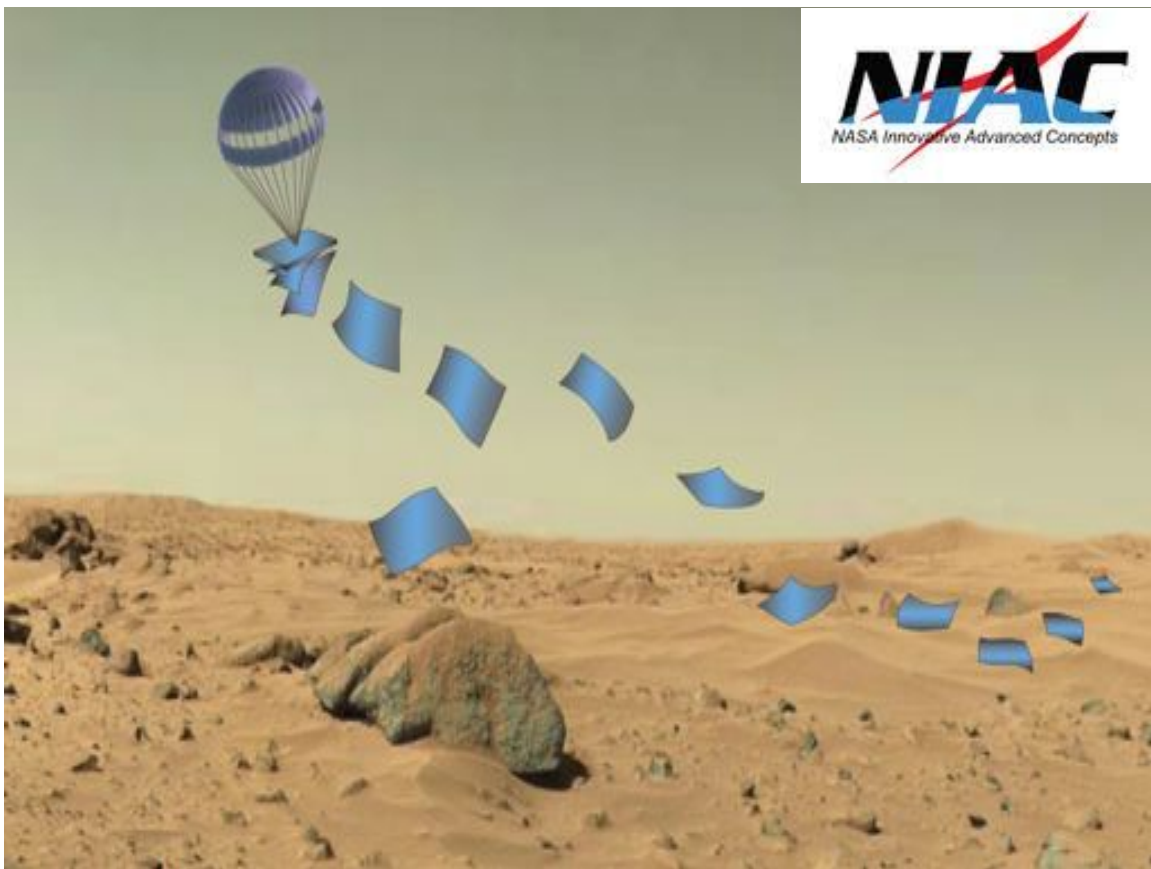




# ***Two-Dimensional Planetary Surface Landers***



**May 2014  
Phase I Final Report**

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**FINAL REPORT  
EARLY STAGE INNOVATION  
NASA INNOVATIVE ADVANCED CONCEPTS (NIAC)**

***Two-Dimensional Planetary Surface Landers***



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***NASA / Jet Propulsion Laboratory (JPL)***

May 2014

### **Acknowledgements**

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Government sponsorship acknowledged.

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## Executive Summary

We proposed to develop a new landing approach that significantly reduces development time and obviates the most complicated, most expensive, and highest-risk phase of a landing mission. The concept is a blanket- or carpet-like two-dimensional (2D) lander ( $\sim 1\text{-m} \times 1\text{-m}$  surface area and  $< 1\text{-cm}$  thick) with a low mass/drag ratio, which allows the lander to efficiently shed its approach velocity and provide a more robust structure for landing integrity. The form factor of these landers allows dozens to be stacked on a single spacecraft for transport and distributed en masse to the surface. Lander surfaces will be populated on both sides by surface-mount, low-profile sensors and instruments, surface-mount telecom, solar cells, batteries, processors, and memory. Landers will also incorporate thin flexible electronics, made possible in part by printable electronics technology. The mass and size of these highly capable technologies further reduces the required stiffness and mass of the lander structures to the point that compliant, lightweight, robust landers capable of passive landings are possible. This capability avoids the costly, complex use of rockets, radar, and associated structure and control systems.

This approach is expected to provide an unprecedented science payload mass to spacecraft mass ratio of approximately 80% (estimated based on current knowledge). This compared to  $\sim 1\%$  for Pathfinder,  $\sim 17\%$  for MER, and 22% for MSL rovers. Clearly, one difference is rovers vs. a lower capability lander.

An outcome of the Phase I study is a clear roadmap for near-term demonstration and long-term technology development.

## 1 Introduction

Visits to celestial bodies help determine solar system origin and how it has evolved since its formation. Landing humans on celestial bodies (e.g., Mars and its moon Phobos and Deimos) has long been desired. Robotic landed missions are synergistic with human exploration. Bodies that are close to Earth require less complex propulsion, power, and telecom systems of the delivery craft (mother-ship), compared to those more distant.

Habitability of the solar system can be assessed measuring volatiles; some of the many questions include: whether comets are the source of Earth's water; whether some asteroids harbor biological agents; the composition of asteroids; and science unique to the surface/subsurface of (often airless) bodies. Furthermore, habitability is best-assessed using in situ analysis.

Landing on celestial bodies is a major engineering and national accomplishment with great appeal for public outreach. However, the complexity of current planetary landers makes them highly expensive, and therefore infrequent. "Low cost" landed mission architectures would be of particular interest in today's competitive and cost-constrained environment.

Some of the most interesting locations for robotic explorers (e.g., the extreme depths of Valles Marineris and the chaotic terrain of Chryse Planitia on Mars, glaciers of Europa, and surfaces of Venus and Titan) are currently off-limits to our robotic landers because of the difficulties and extreme risk associated with landing high-cost spacecraft in these locations. However, a means to augment the impressive data collection capability of these robotic explorers with even limited data and images from the most wondrous of these locations would help complete our understanding of the planetary science, astrobiology, geology, etc., while providing a fuller sense of the grandeur of these magnificent worlds.

Reduction in lander complexity, risk and recurring costs are not the only benefits to this technology. Another key advantage of this approach is the simplicity of system testing and validation on Earth. A further benefit is that by deploying redundant landers, the mission is not dependent on the success of any particular lander; even a high attrition rate of 50% would still provide invaluable data and images that currently cannot be obtained in any other way. Finally, this technology enables certain types of missions such as seismic probing or weather monitoring for which distributed landers are required.

Among the many potential dual-use benefits and intermediate Earth-bound applications of such a system are the possibility of delivering measurement equipment by aircraft or drone to hazardous sites, the deployment of a distributed surveillance network in tactical situations, and continuous remote monitoring of the environment over a wide expanse of ocean, glacier, or forest where it may be difficult to deploy sensitive instrumentation. Indeed, any location where measurement or monitoring equipment is needed, but deployment is difficult or impossible, is a candidate for the use of this technology.

## 2 Phase I Study Approach

### 2.1 Approach to Study

Our approach to the Phase I study was to evaluate a set of missions that are enabled or enhanced by the evolutionary 2D lander architecture. A priority list of missions was drawn so that the merits of the top three candidates could be investigated further in Phase II leading to a well-defined mission with the goal of obtaining revolutionary science at heretofore-inaccessible planetary locations of interest. Considering aerodynamic effects, which are tied to the entry, descent, and landing, a leading candidate, is landed missions to low-gravity airless bodies, such as Phobos, asteroids, and comets, which specifically benefit from the proposed two-dimensional lander. In Phase I we made the following analysis, studies, and prototyping:

- Analyzed mechanical robustness during entry, including aerothermodynamics and mass-to-area ratio.
- Studied thermal/radiation/dust contamination survivability.
- Analyzed the capability bounds of the 2D scheme to identify specific missions feasible within the next decade or so.
- Identified suitable technologies for augmentation of ever more capable landers.
- Engaged an industry partner to explore how 2D lander development time and recurring costs might be significantly reduced when mass-produced.

