Penetrators are not a Panacea: Historical Review and Critical Assessment

Ralph D Lorenz

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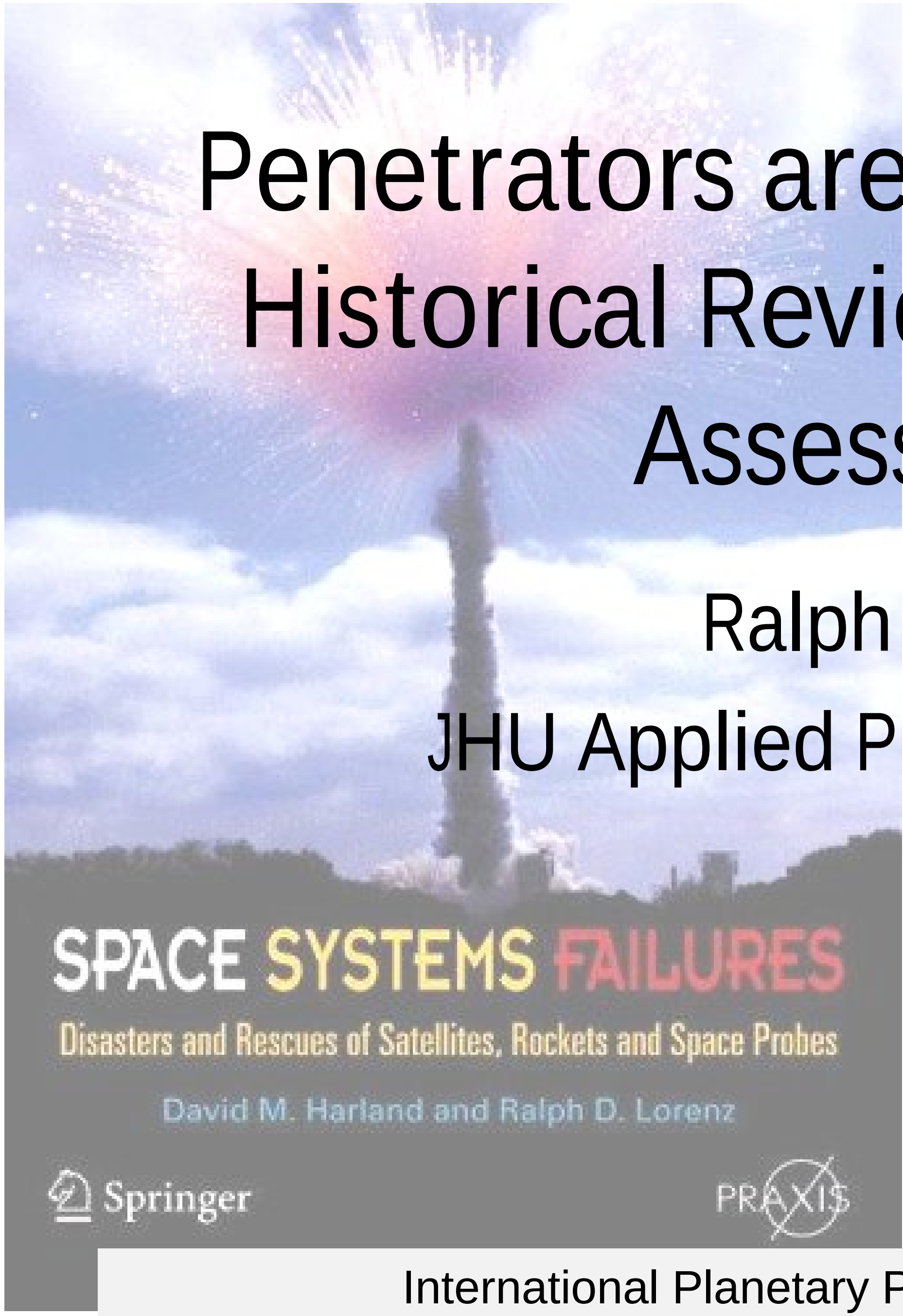
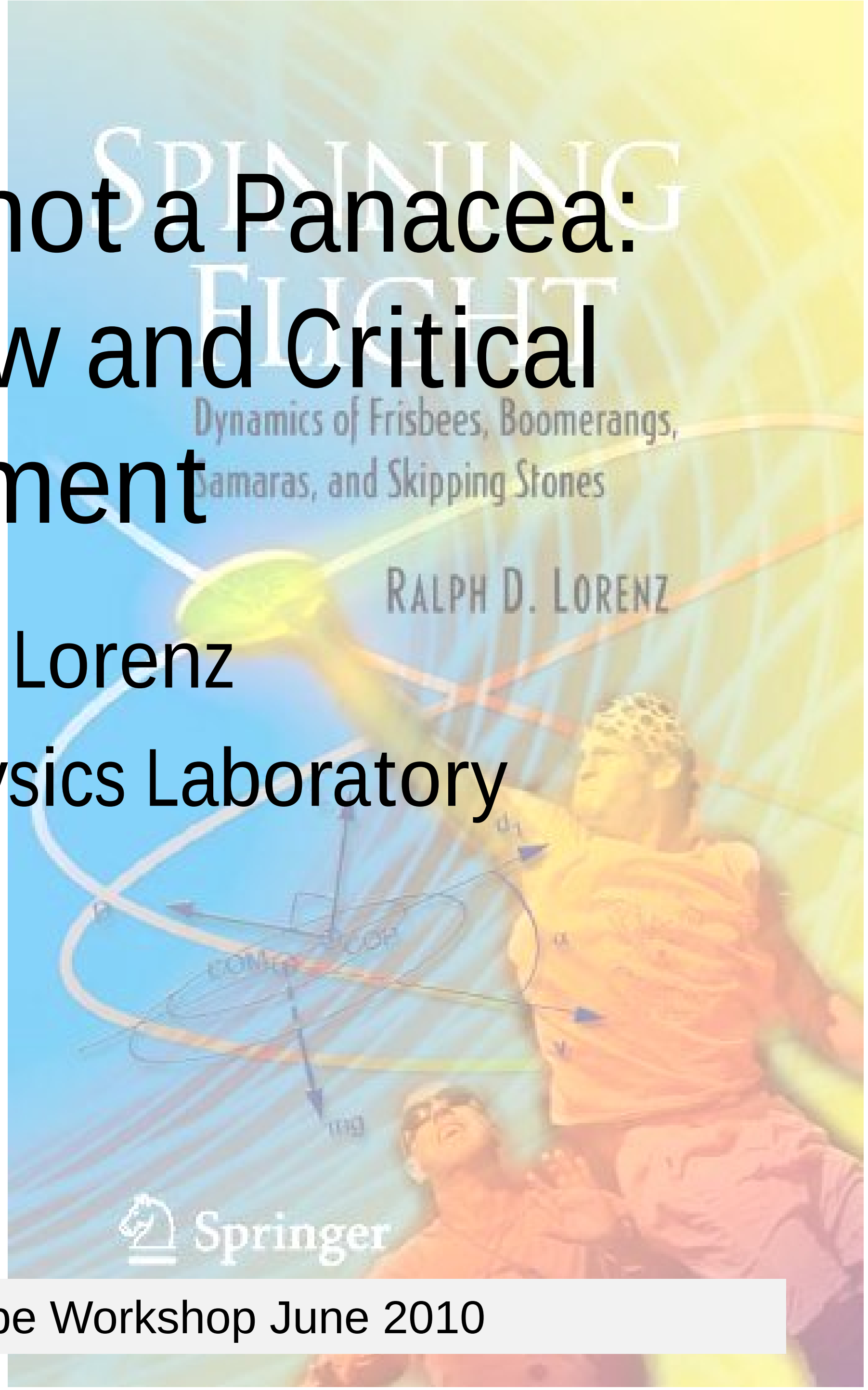




Modern Earth-Penetrating Weapons ('Bunker Busters')

E.g. GBU-28 air-dropped precision penetrating munition developed in haste (~2 weeks) during Gulf War to attack buried command and control facilities.

2270kg
35cm dia; 7.6m long. Main body originally machined from old 8" artillery gun barrels

Can penetrate 30m of Earth or 6m of concrete. (Note same penetration performance as Tallboy, but half as heavy)

New weapons in this class use 'Hard Target Smart Fuze' which use accelerometers to 'count floors' to detonate at a specified floor or depth.

Some recent controversy over proposals during Bush administration to develop a penetrating nuclear weapon cf. NRC Report "Effects of Nuclear Earth-Penetrator and Other Weapons" (2005) - strong seismic effects with reduced fallout. DoD estimates there are ~10,000 Hard and Deeply-Buried Targets (HDPBTs) that can only be 'held at risk' by a penetrating nuclear weapon. Penetration to ~3m enhances shock coupling strongly : penetration >3m decreases probability of survival of weapon to detonation point.

Planetary Penetrators

Launched

- NASA New Millenium DS-2 (2000)
- Russian Mars-96 (1996)

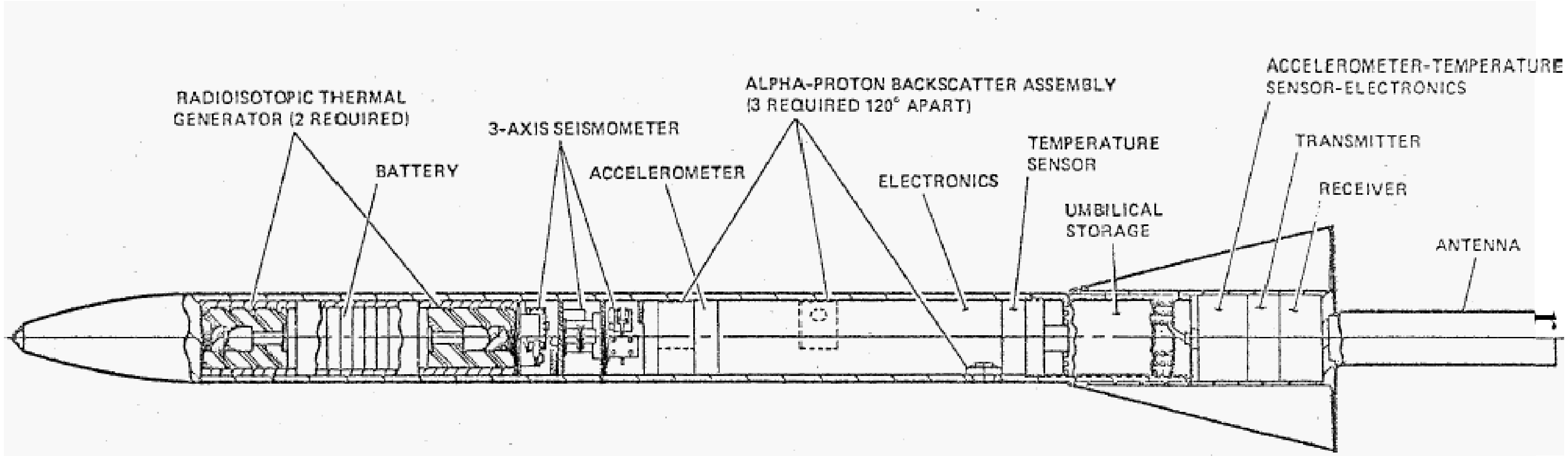
Developed

- Japanese Lunar-A (1997-2005)

Proposed (some hardware development/test)

- Mars Penetrator (NASA/Sandia in 1970s)
- CRAF (NASA/U. Arizona Comet Rendezvous/Asteroid Flyby)
- New Millennium DS-4/Champollion
- MoonLiTE (UK study, funding withdrawn 2009)
- Sampling Penetrators (JPL mid-1990s; Boynton PIDDP, others?)

Numerous studies and proposals in the past (ESA Vesta Phase-A; various comet, moon, Mars Discovery/Scout proposals, etc.) At present there is ongoing EJSM/LAPLACE Ganymede/Europa penetrator study (ESA/UK) and possibly interest in Russian mission (Luna-GLOB), plus Finnish METNET evolution of M-96.



WEIGHT - 31 KG
LENGTH - 140 CM
PRINCIPAL DIAMETER - 9 CM

Sandia Labs Mars Penetrator Design ~1976.

Sandia Labs have large database of penetration tests : equations in the literature by C. W. Young (now somewhat supplanted by more sophisticated numerical models) estimate depth and loads using an empirical 'penetrability index S' describing targets.)   Impact facilities exist at Sandia, EMRTC (U. New Mexico), China Lake in USA ; Pendyne in Wales, UK and elsewhere.

