observed. It is possible, therefore, that evidence of any biological activity might also be delivered to the surface (e.g. Figueredo et al., 2003; Chela-Flores, 2010). It is no longer necessary to consider complex and expensive submarine missions to Europa (e.g. Powell et al., 2005; Böttcher et al., 2009), when a near-surface investigation may be able to answer many of the geophysically and astrobiologically pertinent questions that we outline in the following section.

Whilst orbiting instruments can further investigate the nature of Europa's surface and interior, currently only in situ instruments offer the realistic possibility to detect any evidence of life. The rough surfaces and extreme cold, together with an extreme radiation environment mean that Europa is a challenging, but not impossible, object for in situ measurements. The penetrators described here (those of relatively low mass; ~5–15 kg) are better suited to these conditions than a soft lander, since they are buried on impact in the near-surface regolith, thereby automatically accessing areas subjected to a significantly reduced radiation flux, whilst easing radiation shielding requirements.

As we shall describe, despite the high impact forces experienced on delivery of the penetrator, they are nevertheless capable of incorporating a diverse and capable scientific payload. The in situ observations we propose will yield more direct information on, for example, the geophysics of Europa, using seismometry, as well as mineralogy, chemistry, mechanical, and electrical properties of the surface/subsurface material, and the magnetic, thermal and radiation environment. Also, the directly obtained information on the physical and thermal structure of the ice shell will provide the first data to constrain the rheology of Europa's crust, effectively making the satellite a natural laboratory for understanding the visco-elastic properties of ice at true planetary strain rates; such data will have broad applicability to all other icy bodies in the Solar System. Indeed this work may well be of relevance to future exploration of the Saturnian system (cf. Coustenis et al., 2009). Additionally, penetrator data complements the measurements made from orbit, and provides ground truth not just applicable to Europa, but also to interpreting observations of other icy Jovian moons.

1.2. Penetrators

We consider here low mass (~5–15 kg) probes, delivered to planetary body surfaces by a Penetrator Delivery System (PDS), for hard impact at around 100–300 m s^{-1}, to embed the penetrators in the surface. Unlike simple impactors, penetrators are designed to survive impact and subsequently perform scientific observations. The scientific data would then be telemetered through any overlaying surface material up to an orbiting spacecraft, or possibly at a considerably lower data rate directly to the Earth. Their low mass and ability to be duplicated at low cost, make them an attractive option for vanguard explorations of solar system bodies, and to enable multiple deployments to enable a geophysical network or investigation of diverse terrains.

A particular challenge for penetrators is to survive the impact forces of around 5–50 kgee (where 'gee' is the unit of acceleration equal to gravity at the surface of the Earth, to avoid confusion with 'kg'), which require sufficiently ruggedized scientific instruments.

1.3. Heritage

Though there has yet been no successful planetary penetrator mission, three systems which have been developed and tested on the ground are Deep Space-2 (DS-2) (Smrekar et al., 1999; Smrekar et al., 2001), Mars'96 (Surkov and Kremnev, 1998) and Lunar-A (Mizutani et al., 2001; Mizutani et al., 2005). Of these only DS-2 was deployed, and failed for reasons unknown along with its carrier soft lander. The Mars'96 spacecraft failed to leave Earth orbit; and Lunar-A was cancelled after an extended development period, but after a full ground test of the penetrator was demonstrated. Together with very mature terrestrial (defense) applications of instrumented packages at such high impact velocities into similarly hard targets, a significant technology base of both platform and scientific instruments already exist.

In May 2008 the UK penetrator consortium demonstrated a first successful full scale trial with impacts at over 300 m s^{-1} into a lunar regolith sand simulant (Smith et al., 2010). This trial demonstrated survival of the penetrator shell, power system, accelerometers, magnetometer, radiation detector, micro-seismometer sensors; and mass spectrometer and drill components. The consortium (website: http://www.mssl.ucl.ac.uk/planetary/missions/Micro_Penetrators.php) is formed of experienced space instrument and system providers allied with the defense sector who provide extensive experience of survival of high speed impacting projectiles.

1.4. Cost

Several factors combine to make penetrators a relatively low cost solution:

1. Their low landed mass can significantly reduce launch costs.
2. Avoidance of extra propellant and complex near-surface mechanisms to ensure a soft landing.
3. Direct availability to subsurface material without requiring extra deployment mechanisms.
4. Their subsurface emplacement provides natural protection from the severe radiation environment.
5. Adoption of a highly focused development methodology can greatly reduce 'trial and error' development by employing extensive defense sector heritage for impact survival modeling combined with relatively low cost small-scale impact testing, prior to full scale qualification testing.
6. The adoption of a generic design, allowing ease of AIT (Assembly Integration and Test), will simplify and reduce development costs.
7. The ability to re-use common sub-systems and instruments for different worlds, offers the potential to limit subsequent developments to delta cost levels.

2. Science

The following inter-related science areas may be addressed by penetrators on Europa:

1. Astrobiology
2. Geophysics (whole body, e.g. interior)
3. Geophysics (e.g. local material chemical, mechanical & electrical properties)
4. Environment
5. Ground truth (for remote sensing observations)

However, the proposed astrobiology investigations require interdisciplinary investigations which are likely to make significant contributions to those areas, independent of evidence of life. Such contributions include:

(i) Geophysics: for the presence of a habitable internal ocean, and it's thermal and chemical environment. Also, investigation of seismic activity, for evidence of the ocean's connection with the surface.
(ii) Near-surface geophysical properties: such as chemistry and mineralogy from a search for astrobiological signatures.
(iii) The environment, particularly radiation which is extremely harsh because of Europa's location with Jupiter's inner radiation belts (JEO, 2009).

Penetrators are well suited to meet these global goals, and enable answers to the key science questions of (a) "What is the origin and evolution of Europa?" and (b) "Is there, or has there been, life on Europa?" via the following specific investigations:

1. Determination of the internal structure of Europa and its dynamics.
2. Determination of the existence and characteristics of a subsurface ocean.
3. Search for biosignatures in near-surface material.
4. Characterization of the physical (e.g. radiation, thermal, magnetic, electrical, mechanical) and chemical environment of the near-surface region.

2.1. Internal structure of Europa

Europa's interior is thought to be fully differentiated into a metallic core, silicate mantle, and outer water ice/liquid shell, as inferred from the satellite's measured density, low-degree gravitational field, and shape (Schubert et al., 2009). The satellite's induced magnetic field further suggests the presence of a global subsurface liquid water ocean within Europa's outer shell, probably rich in dissolved salts, beneath a relatively thin and geo-dynamically active icy crust, the total thickness of the ice+water layer being of the order 150 km (e.g. Pappalardo et al., 1999; Kargel et al., 2000; Kivelson et al., 2000; Kuskov and Kronrod, 2005; Greenberg, 2005; Schilling et al., 2007). Europa is probably unique among icy satellites as its subsurface ocean is likely to be in direct contact with its rocky interior, rather than an underlying shell of high-pressure ice, where the conditions could have similarities with those on the seafloor of the Earth (e.g. Marion et al., 2003; Lowell and DuBose, 2005; Abbas and Schulze-Makuch, 2008). The discovery and characterization of hydrothermal vent ecologies on the Earth's ocean floor suggests that such areas are excellent habitats, powered by energy and nutrients that result from reactions between sea water and silicate minerals (e.g. Van Dover and Lutz, 2004). Consequently, Europa is a prime candidate in the search for habitable zones and life in the Solar System (Zolotov and Shock, 2003, 2004; Lowell and DuBose, 2005).