### 2.2 Assessment Against Phase I Goals

The goals of the Phase I study were (1) to explore the viability of the two-dimensional surface lander technique by identifying mission concepts and applications and (2) to survey and assess the availability and capability the state-of-the-art science instruments and spacecraft infrastructure components. Additionally, we sought to characterize the gap between what is currently available commercially and what is required for space applications.

The Phase I proposal identified ten distinct activities, which are listed below with an assessment of whether the intent of the task was met and where the results are discussed in the report.

**1) *Mission Definition - What are suitable missions for this mission concept? Identify specific missions feasible within the next decade or so.***

This was achieved by a dedicated science Co-I on the team, assisted by other Co-Is with significant flight experience, as well as the team's evaluation of the proposed Decadal Survey missions (details found in Section 4). We studied a large set of missions and down-selected one specific mission. Then, we developed investigated landing scenarios for that mission. These include identifying the lander design's greatest challenges to successfully realize the primary mission. We assessed science payload options and estimated their mass/power/dimensional requirements. This study advances a particular mission for focused demonstration development to identify the potential of this technology early on.

**2) *Analysis of landing configurations and architecture definition - For various missions, what are the ranges of safe landing approaches, and what landing***



***aids are required? (e.g., is a parachute adequate? Are retro-rockets required for the delivery system? How do we securely attach to low-gravity bodies?)***

This activity was completed successfully (Section 5). We determined the conditions under which a heat shield, parachute, or other passive landing technology will be useful in facilitating safe landing. Also, we analyzed environmental dynamics and entry velocity impact and energy impulse on the 2D lander during entry, descent, and landing (EDL). These included aero-thermodynamic analysis (where applicable), required mass-to-area ratio for a few candidate missions, and allowable entry velocity for locations with little or no atmosphere and bodies with varying degree of gravity (e.g., Phobos, Deimos, Titan, Europa, Venus, comets, and asteroids). The results of this study identified the bounds of applicable missions that may benefit from the 2D lander technology.

***3) What are the landers' environmental survivability issues and how do we mitigate them? Performed preliminary analysis on the effects of thermal, radiation, vacuum, and dust contamination on survivability of the 2D Lander.***

This activity was partially completed (Section 6). The majority of the remaining work forms part of the Phase II Work Plan. Environmental driving factors for survivability were partially identified. A materials compatibility test program is planned for Phase II.

***4) How do we make a large area (~1 m<sup>2</sup>) 2D lander adequately thin, lightweight and flexible?***

This activity was completed (Section 6).

***5) Technologies and their readiness levels - What useful flight-grade payloads are on the horizon, and which technologies need maturing? What are the technology gaps?***

This activity was completed successfully. A large number of science and lander infrastructure payloads were identified (Section 8). We identified the highest-payoff technologies to augment the 2D lander's science instrumentation as well as opportunities for useful future technology investment. We also identified technology readiness levels of surface-mounted and popup sensors and actuator components, assessed the viability of laboratory-on-a-chip techniques for this application, assessed technology gaps and the feasibility to bridge them within the next decade or two, and evaluated current and near-future manufacturability of the entire 2D lander. The benefit of this study is that it leads to a clear roadmap for near-term demonstration and long-term technology development.

***6) Preliminary design and fabrication approaches - What cost-effective fabrication approaches are suitable to the 2D lander, and what are the (recurring) cost saving estimates for mass-production?***

This activity was partially completed (Section 8). The majority of the remaining work is scheduled as various Phase II activities. We developed a point design where components and subsystems function together in a platform equipped with all the necessary assemblies, including a data-bus backbone and communications architecture. This included identifying the key driving requirements for a lander design commensurate with the proposed mission design, and developing lander concepts that satisfy those requirements. For a given lander concept, the primary challenges, significant opportunities, key enabling technologies, and fabrication approaches were preliminary identified.

**7) *Analysis of mechanical robustness during entry, including aero-thermodynamics and mass-to-area ratio.***

This activity was partially completed (Section 6). The majority of the remaining work is suitably matched to Phase II.

**8) *Identify suitable technologies for augmentation of ever more-capable landers.***

This activity was completed successfully (Section 8).

**9) *Develop and test a functional (but small scale) prototype of the 2D Lander***

This activity was completed successfully. The prototype is functional and has been tested over the range of 100s of meters using all off-the-shelf low-cost (\$120 materials cost from Amazon) and low profile science instruments and lander infrastructure (flexible solar cell, battery, communications, and microprocessor). Results are summarized in Section 9.

**10) *Develop an end-to-end spacecraft system point design to explore the extent of capability and possible limitations of the 2D Lander scheme.***

A candidate mission concept and platform was selected; details of the platform design and fabrication of a larger prototype will be executed in Phase II. One of the many study findings was that the requirements for each of the subsystems would be different depending on the specific mission application (Section 4).

### 3 Technology Overview

#### 3.1 Background

Akin to conventional planetary landers, a 2D lander module had to be self-sufficient in terms of an avionics module that routes data within the spacecraft, stores gathered data, supplies power to payloads, provides telecommunications with a relay spacecraft, and has the capability to survive the thermal environment of the planetary body being visited. Moreover, since any planetary exploration endeavor is invariably a high-budget program, the 2D lander has to carry a set of highly viable and meaningful set of science payloads that can provide vital information about the planetary body for the first time ever, justifying the expense of the mission.

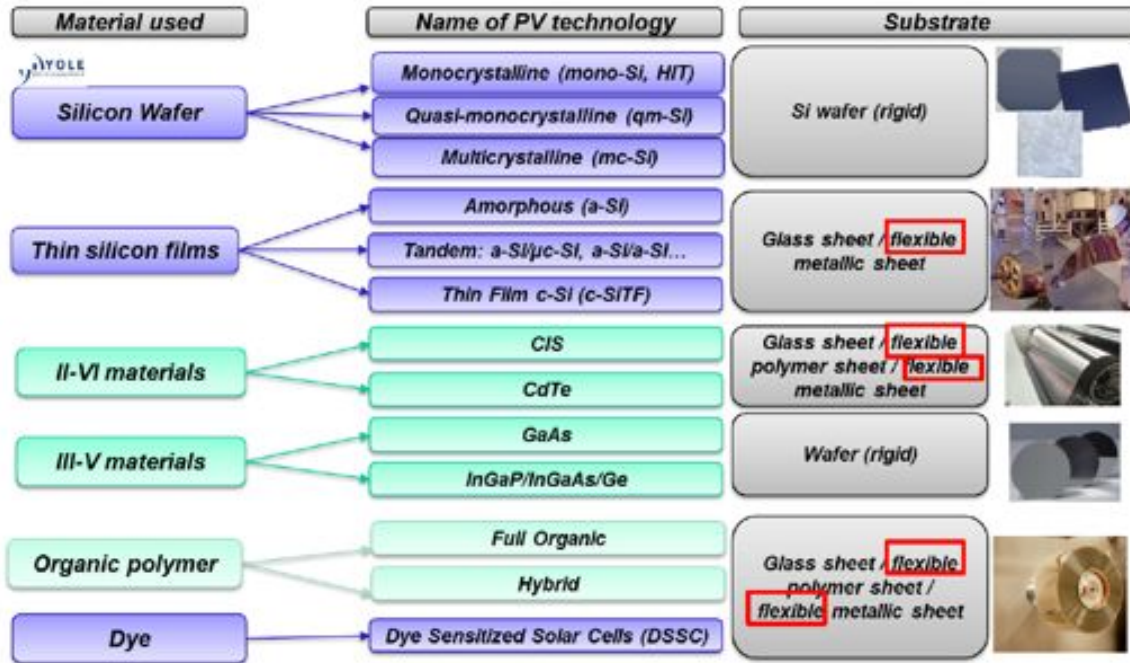
A flat-shaped lander offers key advantages over conventional spherical or cylindrical 3D shapes. Examples are:

- Highly superior packing density efficiency of a swarm (up to 10s or more) of landers in a stack;
- Low mass-to-drag ratio allows high-gravity bodies with significant atmosphere to become accessible;
- Adhesion to low-gravity bodies can be enhanced with the relatively large contact-area of the lander;
- Mass production and processing using standard industrial tooling; and
- Significantly reduced spacecraft integration and qualification time

For the 2D Lander concept to be successful, it is critically important to supply the lander with extremely low profile, yet highly capable, avionics and science instruments.