Surface Penetrators for Planetary Exploration: Science Rationale and Development Program

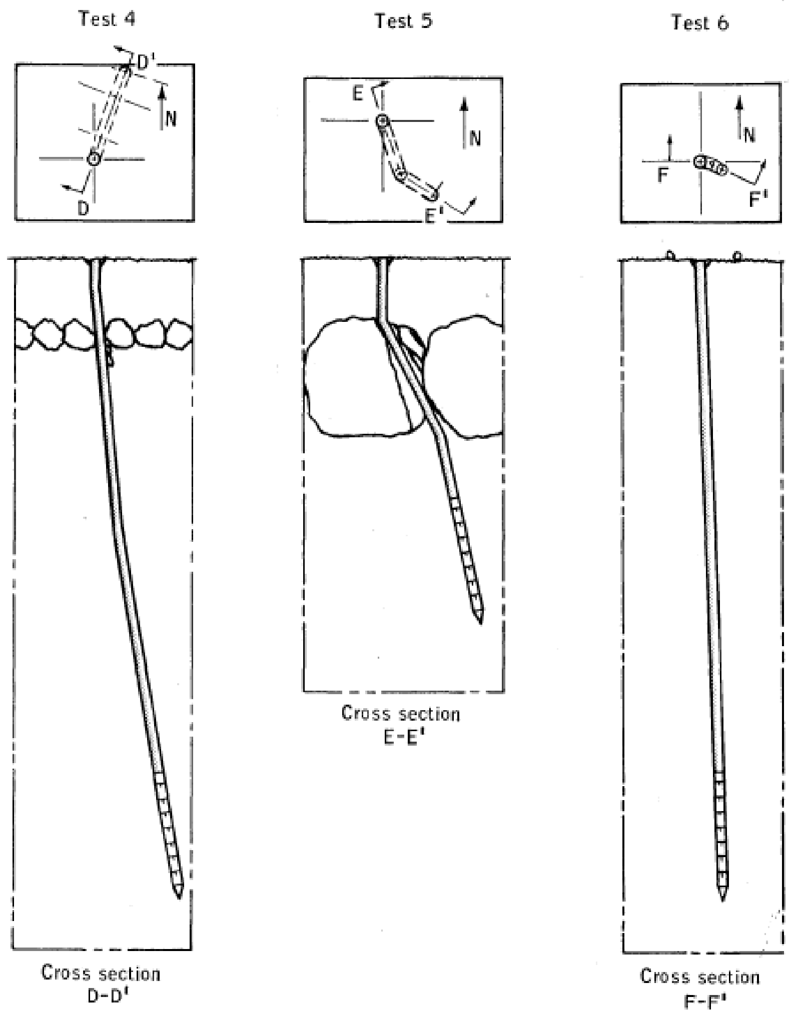
TABLE 3.- SUMMARY OF COMPONENT SHOCK-TEST DATA

Mars penetrator experiment	Components/ hardware	Shock requirement, g	Program	Component	Shock environment, g
Seismic	Biaxial bubble tiltmeter	2,000	Ames Research Center	Plans to test in the future	N/A
	Force balance accelerometer	2,000	Ames Research Center		
Magnetometry	Triaxial fluxgate magnetometer	20,000	Copperhead (AD)	Ferromagnetic core device	10,000
Meteorology	Thermocouple	20,000	Copperhead (AD)	Thermocouple	10,000
	Pressure sensor	20,000		Endevco commercial parts	20,000
Stratigraphy	Accelerometer	2,000	Copperhead (AD)	Endevco commercial parts	10,000
			Navy guided projectile		100,000
Camera	Imager	20,000	Ames Research Center	Fairchild 100 × 100 CCD	19,500
			Copperhead (AD)	Plastic lens and electronic parts	10,000
			Navy guided projectile	Silicon wafer and ceramic rings	30.000

NASA Technical Memorandum 58222

Preliminary Results of Penetrator Field Test Program—Tonopah, Nevada, April 16-28, 1979

Figure 11.- One side of the hole was removed to expose a complete cross section of the hole made by the penetrator.



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PENETRATOR MISSION CONCEPTS FOR EXPLORATION OF THE GALILEAN SATELLITES

by

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Rolling Meadows, IL

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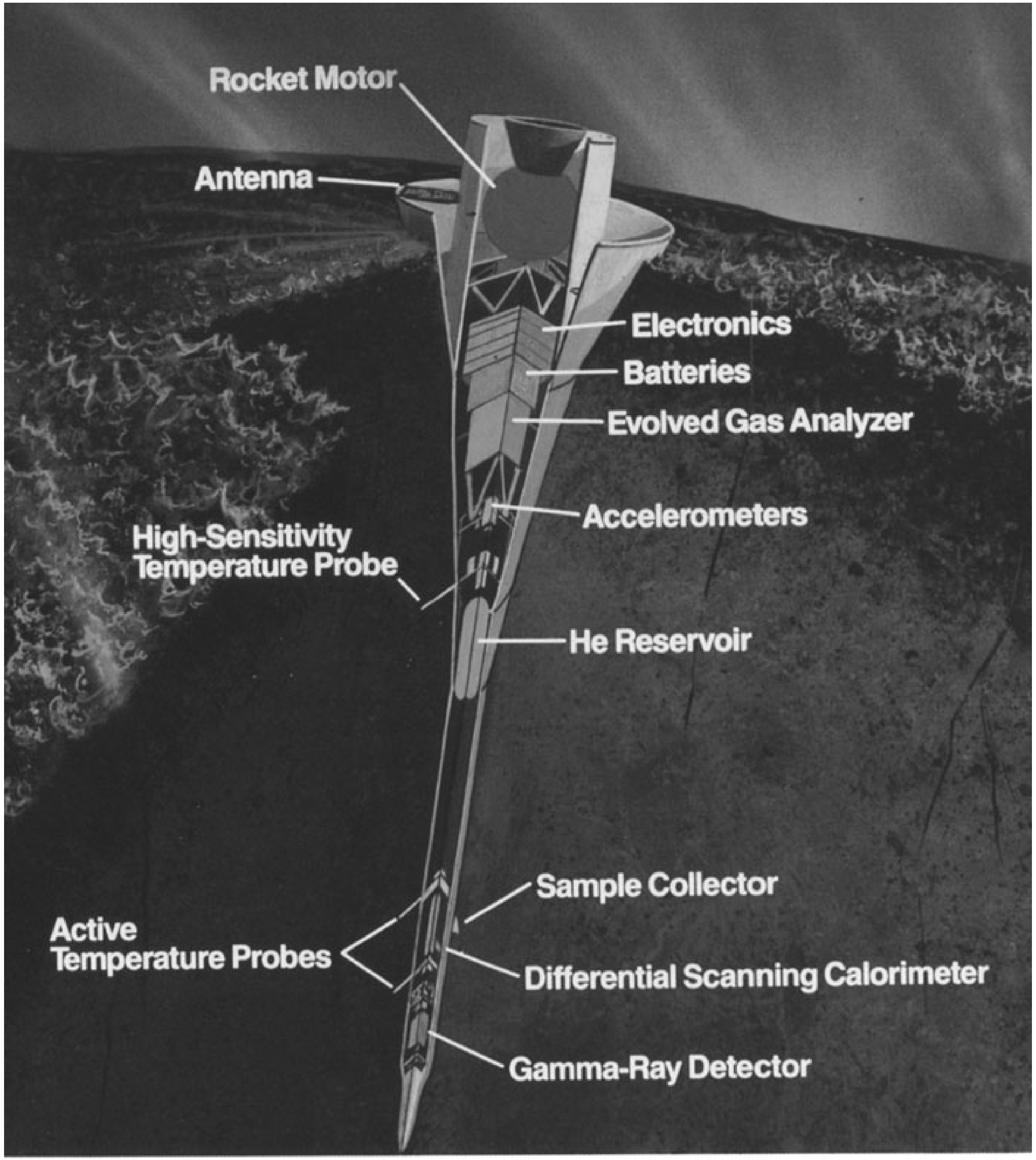
41p

Galilean Penetrators not a new idea

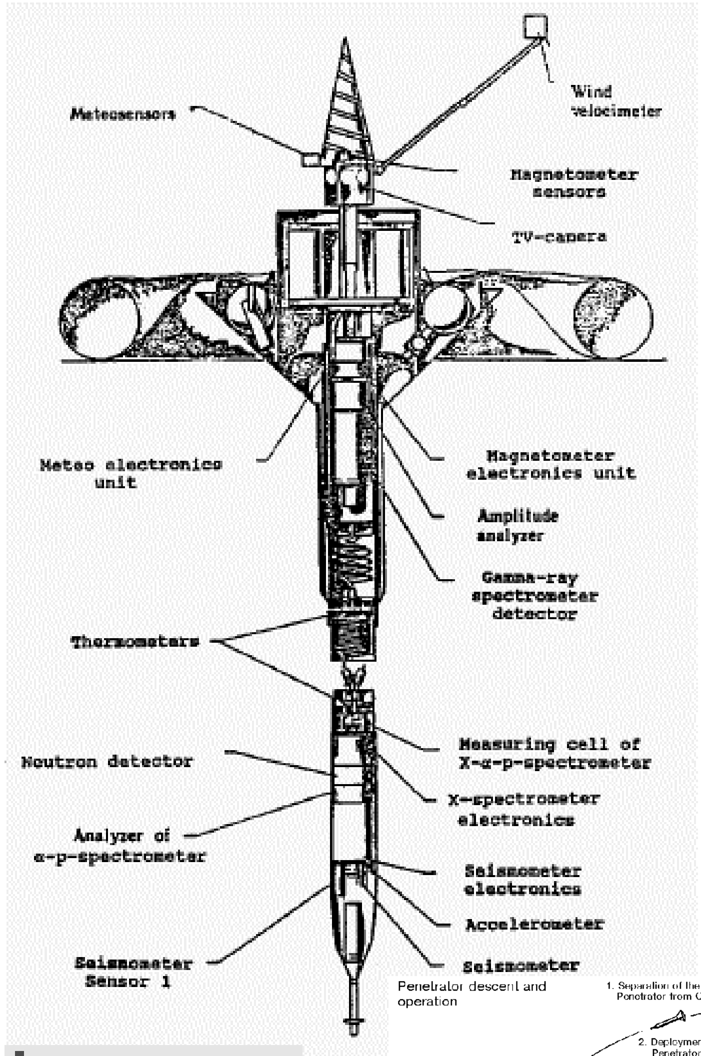


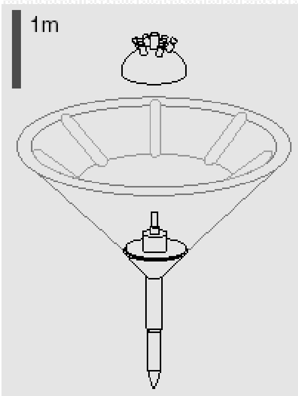
1990 Mariner Mark II, modular multimission bus for outer solar system missions.

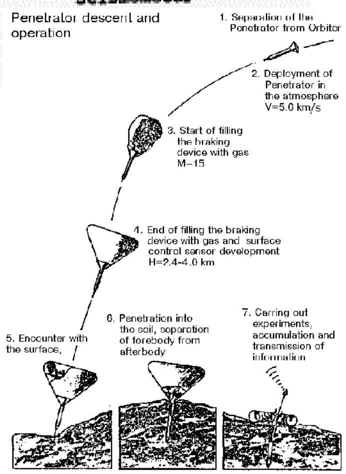
Two initial missions selected, Cassini-Huygens and CRAF (Comet Rendezvous and Asteroid Flyby)

CRAF featured a comet penetrator (W. Boynton, PI) to access cometary material and subsurface. Note aft flare to limit penetration, rocket motor to accelerate to impact speed, and side-scoop sample collector.

Penetrator was first element to be descoped. Then CRAF mission was deleted entirely.







Mars-96

Two penetrators launched (mission lost due to upper stage failure - hardware somewhere in S. America?)

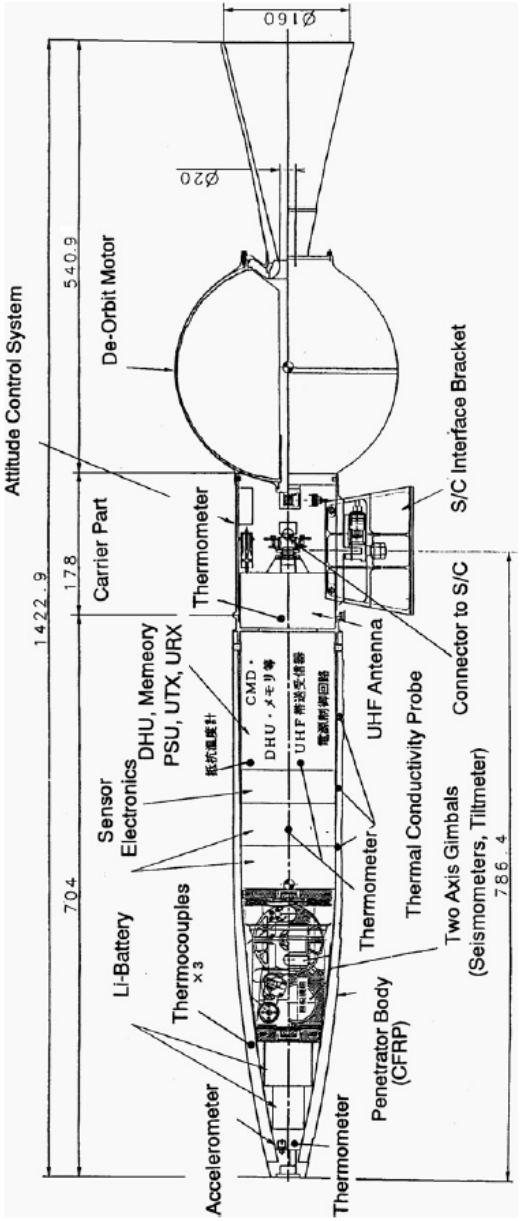
Included 30ms^{-1} deorbit motor, then were to use 3.6m inflatable decelerator (ballute) to enter Mars atmosphere and assure correct orientation at impact. Separable forebody penetrates deeper - aftbody incorporated shock attenuation system to limit decelerations to 500g.

Formidable payload (APXS, neutron spectrometer, seismometer, imager, met station etc.)

62kg each. 5kg payload. Estimated impact speed 60-80 m/s, penetration to ~5m, 500g deceleration. Power from small (0.5We) RTG + 150 W-hr Lithium battery. 8 kb/s UHF relay to Mars-96 or MGS. 1 year lifetime.

