PERGAMON

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Acta Astronautica 57 (2005) 722–732

ACTA ASTRONAUTICA

www.elsevier.com/locate/actaastro

Artillery based explorers: A new architecture for regional planetary geology

Ian Garrick-Bethell*

MIT Department of Earth, Atmospheric and Planetary Sciences, 54-520, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Received 30 January 2004; received in revised form 1 December 2004; accepted 22 February 2005
Available online 13 June 2005

Abstract

Artillery based explorers (ABEs) are small impact-tolerant rockets that are launched from a platform landed on a celestial body. ABEs follow an approximately ballistic trajectory to a nearby site of scientific interest without an active landing system, and are single use only. Due to their high impact velocities, ABEs carry g-tolerant payloads that do not require the use of delicate robotics for sampling rock or soil materials. One advantage of using ABEs for regional exploration is the capability for accurate placement of instrumentation up to kilometers away from the launch site, in any direction. Their impact tolerance allows them to target steep or rugged terrain that may be inaccessible to rovers or aerial vehicles. With a fixed mass of propellant and no need for a guidance system, navigation to the target site amounts to specifying elevation and azimuth launch angles. ABEs can achieve ranges up to 10 km on Mars with impact velocities no greater than those of orbit-deployed penetrators that are currently under construction, or have flown in the past. Simple in form, this combination of artillery and planetary geology requires no fundamental new technology for development. Military rocketry analogs, the Deep Space 2 mission, and the Russian Mars-96 mission are used to demonstrate the feasibility of ABEs. Several example missions and payloads serve to illustrate the usefulness of this new architecture.

1. Introduction

Mobility on planetary surfaces is important if scientists are to explore beyond the local landing site. To date, only rovers have been successfully deployed for this purpose on the Moon and Mars. However, rovers have limited ability to travel long distances and overcome large obstacles or steep and rugged terrain. Exploring valleys, deep craters, or polar ice caps with rovers would be a formidable challenge. To overcome some of these problems many other mobility systems have been proposed for future missions. Most notable of these are flight systems for aerial exploration on the atmospheric bodies Venus, Mars, and Titan. A free-flying balloon flew on Venus in 1985, and balloon systems for landing and mobility on Mars and Titan have been proposed [1,2]. Examples of powered flight

---

* Tel.: +1 617 258 0307; fax: +1 617 258 9697.
E-mail address: iang@mit.edu.

0094-5765/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2005.02.007

systems include Mars airplanes, Mars helicopters, and even insect-like Mars entomopters [3]. A unique Mars Frisbee is proposed in [4], although it generates no lift. The unsuccessful 1988 Soviet Phobos 2 lander was to travel over Phobos' regolith utilizing a novel hopping system designed by Lunokhod engineer Alexander Kemurjian [5]. With spring loaded legs the Phobos 2 hopper was supposed to make 50 m jumps across the low gravity field with its science payload.

Several mobility techniques using rocket power for hopping-type movements have also been proposed. Long-range thousand-kilometer unmanned hopper flights that are refueled by in situ propellant production (ISPP) are proposed in [6]. Zubrin proposes an ISPP long-range rocket system for Mars human transportation on the order of 500 km [7]. A NASA Institute for Advanced Concepts study also explores the idea of an ISPP refuelable rocket for unmanned and manned exploration on Mars [8], and the concept is applied to manned lunar transportation beyond 100 km in [9]. Landis proposes an autonomous ISPP hopper for regional scale robotic exploration on the order of several kilometers [10], and Shafirovich proposes another type of robotic ISPP hopper that uses CO_2 and metal as a propellant [11].

One of the architectural difficulties of most of the above approaches is that they focus on moving an entire vehicle to new locations. Relanding a large system with many components requires a soft low-g landing, calling for high levels of autonomy and complex guidance systems. Since many of the vehicles would be braving multiple landings, and must land in one specific orientation, an active hazard avoidance system would most likely be needed. Airbag landings provide a simpler alternative to active hazard avoidance, but are not adaptable to relaunchable systems since airbags are currently single use only. Time delays in communication further complicate movements, path planning, and science target selection for aerial vehicles. Thus, landings with most powered aerial systems must accomplish the difficult task of fully autonomous, multiple, powered descents to the surface. While the aforementioned vehicles might play a role in future exploration, artillery based explorers (ABEs) are likely to be a more practical approach to mobility for regional geology in the near term.

2. Artillery based mobility

2.1. General description and design constraints

The ABE architecture borrows concepts from hopper systems, penetrator systems that are deployed from orbit, and military rocket artillery systems. ABEs are rockets that make a one time only ballistic flight from a landed launch pad to a science target, using a fixed amount of propellant brought from Earth, Fig. 1. The platform that launches the ABEs can be a rover or a stationary platform, and would nominally contain more advanced instrumentation. However, launcher-only platforms are also possible.

Since the baseline ABE design is not equipped with hardware to land softly, its science instruments and subsystems must be able to withstand high impact loading. Large loads may also be encountered at launch as the ABE is accelerated to its peak velocity. Highly g-tolerant systems have typically been developed for military purposes and space mission penetrators. Two penetrator missions have flown, the Mars Deep Space 2 microprobes (DS2) [12] and the Russian Mars-96 vehicle [13], although neither completed its mission. Other penetrator missions are currently in development for lunar exploration [14,15]. Based on these previous projects, the g-tolerance requirements for ABEs should not be a major technological impediment.