The details of the processes that shape Europa's ice shell, and fundamental question of its thickness, are poorly known (Pappalardo et al., 1999). A broad band seismometer experiment will enable observation of the seismic body-waves of mainly tidally induced deep quakes which may be located close to the ice-ocean interface, thermally induced shallow quakes caused by daily variations of surface temperature, and resonant oscillations of the subsurface ocean itself in response to tidal forcing (Rabinovich, 2009). It is anticipated that the physical extent of individual sources will be smaller than on the Earth, though seismic attenuation is likely to be lower (Cammarano et al., 2006). The seismometer will also allow the characterization of the density structure of the outer ice shell and thus also provide clues regarding the nature of the internal ocean (e.g. Kovach and Chyba, 2001; Lee et al., 2003; Dokuchaev, 2003: Panning et al., 2006). The data will also reveal the deep structure of Europa, including any possible interface between the rocky mantle and a metallic core (Cammarano et al., 2006). The signal to noise ratio of any seismometer is critical, and a minimum lifetime of ~2 Europan days (7.1

Earth days) is required, and periods of at least 4 Europan days are required to detect resonant oceanic oscillations.

Surface heat flow is a key parameter determining the thickness of an ice shell and the existence of a subsurface ocean (Ruiz, 2005). Theoretical estimates vary by more than an order of magnitude, from 7 mW m^{-2} (Hussmann and Spohn, 2004) to values as high as 290 mW m^{-2} (O'Brien et al., 2002). The onset of convection in the ice shell is model dependent but could start below 45 mW m^{-2} (Schenk, 2002), so most of the surface heat flow would be caused by tidal heating (Ruiz et al., 2007). The former value suggests a much lower thickness of Europa's ice shell than deduced from Europa's morphology (Ruiz et al., 2007). Therefore, surface heat flow provides a critical constraint on all models of Europa's interior. Its measurement will enable a better understanding of both the thickness of Europa's ice shell and its deep interior. It is recognized that achieving the required sensitivity will have to be investigated owing to the expected low thermal gradient, combined with a subsurface material of unknown thermal properties, and thermal disturbances generated by the penetrator itself.

2.2. Existence and characteristics of a subsurface ocean

Penetrator measurements would be complementary to those of orbiter radio science, magnetometer and laser altimetry investigations. Europa is subject to tidal forces as it revolves about Jupiter during its 3.55-day orbit. Because of Europa's orbital eccentricity the surface and interior are deformed periodically, and the response to the external forcing strongly depends on whether or not a subsurface ocean is present (Moore and Schubert, 2000). Predicted radial surface peak-to-peak displacements are of the order of 60 m on Europa in case of an ocean, and less than a metre for a completely solid ice shell (e.g. Moore and Schubert, 2000). Furthermore, the amplitudes of the forced librations (periodic variations in the rotation period) strongly depend on the presence of a subsurface ocean (Moore and Schubert, 2000).

A radio beacon emplaced on Europa's surface transmitting its time-dependent (due to periodic radial surface deformation and longitudinal variations because of forced librations) location relative to the Earth or to an orbiter could constrain the tidally varying shape (determination of dynamic radial Love number h_2) and the amplitude of forced libration. It could also precisely determine the satellite's obliquity and pole position. A single penetrator with such a beacon on the surface is sufficient to provide a link from/to an Earth ground station as well as an orbiting spacecraft. Since the instrument is directly coupled to the surface, exposed to seismic and tectonic movements and, possibly, non-synchronous rotation of the outer ice shell, a drift connected to the corresponding tidal cycle is expected. Thus, a minimum lifetime for this instrument is required to be ~1 Europan day (3.55 Earth days). However, effective implementation of such a radio beacon on a penetrator with limited resources is very challenging (see Section 3). Variations of the gravitational potential at the surface (determination of the dynamical Love number $k2$) due to the tidal displacement of mass in the interior could be measured by gravimetry that is less impeded by local cavities and/or heterogeneities of the subsurface. Another major advantage for interpreting those measurements is that the tidal forcing function of a synchronously rotating satellite such as Europa is exactly known. A higher temporal resolution and precision than with ground-based and space techniques alone can be achieved by emplacement of a geophysical network of one or several surface stations. A most promising approach would involve long-term monitoring of tidally induced gravity changes at the surface combined with time-varying gravitational field observations from an orbiting spacecraft.

Complementary to gravity and topography variations, the measurement of the induced magnetic fields as a response to the co-rotating Jovian magnetosphere would indicate the presence of an ocean (cf. Kivelson et al., 2000). Europa is embedded in Jupiter's magnetosphere and subjected to a time-varying inducing field which has two principal frequencies due to Jupiter's rotation and Europa's revolution. The response of electrically conductive material in Europa's interior to this time-varying field is to generate an induced field of opposite polarity. The magnitude of the induced response is a function of the depth of the conductive material and its intrinsic electrical conductivity (Schilling et al., 2007). Magnetometers emplaced on the surface can yield important contributions in addition to orbital magnetometry; since as the dipole component of the field decays as $1/r^3$, proximity to the source is beneficial. The combination of magnetic field measurements in orbit and on the surface would define both the inducing and the induced field, and thus allow us to distinguish signals from internal source and external sources (such as plasma interactions with the satellite). Also, the electrical conductivity and depth of the ocean could be inferred independently (Zimmer et al., 2000), properties which in turn depend on the ocean's composition and the heat flow. In addition, magnetic measurements may address 'Europan oceanography' by monitoring time-variable magnetic field signatures induced by the directed flow of salty subsurface ocean water (ocean currents). With a recording signal as weak as a few nT, the signal to noise ratio is a critical issue. Thus the ideal lifetime of the experiment would extend for at least several Europan days.

2.3. Search for biosignatures in surface material

Constraining the habitability of Europa is one of the prime goals of EJSM (EJSM, 2009). Habitability is defined on the basis of what we know about terrestrial life. Thus, there are three conditions that a planetary object should fulfill to be considered as habitable: (a) liquid water, (b) chemical building blocks, and (c) energy sources to maintain metabolism of micro-organisms. Europa is especially interesting since all three of these characteristics may be present.

Astrobiological exploration should not be restricted to the remote observation of the surface for three main reasons: (1) The likely habitable environments are in the subsurface, where liquid water may be present. (2) The surface has an intense radiation environment where many materials, including organic molecules, may not survive unaltered for a long time. If the aqueous reservoirs are linked with the surface, by fractures for instance, materials indicative of the habitability may ascend from the interior. But exposed materials will be affected and may lose the signatures from the potential habitable environment. So, remote measurements will be from secondary materials, modified on the surface from the original conditions at the interior aqueous reservoirs. (3) The concentration of biosignatures at the surface may not be sufficient for remote detection. Therefore, it is highly advantageous to be able to observe the subsurface in situ as deeply as possible in areas suspected to be connected to the liquid water. A penetrator would enable this because of its capability to penetrate to an anticipated depth of around 20 cm to a metre below the gardened regolith. Traversal through the altered layer would allow sampling of more pristine materials and test the conditions of habitability in more detail.