The technology of low-profile sensors largely based on surface-mount electronics or flexible circuits is enabling many of today's highly capable but super-thin devices, such as smart phones and laptops. It is the same technology applied to generating very low profile sensors and spacecraft avionics that we baseline in the development of large area (at least 1 m × 1 m) nearly two-dimensional spacecraft architecture for deployment as future planetary landers.

The type of substrate used largely influences the property of the flexible devices. Figure 3-1 shows examples of different substrate materials used along with different thin-film coating techniques to develop photovoltaic devices.



**Figure 3-1.** An example, where a variety of flexible substrate materials can be used in conjunction with a variety of thin film coating technologies to develop PV cells. Source: J. C. Eloy (2013).

[http://www.semiconjapan.org/ja/sites/semiconjapan.org/files/docs/S31\\_4\\_Yole\\_Eloy.pdf](http://www.semiconjapan.org/ja/sites/semiconjapan.org/files/docs/S31_4_Yole_Eloy.pdf)

The extremely low profile sensors and actuators have been made possible by the exponential capability increase in microelectronics technology, resulting in a staggering improvement by a factor of 1000 in 10 years, with the expectation of up to a million 20 years from now [1-3].

The infrastructure (power, telecom) and science payloads on both sides of the flat lander could be common to each lander, or vary from one side to the other. In either case, sensors/ actuators facing down will study soil or ice underneath, while those facing outward will characterize or image the environment above. Options (e.g., mass imbalance) will be investigated to favor landing on a particular side, and to avoid landing edge on.

## 4 Science Mission Analysis for 2D Landers

NASA’s Planetary Decadal Survey missions that include a lander/rover, or entry probe are summarized in Table 4-1 below.

**Table 4-1.** Summary of NASA Planetary Decadal Survey missions that include surface exploration

<b>OBJECTIVE: 2023-2032</b>	<b>Mission Scenario</b>	<b>Key Mission Requirements</b>
<b><i>Inner Planets</i></b>		
Venus/Mercury Interior	In situ assessment of seismic networks	<ul style="list-style-type: none"> <li>Advanced chemical propulsion</li> <li>Long duration high-temperature subsystems</li> </ul>
Lunar volatile inventory	Dark crater rover	<ul style="list-style-type: none"> <li>Autonomy &amp; mobility</li> <li>Cryogenic sampling &amp; instruments</li> </ul>
<b><i>Mars</i></b>		
Habitability, geo-chemistry and geologic evolution	Sample return	<ul style="list-style-type: none"> <li>Ascent propulsion</li> <li>Autonomy, precision landing</li> <li>In situ instruments</li> </ul>
<b><i>Giant Planets/their Satellites</i></b>		
Titan chemistry & evolution	Coordinated planetary exploration via platforms: orbiter, surface &/or lake landers, balloon	<ul style="list-style-type: none"> <li>Aero-capture</li> </ul>
<b>PRIMITIVE BODIES</b>		
Trojan & KBO composition	Rendezvous	<ul style="list-style-type: none"> <li>Advanced power/propulsion</li> </ul>
Comet/asteroid origin & evolution	Sample return Cryogenic sample return	<ul style="list-style-type: none"> <li>Advanced thermal protection</li> <li>Sampling systems, verification of samples – ices, organics</li> <li>Thermal Control during EDL</li> </ul>
<b>MEDIUM CLASS MISSIONS</b>		
Comet Surface Sample Return	Acquire sample and return to Earth Characterize the surface region sampled Preserve sample complex organics	<ul style="list-style-type: none"> <li>Sample acquisition</li> <li>Low system mass</li> </ul>
Lunar South Pole-Aitken Basin Sample Return	Same as 2002 decadal survey	
Saturn Probe	Determine noble gas abundances & isotopic ratios of hydrogen, carbon, nitrogen, & oxygen Determine the atmospheric structure	<ul style="list-style-type: none"> <li>Entry probe</li> <li>Payload requirements growth</li> </ul>
Trojan Tour & Rendezvous	Visit, observe, and characterize multiple Trojan asteroids	<ul style="list-style-type: none"> <li>System power</li> <li>System mass</li> </ul>
<b>LARGE CLASS</b>		
Jupiter Europa Orbiter Descope	Explore Europa to investigate its habitability	<ul style="list-style-type: none"> <li>Radiation tolerance</li> <li>Low mass</li> <li>Low power</li> <li>High capability instruments</li> </ul>
Uranus Orbiter & Probe (no Solar Electric Propulsion stage)	<ul style="list-style-type: none"> <li>Investigate the interior structure, atmosphere &amp; composition</li> <li>Observe the Uranus satellite &amp; ring systems</li> </ul>	<ul style="list-style-type: none"> <li>Demanding entry probe mission</li> <li>Long life (15.4 years) for orbiter</li> <li>High magnetic cleanliness for orbiter</li> <li>System mass &amp; power</li> </ul>

From Table 4-1, it is evident that landing and entry probes for most planetary bodies within our solar system are desired. Some of the most intriguing landing sites that will be enhanced by the 2D lander scheme, as pathfinder or piggyback payload, are discussed in the next few pages.

Furthermore, although we describe in detail the relationship of this concept to the medium and large class missions described in NASA's "Vision and Voyages for Planetary Science in the Decade 2013–2022", it should be noted that there are practically an unlimited number of low-cost small missions enabled by this concept that are not addressed in the Decadal Survey. This is made possible by exploiting NASA's Discovery program for low-cost missions.

#### **4.1 Background**

Visits to celestial bodies help determine solar system origin and how it has evolved since its formation. Landing humans on celestial bodies (e.g., Mars and its moon Phobos and Deimos) has long been desired. Robotic landed missions are synergistic with human exploration. Bodies that are close to Earth require less complex propulsion, power, and telecom systems of the delivery craft (mother-ship), compared to those more distant.

Habitability of the solar system can be assessed measuring volatiles; some of the many questions include: whether comets are the source of Earth's water; whether some asteroids harbor biological agents; the composition of asteroids; and science unique to the surface/subsurface of (often airless) bodies. Furthermore, habitability is best assessed using in situ analysis. Science investigations specific to landed missions include:

##### **Near-surface atmosphere**

- Measure of volatiles and organics, which are difficult to identify from a remote spectral signature

##### **Surface composition**

- Measure of isotopic ratios, from which one may infer their primordial source
- Understanding of the fractionation processes that have occurred with time, from which one can infer origins and evolution

##### **Subsurface planetary interior**

- This capability is a major advantage of landing
- Knowledge of subsurface composition and density gradients can potentially yield a wealth of science information. Seismic signals can detect and map interior liquid layers.

##### **Morphology**

- Microscopic investigation of surface layers can lead to the surface materials morphology, which can in turn determine the surface layer's physical state. Also, on comets, Europa, Enceladus, and certain asteroids final in-situ analysis of escaping gas molecules can provide a wealth of science information on the body's rare atmosphere.

An additional benefit is providing ground truth for remote sensing from orbit, such as composition vs. spectral signatures or temperature vs. thermal infrared.

#### **4.2 Preliminary Mission Down-Selection**

High-level self-imposed mission requirements for the in situ assessment of

habitability include:

1. Rendezvous with the target body
2. Surface landing of tens of 2D landers
3. Interrogation of body atmosphere, surface, and subsurface at multiple sites

Table 4-2 shows a comparison of salient characteristics of landing a platform on a variety of planetary bodies: a suite of science payloads; methods of providing electrical power and telecommunications links with the platform; and finally thermal management at predominantly cold environments. The tall tent pole at this time appears to be thermal management of the 2D landers, where nighttime (and some daytime) temperatures of minus 100°C are commonplace. However, no showstoppers have been identified.