The maximum range of an ABE rocket is primarily limited by maximum tolerable impact velocity. For Mars firing ranges much beyond 10 km the impact velocity will be above the 200 m/s impact velocity that the DS2 microprobes were designed to withstand, Table 1. ABE Mars missions are therefore assumed to take place on at most 10 km regional scales, which translates to 310 km^2 of accessible targets on flat land. The same impact velocity on the Moon yields a 25 km maximum range, with 1960 km^2 of accessible targets. In this paper a point design for a more conservative 5 km range mission on Mars (11.6 km range on the Moon), with 78 km^2 of accessible targets (420 km^2 on the Moon), is addressed.

2.2. Advantages of the ABE architecture

There are several technological advantages to utilizing the ABE architecture. One is that ABEs can

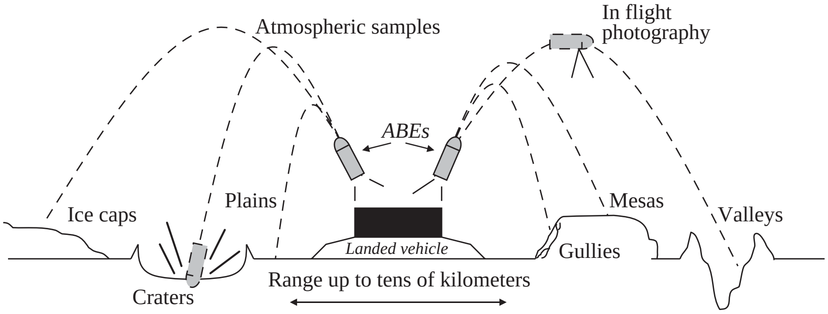

Fig. 1. A variety of geologic features can be accessed by ABEs.

Table 1
Required launch velocity, propellant mass fraction, and time of flight for a ballistic trajectory to different maximum ranges on the Moon and Mars. See Section 4.4 for assumptions

Maximum range	Moon ($g = 1.6\,\mathrm{m/s^2}$)			Mars ($g = 3.7\,\mathrm{m/s^2}$)		
(km)	Launch velocity (m/s)	Propellant mass fraction (%)	Time of flight (s)	Launch velocity (m/s)	Propellant mass fraction (%)	Time of flight (s)
0.1	13	0.6	11	19	1.0	7
0.5	28	1.4	25	43	2.2	16
1	40	2.0	35	61	3.1	23
2	57	2.8	50	86	4.3	33
5	89	4.5	79	136	6.7	52
10	127	6.2	112	192[a]	9.3	74
20	179	8.7	158	272	12.0	104
35	237	11.4	209	360	16.8	138
50	283	13.4	250	430	19.7	164

[a] Approximate maximum Deep Space 2 Mars penetrator impact velocity (200 m/s).

pass over geologic features that would be difficult or impossible for rover systems to navigate. Steep slopes, crater walls, and rough, jagged terrains that are not well suited for landing systems can be accessed by ABEs because of their penetrating ability. Additionally, unlike most aerial vehicles, ABEs require no autonomy or any type of guidance system for navigation and landing at the target site. Targeting is accomplished only by proper aiming. ABEs may be the simplest way to achieve above-ground mobility on airless bodies, since most other proposed aerial vehicles are limited to celestial bodies with an atmosphere. The operation of ABE systems may provide a stepping stone to more advanced aerial vehicles and orbit-deployed penetrator technology.

There are also numerous scientific advantages to using ABEs. The most basic advantage is that ABEs facilitate both aerial and subsurface science due to their movement through the atmosphere and their ability to penetrate into the regolith. More importantly though, the ABE target region can be selected during the mission as new information becomes available from lander platform instruments, or after other ABEs have been deployed. Hard to reach targets that were previously unknown, superior to the originally planned targets, or more interesting based on new science, can be reached. This *adaptable targeting* feature allows ABEs to complement the science objectives of the primary lander and ensure that the best targets are selected. Such precise planning is more difficult with traditional aerial vehicles that stay aloft and select targets autonomously.

Another advantage is that the modular nature of ABEs permits multiple units to fly, allowing both redundancy and multiple target selection. Several ABEs can serve as science stations to provide statistical data over an entire region that would take much longer for a rover to cover. The combined complementary and modular nature of ABEs makes them an attractive add-on to any lander mission already being proposed.

2.3. Comparison with orbit-deployed penetrators

While ABEs may seem like a more complicated version of orbit-deployed penetrators [14,15], their mission objective is fundamentally different. Penetrators have usually been proposed to accomplish large-scale objectives, such as global seismology, rather than the detailed regional investigations that ABEs provide. Nonetheless, if one was interested in using orbit-deployed penetrators for regional studies (e.g. a single large crater) there are several advantages that may make ABEs a better choice. These advantages must be balanced against the complexity of soft-landing a launch platform.