Multiple non-ice constituents in the surface material of the icy Galilean satellites were detected more than a decade ago using the reflectance spectra returned by the Galileo near-infrared mapping spectrometer (NIMS) experiment (McCord et al., 1998). Large organic molecules such as tholins were considered candidates for IR spectral features at 4.57 and 3.4 μm. In laboratory experiments tholins are the residue formed by subjecting gas mixtures of C-, H-, O-, and N-bearing molecules to electrical discharge currents (McDonald et al., 1991), with the triple-bonded CN molecule the most likely source of this prebiotic spectral signature. Curiously, no spectral signatures were detected for the polycyclic aromatic hydrocarbons (PAHs), probably the most dominant organic molecular signature identified in the interstellar medium (Ehrenfreund and Charnley, 2000). Laboratory studies also predict the formation of hydrogen peroxide (H_2O_2) in water ice following UV photolysis and proton irradiation similar to fluxes encountered at the surface of Europa. It is not clear how long peroxide remains active in the Europan surface and what impact it has on the survival of organic carbon in the Europan water ice (Hudson and Moore, 2001). Mixed communities of photosynthetic and non-photosynthetic microbial life are able to live and multiply within the ice of Antarctic lakes [Priscu et al., 1999]. These organisms and their accompanying metabolic products including photopigments and pigments known to be essential for protection from radiation (Edwards, 2007) can be detected in situ using simple laser induced fluorescence emission (L.I.F.E.) imaging and spectral techniques (Storrie-Lombardi and Sattler, 2009). Similar L.I.F.E. techniques have been proposed to search for organic compounds during exploration of the Mars regolith (Storrie-Lombardi et al., 2008, 2009).

Arguably the single most important astrobiology question for Europa centers on whether the prebiotic and biotic carbon molecules necessary for life can survive in the presence of a high radiation load and radiation-induced peroxide formation (Cooper et al., 2009). Estimates of radiation load at the surface of Europa range between 40 and 500 rads year^{-1} (McKay, 2002). Such levels would limit the lifetime of even the most radiation resistant terrestrial microbes to a few tens to a few hundred-thousand years down to depths of several metres if the surface of Europa is geologically and hydrologically static. However, recent remote sensing data implying a more active history for Europa's ice with possible upwellings from deeper, more radiation-protected zones, make it likely that accurate estimates of organic survival must await in situ investigation. Interestingly, a recent set of experiments in anoxic sediments with low organic content predict that the radiation-mediated hydrolysis of water can provide electron donors sufficient to sustain significant microbial communities (Blair et al., 2007).

The formation and destruction of both peroxides and large organics including tholins, PAHs, metabolic enzymes, and photosynthetic pigments, can be monitored by ultraviolet and infrared reflectance and/or Raman spectroscopy via an optically transparent window in the side of the penetrator. These non-contact instruments require no moving parts, no sample handling, and no consumable resources except power (Storrie-Lombardi, 2005). If, indeed, biotic signatures are detected, these same instruments can monitor metabolic activity across a Europan day/night cycle.

Important measurements for astrobiology would also be related to (a) physical–chemical environmental constraints of the original aqueous solution, such as conditions of pH and redox, temperature, conductivity, or composition, and (b) biosignatures, such as organic compounds related to life or isotopic ratios. In situ characterization of the local mineralogical assemblages and direct physical–chemical measurements will provide information about the environment. Raman spectroscopy and gas chromatography–mass spectrometry GCMS are useful instrumentation for mineral and organics determination. In addition, a micro-camera is would allow recognition of mineralogical and, if present, life-related structures and patterns. Such a micro-camera, fitted with UV illumination would be particularly capable of detecting fluorescence from organic and perhaps biological molecules.

2.3.1. The question of habitability of Europa

Prominent in the priorities of the question of habitability is the interpretation of the sulphur-bearing patches on the Europan icy surface. Is their origin astrobiological or geophysical?

Based on combined spectral reflectance data from the Galileo mission's Solid State Imaging (SSI) experiment, the Near-Infrared Mass Spectrometer (NIMS) and the

Ultraviolet Spectrometer (UVS), it has been argued that the non-water ice materials are endogenous in three diverse, but significant terrains (Fanale et al., 1999). Effusive cryovolcanism is clearly one possible endogenous source of the non-water-ice constituents of the surface materials (Fagents, 2003). The most striking feature of the non-water surficial elements is their distribution in patches. Indeed, implantation would be expected to produce a more uniform surface distribution if the source were ions from the Jovian plasma. It may be argued that if the plasma from the magnetosphere were responsible for the sulphur distribution, some geologic process has to be invoked to allow for a non-uniform distribution (Carlson et al., 1999). Alternatively, the sulphurous material on the surface may be endogenous. In other words, the cryovolcanism on Europa would not be from its core, but rather from the bottom of the global ocean. It might be more like the "black smokers" that are found on the Earth seafloor. The compounds produced at the bottom of the ocean would make their way up to the surface.

2.3.2. Testing biogenicity on the icy surface of Europa

Following the promising possibility that the surface sulphurous patches on Europa originate from a subsurface ocean, we now discuss the possibility that they may be of biogenic origin.

Life is known to exist in some extreme terrestrial environments which are, at least in part, analogous to possible conditions on Europa (see Table 5 of Marion et al. (2003) for an overview). These include life in sub-glacial lakes, sea ice, permafrost, and the dry valleys of Antarctica (e.g. Marion et al., 2003; Wynn-Williams, 1996; Mikucki et al., 2009). Probably the best such analogue is the Antarctic sub-glacial Lake Vostok (Priscu et al., 1999; Karl et al., 1999), which possesses a perennially thick (3 to 4 km) ice-cover that precludes photosynthesis, thus making this environment a good model system for determining how a potential Europan biota might evolve and distribute itself (Price, 2000; Marion et al., 2003). Disequilibrium chemistry driven by charged particles from Jupiter's magnetosphere could produce sufficient organic and oxidant molecules at the surface of Europa which, if advected down into the underlying ocean, could support a Europan biosphere (Chyba, 2000).

The issue of biogenicity (Singer, 2003; Chela-Flores, 2010) is amongst several hypotheses that penetrators with potential direct contact with these materials could be ideally placed to investigate.

2.4. Physical and chemical environment of the near-surface region

The characterisation of near-surface material and of the environment for different terrains (including chemistry, structure, mineralogy, permittivity, and temperature) is important for astrobiology, geophysics, the interpretation of ground penetrating radar data, and for future mission landers.