In situ spacecraft (e.g., MERs or MSL) typically require a warm electronics box (WEB) due to thermal dissipation from the surrounding atmosphere. Our mission concept will also require such a WEB. However for very thin spacecraft, the surface-to-area ratio is very high, leading to highly efficient thermal transfer from the spacecraft to the environment. This thermal transfer is made increasingly efficient for progressively higher-pressure environments such as those found on Titan, and, to a lesser extent, Mars.

**Table 4-2.** Comparison of key characteristics of 2D lander avionics and payload implications, given the requirement for safe landing and survivability on planetary bodies.

Mission	Science Instruments	Thermal Environment	Power	Telecom	EDL
Asteroids, Comets		<-100°C*	Solar	RF/Optical	
Enceladus		<-100°C**	RHU	RF	Retro-rocket on mother-ship or ballistic impact
The Moon, Phobos, Deimos		<-100°C	Solar	RF/Optical	Retro-rocket on mother-ship or ballistic impact
Europa		<-100°C	Power beaming	RF/Optical	Retro-rocket on mother-ship or ballistic impact
Titan		<-100°C	RHU	RF	Parachute
Mars		<-100°C	Solar	RF/Optical	Parachute
Venus		>+400°C	Solar	RF/Optical	

Color code: Feasible, Somewhat complex landing, Difficult  
\* Depends on distance    \*\* Depends on location

Supplying power to the 2D lander seems feasible for most missions. For Enceladus and Titan next generation of radioisotope heater units (RHU) that are flatter (thinner)

than the present pencil size (1.2-cm thick) heaters will be required. Given the availability of such (thin RHU) devices, which generate 1-Watt of continuous power each, the job of thermal management will be considerably simplified. Alternatively, for bodies (such as Mars and certain asteroids and comets) with daytime temperatures of 20 to 30°C, the landed assets operation may be confined to daytime only, provided the electronics can survive nighttime temperatures. Most electronics components are known to survive the low temperatures of these bodies. (Circuit board failure almost always occurs due to the solder used in these circuits after repeated temperature cycling [4]). These low temperature effects were considered carefully during a recent study involving a collaborative effort at the Keck Institute for Space Studies, which addressed the unique challenges posed by the Titan environment for sample handling and chemical analysis [5], <http://kiss.caltech.edu/workshops/titan2010/index.html>].

Landed mission architectures can be divided into two:

- a) A mother-daughter combination
  - The orbiter spacecraft or mothership releases multiple flat landed elements
  - A dedicated landing element may be guided, but it is envisioned that the separable 2D landers would be unguided; a current thinking that might change during the Phase II studies.
  - Will use relay telecom to the carrier spacecraft or mothership, since direct-to-earth (DTE) is not practical for 2D landers, and is not the primary mode of operation for MER or MSL landers, either.
- b) Directly targeting the body
  - Need to withstand a high impact velocity ( $> 10,000$  g's)
  - Need more precise knowledge of position.

For lowest landing risk in its maiden voyage (pathfinder-type technology demonstration), and best data-return possibility we chose option (a) with mother-daughter combination.

### 4.3 Landing on Asteroid Vesta or Ceres

Most asteroids in the 2 to 3 AU range have minimal gravity. Therefore, once released from the mothership, the lander will basically rendezvous with the asteroid and grab onto the surface. Rendezvous with a small body requires a large delta-V cost of typically  $>1$  km/s, but such missions will provide data on asteroid rotation rates and gravity as well. With the 2D lander scheme, we are not concerned about the other two sets of information that are of prime importance to any landed mission, namely, landings sites and terrain hazards knowledge.

Since the Dawn spacecraft has successfully surveyed asteroids Vesta and Ceres, the required information about rotation rates and gravity are already known; orbiter payload and mission operations costs are reduced significantly since a survey phase would not be required. Specific science that can be gleaned from a pathfinder mission to either of one of these bodies will have to be traded (in Phase II) against the science value that can be achieved from visits to other bodies.

Entry, descent, and landing (EDL) for the airless and low-gravity planetary bodies, such as asteroids and comets are relatively simpler than for the other bodies. For telecommunications, an orbiting mothership will be required. Thermal management will



be an issue that, as discussed earlier, can be solved with the use of (to be developed) thinner RHUs. Furthermore, thermal management is much simpler on airless worlds because the effects of conduction by gas are minimized.

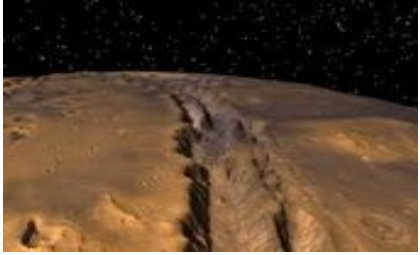
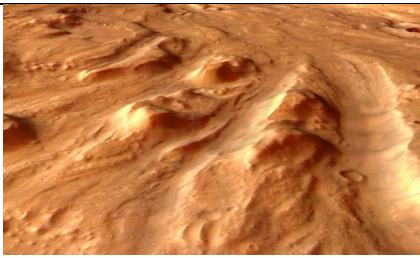
**4.4 Mars Missions**

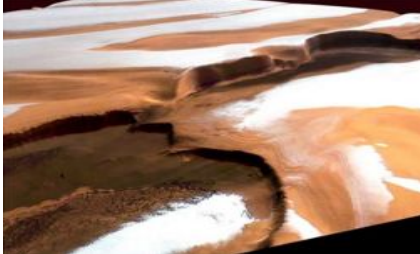
The 2D lander is particularly suited to study those areas of Mars that are deemed too risky to land on and to explore widely in order to meet mission objectives. As it turns out, these difficult to land and navigate regions are of deep intrinsic interest for Mars exploration. Our approach would be to distribute a network of sensors on 2D planetary landers placed over the entire region, rather than design a single spacecraft with an extremely small landing ellipse and extreme mobility capabilities.

Table 4-3 illustrates certain locations on Mars that are of high geological interest. Some of these sites (e.g., Valles Marineris and Chryse Planitia) pose major EDL challenges to conventional landers, but are ideally suited to the 2D lander concept. The Phoenix spacecraft visited Mars’ pole, but much remains unexplored about the strong possibility of discovering water ice. Further exploration using an array of 2D landers dispersed throughout the pole region should be able to provide a wealth of information not possible from conventional landers.


NASA’s Insight spacecraft will perform the very first seismometry on any planetary body!! This will be performed at a single location only. It is known that the highest quality seismometry data is achieved from multiple locations [6], a feat that is not possible with conventional landers, but is easily achievable with the 2D lander concept (although without as high precision).

**Table 4-3.** A few examples of locations on Mars that would be of great scientific interest for exploration.

<p>Studies of depths of Valles Marineris on Mars</p>	
<p>Studies of Chryse Planitia’s chaotic terrains on Mars</p>	

<p>In situ examination of water ice on Mars poles</p>	
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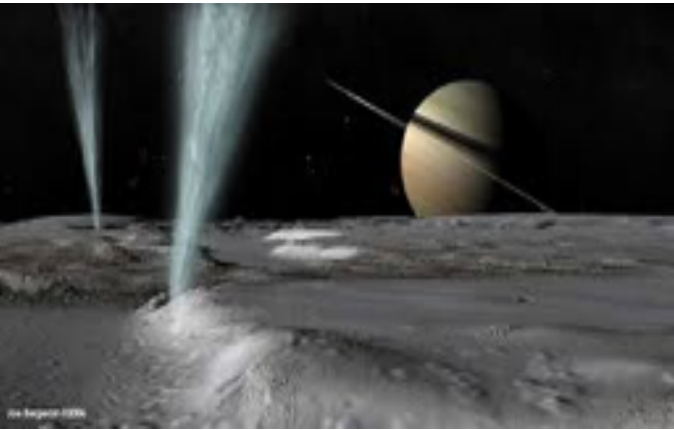
#### 4.5 Europa – Studies of Geysers and Icy Surfaces

<p><b>Study subjects:</b></p> <ul style="list-style-type: none"> <li>• <b>Deep ocean properties</b></li> <li>• <b>Water geysers</b></li> <li>• <b>Astrobiology</b></li> <li>• <b>Planetary habitats</b></li> <li>• <b>Prebiotic chemistry</b></li> <li>• <b>Geology and geophysical processes / evolution</b></li> <li>• <b>Organics distribution / composition</b></li> <li>• <b>Organic processes and sources</b></li> <li>• <b>Meteorology and atmospherics</b></li> <li>• <b>Atmosphere / surface interactions</b></li> <li>• <b>Magnetometry during approach (Europa interior)</b></li> <li>• <b>Seismology</b></li> </ul>	 <p>Hubble Space Telescope Sees Evidence of Water Vapor Venting Off Jupiter Moon Europa (2013) [7] By far the simplest explanation for this water vapor is that it erupted from plumes on the surface of Europa</p>
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There is a tremendous amount of interest among scientists to make in situ measurements of Jupiter’s moon Europa. Past observations have all been performed remotely. Even though the possibility of a huge ocean under the ice-covered surface is a great possibility and of great interest to astrobiologists, in the next few decades, the possibility of sending a planetary probe lander/rover to the surface seems extremely remote. The reason is that the surface characteristics are unknown, and landing a billion dollar asset safely on the surface is deemed too risky. But, a pathfinder-type mission involving a stack of 2D landers to closely examine the surface is perfectly suited to the flat lander concept.