The first advantage is that the landing site can be selected with much higher accuracy compared to the large landing ellipses of penetrators. The second is that lower impact velocities are possible if the ABE targets are within a short enough range. This impact velocity difference is especially important if the target body does not have an atmosphere that can be used to slow the orbit-deployed penetrator before impact. The third advantage is that with ABEs targets can change as the mission progresses and new science becomes available. If orbit-deployed penetrators are flying piggyback on a direct entry lander there is little ability to change their target.

2.4. Analogous military systems

Numerous analogs of ABEs have already been used in the military for decades. One system is the M-72 light anti-tank weapon. The M-72 is an unguided shoulder fired rocket, launched from a compact tube carried by a solider. Six spring loaded passively stabilizing fins flip outwards when the rocket leaves the tube. The rocket for the A2 version of the M-72 has a total mass of approximately 1.8 kg, of which 0.3 kg is the explosive payload [16]. The launch tube has a mass of 2.3 kg, with a length of 88 cm. The A2's maximum range of 1.0 km on Earth would translate into approximately 2.6 km on Mars, and 6.1 km on the Moon, neglecting atmospheric effects. Another unguided free flight rocket system, the M-136 AT4, has a maximum range of 2.0 km on Earth, with the same rocket mass as the A2 [16]. The technology used for these two compact rockets may be helpful in developing an ABE system.

3. Science from ABEs

3.1. Example missions

Each of the following missions benefit from the ABE architecture because either they have target sites that are difficult to reach by traditional methods, or they require covering regions of land with multiple instrument packages. A combination of both is true in some cases.

One possible mission target is the gully-like formations observed on Mars. Mars gullies are features where liquid water appears to have flowed outward from the sides of cliffs as the result of a subsurface aquifer release [17], or melting of water-rich snow [18]. Exploring these areas with ABEs would be advantageous because targeting steep cliffs with a rover, airplane, or landed spacecraft would be difficult. Instead, a rover could approach a set of gullies from several kilometers away and launch multiple ABEs to explore their content. Upon impact the ABEs would sample the local regolith and photograph the area with a surface camera. By deploying multiple ABEs statistical information could be collected from separate sites located many kilometers apart. Both the lower apron areas and the upper alcove heads of the gullies, which appear on the order of hundreds of meters in size [19], should be within the ABEs targeting limitations from a 5 km range (Section 5.2). Targeting the often smaller v-shaped channels of the gullies, which appear on the order of tens of meters in size, should be possible from a 0.5–1.0 km range.

Another target in tune with searching for water on Mars is the northern polar latitudes that contain shallow subsurface deposits of water ice [20]. Deploying multiple ABEs out to several kilometers from a landed site would provide regional data that could take much longer for a single rover to obtain. Experiments such as neutron spectroscopy and thermal conductivity could be accomplished, and the penetrating ability of the ABE would ensure that subsurface ice is sampled. Similarly, exploring the deposits of volatiles at Mars' South Pole would also be a viable mission for ABEs. The South Pole of Mars has icy pit-like "Swiss cheese" depressions several hundred meters across that grow in size each year [21,22]. Several pits over a 200–300 km^2 region could be accessed by ABEs from a fixed lander in a central location, rather than attempting to move over the difficult terrain with a rover or aerial vehicle. These ABE stations could use instruments and cameras to monitor volatile flux and local weather over weeks or possibly years with adequate power sources.

The range of possible ABE missions is not exclusive to Mars. One lunar mission could be to use neutron spectroscopy to search for hydrogen deposits in shadowed polar craters. By deploying ABEs from inside these craters, or from just outside their rims, shadowed regolith could be tested for water, and ground truthing data could be compared with satellite data. Missions to deploy seismic networks to study near-surface geologic formations such as crater roots, faults, and bedrock layering, could be useful on all terrestrial bodies, including asteroids and comets. Additionally, crater science such as imaging and sampling of the interior walls could be achieved with ABEs.

Active or extinct volcanoes could be studied on Mars, Venus or Io. Looking further into the future, active volcanoes on Io could be studied by landing a launch platform clear of any difficult volcanic terrain, and launching ABEs into more interesting or rugged locations. Even the exploration of Europa's ridges could benefit from having ABEs launched onto and throughout the features from a distant platform landed on a more negotiable surface.[1]

3.2. Instrument payloads

In the simplest scenarios ABE instruments will not be capable of moving beyond their emplacement at the time of impact and should be chosen accordingly. The DS2 microprobes carried a sample collecting auger, a sample heater, a tunable diode laser, and temperature and pressure sensors. The much larger 125 kg Mars-96 penetrator carried an impressive collection of surface and subsurface instruments, including wind and humidity sensors, a seismometer, a television camera, a neutron detector, and X-ray, γ-ray, and alpha proton X-ray spectrometers, but was designed for lower impact velocities than DS2 [13]. Currently under development for lunar missions are mass spectrometers and neutron spectrometers [14]. It is possible that any of these instruments could be adapted for use on ABEs. Several basic instruments that could be developed in the near future include atmospheric samplers (including volatiles), dust collectors, and aerial or ground based cameras.