Mars-96 lost on launch.
Concept revival via FMI/METNET

Lunar-A



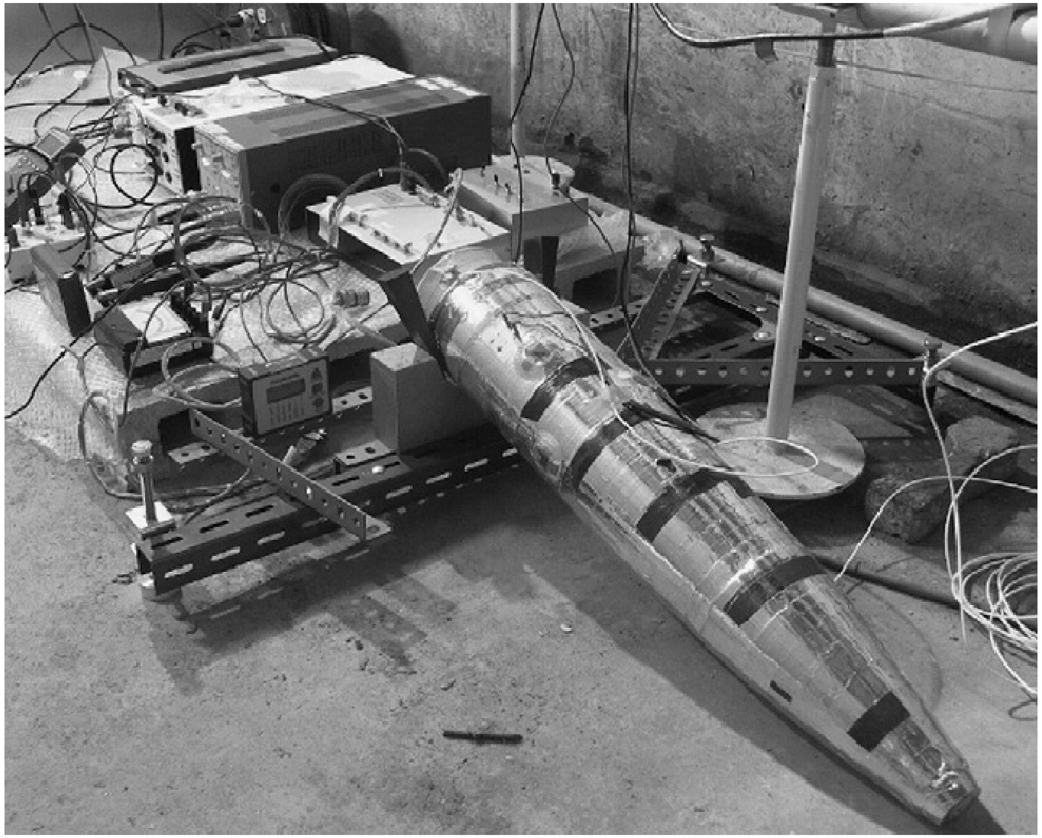
Nearly-implemented Japanese moon mission (originally 3, then 2 penetrators with heat flow and seismic measurements). Entered development circa 1995.

ISAS/JAXA doggedly pursued development of instrumentation, delivery system and penetrator vehicles. Airgun tests at Sandia Labs. Some initial surprises with non-axial G-loads. Further problems - failure to communicate post-shot with test in November 2003 (ESD?)

More-or-less reached launch pad (late-stage issue with US propulsion valves recall)

Mu-5 vehicle had unique upper stage for moon mission originally intended for 1990s - by 2005 some elements may have exceeded qualification lifetime. Concern over telecom reliability with only 2 vehicles.

Project officially cancelled in February 2007



Lunar-A penetrator in quiet tunnel for post-shot seismometer verification. From H. Shiraishi et al., Present status of the Japanese Penetrator Mission :Lunar-A , Advances in Space Research, 2008

Lunar-A Seismometer

Seismometers require caging and/or levelling mechanisms.

Functionality (comparable/better than Apollo seismometer) demonstrated post-impact by tests in quiet tunnel with co-located commercial seismometers.

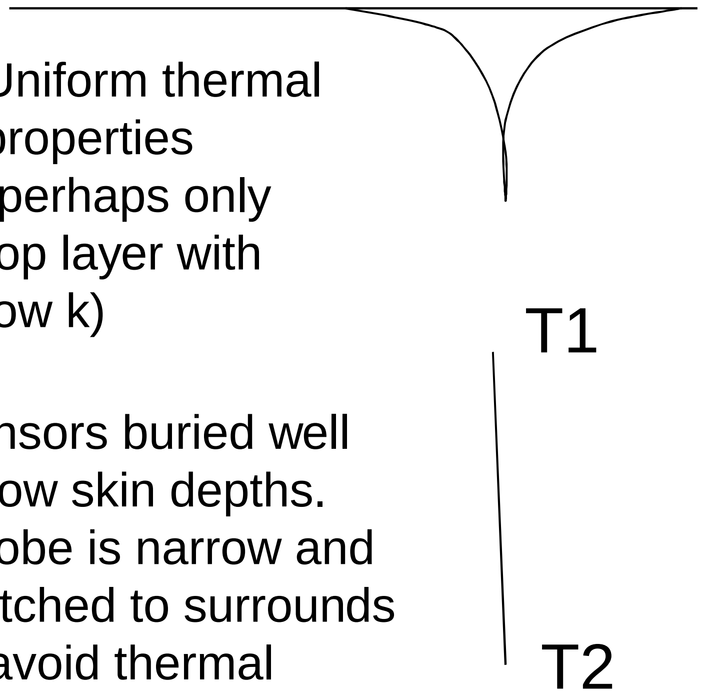
Heat flow sensors tested, but not in geological setting (i.e. can measure thermal diffusivity and temperature - how those measurements relate to desired planetary thermal conductivity and heat flow depends on emplacement)

Penetrator disadvantage - need for shockproofing. Advantages - reduced wind effects (Mars, Titan), reduced thermal cycling. Seismic coupling improvement may be overestimated (typical geophysical accelerations are small, sensor resting on ground adequate - cf Apollo.)

Why Measuring Heat Flow with a Penetrator is Difficult

IDEAL

Flat, horizontal, surface

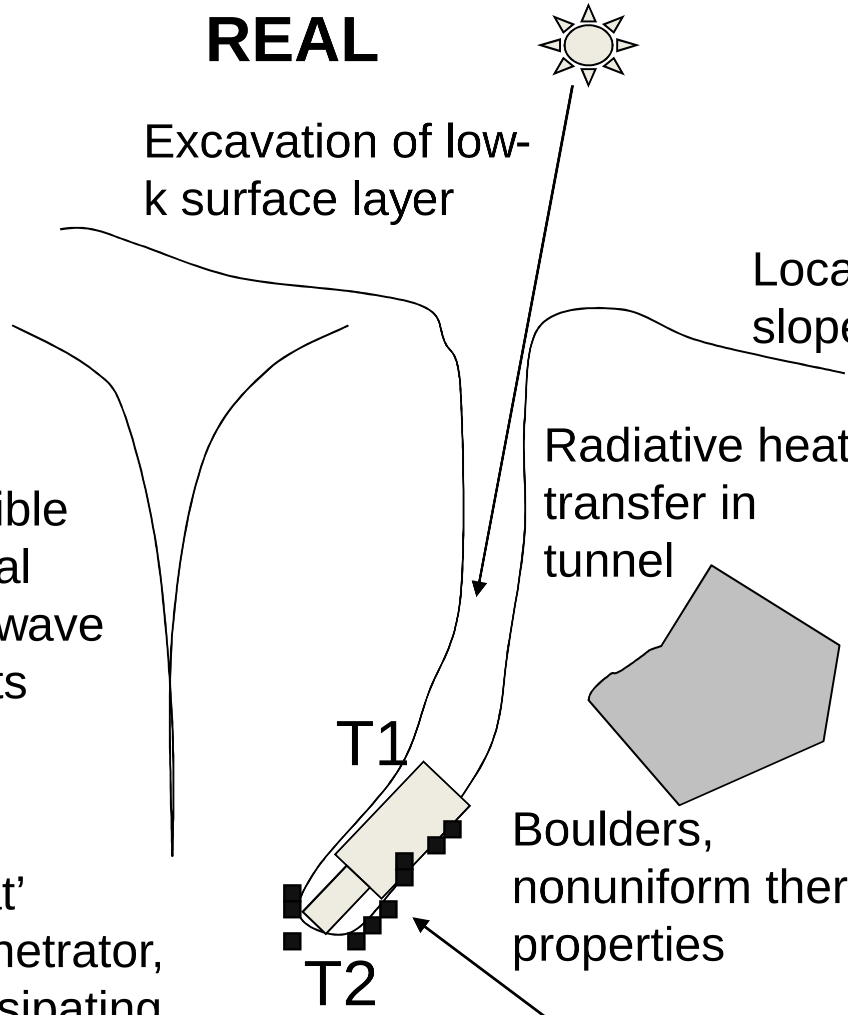


Uniform thermal properties (perhaps only top layer with low k)

Sensors buried well below skin depths. Probe is narrow and matched to surrounds to avoid thermal short. Emplaced exactly vertical, and gently so no compaction

From Lorenz Lunar-A participating scientist proposal (solicitation was withdrawn after proposals submitted. Yay NASA!)

REAL



Excavation of low-k surface layer

Local slope

Radiative heat transfer in tunnel

Possible annual heat wave effects

Boulders, nonuniform thermal properties

'Fat' penetrator, dissipating heat

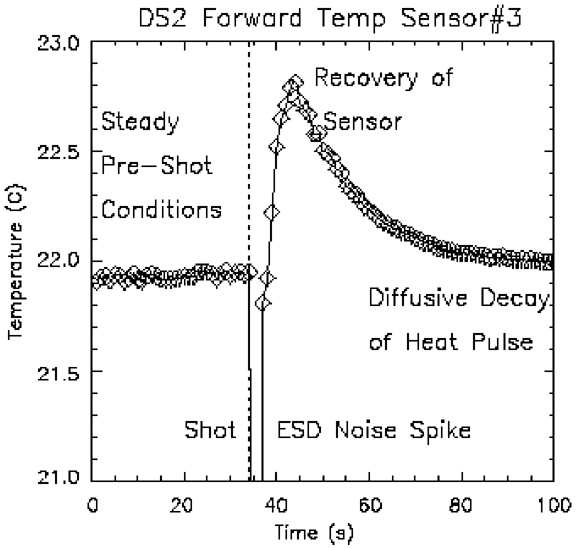
Tilted. Different thermal contact top and bottom side

Compaction of regolith around penetrator

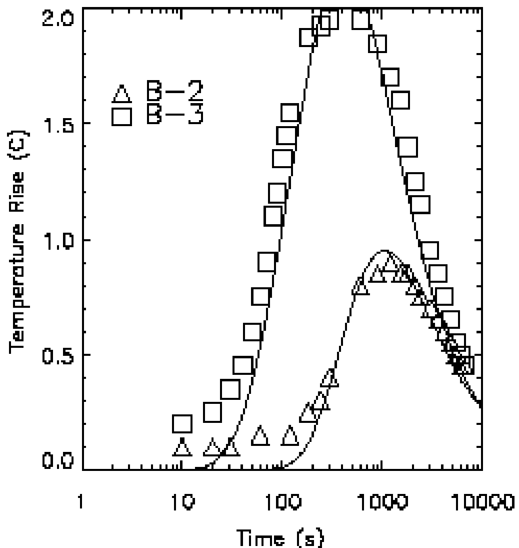
Impact Heating-Related Effects (oft-misunderstood)

1. Bulk heating due to dissipation in target material as it rearranges to accommodate volume of projectile (first documented Lorenz & Shandera, 2002 ?)
2. Skin friction.- stronger heating at faster speed, but affected layer is thinner (can cause mineralogical changes – see 1976 Mars work)

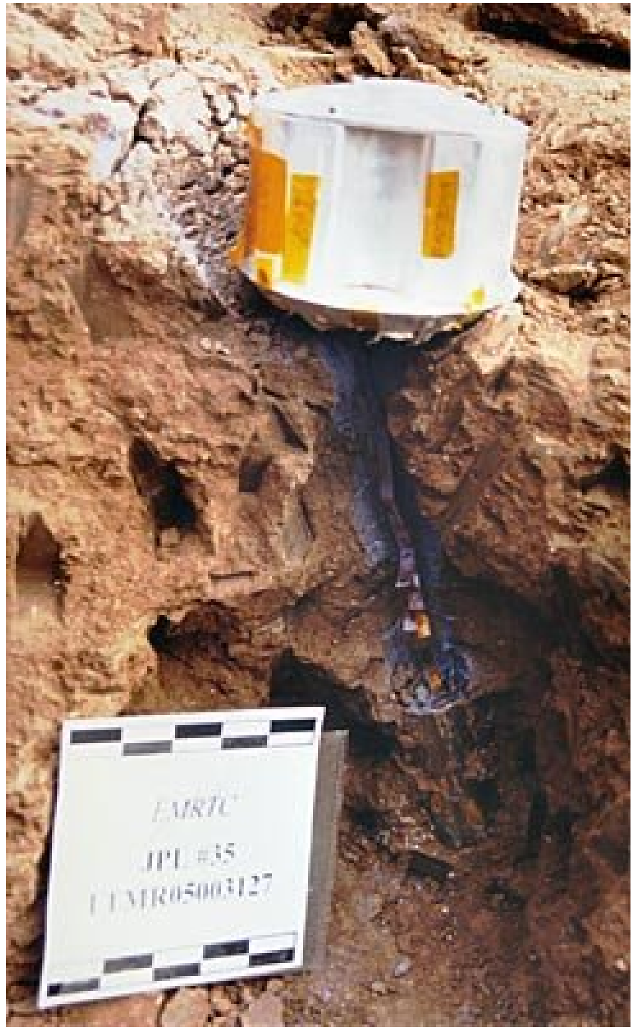
(3. Mixing of material from different depths)



DS-2 (40m/s U. Arizona gun trial) temperature sensor data (L&S,2002) showing ESD and diffusive decay of skin friction



Idealized fit to diffusion of impact heat pulse away from vehicle into ground recorded by pre-installed thermistors (Reece et al., 1976)



DS-2 shot after excavation of forebody. Note slick blackened 'tunnel'. Note aftbody resting on surface

PERGAMON

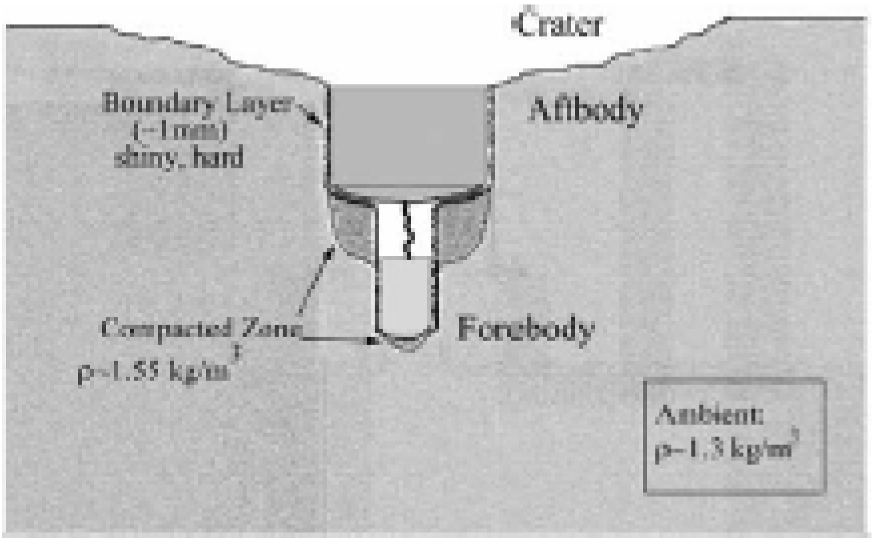
Planetary and Space Science 50 (2002) 163–179