NASA’s Hubble Space Telescope detected strong evidence of water vapor venting of Europa in 2005. The simplest explanation by scientists is that this is water vapor that erupted from plumes on the surface of Europa. A set of 2D landers, in close proximity to these plumes, collectively can in just one day provide much scientific data matching the performance of any high-cost conventional lander including atmospheric constituents, surface characteristics, morphology, seismometry of Europa, and what exactly is being spouted from the surface.

#### 4.6 Enceladus – Studies of Plumes and Environments

<p><b>Study subjects:</b></p> <ul style="list-style-type: none"> <li>• <b>Deep ocean properties</b></li> <li>• <b>Water geysers</b></li> <li>• <b>Astrobiology</b></li> <li>• <b>Planetary habitats</b></li> <li>• <b>Prebiotic chemistry</b></li> <li>• <b>Geology and geophysical processes / evolution</b></li> <li>• <b>Organics distribution / composition</b></li> <li>• <b>Organic processes and sources</b></li> <li>• <b>Meteorology and atmospheric</b></li> <li>• <b>Atmosphere / surface interactions</b></li> <li>• <b>Seismology</b></li> </ul>	 <p>Hubble telescope detected jets of water vapor, ice and dust spewing off the surface of Saturn's moon Enceladus (2005). [8]</p>
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Similarly, Enceladus and Titan are the subjects of much scientific interest and the points made about Europa, largely apply to these bodies as well (next page).

#### 4.7 Titan – Studies of Lakes and Environments

<p><b>Study subjects:</b></p> <ul style="list-style-type: none"> <li>• Planetary habitats</li> <li>• Prebiotic chemistry</li> <li>• Lakes of hydrocarbons /methane</li> <li>• Hydrological cycle</li> <li>• Geology and geophysical processes / evolution</li> <li>• Organics distribution /composition</li> <li>• Organic processes and sources</li> <li>• Meteorology and atmospheric</li> <li>• Atmosphere / surface interactions</li> <li>• Magnetometry during approach (Titan interior)</li> </ul>	
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#### 4.8 Conclusion

To conclude the discussion on mission down-selection based on preliminary investigations of the benefits and challenges of introducing 2D landers to planetary bodies, (Table 4-4) presents a high-level list of missions in order of priority, and the reasoning behind this selection [ . In Phase II, we intend to investigate in greater depth the missions suitable for 2D landers and select a particular mission.

**Table 4-4.** Classes of missions of interest, and rational for order of priority

<b>Mission Sets</b> (in order of priority)	<b>Commonality</b>	<b>Rational for Selection</b>
<b>Asteroids, Comets, NEOs (Near Earth Objects)</b>	Airless bodies with very low gravity, similar EDL approach. Similar power and communications requirements. Similar thermal management	Simpler EDL. Likely the best first test of the concept
<b>Mars Titan</b>	Similar EDL due to partial atmosphere. Mars telecom largely facilitated due to continuous presence of orbiters (for UHF relay). Similar thermal management	Both Mars and Titan are the subjects of scientific interest
<b>Europa, Enceladus, The Moon, Phobos, Deimos</b>	Airless bodies with low to medium gravity, similar EDL approach. Similar power and communications requirements. Similar thermal management	There are so many unknowns and so much interest/curiosity about Europa and Enceladus

## 5 Entry, Descent, and Landing (EDL) for 2D landers

### 5.1 Introduction

From the EDL point-of-view, small low-gravity bodies (e.g., asteroids and comets) do not require load attenuation, but may require an anchoring system. EDL approach for small airless bodies is quite different from EDL approaches that make use of a planetary atmosphere for energy dissipation and stability. The primary design drivers for an “airless body” lander include:

(1) In space propulsion type

This is independent of whether the mothership carries a conventional lander or a 2D lander

(2) Approach scheme

Examples include: guided, unguided, and ballistic schemes; strongly driven by target’s gravity magnitude, target’s triaxial rotation rates, terrain hazards, and science-driven landed accuracy (a concern for large conventional landers only)

(3) Landing scheme

Key drivers here are the body’s gravity, surface type (i.e., strength), and terrain topography. Low gravity may in some cases necessitates anchoring, whereas, high gravity necessitates deceleration and attenuation of the landing load.

(4) Surface knowledge

This affects the anchoring and the momentum compensation method. Asteroids are thought to be hard, dusty, and not amenable to a penetrator. Cometary surface is expected to be soft [9]. The strength of cometary surface material: Relevance of Deep Impact Results for Philae landing on a comet, In: *Deep Impact as a World Observatory Event: Synergies in Space, Time, and Wavelength*, Eso Astrophysics Symposia 2009, pp. 285-300]. Similarly, terrain hazards on the larger moons, such as boulders, crevasses, and chasms will typically drive prior surface knowledge and potentially a smaller landing ellipse; however, again, this is not a concern for the 2D flat landers. Therefore, a 2D lander designed to be less sensitive or more accommodating of a range of surface types, will have lower overall mission risk.

(5) Landing precision

This is not a concern for 2D flat landers because access to specific sites is not expected as a result of the deployment of multiple assets.

### 5.2 Lander Propulsion

The landed element may require dedicated propulsion to place it on the surface. In that case, an attitude-control capability is required regardless of the size (gravity) of the target body. But small bodies, with minute gravity do not require deceleration and therefore do not require a retro-propulsive braking system.

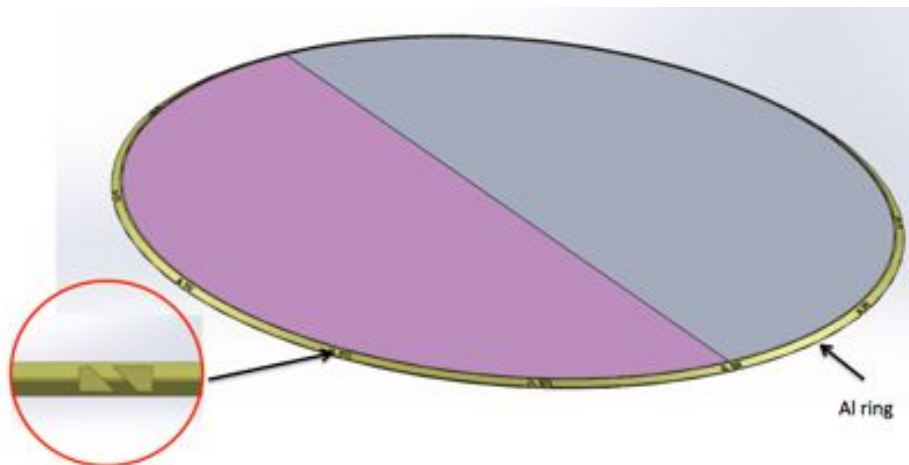
Larger moons may require a retro-propulsive system for gravity deceleration. The landing load will determine how much delta-V is required. Small off-the-shelf solid rocket motors are known as the lowest cost option for proving retro-propulsive delta.

In all cases, safe landing, would require deceleration to <10m/s. For landing on certain bodies (e.g., the Moon or Mars) miniature retro-propulsive stages may be required to decelerate the flat lander to <10m/s. Table 5-1 summarizes the EDL requirements for the flat landers. No showstoppers have been identified for most bodies.