4. System description

4.1. Overall system description

An ABE system as a whole consists of three elements: ABE rockets, a lander base, and a launch tube and aiming system associated with the base. A possible fourth element may be an orbiting satellite that serves as a communication relay for the ABEs. The payload for the 5 km Mars point design is a refly of the DS2 experiments, with the addition of wind sensors and an aerial camera that doubles as a surface camera. Table 2 shows the mass budget for this ABE. Section 5.3 outlines many possible additions to each of the subsystems beyond the reference mission.

4.2. Structure

Two basic structural forms are possible for ABEs. One form is a bullet shaped vehicle that is buried entirely below the surface on impact, as planned for the Lunar-A mission, Fig. 2a [23]. This design is useful for missions that perform mostly subsurface science. The communication antenna would either be pre-deployed to remain above the surface after impact, or be mechanically pushed up through the regolith after impact. A second possible form is a two-component system similar to the DS2 and Mars-96 configurations, Fig. 2b. This form consists of an aftbody structure that remains on the surface after impact, and a bullet shaped forebody that buries itself into the regolith [12,13]. The aftbody is wider and blunter than the forebody

---

[1] Europa gravity is 1.3 m/s^2. A 30 km mission would sustain an impact velocity of 197 m/s after a 214 s flight.

Table 2
Summary mass estimates for the 5 km Mars (11.6 km Moon) ABE reference mission

Subsystem	Mass (kg)	Comments	Comparison values
Structure	1.5	Estimate for fore and aft bodies	—
Avionics	0.15	includes microprocessor, power electronics, and comm. hardware	DS2[a]: 3.2 g for microprocessor, 5 g for power electronics
Power	0.2	25 Whrs of energy	—
Propulsion	0.3	10% dry mass	—
Cables	0.06	2% dry mass	—
Science payload	0.8	Camera, diode laser, auger, temperature and pressure sensors	DS2: 50 g sample collection, 1.0 g laser
Subtotal	3.0	—	—
30% contingency	0.9	30% for first design	—
Dry mass	3.9	—	DS2: 2.4 kg without entry shell
Propellant	0.28	Delta-v 136 m/s, Table 1 (6.7%)	
Wet mass	4.2	—	1.8 kg for M-72A2 rocket
Launcher tube	1.5	90 cm composite tube	2.3 kg for M-72A2 launcher
Mounting hardware and aiming motors	3.0	Low temperature motors	—
Total mass for 1 ABE	8.7	—	—
Multiple ABE loader	2.0	For one additional 4.2 kg ABE	—
Total mass for 2 ABEs	14.9	—	—

[a] Deep Space 2 Mars penetrator.

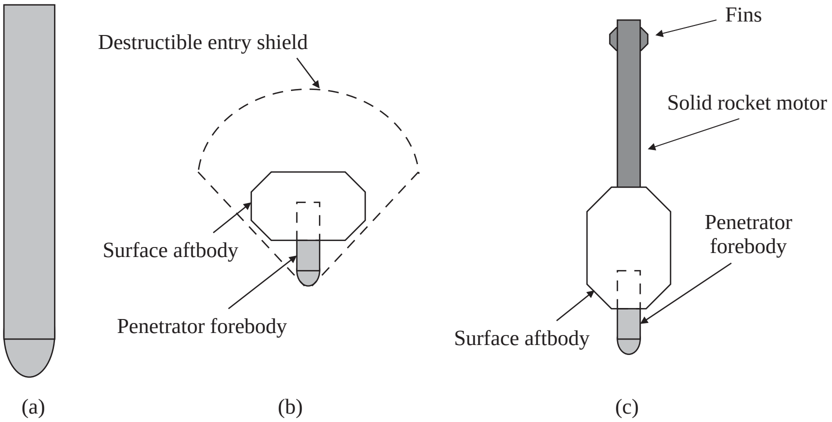

Fig. 2. Three forms for high velocity impactors. (a) one-component Lunar-A bullet shaped penetrator; (b) the Mars Deep Space 2 penetrator, a two-component configuration with a surface aftbody and separable tethered penetrator forebody; (c) ABE two-component configuration chosen for the Mars reference mission, utilizing a surface aftbody, separable penetrator forebody, and a solid rocket motor.

to prevent its penetration, leaving antennas and instrumentation at the surface. In the DS2 mission the forebody separates from the aftbody, but remains connected by a tether. While the awkward shape of a two-component system may seem more difficult to launch as a rocket, it is similar to the shape used for some military shoulder launched systems. A variant of the DS2 two-component form is chosen for the reference mission, and Fig. 2c shows the configuration with a solid rocket motor.

To help understand how impact tolerance requirements influence the mass of the structure, a comparison with the DS2 microprobes and Lunar-A penetrator is useful. The impact velocity to achieve a 5 km range on Mars is 136 m/s (Table 1). The DS2 probes were built to impact the surface at up to 200 m/s with an angle of attack of no more than 12° [12]. The expected possible g-load was up to $30,000g$ for the penetrator forebody, and up to $60,000g$ for the aftbody that remained on the surface. When compared to a 200 m/s impact speed, the 5 km ABE design has 54% less specific energy at impact. Also, when compared to Japan's Lunar-A 13 kg penetrators, which are designed to strike the Moon at up to 300 m/s [23], the 136 m/s impact speed for the ABE seems a reasonable starting point. The total structural mass of the ABE is 1.5 kg, of which 0.4 kg is for the penetrator, and 1.1 kg for the aftbody. These masses are 60% of the DS2 microprobe aft and forebody total masses.