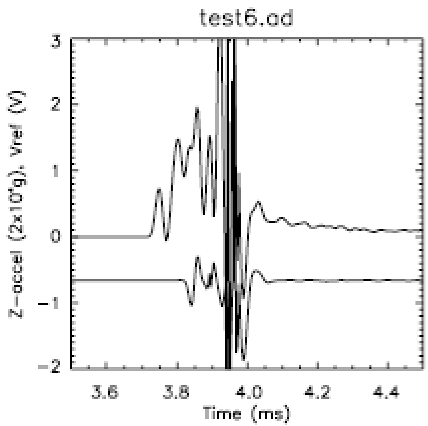
Planetary and Space Science

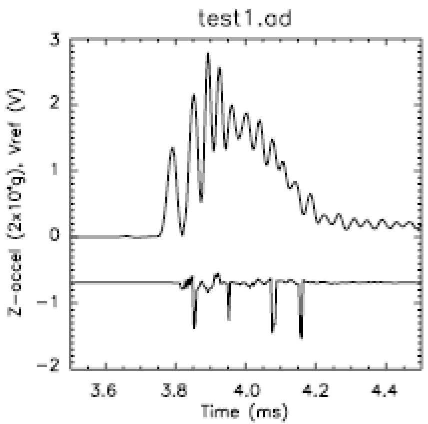
www.elsevier.com/locate/planspasci

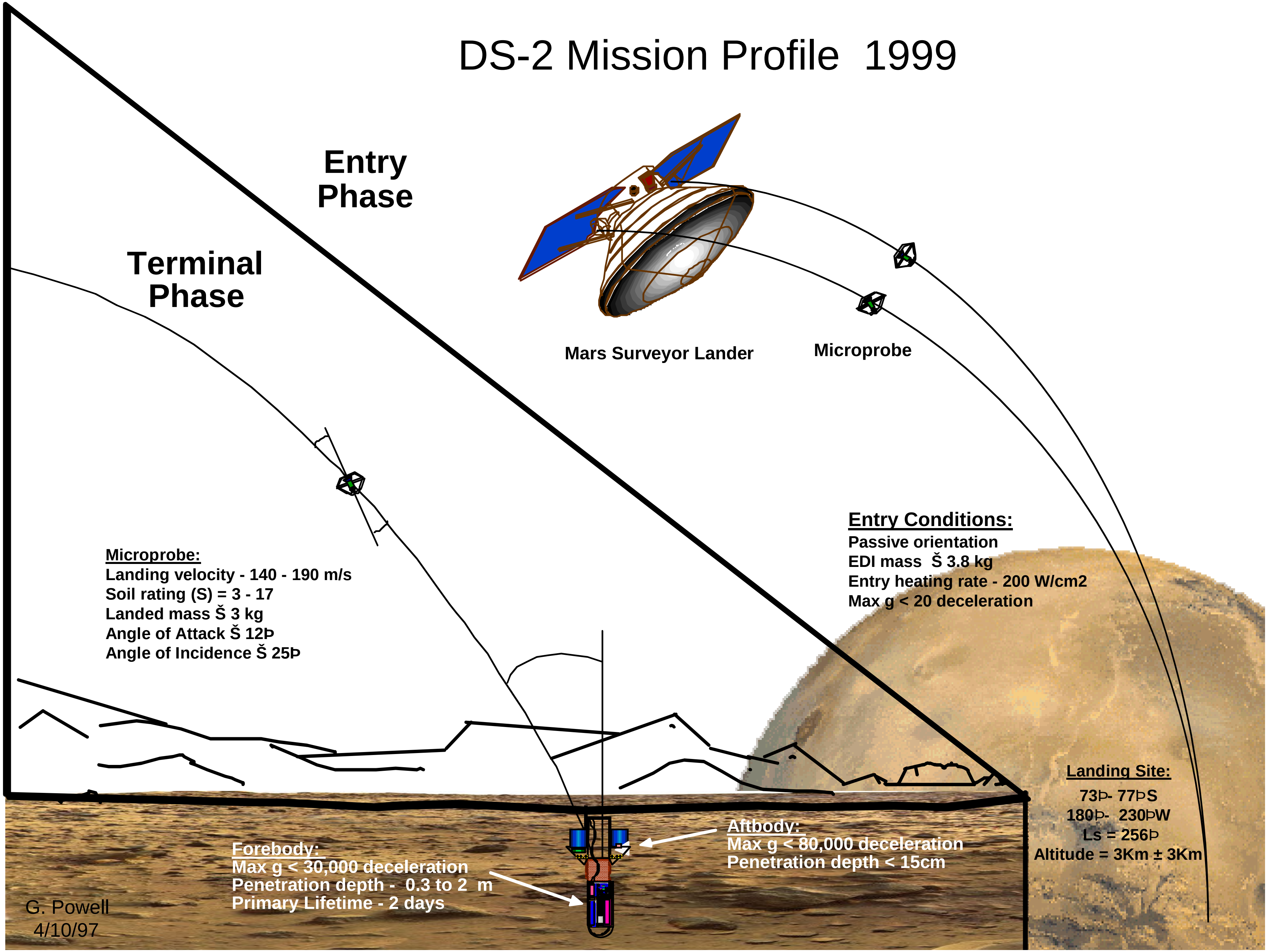
Target effects during penetrator emplacement: heating, triboelectric charging, and mechanical disruption

Ralph D Lorenz *, Sarah E Shandera

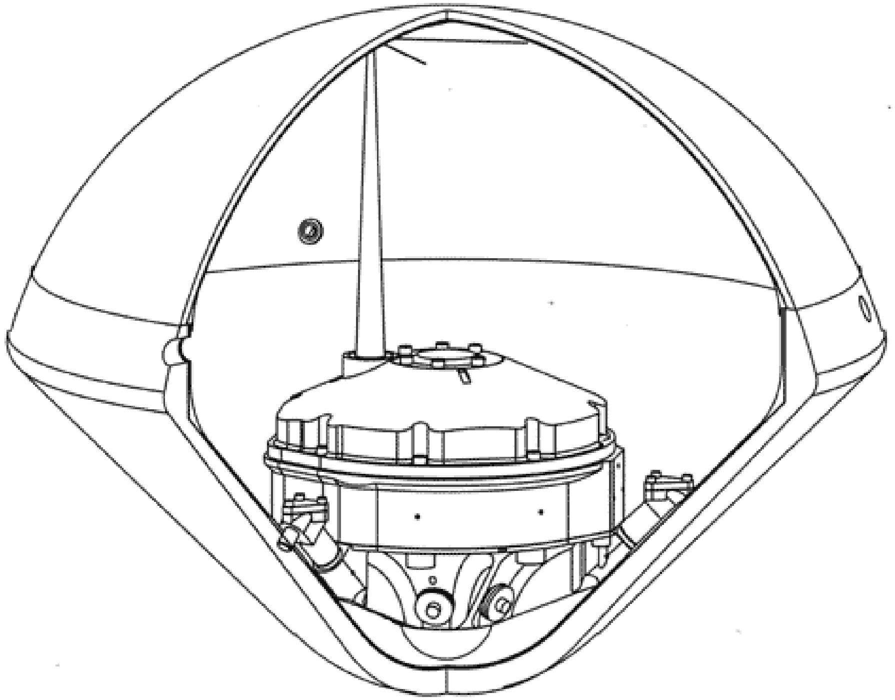








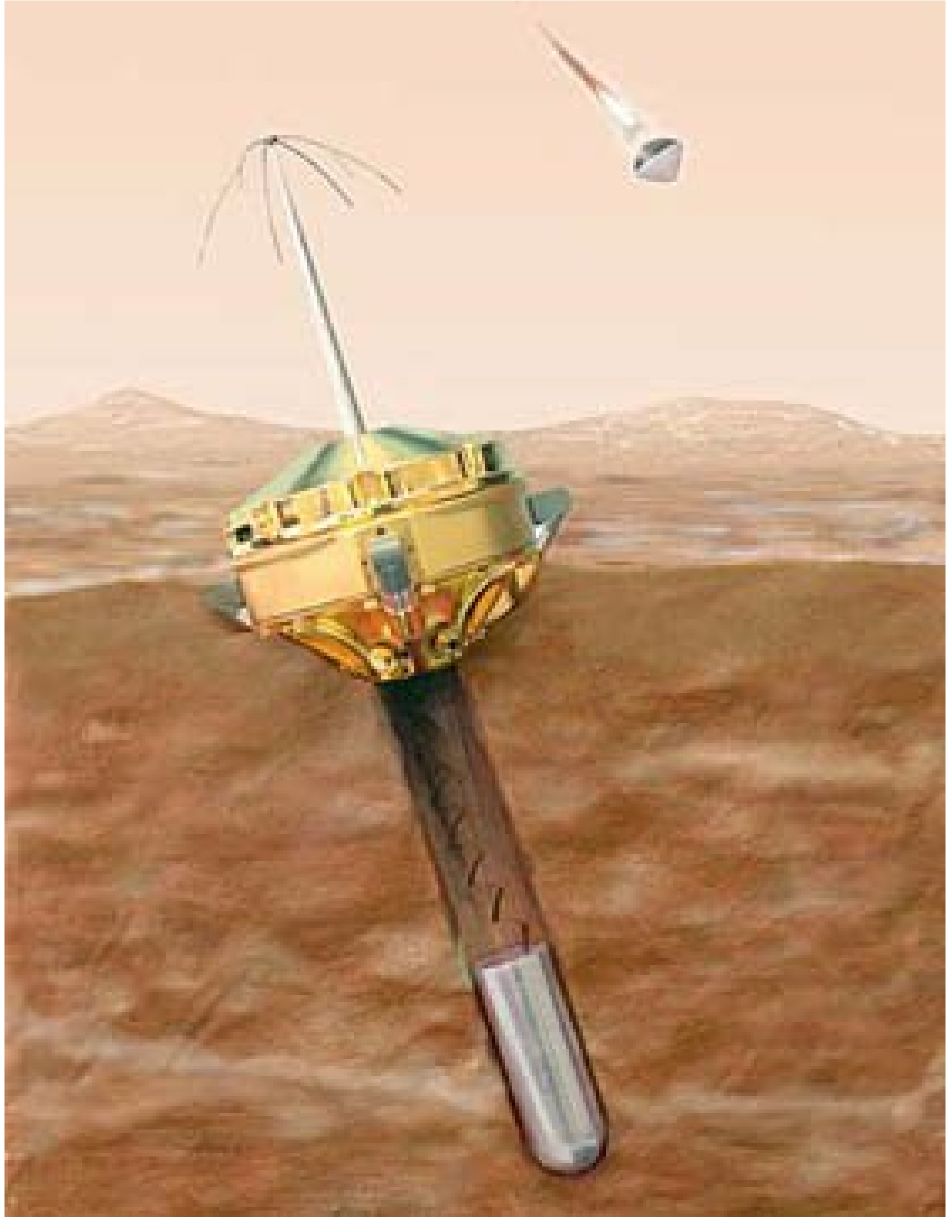
DS-2 Mission Profile 1999
Entry Phase
Terminal Phase
Mars Surveyor Lander
Microprobe
Entry Conditions:
Passive orientation
EDI mass Š 3.8 kg
Entry heating rate - 200 W/cm2
Max g < 20 deceleration
Microprobe:
Landing velocity - 140 - 190 m/s
Soil rating (S) = 3 - 17
Landed mass Š 3 kg
Angle of Attack Š 12Þ
Angle of Incidence Š 25Þ
Landing Site:
73Þ- 77ÞS
180Þ- 230ÞW
Ls = 256Þ
Altitude = 3Km ± 3Km
Aftbody:
Max g < 80,000 deceleration
Penetration depth < 15cm
Forebody:
Max g < 30,000 deceleration
Penetration depth - 0.3 to 2 m
Primary Lifetime - 2 days
G. Powell
4/10/97



Frangible entry shell 35cm diameter, 28cm high (1.2kg PICA/SIRCA aeroshell)
40mm wide forebody - 0.67kg
1.7kg Aftbody contains batteries, telecom.

Passive entry stability drives squat configuration - including 'ballast' - tungsten nose on forebody to bring cg forward)

No EDL actuations. Vehicle punches through heatshield at impact.



Concertina'd thin-film umbilical connects fore- and aft-bodies.