Galileo Near-Infrared Mapping Spectrometer (NIMS) spectra of the surface of Europa exhibit absorption bands attributable to H_2O bending and stretching overtones. Over large parts of the surfaces, the shapes of these bands are what would be expected from clean water ice; it is worth observing that these would be identical if the surface were instead composed of a clathrate hydrate.[1] However, in other areas the near-IR water bands exhibit considerable distortion indicative of either water or hydronium ions (H_3O^+) bound into non-ice solids (e.g. McCord et al., 1998). Although there is disagreement concerning the interpretation, comparison with a range of laboratory spectra suggests that the non-ice component may include hydrated Mg-sulphate (either epsomite, $MgSO_4{\cdot}7H_2O$, or meridianiite, $MgSO_4{\cdot}11H_2O$), Na-sulphate (mirabilite, $Na_2SO_4{\cdot}10H_2O$), Na-carbonate (natron, $Na_2CO_3{\cdot}10H_2O$), sulphuric acid ($H_2SO_4{\cdot}61/2H_2O$ or $H_2SO_4{\cdot}8H_2O$), or hydrogen peroxide ($H_2O_2{\cdot}2H_2O$) (McCord et al., 1999; Dalton et al., 2005; Carlson et al., 2005; Loeffler and Baragiola, 2005). It has been speculated that these non-ice materials have been emplaced as aqueous solutions, erupted from a liquid reservoir beneath the surface, possibly from a subsurface ocean. In this case, the composition of the non-ice material is a signature of the ocean chemistry, and places constraints on the interactions between aqueous fluids and the rocky interior (cf. Zolotov and Shock, 2001). Given that the non-ice spectra on Europa are correlated with reddish-brown markings on the surface, which are in turn correlated with areas of purported rifting and diapirism (Geissler et al., 1998), then this hypothesis appears well supported (e.g. Orlando et al., 2005).

It is certain that the radiation environment has acted to modify the surface composition of Europa, perhaps by implanting sodium and sulphur ions, originating on Io, into the surface ices to form sodium sulphate hydrates and sulphuric acid hydrates (Paranicas et al., 2001; Carlson et al., 2002). Radiation is almost certainly a driver for the production of highly oxidising species, such as O_3 and H_2O_2 (Gomis et al., 2004; Loeffler et al., 2006). Moreover, if CO_2 is present in the ice matrix then irradiation will also drive the formation of organic species, such as formaldehyde, CH_2O (Hand et al., 2007). It has been speculated that these species could be mixed back down into Europa's ocean, providing a source of nutrients for an active biosphere (Hand et al., 2007). Radiation will also destroy organic material present on the surfaces of the icy Galilean satellites, whether it is endogenic or exogenic (supplied by cometary or chondritic impactors) to estimated depths of 1–10 cm (the expected depth of regolith gardening on a 10^7 yr timescale) (Chyba and Phillips,

[1] This is not a trivial distinction since clathrate hydrates have a significantly lower thermal conductivity, and are much stronger, than water ice under the same conditions; there are consequences for the resulting thermal evolution of the satellite (Prieto-Ballesteros et al., 2005).

2002; Cooper et al., 2001, and website: http://icymoons.com/europaclass/Chyba_Life_Detection.pdf), resulting in a predicted steady-state abundance of roughly 1 part per 1000 on Europa. However, this is strongly time dependent such that material may be altered down to tens of metres for much older terrains of the order of 1 Gyr (Johnson et al., 2009; Paranicas et al., 2009).

Key objectives of penetrators with respect to near-surface materials are to: (1) determine the physical state of the solid H_2O component that likely comprises the bulk of the Europan crust; is it water-ice or a clathrate hydrate? This may be achievable by measuring low-wavenumber lattice vibrations with a Raman spectrometer; (2) identify the composition of the non-ice component and determine its vertical distribution, i.e. determine if it is a ‘skin’ deposit or mixed deeper into the regolith; (3) identify the presence of any organic material and determine its vertical distribution; (4) attempt to measure, either by mass spectrometry or X-ray fluorescence, the abundance of noble gases trapped in the regolith with a view to determining the absolute age of surface materials by the potassium-argon method (Swindle et al., 2005).

As noted by Figueredo et al. (2003) and Orlando et al. (2005), low-albedo ridge-bands and chaos regions are of particular interest in the respect of determining surface chemistry because of the evidence for recent material exchange with the subsurface, as described earlier.

2.5. Ground truth

The analysis of data on all the Jupiter moon surfaces including Europa and Ganymede from an orbital platform is subject to assumptions regarding the nature of the surface. Clearly, direct measurements of surface properties, e.g. density, regolith structure, composition of non-ice components, temperature and temperature variations would yield ground truth for the orbiter instruments (spectrometers, radar). For example, the permittivity of the surface material is an assumed parameter in the interpretation of ground penetrating radar data.

Additionally, implementation of a penetrator on the JGO, the proposed Jupiter Ganymede orbiter will allow comparison of ground measurements of these two worlds. This could be important in removing potential ambiguities in astrobiological signature detections, as well as reveal significant differences in inner geological structures and near-surface chemistry.

Finally, engineering data on potential landing sites including mechanical strength of the surface, temperature, and radiation environment are all important factors for the success of a future lander mission.

3. Instruments

The scientific instrument complement for such penetrators is flexible according to need, TRL and resources, though it is envisaged that a modest ~2 kg payload selected from the candidates listed below in Table 3-1 could address in full the science objectives listed above. In particular, this table identifies many instruments which provide key astrobiology investigations as well as contributing knowledge of the geophysics and environment.

The listed instruments are those which have to date been identified as potentially suitable for penetrator application, but is by no means exclusive. Many have existing space heritage, and demonstrated appropriate low resource requirements and high ruggedisation.

More details of the applicability and heritage of each of these instruments are described below:

(a) Geophysics – Subsurface Ocean/interior, Astrobiology – Habitat instruments

1. A **Seismometer/Engineering tiltmeter** could determine the existence of, and characterize, a subsurface ocean, interior body structure; and seismic activity levels. A single seismometer could determine both the upper ice shell thickness and ocean depth (Kovach and Chyba, 2001; Lee et al., 2003), though two seismometers emplaced at different positions on the surface of Europa would significantly improve its capabilities. Microseismometer developments are continuing for penetrators following their development for ExoMars (Pike et al., 2009). Protected suspension sensors survived Pendine full scale impact trials (Hopf et al., 2010).
2. A **Magnetometer** could determine presence of internal oceans, through measurement of the induced field. Solid state sensors have some advantages over fluxgates for penetrators due to their much lower mass and volume. Anisotropic Magneto-Resistance (AMR) has the best low frequency performance (<100pT.Hz-$^{1/2}$ above 1Hz) and these have recently survived a hi-gee test (Brown et al., submitted for publication). If the local

Table 3-1
Potential Instruments for a Europa Penetrator and their primary science relevance.