4.3. Stability and pointing on planets with and without an atmosphere

Generally, after an ABE leaves the launch tube it will retain its center of mass trajectory except for perturbations due to the planet's atmosphere. Adding fins and spin to an ABE on an atmospheric body provides stability in flight. This stability ensures that aerodynamic forces on the ABE are predictable and that the trajectory error is minimized. The atmosphere of Mars is thin, but it is still probably worthwhile to impart spin to the ABE and incorporate stabilizing fins (Fig. 2c). For airless bodies, spin and fins are useless, and minimizing trajectory error is entirely a problem of constraining the velocity of the ABE just as it exits the tube.

Counter-intuitively, an ABE launched in a vacuum or low pressure environment will not naturally begin to turn over during the flight to align its nose close to the velocity vector, as a projectile might in Earth's atmosphere. Instead, an ABE in vacuum will land with the same orientation that it had when it left the launch tube (assuming no pitch or yaw velocities were present), and suffer off-axis impact forces. To solve this problem it may be necessary to impose a well-calculated pitching motion on the ABE, so that it is aligned appropriately when it hits the surface. The necessary torque could be applied with a set of very small solid rocket motors set to burn just after launch [24]. Programming the number of rockets fired just before the launch would allow users on the ground to control the amount of torque, and therefore the amount of pitch, needed for a given target. Alternatively, a set of small reaction wheels and sensors could be used to rotate the rocket and offer more precise control [25].

In theory ABEs on both airless and atmospheric bodies could achieve complete active navigation, guidance, and control by applying forces from many small rockets or a gas generator system. However, this would add significant complexity and mass to the entire system.

4.4. Propulsion

The main propulsion hardware in the reference mission is a high thrust solid rocket motor with a short burn time. High thrust and short burn times are required so that the acceleration phase can be accomplished within the launch tube, thereby reducing the ABE's deviation from an ideal parabolic trajectory, and simplifying the problem of in-flight stability. Rocket motors for military shoulder launched rockets can satisfy these requirements. Fortunately, the reduced gravity of Mars and other terrestrial bodies greatly reduces the launch velocity, v, and propellant mass fraction, m_{p}, required to obtain the same range on Earth. The m_{p} value required for an ABE depends on v, which is given by the range equation

$$v = \sqrt{Rg_{\mathrm{p}}/\sin(2\theta)}, \tag{1}$$

where g_{p} is the gravitational acceleration of the planet, θ is the launch elevation angle, and R is the range to the target in meters, assuming the target and launch platform are at equal elevations. It is assumed that the amount of propellant is pre-calculated for a maximum desired range, which occurs at a launch angle of 45°, reducing Eq. (1) to

$$v_{\max.\mathrm{range}} = \sqrt{Rg_{\mathrm{p}}}. \tag{2}$$

Note that impact speeds are equal to launch speeds when at equal elevation. The time of flight is given by

$$t_{\mathrm{f}} = \sqrt{2}v_{\max.\mathrm{range}}/g_{\mathrm{p}}. \tag{3}$$

The propellant mass fraction follows from the inverted rocket equation, substituting Eq. (2) for delta-v:

$$m_{\mathrm{p}} = 1 - \exp\left(-\sqrt{Rg_{\mathrm{p}}}/I_{\mathrm{sp}}g_{\mathrm{E}}\right), \tag{4}$$

where I_{sp} is the specific impulse of the rocket and g_{E} is the Earth's gravity. Table 1 shows values of m_{p}, $v_{\max.\mathrm{range}}$, and t_{f} for a variety of ranges out to 50 km on Mars and the Moon. An I_{sp} of 200 s is assumed, which can easily be achieved with high performance military nitroglycerin double-base propellants. Some gain in I_{sp} is also realized when operating in the lower pressure environments of Mars or the Moon. For a 5 km range on Mars a 6.7% mass fraction is required, resulting in 0.28 kg of propellant. Equivalent Earth ranges for testing ABEs can easily be calculated by $R_{\mathrm{Earth}} = (g_{\mathrm{p}}/g_{\mathrm{E}})R_{\mathrm{p}}$, where R_{p} is the desired range on the planet.

Certain propellants that are well suited for producing high thrust over short burn times on Earth may not endure long exposure to vacuum in space. Nitroglycerin based propellants are one such example. However, this problem has largely been solved already since some shoulder fired rocket motors are tightly sealed against water emersion and other harsh environmental conditions. To hermetically seal such motors would not be difficult. Shoulder launched rocket motors are also built to accommodate temperature cycling, shock loading, vibration, long storage times, and other demanding military requirements.