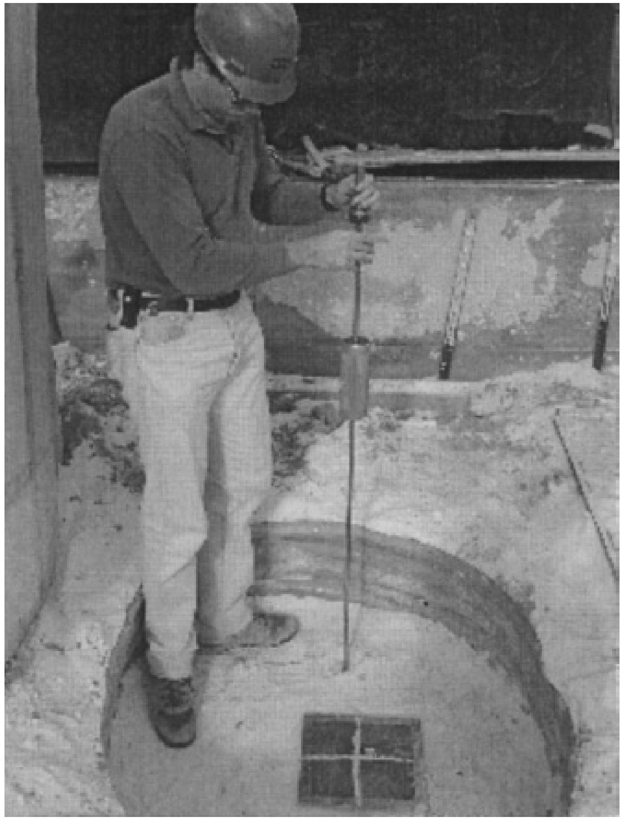
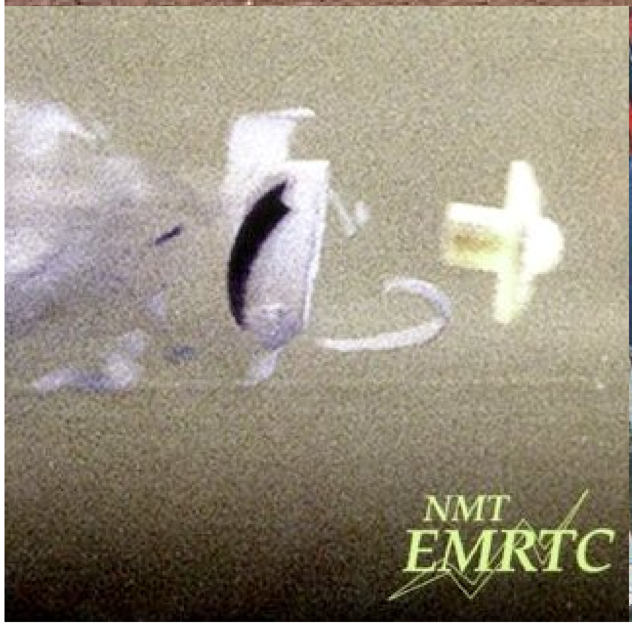


Fig. 15. Testing the hardness of the target at EMRTC. To the left is the X-ray film panel. Square with cross is a panel simulating the entry shell of the penetrator (Photo: J. Moersch).

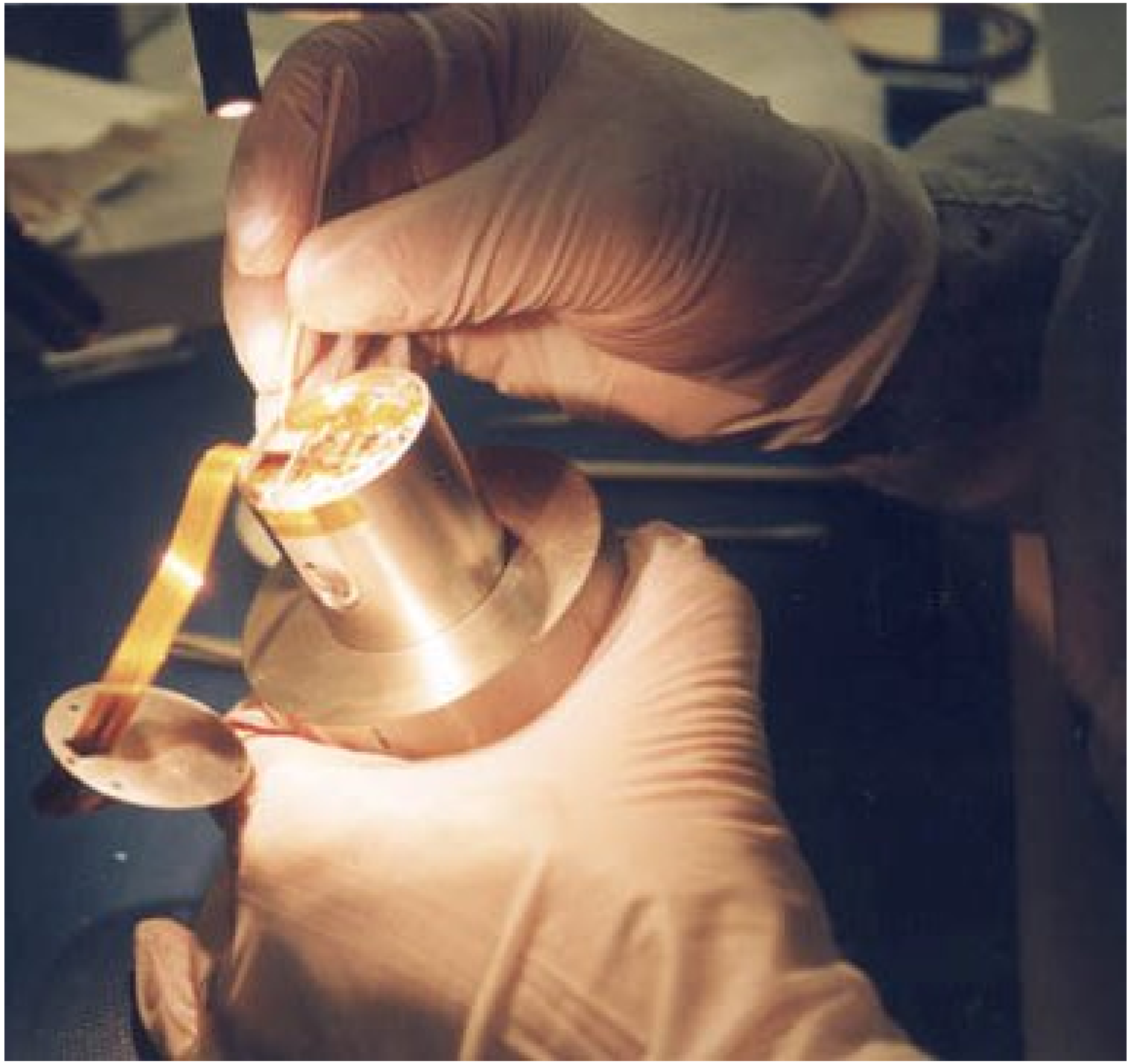


Impact testing at EMRTC in New Mexico 200m/s. ~60 development shots (incl. 2 into cryogenic ice targets)
~6 instrumented science shots. Some post-mission tests. Note testing environment is anathema to spacecraft engineering practice - dirt !

Technology Developments

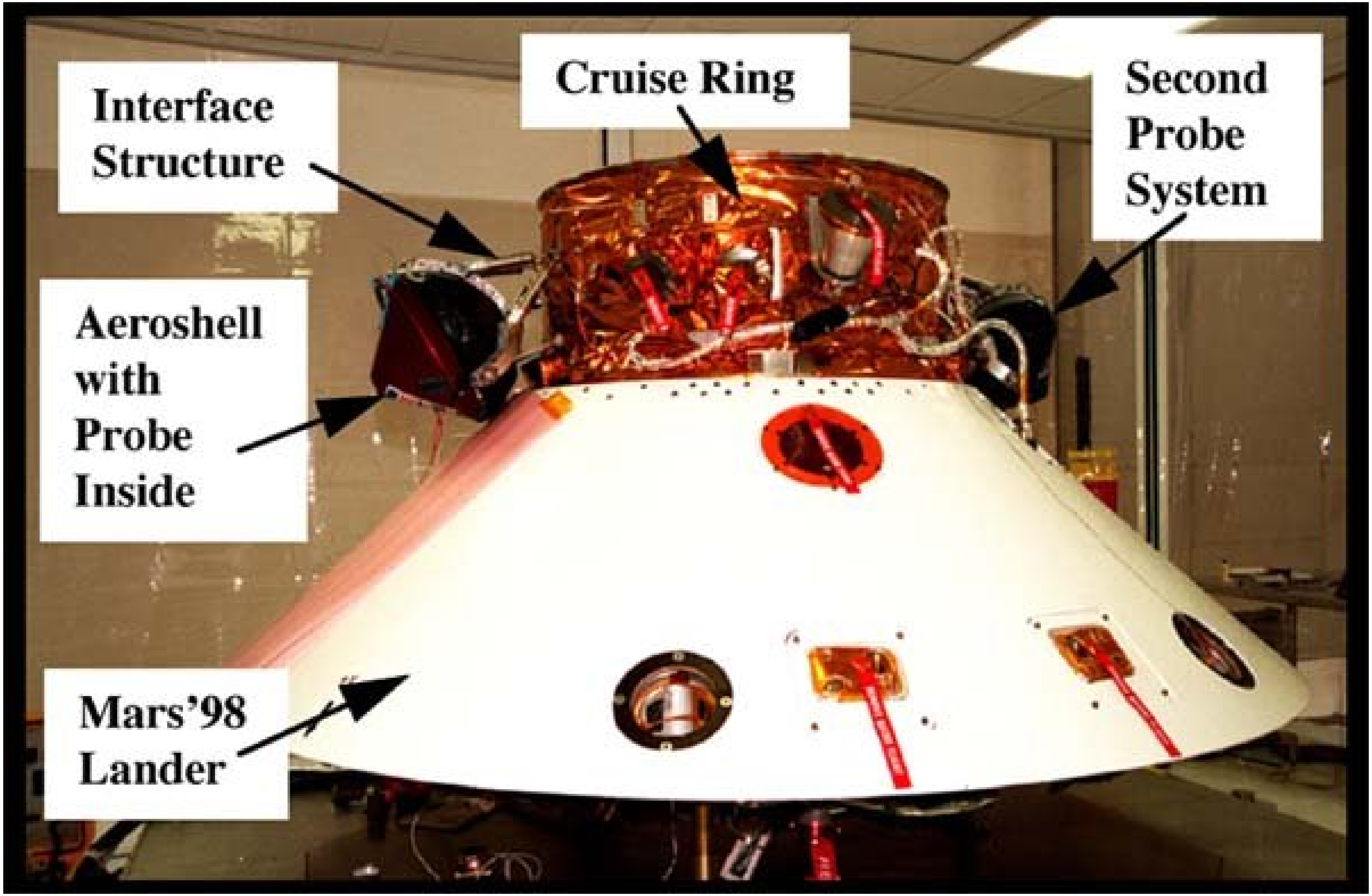
Impact- and cold-tolerant Lithium Thionyl Chloride batteries (lithium tetrachlorogallate salt instead of the more conventional lithium aluminum chloride salt to improve low-temperature performance) by Yardney. 4 cells each 40g, 600 mAh. Batteries and systems tolerant to -50 (perhaps -80C)

Custom Power Management Unit electronics and Advanced Microcontroller (80C51 @ 10 MHz with 32 channel ADC, 6 mW operating, 0.5mW sleep)

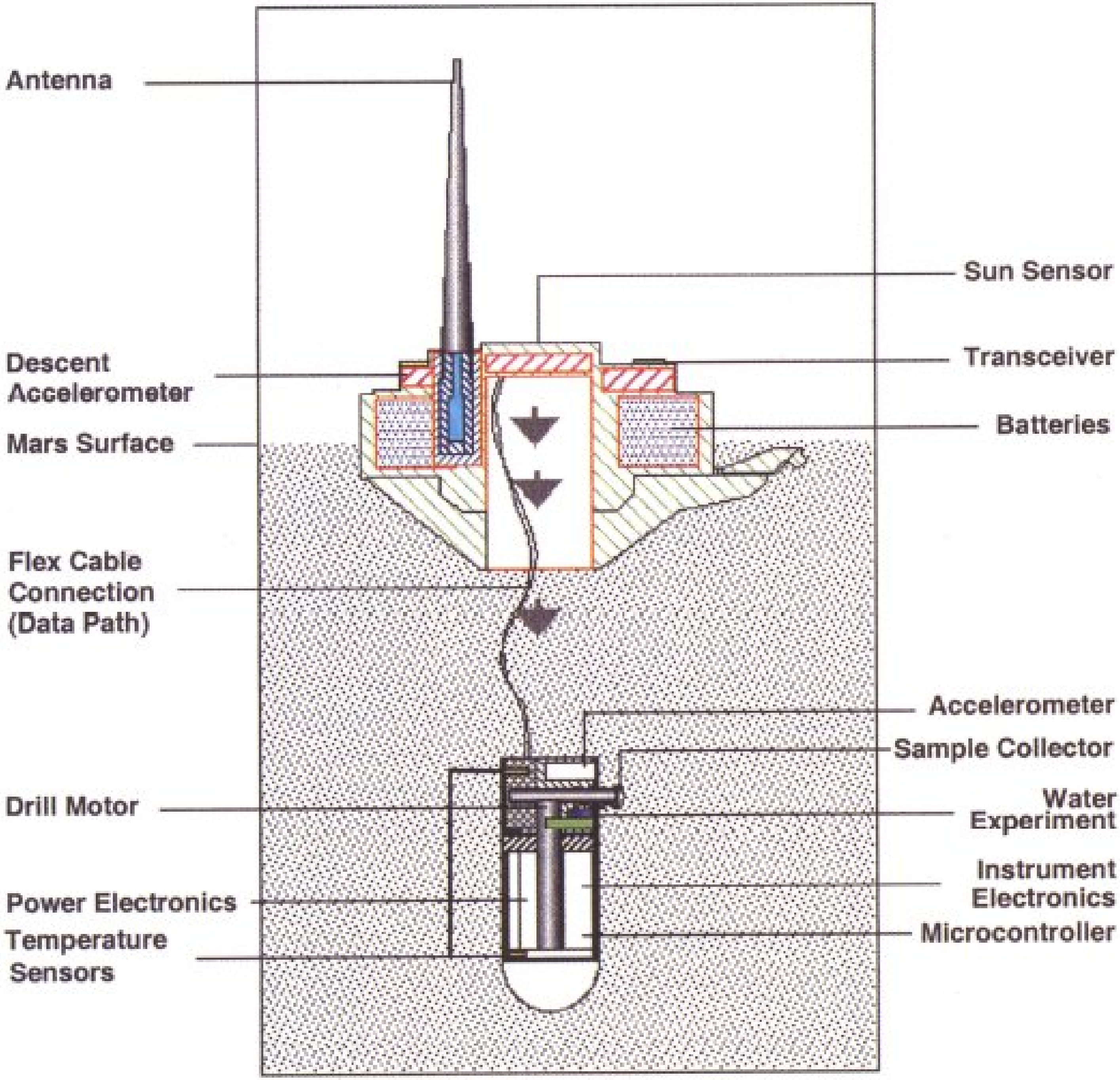


Penetrators have very tight volume constraints - have to build all systems into a whole (not provide a set of 'boxes'.)