Geophysics ocean/interior *Astrobiology habitat*	**Geophysics surface/chemistry** *Astrobiology biosignatures*	**Environment** *Astrobiology relevant*
Seismometer engineering tiltmeter	*Mass spectrometer*	*Light level monitor*
Magnetometer	*Thermo gravimeter*	*Radiation monitor*
Radio beacon	*X-ray spectrometer*	Thermal sensor
Gravimeter	*Raman, IR, or UV–Vis–NIR spectrometer*	
Geophysical tiltmeter	*Microscopic imager*	
Heat flow probe	*Astrobiology Habitability Package*	
Microphone	*Descent camera*	
	Accelerometer	
	Dielectric/permittivity	

Note: Italicized instruments also have astrobiological relevance as indicated in column header.

sensor temperature at Europa is less than 90K an alternative implementation could employ Giant Magneto-Resistive (GMR) elements with superconducting flux concentrators. These can exhibit sub-pT sensitivity, superior to that of the best fluxgates (Pannetier et al., 2004). As such sensors would measure relative fields they would need to be combined with the AMR for recovery the DC field component. Nevertheless they would be extremely sensitive to very low amplitude small-scale variations associated with subsurface currents. Driving requirements include the need to have measurements made over periods of months in order to resolve multiple frequencies. For example, to resolve the effects of a single frequency (that of Jupiter's rotation period ~10 h) one would need 10 h × 20 rotation periods so ~10 days. In order to study frequencies linked to Europa's orbital period would require, say, 10–20 orbital periods.

3. A **Radio Beacon** could measure crustal tidal and seismic movements. Achieving the required sensitivity of ~1 m with VLBI (Very Long Baseline Interferometry) from the Earth is challenging for a penetrator emplacement with limited power available, and would require a higher frequency band than the envisaged penetrator UHF communication system. Visibility to the Earth is also severely restricted by subsurface and non-equatorial emplacements. Additionally, JEO would only provide frequent (every ~2 h) communication slots for polar emplacements, whereas equatorial emplacement orbiter contact periods would only occur every ~1.7 days. Thus, current studies are investigating the possibility of utilizing the penetrator-orbiter communications link to achieve a useful sensitivity. Such radio links have been previously employed on Huygens (DWE) (Bird et al., 2005), and are being developed for ExoMars (LaRa) (Dehant et al., 2009). A possible role in joint experiments with the Penetrator and Earth-based networks of radio telescopes, including a global VLBI network and the Square Kilometre Array (SKA) is being investigated in the framework of the ongoing assessment of the Planetary Radio Interferometry and Doppler Experiment (PRIDE) of the Europa Jupiter System Mission.
4. **Geophysical Tiltmeter** measurements would constrain surface tidal displacement, and aid interpretation of seismometer and thermal measurements. Much greater precision is believed to be required than engineering tiltmeters with spaceflight heritage, though some engineering tiltmeters are reported to have high gain sensitivities of around 0.4 arcsec which may be capable of detecting such tidal distortions.
5. A **Gravimeter** could detect gravity changes at the surface in response to internal body tidal motions. Such instruments based on micro-technology MEMS (Micro-Electro Mechanical Systems) such as very sensitive accelerometers and similar to micro-seismometers may be appropriate to perform this role sensitively.
6. A **Heat flow probe** would employ thermometers in contact with the regolith on the outside of the penetrator along its length, and use the obtained differential temperatures to determine the heat flow (e.g. Spohn et al., 2007). However, such measurements require a high degree of precision and much care is needed to ensure that disturbing thermal influences from the penetrator, or indeed natural diurnal variations, are not significant. This requires careful thermal design of the penetrator and temperature probes, including, for example, the use of thermal needles to extend significantly far through the penetrator body to reduce the thermal disturbances of the penetrator (Hagermann and Spohn, 1999; Hagermann, 2005).
7. A **Microphone** solidly emplaced by a penetrator would provide an ideal contact to measure acoustic signals from ice quake activity levels and their associated frequencies. The envisaged frequency range from ~100–10^4 Hz, would be a natural extension to the micro-seismometer upper limit of around 100Hz. This technology has Huygens space based heritage.

(b) Geophysics – surface/chemistry, Astriobiology – biosignature instruments

8. **Mass Spectrometer:** A variety of micro-technology instruments exist which could determine chemical species with isotopic identification, including those with biological importance. Potential methods for access to the local material includes (i) sample ingestion utilizing a sample chute on entry, or (ii) a drill post-entry (e.g. Gouache et al., 2009a,b, or similar to that used for Deep Space-2), or (iii) laser ablation of material external to the penetrator via a window. Material ablated externally could be viewed spectroscopically via a window in the penetrator wall, or via ingress of the produced gas via electronic nose technology. Mass Spectrometers would be particularly suited for analysis of released gases (Sheridan et al., 2003), and current developments of miniaturized instruments employing heritage from e.g. the Ptolemy and COSAC GC/MS instruments (Wright et al., 2006; Todd et al., 2007; Goesmann et al., 2007) on-board the ROSETTA lander package, and Beagle-2 Gas Analysis Package (Wright et al., 2003), and could cover a large mass range of species including some isotopic differentiation (for example, of particular importance would be the S^{32}/S^{34}ratio for the common sulphur stains on the Europan surface which are expected to be quite different between a biological and a geological origin).
9. A **Micro-ThermoGravimeter** employing a quartz micro-balance technology, with a built-in micro-heater, could be particularly suitable for identification of e.g. specific volatile and refractory molecules of astrobiological interest (Palomba et al., 2008a,b). This instrument is under study for the Marco Polo candidate M-class Cosmic Vision mission and requires ingress of a chemical sample which will be locally

micro-heated under controlled thermal cycles and the change in mass measured. Since, each volatile sublimates at specific temperatures, it is possible to easily discern the compounds under study (thermogravimetry technique).