**Table 5-1.** EDL scheme for different celestial bodies as it pertains to for 2D landers

Mission	EDL ( <i>Entry, Descent and Landing</i> )
<b>Asteroids, comets</b>	Adhesion to surface via Van der Waals force
<b>Enceladus</b>	Requires retro-propulsive stage to reduce velocity to <10 m/s, or ballistic impact
<b>The Moon, Phobos, Deimos</b>	The Moon Requires retro-propulsive stage to reduce velocity to <10 m/s, or ballistic impact. Phobos and Deimos do not require retro-propulsive stage
<b>Europa</b>	Requires retro-propulsive stage to reduce velocity to <10 m/s, or ballistic impact.
<b>Titan</b>	Heat shield and parachute system for terminal descent
<b>Mars</b>	Heat shield and parachute system. Terminal descent on 2D lander. $V_{\text{landing}} < 10 \text{ m/s}$ .
<b>Venus</b>	Heat shield and possibly (TBD) parachute system. Terminal descent on 2D lander. $V_{\text{landing}} < 10 \text{ m/s}$ .

During landing in microgravity and rarified atmospheres, the motion of planar and flexible structures is fairly unpredictable. As a remedy, a passive stabilization assembly is mated to the perimeter of the lander. The assembly consists of a two-piece aluminum ring mated to its perimeter. Each ring contains six blades machined into its structure, and is intended to provide stability to the lander during decent. This concept is shown in Figure 5-1.



**Figure 5-1.** Proposed passive platform isolation during landing on bodies such as Mars, with partial atmosphere

## 6 Lander Structure, Thermal Analysis, and Power

### 6.1 Lander Structure

Preliminary analysis indicated that a substrate made from Kevlar woven fabric is suitable since Kevlar maintains its strength and resilience down to cryogenic temperatures ( $-196^{\circ}\text{C}$ ). In fact, Kevlar is slightly stronger at low temperatures. At higher temperatures the tensile strength is immediately reduced by about 10–20%, and after some hours the strength progressively reduces further. For example at  $160^{\circ}\text{C}$  about 10% reduction in strength occurs after 500 hours, and at  $260^{\circ}\text{C}$ , 50% strength reduction occurs after 70 hours. The low-profile science payloads, electronics, solar panels, and other avionics will be attached to Kevlar substrate. Kevlar degrades under ultra-violet (UV) radiation, hence, a reflective blanket made from aluminum coated polyamide film (Mylar) will be used to cover both faces, for the aluminum coating on Mylar to reflect out large fractions of the UV radiation.

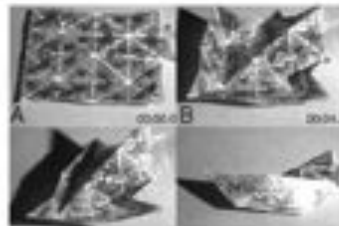
### 6.2 Mobility

Mobility of the lander investigating a body is of great interest, as evidenced by the number of rovers deployed to the surface of Mars. Since the 2D Lander scheme deploys lands to a large number of areas, the need for mobility is not as urgent. However, limited mobility would be highly useful. Earthmovers that enable exposure of the areas underneath the 2D Lander surface to look underneath would be interest. Figure below shows example of such devices that are available today for mobility and for soil moving.

- **Inclusion of pop-up legs to enable the landed sheets to crawl**



- **Inclusion of actuators to turn sheets into spheres for wind-driven mobility (e.g. Mars), and back to sheets again**



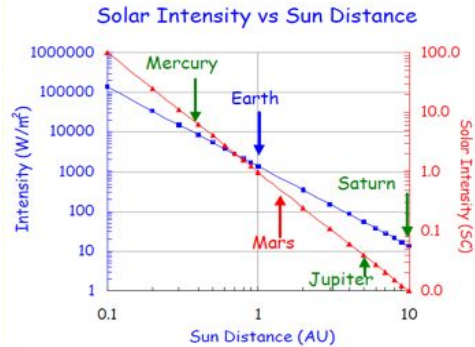
- **Wind-driven (Mars)**

### 6.3 Thermal Effects

Thermal effects include radiative cooling during landing, and conductive and radiative thermal effects after landing. Thermal analysis indicates that thermal insulation can be achieved by covering both faces of the Kevlar substrate with aluminum-coated polyamide film (Mylar), with provisional cutaways in thermal blanket sheet for solar panel, camera aperture, and any other science payload that requires exposure to the outside environment.

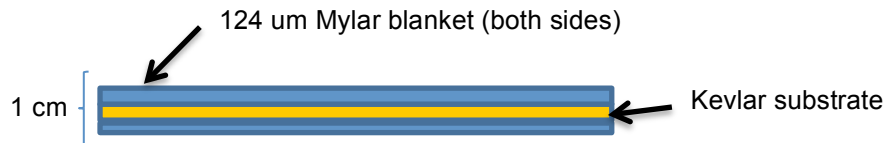
Typical spacecraft design temperatures and solar intensity flux as a function of distance to the Sun is given in Figure 6-1.

Component/System	Operating Temperature (C)	Survival Temperature (C)
Digital electronics	0 to 50	-20 to 70
Analog electronics	0 to 40	-20 to 70
Batteries	10 to 20	0 to 35
IR detectors	-269 to -173	-269 to 35
Solid-state particle detectors	-35 to 0	-35 to 35
Momentum wheels	0 to 50	-20 to 70
Solar panels	-100 to 125	-100 to 125



**Figure 6-1.** Typical spacecraft design temperatures, and solar flux as a function of Sun distance

Two geometrical cases were studied: 1) a Kevlar substrate with Mylar face sheets; and 2) Kevlar substrate with Mylar face sheets plus solar panels attached to the substrate. Assumed overall dimensions include: 1-meter diameter and 1-cm thickness. Figure 6-2 schematically illustrates the assumed architecture for the substrate.

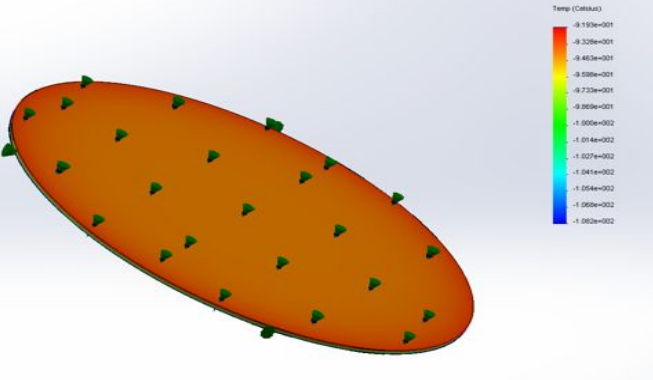
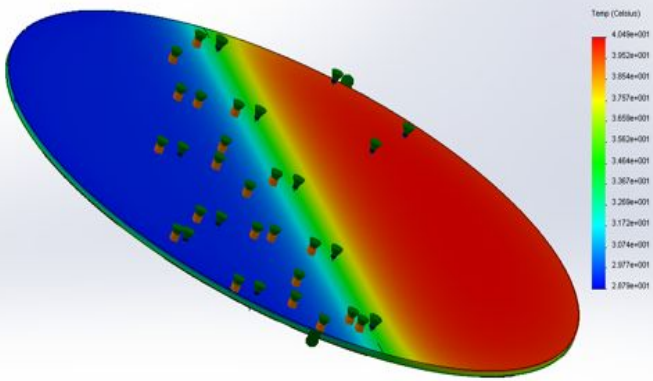


**Figure 6-2.** Substrate architecture.

Examples of thermal analyses under differing assumptions of soli and environment temperature are given below. In all cases assumed a 1-meter diameter surface area, 10mm thick Kevlar, and 0.124mm thick Mylar blanket.