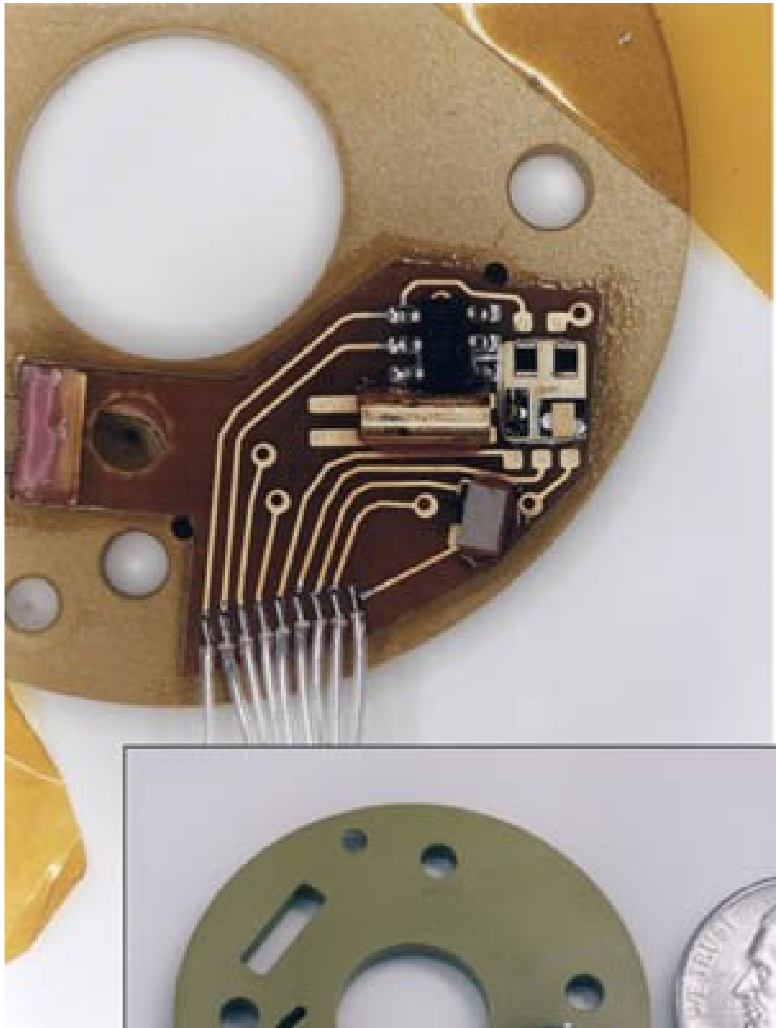
A particular challenge with very small tightly-integrated systems - insufficient volume for fasteners and access - press-fit or adhesive attachment makes it impossible to non-destructively disassemble after assembly….

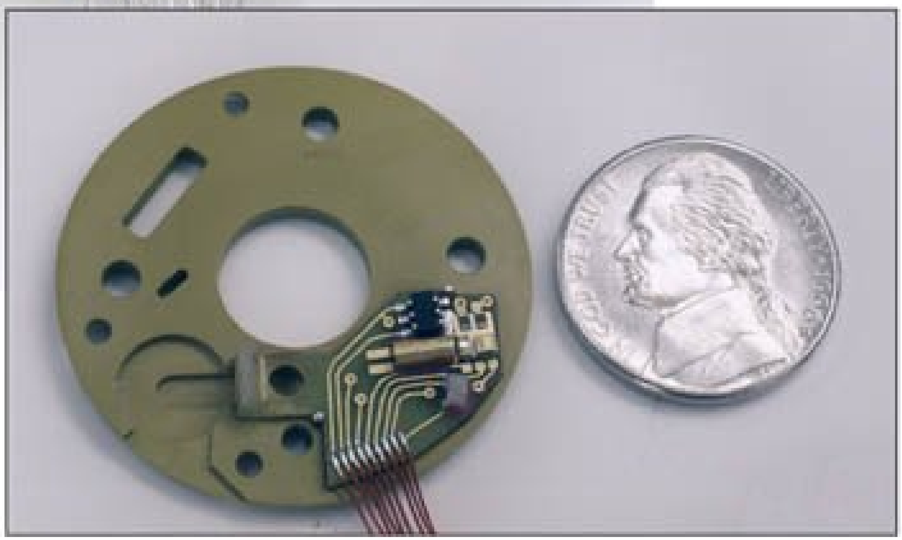

Interface Structure
Cruise Ring
Second Probe System
Aeroshell with Probe Inside
Mars'98 Lander

Bioassay swab for Planetary Protection



Antenna
Sun Sensor
Descent Accelerometer
Transceiver
Batteries
Mars Surface
Flex Cable Connection (Data Path)
Accelerometer
Sample Collector
Drill Motor
Water Experiment
Instrument Electronics
Power Electronics
Microcontroller
Temperature Sensors

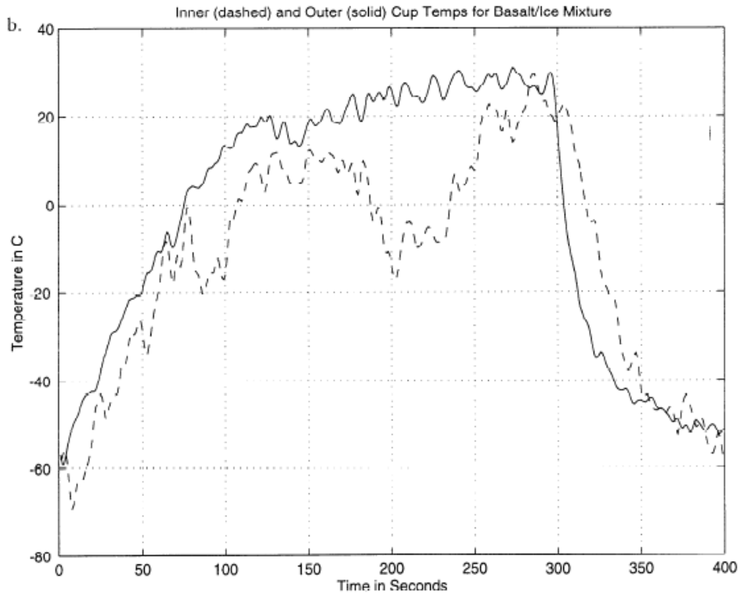




Soil Water detection Experiment

0.9W electric motor runs drill for 5 mins (1cm travel). First three turns opens door. Door sealed afterwards by single pyro.

160 ml heated cup (crude thermal analyzer) with evolved H2O detection by 1.37mm Tunable Diode Laser. (modulated at 5kHz)
2.6cm pathlength defined by single mirror.



DS-2 Development was ~$28M, including ~$1M science team. Note team overall quite small, and quite young.

Launch 3.21pm   3rd January 1999 on Delta II

Thermal control

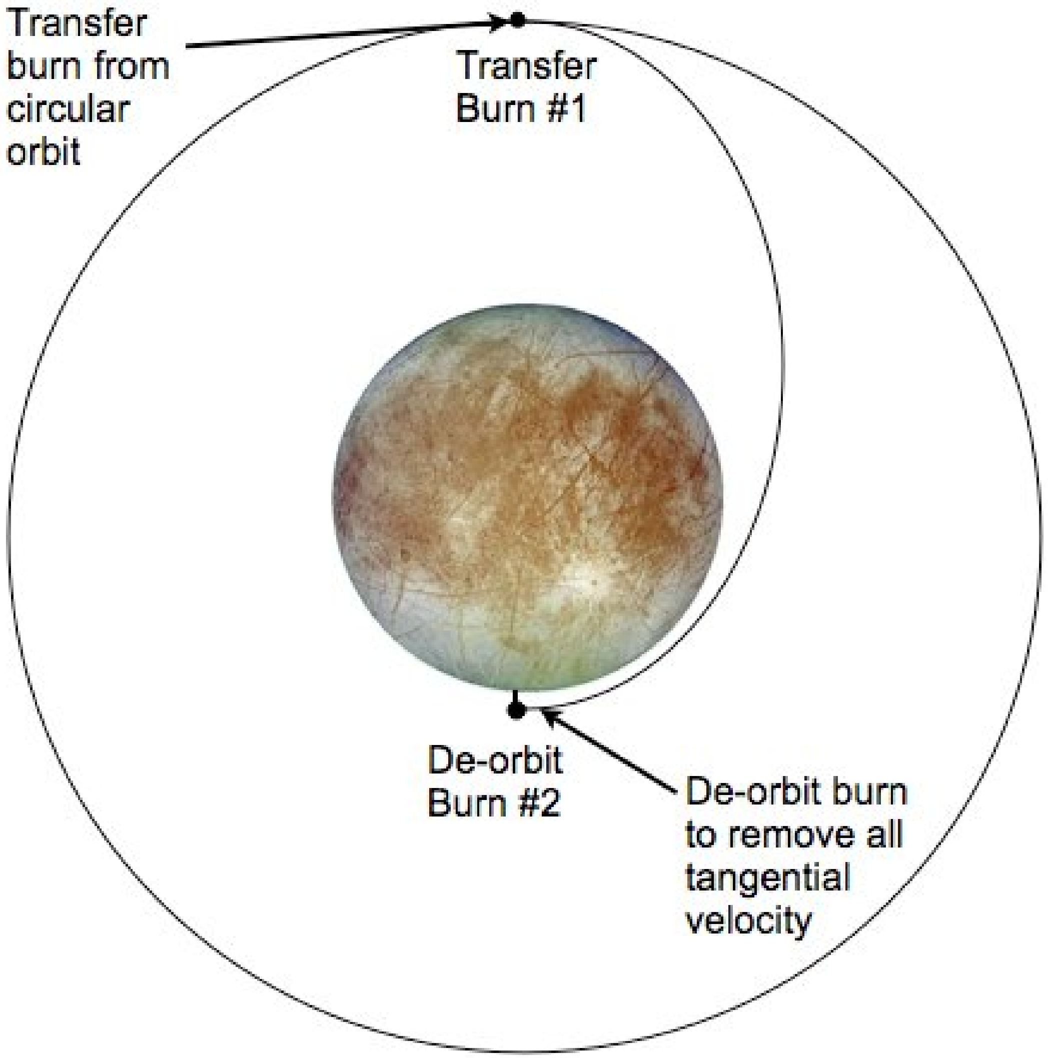
Somewhat benign for Moon & Mars low latitude (burial eliminates thermal cycling). But for Moon/Mars polar regions and icy satellites, thermal design is a major challenge (possibly a 'surprise' difficulty for EJSM study)

Vehicle is (possibly) strongly-coupled by conduction to cold medium and narrow diameter makes the relaxation time short. Unless cold-tolerant electronics (and battery) are available, the heat soak into the environment becomes the dominant energy demand (10-200W for bulk solids k~2 $Wm^{-1}K^{-1}$)

Solution is to engineer high thermal resistance so that heat leak is known. Not obvious how well aerogel/foam/MLI behave after shock/compression loading so Vacuum bottle (plus labyrinth cabling or inductive coupling to minimize heat leak) is most likely solution :. Again, LIKELY to work, testing adds confidence, but difficult to know for sure given exact circumstance of flight.

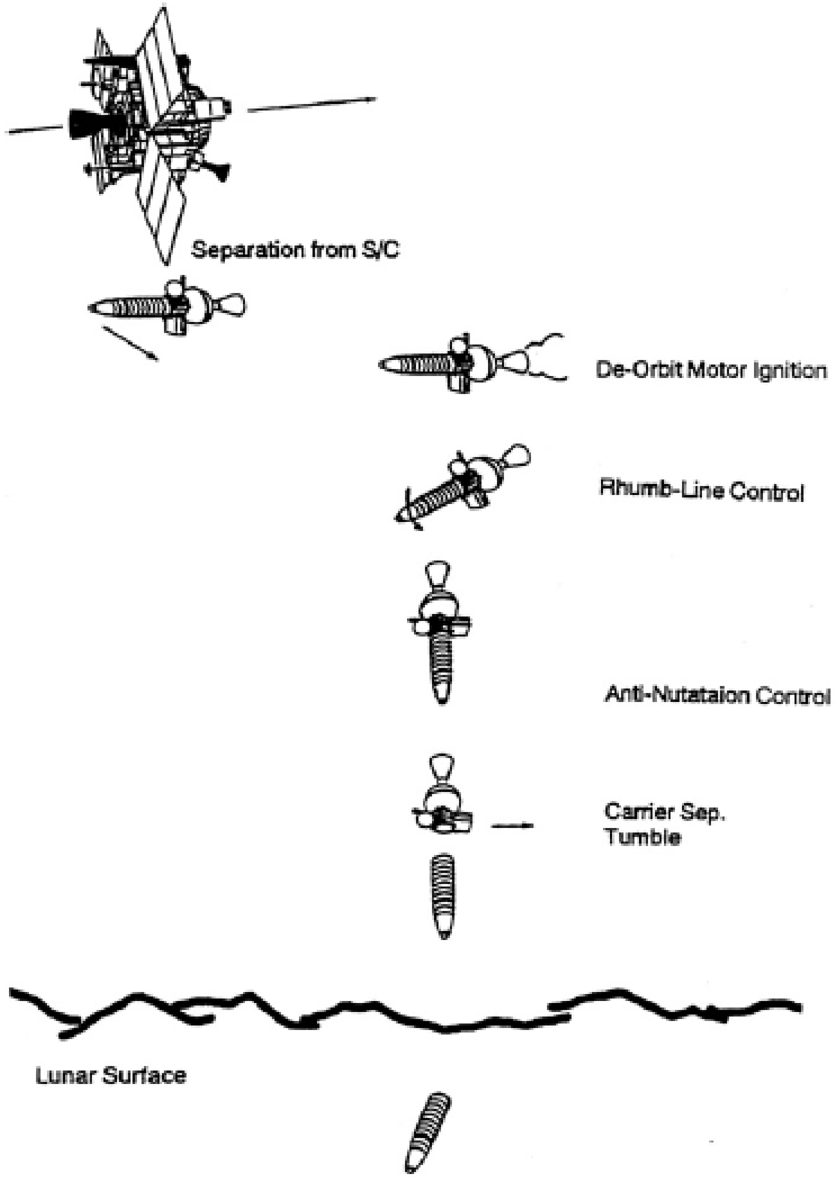
On the other hand, a porous regolith (K~0.01 $Wm^{-1}K^{-1}$) could lead to overheating if RHU/RTG heating or power dissipation >1W.