10. A low Z **X-ray spectrometer**, capable of measuring down to carbon, could provide elemental chemical information of bulk material in the immediate environment surrounding the penetrator. Though having more limited and indirect inference of chemical species, this may not require direct access to the local material. This instrument would employ a radioactive source/s to generate fluoresced X-rays from external material, which could pass through the penetrator walls and so might not require any external window. This instrument has space heritage via Beagle-2 XRS (Talboys et al., 2009), and γ-ray backscatter densitometers.
11. **Raman, IR, or UV–Vis–NIR spectrometers** are also potential candidate instruments with ability to characterize the chemistry of the subsurface material and detect astrobiological signatures, though their suitability for micro-penetrator applications has not yet been assessed.
12. **A Microscopic Imager** could provide key astrobiological and mineralogy information and would form a strong complement to a mass spectrometer. An internal microscopic imager could image a sample ingressed into the penetrator or view material though a window in the penetrator wall. If the imager views the same sample to be analysed by a mass spectrometer, then it could provide key mineralogy information about the sample for which chemical analysis is made. Additionally, imaging a sample before and after heating could identify which mineralogy elements were volatile. It could also provide information on grain size distributions, shapes (e.g. ragged, smooth edged), and colours. Ideally, a sample whose mechanical grain structures have been minimally affected by the impact process would provide the best information. Imaging a sample before and after illumination by a small UV LED or tuned lasers would be particularly capable of detecting fluorescence from prebiotic or biotic organic molecules, as well as determination of any tiny life form shapes. By itself, or in combination with a chemical analyser it could a powerful analysis capability. Such imaging systems have space heritage from Beagle-2 SCS, ExoMars PANCAM and MSSL WALI development (Griffiths et al., 2005, 2006; Storrie-Lombardi et al., 2001 and 2005; Nealson et al., 2002; Mormile and Storrie-Lombardi, 2005).
13. An **Astrobiology Habitability Package** (Prieto-Ballesteros et al., 2009) could provide physical–chemical characteristics of the subsurface environment from a liqueified portion of an ingressed sample. The instrument is conceived to measure pH, conductivity, redox and temperature which condition the state of the water solution which is potentially available for life. Extreme values of these parameters would be problematic to some biological processes. On the other hand, specific anomalous values could be due to life presence. An advantage of this type of measurement is that such astrobiological signatures would be broadly distributed, not requiring the presence of very localised signatures. Irrespective of the presence of life indicators, the provision of such information is also of general geophysical interest, and such sensors have extensive Earth-based heritage.
14. A **Descent Camera** could provide geological context of the impact site to the order of metre resolution, and be excellent for inspiring public interest in the mission and outreach. Also, e.g. whether the penetrator impacted into an area of potential astrobiological material (e.g. sulphur deposits) would be of key interest. This instrument does not need to survive impact, and so conventional space heritage is particularly applicable such as that from Beagle-2 and ExoMars developments (Griffiths et al., 2005, 2006). Of course, along with all other instruments it would have to survive the harsh Europan radiation environment.
15. **Accelerometers** would measure the regolith mechanical properties, important for local geophysics knowledge and for future landers. This includes detection of any near-surface layering related to regolith gardening processes, and can provide determination of the resting depth of the penetrator below the surface. This regolith depth is related to the age of the surface and hence the degree of radiation and micrometeoroid damage for which any astrobiological material might have undergone. Together with tilt measurements, the total penetration depth is also relevant to interpretation of thermal environment, determination of heat flow, and interpretation of light level measurements. Such accelerometers have very high TRL including survival of high impact forces as would be expected for a Europan penetrator, and have mature defense application, and space heritage from DS-2.
16. A **Dielectric Permittivity instrument** can determine the physical state of local material, including abundance of non-ice components (e.g. Spitzer et al., 2008). Such measurements are also relevant to interpretation of data obtained from any orbiting ground penetrating radar instruments. A similar instrument has been under development for ExoMars.

(c) Environment and Astrobiology Relevant Instruments

17. A **Light level monitor** could measure the ambient light levels at the surface or just below to determine subsurface habitability, materials translucency and packing, and oxidant levels.

This could conveniently form part of the microscopic imager if it views through a window in the penetrator wall.

18. A **Radiation monitor**would measure subsurface dose rate, relevant to astrobiological material decay according to surface age, and the density of the near-surface material. The surface dose rate is also relevant to future landers. Such radiation monitors have been developed by QinetiQ and survived the Pendine hi-gee impact test.
19. **Thermal sensors** can measure the temperature of regolith and determine its diurnal variation, and variation with depth. Use of simple heaters would allow thermal conductivity determination of surface material. At its most challenging these could form part of a heat flow determination. These have heritage from the Lunar-A penetrators (Tanaka et al., 1999, 2000)

4. Technology

We propose two hard landers (penetrators) which impact at around 100–300 m s^{-1} to bury them a short depth below the surface (around 20–100 cm). These probes will contain impact hardened scientific instruments which perform key scientific measurements, whose data are nominally transmitted to the orbiting spacecraft.

Two penetrators provide redundancy and improved scientific return, including enhanced networked seismometer performance and diversity of sampled regions.

The basic architecture of each penetrator system consists of three basic elements: A spacecraft support system: a descent module, and the penetrator, as described below.

4.1. Spacecraft support system

The spacecraft support system provides an attachment and ejection system for the descent module from the spacecraft, together with power and data interfaces with the spacecraft when attached. These interfaces will be required for engineering support of the penetrators during cruise phase and just before release. Of particular interest will be to monitor the health of internal penetrator systems including processing system, batteries charge status, and internal temperatures particularly with regard to any internal RHU (Radio-isotope Heating Unit). It is also envisaged that just prior to ejection this should allow systems within the penetrator descent module to be initiated ready for the descent and post-landed operations. Post-delivery, the spacecraft will need to provide communications support with the emplaced penetrator for telemetry and commanding.

4.2. Descent module

A descent module (DM) is required to deliver the penetrator to the surface, such as depicted in Fig. 4-1. A DM could consist of a single penetrator and its Delivery System (PDS), plus a descent camera, as shown in Fig. 4-2.

This module enables communication with the orbiting spacecraft during descent to at least provide descent status information. It is envisaged that the descent system will arrange to separate the PDS from the penetrator to avoid the PDS contaminating the penetrator landing site. The descent module will, in effect, comprise a small spacecraft, albeit for a short duration. On separation from the orbiter, the PDS attitude control and de-orbit motor system will act to control the descent to impact at a controlled impact speed, incidence and attack angles to Europa's surface

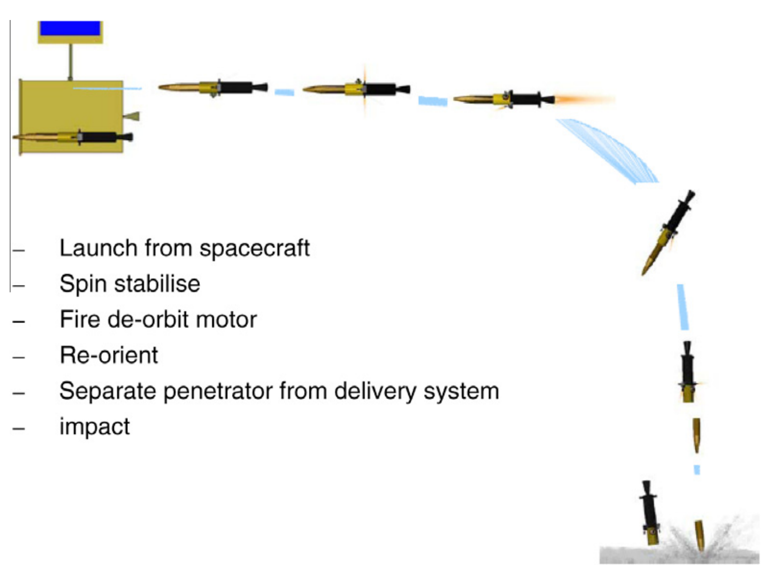

Fig. 4-1. Penetrator descent module (DM) concept (courtesy of SSTL).

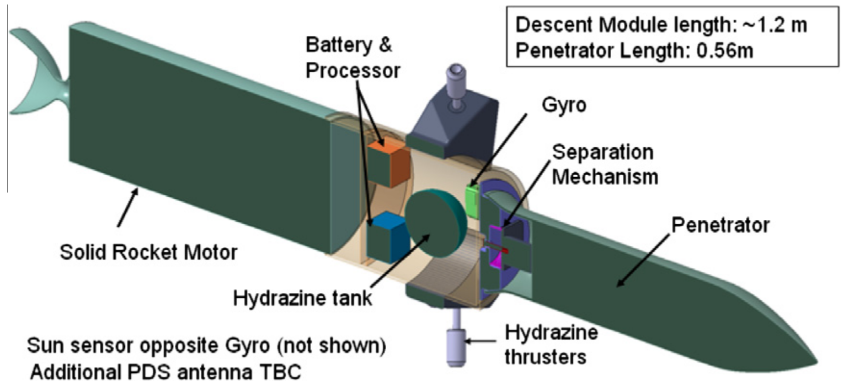

Fig. 4-2. Example descent module design (courtesy of Astrium UK).