4.5. Launch system

The launch system consists of a guiding launch tube adjustable from 0–45° from the vertical, with 360° of horizontal freedom, and a blast deflector. The maximum range of the projectile is predetermined by the amount of loaded propellant, since preloading greatly simplifies operations. Different ranges are obtained by raising or lowering the tube appropriately, although because of the predetermined launch velocity, the impact speed is the same for any range at equal elevation. Using the launch angles from 0–45° from the vertical, compared to 45–90°, offers the same access to all possible ranges with the added benefit of reduced tangential velocity. Operating at high angles from the horizontal also allows the tube to rotate around without interfering with other instrumentation on the spacecraft. Two electric motors are required to aim the tube with the desired elevation and azimuth angles. If multiple ABEs are being used they can be automatically inserted into the tube one after the other by a loading system.

An important concern for the propulsion system is the backblast and recoil force from the ABE's rocket motor. An open-ended launch tube is best suited for ABEs to prevent a destabilizing recoil force on the lander. The backblast must be directed away from the lander as much as possible, otherwise instruments could be damaged by any debris kicked up by the blast, or by the blast itself. Recent technology developments in confined space firing capabilities for shoulder launched weapons may be helpful in addressing this challenge. A mass of 1.5 kg is assumed for the launch tube.

4.6. Thermal

All subsystems must be designed to withstand the minimum temperatures expected on Mars, approximately −80 °C at the surface, and −120 °C below the surface. These temperature limits are the same as those prescribed for the DS2 mission. No active thermal control is provided in the reference mission.

4.7. Avionics subsystems

The avionics subsystems, which include a minimal computer, power electronics, and communication hardware, are all assumed to be of equivalent scale to the DS2 microprobes. An inertial measurement unit (IMU) may also be used for tracking the flight path and impact acceleration of the ABE. For communications a small UHF antenna is deployed from the aftbody, or may be built within the extended rocket motor (Fig. 2c). Ideally, data is sent to the lander that launched the ABE, but if line of sight communication with the lander is not possible, as will most likely be the case, communication will need to be accomplished by downlinking data to an orbiting relay satellite. Data is stored onboard before being transmitted once a day, and data rates of 7–8 kbits/s can be expected [13,26]. For some applications wire or fiber optic tethers may be useful, allowing operations when radio communication with neither a satellite or launch platform is available (Section 5.3). A total of 0.15 kg is allotted to the avionics subsystems.

4.8. Power and mission lifetime

For the reference mission power is provided by lithium thionyl chloride primary batteries. These batteries can nominally supply an energy density above 600 Whrs/kg, but an energy density of 125 Whrs/kg is assumed at −80 °C. During the first two days, two high power experiments are conducted, each using 5 W and lasting 30 min. Other experiments such as temperature and pressure measurements, imaging, and wind monitoring are conducted using an average of 0.025 W continuously. Additionally, for the first two days, 6 min communication sessions at 5 W are conducted every 8 h. After two days power is assumed to average to a constant 0.025 W, with communication sessions every 96 h for 6 min at 5 W. This power schedule yields a mission lifetime of 23 Earth days for 0.2 kg of batteries (25 Whrs of energy). Implementing lower power dormant modes would considerably increase mission lifetime.

5. Discussion

5.1. Mission profile

The rover or fixed base lander that carries the ABEs arrives at the celestial body's surface using either airbags or a retrorocket controlled system. The lander would likely carry a primary science payload for studying the local terrain with more complex instrumentation than provided on the ABE. After systems checkout the science team will probably first perform experiments, but may wish to deploy the ABEs to a target immediately. In either case target selection for the ABE is determined through a variety of data sources, including images acquired from the lander during descent and while on the surface, orbital imaging data, and global digital elevation models. Targets outside the view of the lander camera should be valid targets as long as sufficient data are available from the descent imager and other sources. For rover architectures the rover could carry the ABEs and launch them at any time during its traversals as new targets of interest become clear.

After selecting a target the operator calculates the required ballistic path for the ABE to follow, taking into consideration changes in elevation between the lander and the target. Once the pathway is determined and an ABE is loaded in the launch tube, the operator then programs the tube to turn to the required elevation and azimuth angle, and fire the ABE. The pitch rate to provide nose first impact may also need to be programmed or otherwise considered. Verifying the actual ABE impact site can be achieved with aerial photos taken by the ABE during flight, photos taken by the ABE on the ground at the target site, ABE IMU data, and Doppler shifts in the ABE radio signal to an orbiting spacecraft.

5.2. Accuracy

Comparison with some analogous military systems will serve to illustrate the possible accuracy of ABEs. The accuracy of artillery systems is usually expressed as the mean deviation of projectile landing distances from the target, converted to a percentage of the firing range, with units of mils. One mil is one-tenth of 1 percent. For example, a rocket that has an accuracy of 8 mils would on average fall within 8 m of a target 1 km away. With the M-72 and M-134 systems discussed in Section 2.4, soldiers are trained to hit stationary tank targets at a distance of 200 and 300 m, respectively [16]. Publicly available accuracy data for shoulder fired missiles are difficult to obtain, but for the M-134, assuming that a tank is about 7 m in length, the accuracy would be about $7\,\mathrm{m}/300\,\mathrm{m} = 23$ mils. For comparison, the M-26 truck launched rocket artillery system is large, spin stabilized, and has stationary fins, with an accuracy of 11 mils [27].