It is not clear if a buried radioisotope power source can function in a porous regolith ; output is certain to be degraded since heat sink is not efficient.



For Galilean satellites, 100-200km orbit, Burn 1 ~10-40 m/s. Burn 2 ~1400-1500 m/s.
For typical Isp the ~1500 m/s DV requirement demands propellant mass fraction 30-50%
For 1-20km 'drop' altitude, impact speed ~30-200 m/s, fall time 1-3 minutes.

(image courtesy K. Hand)



Lunar-A Delivery sequence mirrors that which would be needed for large icy satellites. Propulsive delta-V to null orbital velocity. Subsequent free-fall. System uses cold-gas thruster to precess attitude to vertical (and actively suppress nutation : note moments of inertia mean spin is unstable cf Explorer-1)

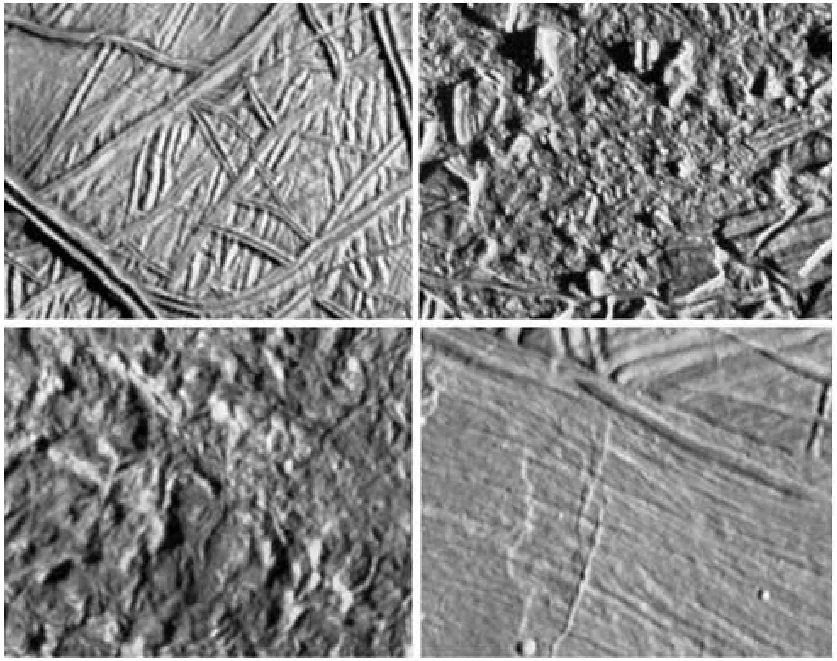
Free-fall descent time (~1 minute) defines window during which precession to vertical and separation of delivery system must occur.

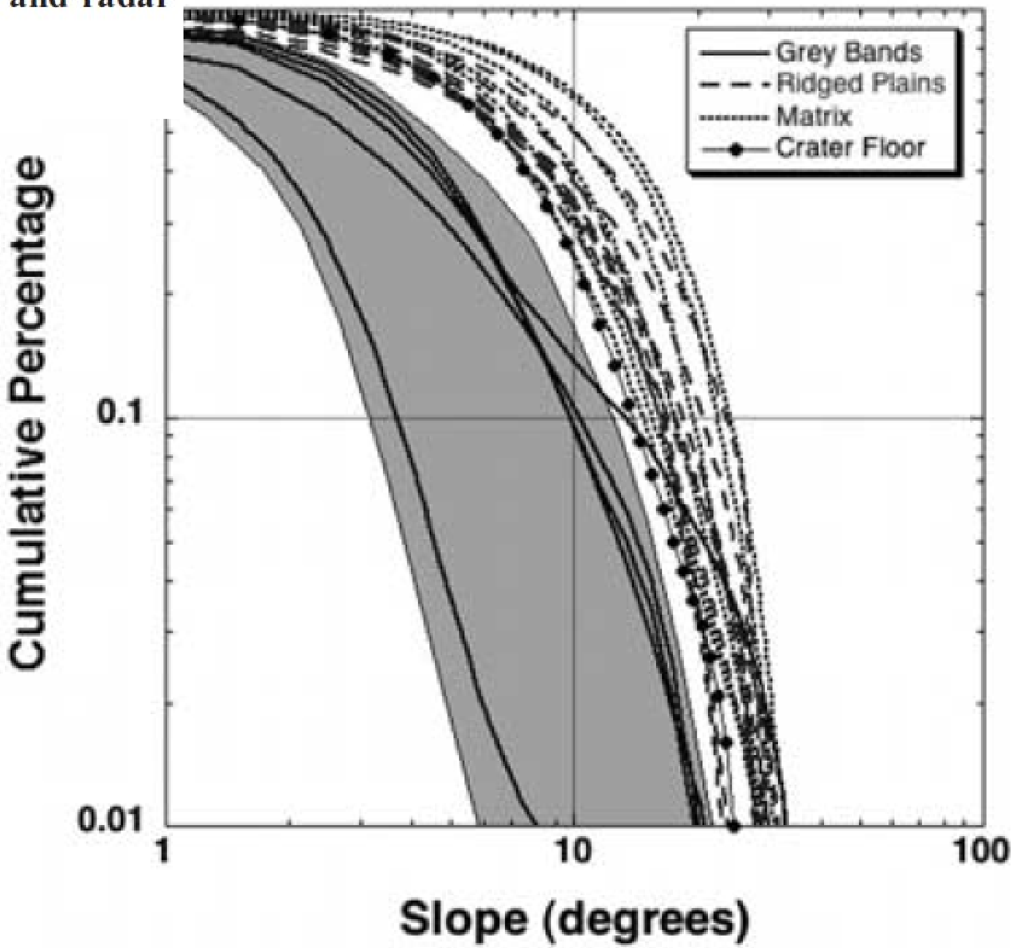
Flight path angle uncertainty at impact depends on motor DV dispersion and/or IMU capability. (if impact speed = 100 m/s, then 10^{o} FPA uncertainty demands horizontal speed < 6 m/s.

Slope characteristics of Europa: Constraints for landers and radar Sounding

Paul M. Schenk[1]

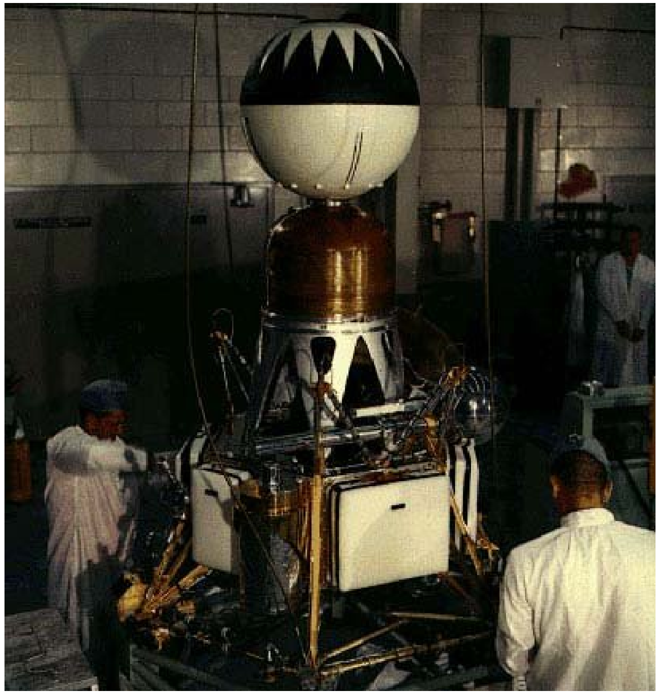
GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L15204, doi:10.1029/2009GL039062, 2009

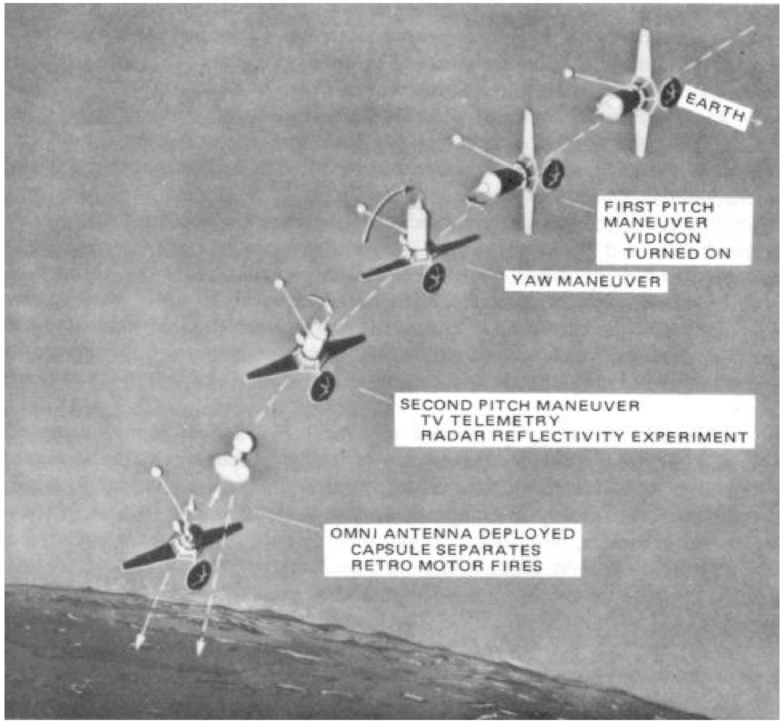




Available topographic data for Europa (roughness>Mars) suggests probability of ~5-20% of encountering slopes of 20-30^{o}.

A penetrator mission must therefore accept this level of risk (could be mitigated by better EJSM data to identify smoother target areas), or buy down risk stochastically via multiple penetrators, or use different landing system.





Since penetrator delivery to large moons must perform delta-V and attitude control, why not just carry a bit more fuel and either soft-land or deliver a semi-hard lander ?

E.g. Luna-9 (first successful moon lander) was egg-shaped capsule, ejected from delivery system hovering a few m above lunar surface - bounce/roll, then righted with petals.
Original Ranger missions had similar seismometer capsule to be separated with a retromotor prior to impact. Capsule had balsa wood impact attenuation system to tolerate some 10s of m/s.

These approaches impose a thrust/throttling requirement, fuel for another ~100m/s DV (~5% of dry mass?) and certain guidance capability (possibly radar altimeter).

However, by sitting on surface, a lander avoids thermal and communication uncertainties and allows for much lower shock loading.

Conclusions

Penetrators are a means of addressing a 20-200 m/s arrival DV structurally rather than propulsively, depositing energy in (incompletely-known) target material rather than an engineered absorber.   They offer some modest advantages for subsurface sampling and seismic coupling.

They are unlikely to offer sufficient probability of mission success to fly singly (always at the mercy of 'what if we hit a rock?' Hence appropriate to fly 2,3,6…?) Logically an array of penetrators may form part/all of a network mission, or be considered as a secondary payload (qv Mars-96 ; DS2 on MPL ; Sojourner rover on MPF ; Balloons on VEGA)

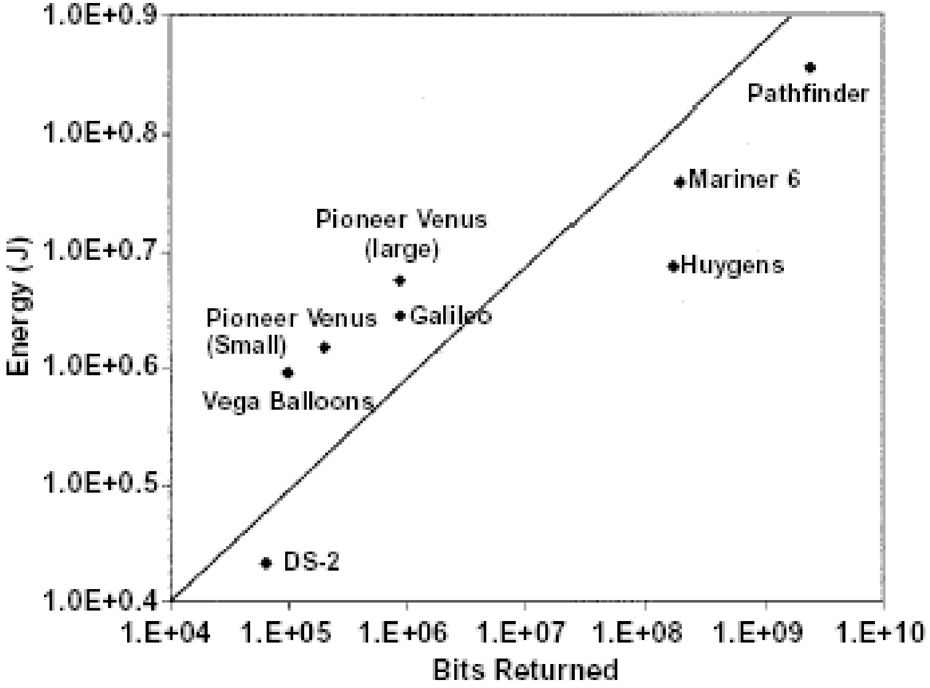
Penetrators present thermal design challenges, since they are well-coupled to local environment. Conventional radiative thermal management techniques are inapplicable. (NB RTG) Communications may be influenced by antenna burial.

Mars is an environment relatively well-suited to penetrators (atmospheric deceleration and orientation to impact conditions), as evidenced by two actual flight projects.   For small bodies, penetrators may or may not present some simplifications   (positive emplacement).