(The attack angle is the angle between the penetrator long axis and its velocity vector).

4.3. The penetrator

The penetrator is the only element which has to survive impact. It consists of (a) platform elements comprising shell structure, thermal, power, communications, data handling, and (b) scientific instruments. This subsection discusses these elements and the associated impact factors.

4.3.1. Impact

The impact is a major challenge for which a key factor is the nature of the surface material being impacted which may vary from solid ice, which has strength similar to concrete and a loose snow with very little compressive strength. This can have a dramatic effect on the deceleration forces experienced by the penetrator. For example, the peak global deceleration of the penetrator impacting the sand used in the Pendine MoonLITE trial at 300 m s^{-1} was about 5–10 kgee, whereas for the same penetrator impacting concrete it would be about 30–40 kgee. This has significant consequences in terms of the penetrator shell material in that for the sand, aluminum alloy is more than adequate with the consequent benefit of lower mass. However, for concrete/solid ice high strength steel (e.g. EN24) would have to be seriously considered, for which there is a massive legacy of experience in the defense sector. An alternative is titanium alloy, which could offer much lighter strength, though requires qualification, with special attention to its strength related microstructural properties.

The **penetration depth** and internal forces experienced by the penetrator can be partially controlled by its shape including nose, tail and length to diameter ratio of the penetrator, and choice of impact mitigant materials for the instrument compartments. This also allows for the possibility of the nose material being different from the main penetrator shell giving added flexibility to the penetrator configuration.

The **orientation** of the penetrator in the target is also a factor as it is well known that they can and do move away from the shotline. Indeed, in the MoonLITE trial the penetrator impacted in a 6–7° nose-up condition resulting in a parabolic trajectory in the target material such that the penetrator was 1m off the normal shot line in a penetration depth of 3.7m. A classic way of improving stability is to arrange the centre of gravity as far forward as possible, although it is recognised that a compromise is required, since some sub-systems (e.g. communications) need to be toward the rear of the penetrator.

Another key issue is that at more oblique impact conditions there is a possibility of **ricochet**. This can be a strong function of the surface material and penetrator design, and can be assessed by a combination of small-scale trials and associated modelling. A novel way of mitigating this problem could be use of an explosive shaped pre-cursor charge to produce a hole into which the penetrator impacts. This technology is very mature (i.e. to TRL 7–8) in the military field but would cause significant issues regarding potential contamination of the surface being investigated, which, whilst not insurmountable, would represent a major challenge. An example of a pointed penetrator design is shown in Fig. 4-3 which is well suited to achieve a solid emplacement for sensitive seismic investigations, and an upright orientation for communications to the orbiting spacecraft via a patch aerial located at the rear of the penetrator. The oriented entry and resting configuration are also well suited to achieving a sample of the near subsurface material for chemical and astrobiological analysis. This does, however, require entry into surfaces which either have been significantly regolith gardened or have limited slopes to avoid

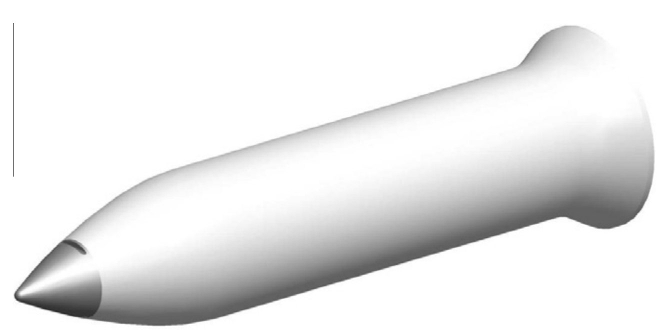

Fig. 4-3. Pointed penetrator.

ricochet. Fortunately, Schenk (2009) provides data that certain Europan terrains such as gray dilational bands have small slopes (average $5 \pm 2°$) which also do not appear to increase dramatically for small-scale sizes as would be relevant to penetrator impact. These slopes are significantly less than the preliminary estimate of 30° at which ricochet become a potential risk for hard surfaces. Also, Prockter et al. (2009) indicate that such dark bands are relatively old, for which increased regolith gardening would be expected, thereby further assisting a ricochet free entry. Additionally, at ~10 km wide or more they appear large enough for a feasible landing ellipse. Though such older terrain would have enabled greater radiation breakdown that could have degraded the complex chemical structures, the overall distribution of astrobiologically important lifeform chemicals would still be contained and therefore observable.

Alternative **penetrator body shapes**, such as spherical have been proposed (Hand et al., 2009), which do not have surface roughness impact constraints, and could be engineered to remain on the surface with less attenuation for communications, though with reduced seismic sensitivity due to lack of a solid implantation. Also, their lack of orientation control also mean these would face much greater difficulties in acquiring a surface material sample without invoking significant complexities and consequently greater mass.

4.3.2. Penetrator platform

This comprises all the non-scientific instrument sub-systems of the penetrator, including the structure, thermal control, communications, power, and digital electronics.

- **The Penetrator structure** consists of the outer shell and inner bays, impact protection mechanisms, and thermal insulation. An example shell, inner bay stack, and seismometer bay are shown in Fig. 4-4. The shell is required to survive impact with its internal contents undeformed. Preliminary indications are that either titanium alloy or steel could provide suitably strong materials for the shell, where impact into hard ice is likely. The penetrator rear flare could aid maintenance of penetrator orientation during impact to help ensure a good post-impact orientation for communications; help prevent over penetration; protect the rear communications assembly during impact; and possibly reduce lateral backfill and minimize side lobe signal attenuation. The inner bays are designed to enable quick and easy AIT (Assembly, Integration and Test), and isolate any damage to a single bay. Impact protection can be provided by various methods which include void fills. Thermal insulation is envisaged to limit heat losses in the cold landed phase, thereby increasing the lifetime, and improve the ability to make more precise external temperature measurements.
- **Power** would be provided by primary batteries via a PCU (Power Conditioning Unit) routed through an internal backbone harness within the penetrator.