We assume that the ABE's accuracy is equal to the M-134 system for Mars and airless body operations. The launch tube and rocket motor are configured so that the velocity upon leaving the tube is as well constrained as it is for the M-134. Therefore, for a 5 km mission, the accuracy of 23 mils would translate into 120 m accuracy. This accuracy is sufficient to access the Mars targets discussed in Section 3.1.

5.3. Design variations and advanced additions to baseline system

The first modification is to supplement the power system with a small nuclear heat source linked to a thermoelectric converter. This would greatly extend the lifetime of the probes and could allow experiments to run for over a year. The nuclear material would also provide a heat source that could relax the thermal requirements. If the added complexity and cost of nuclear power is prohibitive, the power subsystem could be supplemented with rechargeable batteries and solar panels left at the surface with an aftbody. Geothermal power production from diurnal surface temperature changes is also possible [28].

For surface only applications the forebody need not be an active system, but could be a dart shaped device used exclusively for impact load absorption. In this scenario the ABE could fly more delicate instrumentation, and greater control over the final orientation of the surface element would be possible. This kind of structural design may also be applicable to targeting vertical walls.

One way to reduce impact forces during low velocity missions would be to deploy an airbag system prior to landing. Additionally, parachute assisted landings may be useful on bodies with thicker atmospheres such as Venus and Titan (see [29] for another mission that uses micro-parachutes and airbag systems). If the impact loading of the ABE is low enough and sufficient mass margin is available, complex payloads such as microrovers, digging devices, or any of the advanced instruments discussed in Section 3.2 may be possible. A particularly novel payload to add might be a small tethered balloon that deploys after impact [30].

For short-range applications the communication subsystem could benefit from a wire connecting the ABE to the launcher. The wire would pay out behind the ABE during launch and provide a data connection that would ease the lander line of sight or orbital communication requirements. Such wire systems have already been used for guided shoulder fired missiles such as the M-47 Dragon, with an Earth range of 1.0 km [24]. Power may be also transmitted to ABEs through wires for ranges short enough to allow minimal line losses. Fiber optic tethers are also a candidate technology for supplementing ABE communication, and have been successfully used for anti-tank missiles up to ranges of 15 km. For any tethered connection the mass of the tether must be considered, as well as tangling and thermal problems.

For targeting particularly small features that are difficult to reach, active guidance could be added to the ABE system. Infrared target illumination could be incorporated, as used by the United States shoulder fired Javelin missile. This missile can track a moving tank target at distances up to 2.5 km [31]. Extrapolating this performance linearly, equivalent capability on Mars would be hitting a 20 m target from 6.6 km. Of course, the system to steer the rocket and identify the target from the launch pad adds significant mass and complexity to an otherwise basic system.

6. Conclusion

Artillery based exploration is a simple concept that offers the possibility of exploring hard to reach features with multiple instrument packages. While rovers are currently the favored method of mobility, ABEs can provide science in locations where rovers cannot traverse, or when sampling from multiple sites within a region is important. Compared with proposed aerial vehicles, ABEs provide the advantage of a zero-autonomy, zero-guidance, land-anywhere system that can reach targets carefully defined by the scientists on the ground. ABEs can also be launched from immobile platforms, which are generally not as complicated and expensive as rovers, yielding a fixed base capable of accessing distant targets. Compared to orbit-deployed penetrators, ABEs supplement lander missions with higher-accuracy vehicles that are distributed on-demand with potentially lower impact velocities.

Based on similarities with military systems ABEs should be able to target sites 120 m in size from 5 km. A total mass of 8.7 kg is required for the 23 day 5 km range Mars reference mission, of which 4.2 kg is for the ABE, including a 30% contingency. The technology required for ABEs is not far off, since many of the components have already been developed for rocket artillery systems and orbit-deployed penetrators.

Acknowledgements

The author would like to thank Professor Jeff Hoffman of the MIT Department of Aeronautics and Astronautics.

References

[1] J.A. Jones, S. Saunders, J. Blamont, A. Yavrouian, Balloons for controlled roving/landing on Mars, Acta Astronautica 45 (1999) 293–300.

[2] E.C. Sittler, M. Acuna, M.J. Burchell, A. Coates, W. Farrell, M. Flasar, B.E. Goldstein, S. Gorevan, R.E. Hartle, W.T.K. Johnson, D.R. Kojiro, H. Niemann, E.N. Nilsen, J. Nuth, D. Smith, J.C. Zarnecki, Titan orbiter aerorover mission, Forum on Innovative Approaches to Outer Planetary Exploration 2001–2020, LPI Contribution Number 1084, Houston, Texas, abstract 4096, 2001.

[3] P. Weiss, Bugs on Mars, Science News 161 (2002) 330.

[4] D.T. Britt, The Mars Frisbee: a small, lightweight deployment mechanism for in-situ instruments on the proposed Mars scout lander, Concepts and Approaches for Mars Exploration, LPI Contribution No. 1062, Houston, Texas, abstract 6097, 2000.

[5] J.W. Head, The 1988–89 Phobos mission, The NASA Mars Conference, San Diego, California, AAS Paper 86-163 (1988) 215–240.

[6] J.C. Sercel, J.J. Blandino, The ballistic Mars hopper: an alternative Mars mobility concept, AIAA 23rd Joint Propulsion Conference AIAA-87-1901, 1987.