Assumed Conditions	Analysis Results
Soil temperature = $-173^{\circ}\text{C}$ Radiation to 4K sky No internal power	<p>Top and bottom Mylar face sheet = <math>-173^{\circ}\text{C}</math></p>

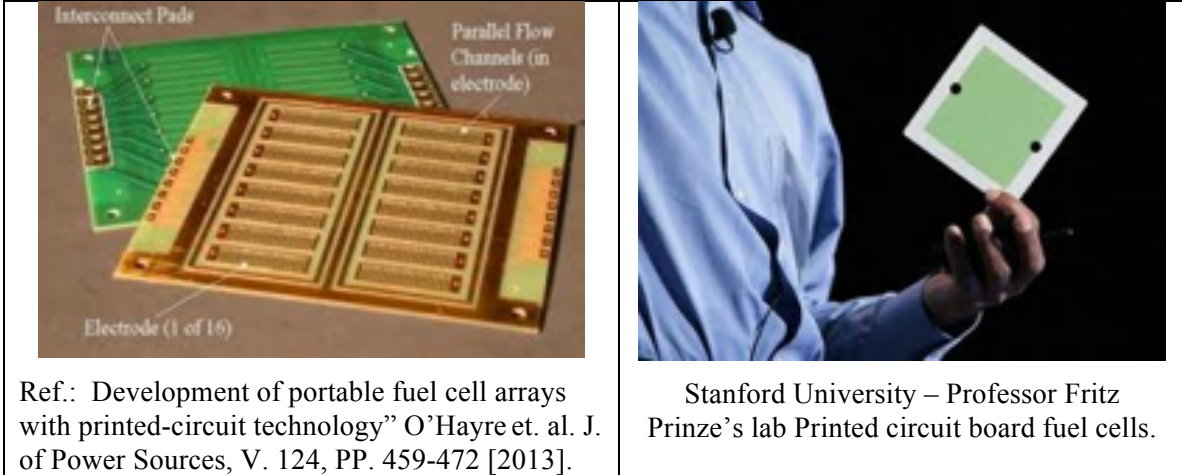


<p>Soil temperature = <math>-108^{\circ}\text{C}</math>          Radiation to <math>-159^{\circ}\text{C}</math> sky          Ambient temperature = <math>-65^{\circ}\text{C}</math>          Solar flux = <math>0 \text{ W/m}^2</math>          No internal power</p>	 <p>Top face sheet=<math>-94^{\circ}\text{C}</math>, bottom face sheet = <math>-106^{\circ}\text{C}</math></p>
<p>Soil temperature = <math>35^{\circ}\text{C}</math>          Radiation to <math>-97^{\circ}\text{C}</math> sky          Ambient temperature = <math>12^{\circ}\text{C}</math>          Solar flux = <math>100 \text{ W/m}^2</math>          No internal power</p>	 <p>Assumed that half the lander is covered by solar panels          Results: Top face sheet = <math>10^{\circ}\text{C}</math>, solar panel = <math>28^{\circ}\text{C}</math>,          bottom Mylar face sheet = <math>28^{\circ}\text{C}</math></p>

## 6.4 Power

Table 7-1 summarizes the avionics approaches for different missions to bodies within the solar system. As indicated earlier, thermal management, which relates to availability of power is the primary challenge that has been identified.

Future availability of slightly smaller RHUs (than what is available today) will mitigate that challenge. Alternatively, recent developments in flat fuel cells that are operating at increasingly lower temperatures are a possibility as well. Figure 6-3 shows two examples of such devices.




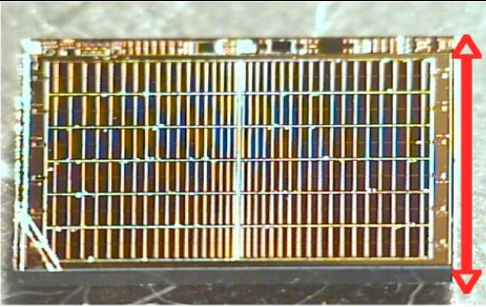

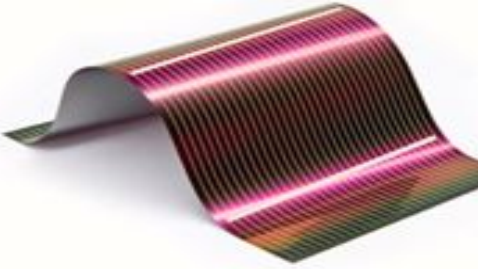
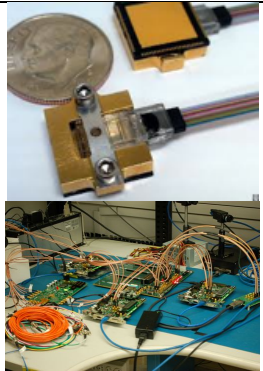

**Figure 6-3.** Examples of recently developed flat fuel cells.




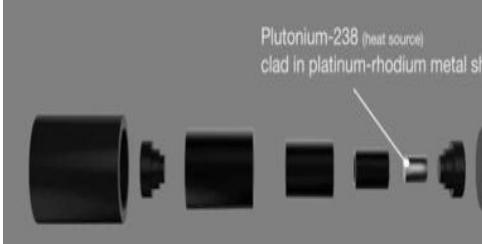
## 7 Avionics and Telecommunications for 2D Landers

### 7.1 Avionics

Table 7-1 shows examples of a variety of components and assemblies that will support the 2D Lander’s avionics infrastructure needs. All requirements for the 2D lander are being met by these components, which are expected to improve substantially in the next decade [10-34].

**Table 7-1.** Examples of highly capable components well suited as the avionics infrastructure for the 2D lander concept.

	Example 1	Example 2
Tele-communication	 <p><b>Flexible RF Transmitter</b> [(Myoung et. al.)]</p>	 <p><b>Modulating (laser) Retro-reflector Array</b></p>
Solar Cells	 <p><b>40% Efficiency Thin-film GaAs Solar Cells</b></p>	 <p><b>~30% Efficiency Thin-film Si Solar Cells</b></p>
Spacecraft Data Bus	 <p><b>Top: Fiberoptic data-bus Nodes. 4 transmit, 4 receive channels in each node.</b></p> <p><b>Bottom: JPL proof of concept spacecraft fiber-optics data-bus demo at 10 Gb/s</b></p>	 <p><b>MSL (Curiosity) Data Bus (2 Mb/s)</b></p>

	Example 1	Example 2
Battery, Memory, ...	 <p>400 Wh/kg Flat batteries</p>	 <p>Thin-film Addressable Memory</p>
RHU (Radio-isotope Heater Unit)	 <p><b>RADIOISOTOPE HEATER UNIT</b></p> <ul style="list-style-type: none"> <li>+ HEAT OUTPUT – 1 WATT</li> <li>+ FUEL LOADING – 33.6 CI</li> <li>+ WEIGHT – 1.4 OZ</li> <li>+ SIZE – 1 IN x 1.3 IN</li> </ul>	 <p>Plutonium-238 (heat source) clad in platinum-rhodium metal shell</p> <p>RHUs are commonly used in spacecraft, landers and rovers. May, for example, be used to keep batteries warm (if needed)</p>

**Table 7-2.** Summary of avionics approaches for different missions to solar-system bodies via 2D Lander.

Mission	Power	Telecom	Avionics
Asteroids, comets	Solar and batteries	UHF/X-band, or modulating laser retro-reflector	Copper or fiber data bus both viable + Memory, and Micro-processor
Enceladus	RHU	UHF/X-band, or modulating laser retro-reflector	Copper or fiber data bus both viable + Memory, and Micro-processor
Moon, Phobos, Deimos	Solar and batteries	UHF/X-band, or modulating laser retro-reflector	Copper or fiber data bus both viable + Memory, and Micro-processor
Europa	RHU, Power beaming from S/C to surface	UHF/X-band, or modulating laser retro-reflector	Copper or fiber data bus both viable + Memory, and Micro-processor

<b>Mission</b>	<b>Power</b>	<b>Telecom</b>	<b>Avionics</b>
<b>Titan</b>	<b>RHU</b>	<b>UHF/X-band relay</b>	<b>Copper or fiber data bus both viable + Memory, and Micro-processor</b>
<b>Mars</b>	<b>Solar and batteries</b>	<b>UHF/X-band, or modulating retro-reflector</b>	<b>Copper or fiber data bus both viable + Memory, and Micro-processor</b>
<b>Venus</b>	<b>Solar and batteries</b>	<b>UHF/X-band relay</b>	<b>Copper or fiber data bus both viable + Memory, and Micro-processor</b>

## 7.2 Telecommunications

Two leading options are available for most telecommunications with the lander: (1) UHF with flat (patch) antennas, (2) laser retro-modulator communications scheme. Each is described briefly below

### 7.2.1 UHF Telecom Architecture

Telecom Architecture Components

- Orbiter side: MRO Class (or equivalent) orbiter containing an Electra Payload, nominal 200–400 km circular orbit
- 2D Lander side:
  - Semi-Custom low-mass, low-power, two-chip telecom electronics implementation using COTS (Custom/commercial off-the-shelf) IC hardware
  - Antenna can be either low mass (and lower performance) COTS ceramic chip antenna or higher mass (and higher performance) JPL custom antenna

There are two telecom implementation options for 2D lander: (1) Lowest mass configuration and (2) Lowest mass configuration with higher performance antenna.