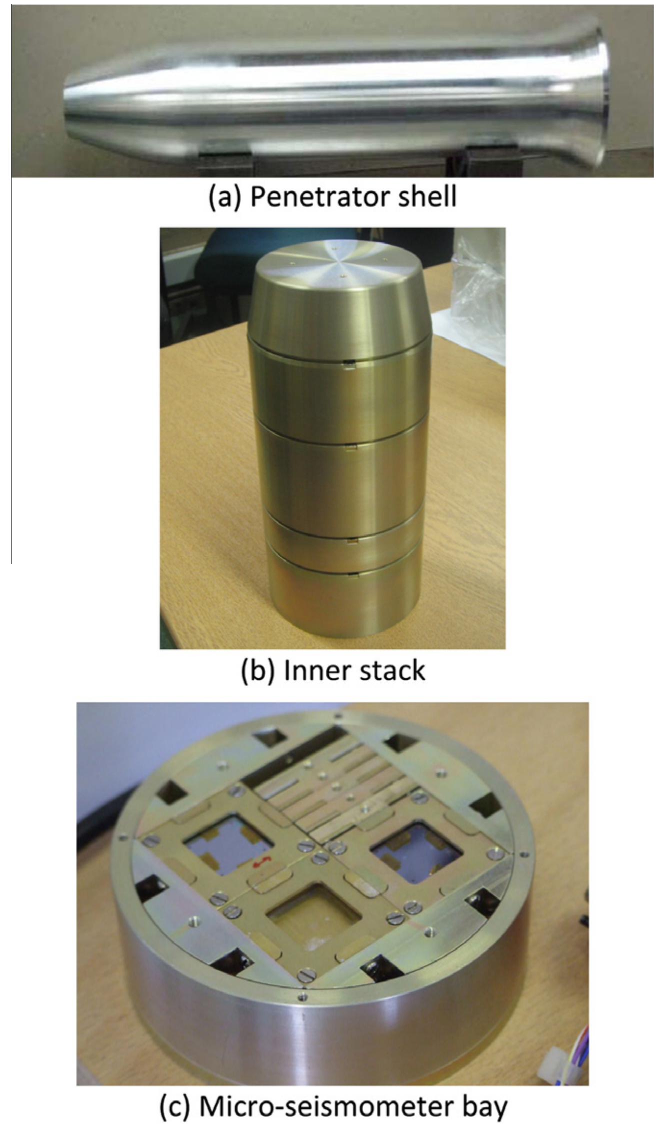

Fig. 4-4. Penetrator hardware elements for May 2008 impact trials.

- A **Thermal control system** is needed to maintain the internal temperature of the penetrator to within the operating limits of the internal sub-systems. A major factor for this is the external thermal environment which is expected to consist of a large proportion of water ice at temperatures in the range ~50–125 K. To limit thermal losses to this external environment sufficiently to enable an operational lifetime of around a week (for e.g. seismometer observations) without an excessive mass penalty, a vacuum flask thermal insulation system would be required. Incorporation of an RHU could be used to reduce battery mass, and extended operational lifetime if desired. It is possible that such an RHU may require a heat switch to prevent overheating during pre-launch and cruise phases, and it is envisaged that the impact event could be used to mechanically disable such a cooling path.

- **Communications** are planned to be via the JEO, where the high inclination orbit around Europa (JEO final report, 2009) would provide much greater science data return for a polar impact site with contact periods every ~2 h, compared with ~1.7 days for an equatorial emplacement. The communications system would include a transmitter via patch antennae located in the rear body of the penetrator. It would also include a transceiver to enable robust and flexible communications which allows flexible contact periods with the orbiter to cope with landing anomalies including off-vertical emplacement, or communications blocking paths due to e.g. large ice blocks or nearby crater walls. Non-fixed communication slots would also allow re-targeting the penetrator impact site if desired due to new information becoming available post-launch including in-orbit operations. A commanding capability could also be useful to improve the scientific performance of the penetrator, for example optimizing seismic event selection criteria, or requesting a new sample image with different instrument parameters. A key aspect for communications system from below the surface is that attenuation from the near-surface material shall not be excessive for the link budget. This is dependent on the surface material dielectric and mechanical properties; the penetration depth; impact crater shape; and expected backfill. Study of potential landing sites will provide constraints on surface material properties, which, in combination with careful design of the penetrator shape and its impact velocity, will allow control of impact depth ranges and cratering morphology. Determination and optimization of these parameters will be a priority study to ensure an effective communications systems. If necessary, a possibility to avoid high signal attenuation from overlying material, could be implementation of a trailing antennae. This would have to lie on the surface, rather than just be a vertical wire, to enable transmission power to be directed upwards. However, such a deployment would be considered a major challenge though would not require any additional surface mechanical or electronic elements to survive impact.
- **Digital electronics** will be required for instrument control; collection of data; data processing, including data compression; and transmission via the communications subsystem.

Development of the penetrator and descent module system will have to comply with stringent **planetary protection** category IV requirements for Europa, which will include bioburden reduction possibly by low level anti-microbial heating over an extended period, and taking into account in the sterilizing affect of significant pre-delivery radiation. The potential presence of an RHU may require additional measures due to the long term presence of a heating source on the surface. There may also be implications on the attachment to the spacecraft regarding microbial barriers, associated sterilization, and maintenance of sterilized elements, though there are no current barriers identified if delivery is from JEO, owing to its planned end of mission impact onto Europa.

In addition, though subsurface operations will be shielded to a significant extent from **radiation**, the whole penetrator system will have to withstand this harsh radiation environment prior to delivery, which would be expected to be near the end of the mission. However, this will be mitigated to some extent since, except for brief cruise operations, most of the penetrator systems will be switched off. A radiation model will be constructed for the penetrator system, against which parts selection will be made according to location. Selection of parts will have to be performed for each individual component for each sub-system and scientific instrument, and include both electronic and other elements, such as lenses.

5. Current status and conclusions

Though penetrators have yet to succeed in a space mission, a considerable body of international institutions and individuals have expressed interest in establishing surface investigations on Europa using penetrators. May 2008 saw the successful full scale impact trials of 3 penetrators at Pendine in Wales (Smith et al., 2010), and Oct 2009 saw the beginning of an ESA 9 month system study (ESA, 2009), into the viability and definition of suitability of penetrators to investigate Ganymede and other icy moons. If that is successful, a significantly larger continuation follow-on program will be initiated.

We have demonstrated the potential feasibility of such a landed mission with a very low mass penetrator(s), capable of high scientific return, including significant synergy with orbital instruments, between Europa and Ganymede, and to other Jupiter moon bodies visited as part of the EJSM mission, as well as providing information for future landed missions. We have also established the benefits of a pointed penetrator for sampling local material for key astrobiological and chemical analysis, and identified a potentially suitable candidate impact terrain. We have further identified the advantages of polar implantation sites for vastly increased data return.

A system study currently in progress, though focused on Ganymede application, will further refine these initial findings; significantly improve penetrator definition and resource estimates; impact site selection and risk assessments. Future work is directed to bring relevant subsystem and instrument technology up to TRL5 by end of 2012, including complete impact ruggedization of all relevant components.

For Europa, we recognise that additional developments are required which include demonstration of successful impact into ice, and survival in the radiation environment. Existing defence sector experience with impact into concrete and other geological materials indicate that impact survival is feasible. Though the radiation environment experienced by the penetrators will be ameliorated by the systems being switched off for the majority of the cruise phase, and shielded by the Europan material for its relatively short operational lifetime, this is recognised as a key issue which has yet to be addressed in detail. However, as a first step, results from the existing study will greatly improve the definition of the radiation environment experienced within the penetrator at all mission phases, including shielding by the shell and its internal elements including impact mitigation materials.

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