[7] R. Zubrin, Long range mobility on Mars, Journal of the British Interplanetary Society 45 (1992) 203–210.

[8] E.E. Rice, Advanced System Concept for Total ISRU-based Propulsion and Power Systems for Unmanned and Manned Mars Exploration, NASA Institute for Advanced Concepts, Phase II Study, Orbital Technologies Corporation, 2000.

[9] P. Eckart, The Lunar Base Handbook: An Introduction to Lunar Base Design, Development, and Operations, McGraw-Hill Primis Custom Publishing, New York, 1999, p. 597.

[10] G.A. Landis, D.L. Linne, Mars rocket vehicle using in situ propellants, Journal of Spacecraft and Rockets 38 (2001) 730–735.

[11] E. Shafirovich, M. Salomon, E. Iskender, I. Gökalp, Mars hopper versus Mars rover, in: 5th IAA International Conference on Low-Cost Planetary Missions, Noordwijk, The Netherlands, 2003.

[12] S. Smrekar, D. Catling, R. Lorenz, J. Magalhães, J. Moersch, P. Morgan, B. Murray, M. Presley-Holloway, A. Yen, A. Zent, D. Blaney, Deep Space 2: The Mars microprobe mission, Journal of Geophysical Research 104 (1999) 27,013–27,030.

[13] T.A. Surkov, R.S. Kremnev, Mars-96 mission: Mars exploration with the use of penetrators, Planetary Space Science 46 (1998) 1689–1696.

[14] P.G. Lucey, Polar Night: a mission to the lunar poles, The Moon Beyond 2002: Next Steps in Lunar Science and Exploration, LPI Contribution No. 1128, Taos, New Mexico, abstract 3067, 2002.

[15] H. Mizutani, A. Fujimura, S. Tanaka, H. Shiraishi, S. Yoshida, T. Nakajima, Mission outline of Lunar-A, The Moon Beyond 2002: Next Steps in Lunar Science and Exploration, LPI Contribution No. 1128, Taos, New Mexico, abstract 3072, 2002.

[16] U.S. Military Field Manual No. 3-23.25, Light Antiarmor Weapons, Department of the Army, Washington, DC, August 30, 2001.

[17] M.C. Malin, K.S. Edgett, Evidence for recent groundwater seepage and surface runoff on Mars, Science 288 (2000) 2330–2335.

[18] P.R. Christensen, Formation of recent Martian gullies through melting of extensive water-rich snow deposits, Nature 422 (2003) 45–48.

[19] M.T. Mellon, R.J. Phillips, Recent gullies on Mars and the source of liquid water, Journal of Geophysical Research 106 (2001) 23,165–23,180.

[20] I. Mitrofanov, M.T. Zuber, M.L. Litvak, W.V. Boynton, D.E. Smith, D. Drake, D. Hamara, A.S. Kozyrev, A.B. Sanin, C. Shinohara, R.S. Saunders, V. Tretyakov, CO_2 snow depth and subsurface water ice abundance in the north hemisphere of Mars, Science 300 (2003) 2081–2084.

[21] P.C. Thomas, M.C. Malin, K.S. Edgett, M.H. Carr, W.K. Hartmann, A.P. Ingersoll, P.B. James, L.A. Soderblom, J. Veverka, R. Sullivan, North-south geological differences between the residual polar caps on Mars, Nature 404 (2000) 161–164.

[22] S. Byrne, A.P. Ingersoll, A sublimation model for Martian south polar ice features, Science 299 (2003) 1051–1053.

[23] T. Nakajima, M. Hinada, H. Mizutani, H. Saitoh, J. Kawaguchi, A. Fujimura, Lunar penetrator program: Lunar A, Acta Astronautica 39 (1996) 111–119.

[24] U.S. Military Field Manual No. 3-23.24, M47 Dragon Medium Antitank Weapon System, Department of the Army, Washington, DC, August 30, 2001.

[25] J. Connelly, N. Dennehy, P. Hattis, W. Johnson, D. Sargent, M. Socha, MEMS-based GN & C sensors and actuators for Micro/Nano satellites, Advances in the Astronautical Sciences 104 (2000) 561–576.

[26] R.C. Blue, Mars microprobe project instrumentation package, Acta Astronautica 45 (1999) 585–595.

[27] Personal communication with artillery specialist at Fort Sill, Oklahoma, USA.

[28] R.D. Lorenz, Subsurface Thermoelectric Micropower for Moles and Penetrators, IEEE Aerospace Conference, Big Sky, Montana, IEEEAC paper 1055, 2003.

[29] R.M. Haberle and the Pascal Team, The Pascal Mars scout mission, Third Mars Polar Science Conference, LPI Contribution 1184, Alberta, Canada, abstract 8075, 2003.

[30] M.H. Sims, R. Greeley, J.A. Cutts, A.H. Yavrouian, M. Murbach, TMBM: Tethered micro-balloons on Mars, Concepts and approaches for Mars exploration, LPI Contribution No. 1062, Houston, Texas, abstract 6137, 2000.

[31] US Military Field Manual No. 3-22.37, Javelin Medium Antiarmor Weapon System, Department of the Army, Washington, DC, January 23, 2003.