For large moons, penetrator delivery DV and attitude control requirements are little less demanding than for a soft or semi-hard lander.

backup

Mission Energy and Data Return



Rule of thumb 1 Joule = 1 Bit

Batteries ~100-400 W-hr/kg, or 1 MJ/kg

10 Mbit of data requires 10 kg of batteries, or ~100 days of a 1W RTG

Minimal mission (impact, thermal, composition) might be ~0.1 Mbit. Long-term seismic, magnetic monitoring is a strongly compressible dataset - 1 Mbit/week is a representative starting point.

R. Lorenz, Post-Cassini Exploration of Titan: Science Rationale and Mission Concepts J. British Interplanetary Soc., Vol. 53, pp.218-234, 2000

Why me?   Like myself, penetrators straddle the science and engineering worlds.

As Ph.D. student I developed numerical crash model for Huygens (and splashdown dynamics simulations). Designed and built penetrometer * instrument on Huygens probe. Surveyed impact and penetration literature extensively.

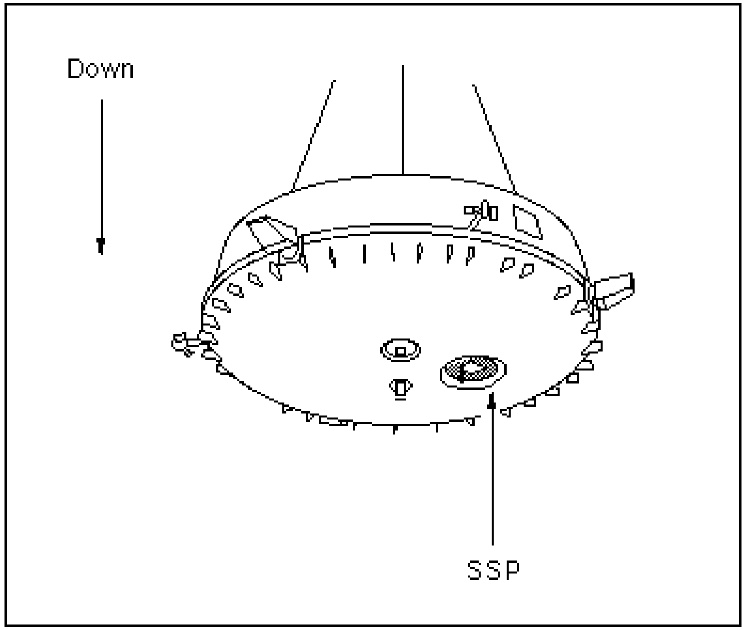
Selected by NASA in 1998 for New Millenium DS-2 Mars Microprobes science team, charged with interpretation of impact accelerometer data. Conducted 200m/s airgun tests at EMRTC in New Mexico; more heavily instrumented tests at 40 m/s at U. Arizona. First publication of impact heating and triboelectric effects.

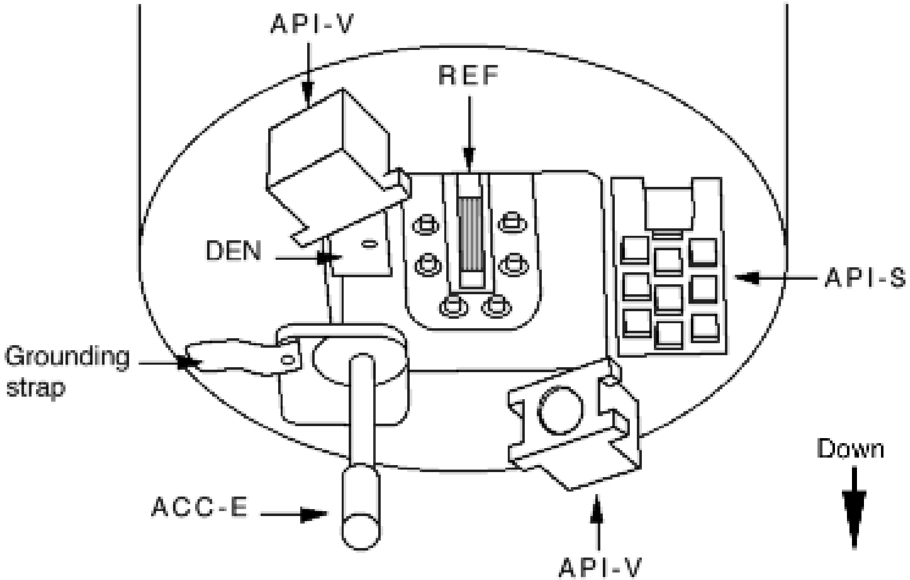
Co-I on UA Boynton Sampling Penetrator PIDDP - conducted ice-coring tests. Sometime co-I / collaborator on 4 Discovery/Scout/Rosetta penetrator proposals. Proposed to NASA Lunar-A participating scientist AO. EJSM Penetrator working group

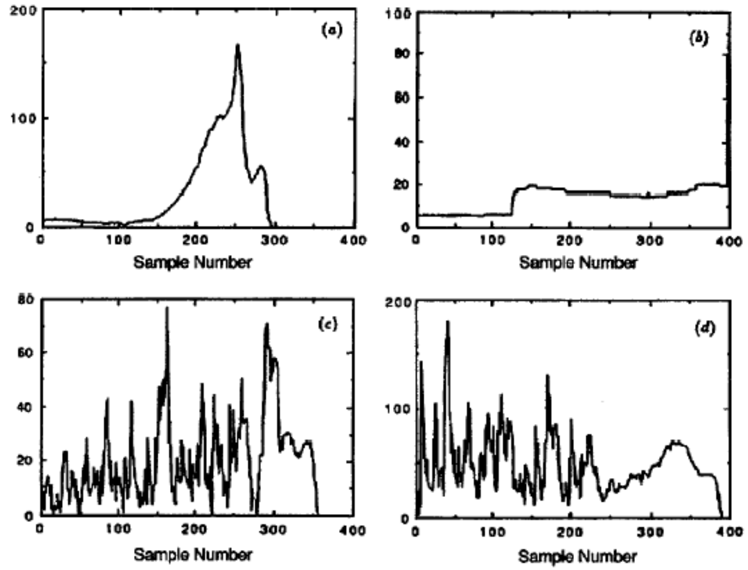
Co-organized two International Workshops on Penetrometry in the Solar System in Graz, Austria 2000 and 2006. (Proceedings books are published by Austrian Academy of Sciences). Co-Author, 'Planetary Landers and Entry Probes' Cambridge UP, 2006, an encyclopaedia of landers including penetrators.

* The words 'penetrator' and 'penetrometer' are often rather sloppily interchanged. It should be understood that a 'penetrator' is a free-flying vehicle, while a 'penetrometer' is an instrument.   Penetrometers are diverse in form and size, from large civil engineering devices to small instruments used to assess fat content in cheese. The definition is blurred occasionally when the penetration dynamics of a vehicle are analyzed to infer target properties .

The Penetrometer on the Huygens Probe



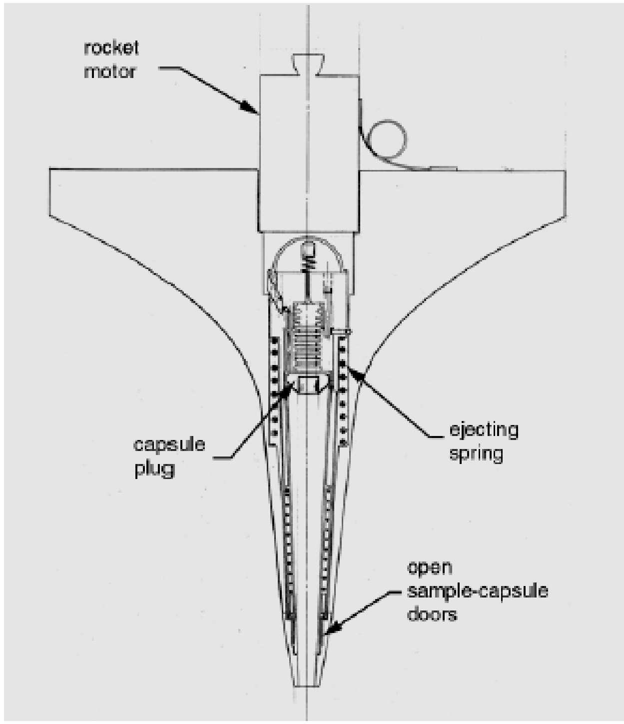




Data taken in the lab in 1994 – (a) dry sand (b) wet clay (c) fine gravel (d) coarse gravel (from *R. D. Lorenz,et al 'An Impact Penetrometer for a Landing Spacecraft', Measurement Science and Technology, vol.5 pp.1033-1041, 1994* also at http://www.lpl.arizona.edu/~rlorenz

Boynton/Honeybee Sampling Penetrator
PIDDP circa 2003-2004

Demonstrated ability to preserve stratigraphy in a ~3cm wide, 30cm long cryogenic (190K) layered ice target with airgun launch to ~20m/s. Spring-actuated mechanism seals forward knife doors of sample canister : canister can be withdrawn or ejected through back of penetrator .



Communications

For the moon it has been assumed (supported by Apollo data) that the regolith is adequately radio-transparent to permit transmission with modest loss through a few m of regolith*. Nonetheless, JAXA review of Lunar-A project noted radio link as a risk (note also defocusing due to dielectric constant of medium - so SOME loss is inevitable.

For Mars, transmissivity is less certain since oxidized iron compounds are can be radio-opaque (MARSIS/SHARAD data might be fruitfully examined in this context.) Both Mars-96 and DS-2 incorporated separable fore- and aft-bodies to allow aft body to remain substantially on the surface.

For 'clean' ice targets, radio opacity is likely to be rather low and so transmission through penetrated target should be achievable. But for e.g. Saturnian satellites some further assessment might be required (Cassini radar data indicate some microwave absorption in outer moons.)

Burial/backfill effects are difficult to test - wake and/or airblast scour impact zone. Thus RF performance is LIKELY to be OK, but is difficult to be certain about…

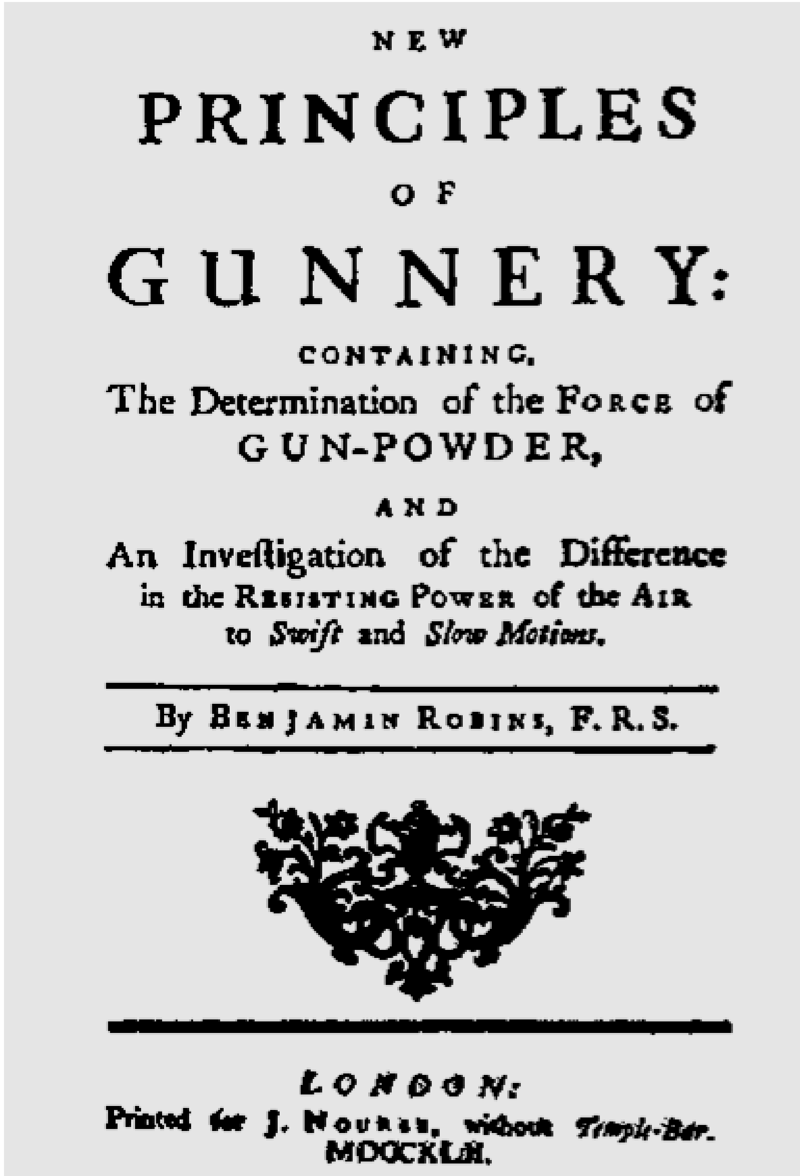
(*cf Belostotskaya , 2nd Conf. on Microwave and Millimeter Wave Technology, 2000)

First quantitative assessment of projectile penetration into the ground was by Benjamin Robins, Engineer-General to the East India Company, notably in his 1742 treatise 'New Principles of Gunnery', which applies Newton's (1698) analytic methods to artillery.

He devised the ballistic pendulum to measure launch velocity and a whirling-arm apparatus to measure aerodynamic drag.

His scientific measurement approach (special precision cannonballs, carefully-measured powder charge) allowed him to understand the effect of streamlining, to detect the effect of spin on projectiles (the Robins-Magnus effect, often rather unfairly referred to only by the latter) as well as the transonic rise in drag coefficient (the 'sound barrier').

He determines that the penetration of shot into solid materials varies as the square of velocity.



NEW

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OF

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The Determination of the FORCE of GUN-POWDER,

AND

An Inveſtigation of the Difference in the RESISTING POWER of the AIR to *Swift* and *Slow Motions*.

By BENJAMIN ROBINS, F.R.S.

LONDON:

Printed for J. NOURSE, without *Temple-Bar*.

MDCCXLII.