Block diagrams for the two configuration options are shown in Figures 7-1 and 7-2.

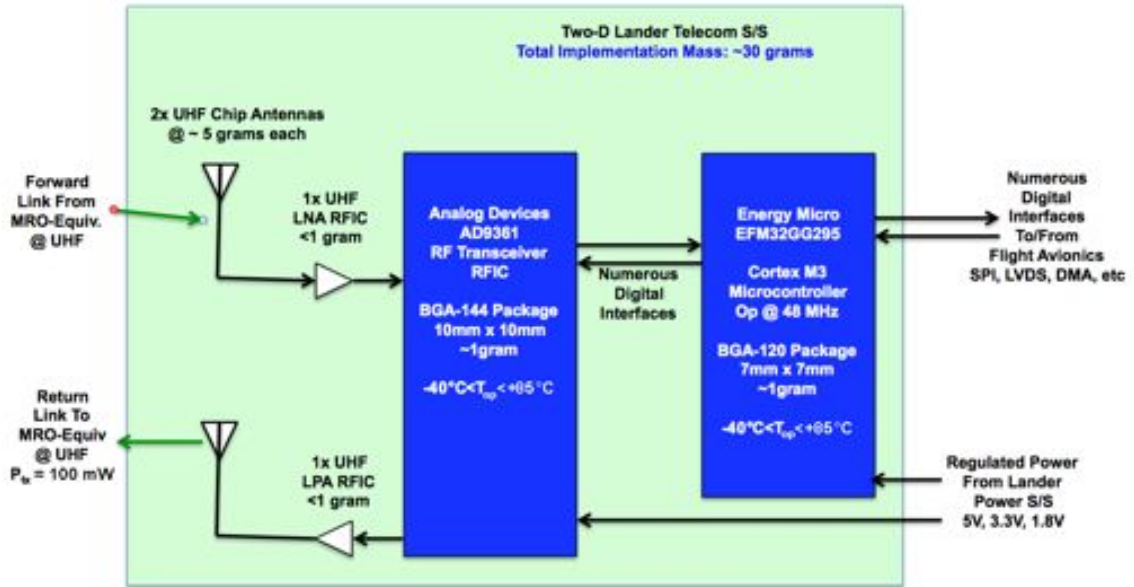


Figure 7-1. Lowest mass configuration.

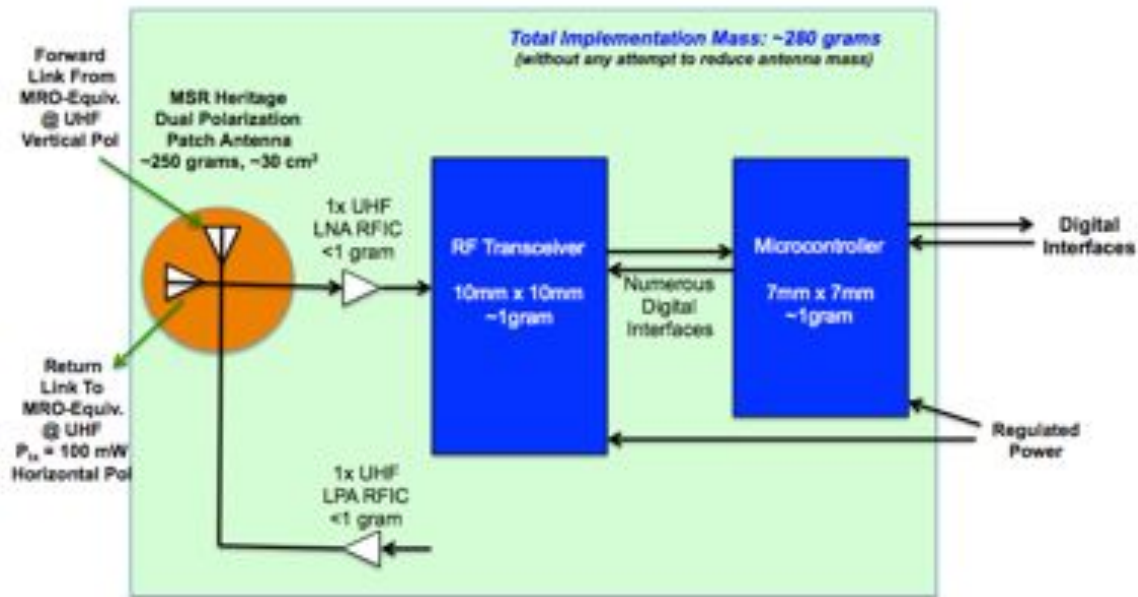


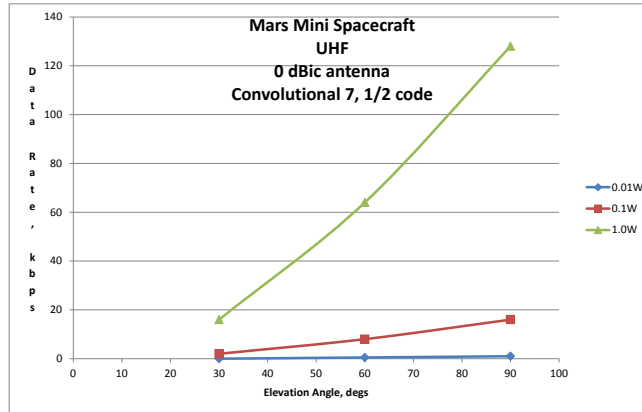
Figure 7-2. Lowest mass configuration with higher performance antenna.

### 7.2.1.1 UHF Telecom Link Performance

Assumptions:

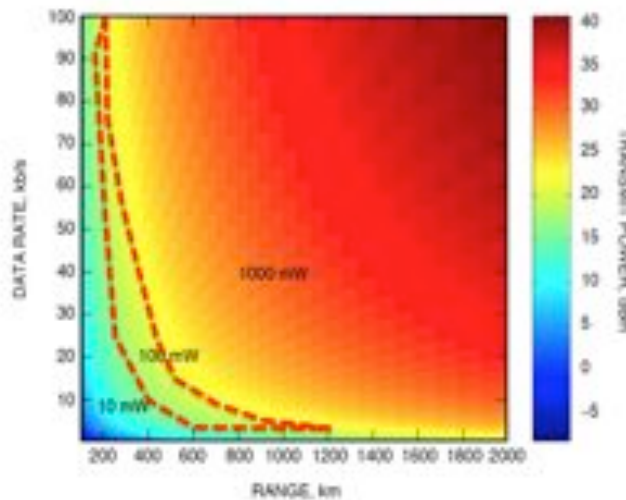
- Return link to an orbiting spacecraft with Electra receiver (as used for reception of signal from conventional rovers).
- 1 dB circuit loss, 0 dBi antenna gain (MSR heritage antenna at 30 degree elevation angle), 370 km orbit altitude, Convolutional K=7, R=1/2 code, minimum 3 dB margin, direct line of sight, no multipath or blockage, BPSK modulation, antenna is linearly polarized.

- Increased rate at higher elevation angles is due to decreased slant range for constant antenna gain.
- Power Numbers quoted below are 2D Lander RF Transmit power (not DC power).
- If the lower mass, lower performance antenna is used, the performance is reduced by 10 dB (Figure 7-3).



**Figure 7-3.** UHF data-rate (kb/s) vs. elevation angle (in degrees). The 1 W power performance is depicted in the red line, and the 0.1 W performance is shown in blue line.

Figure 7-4 shows UHF data-rate vs. range. Here we assume 0 dBi antenna (MSR patch equivalent). Power numbers quoted are RF transmit power (not DC power).

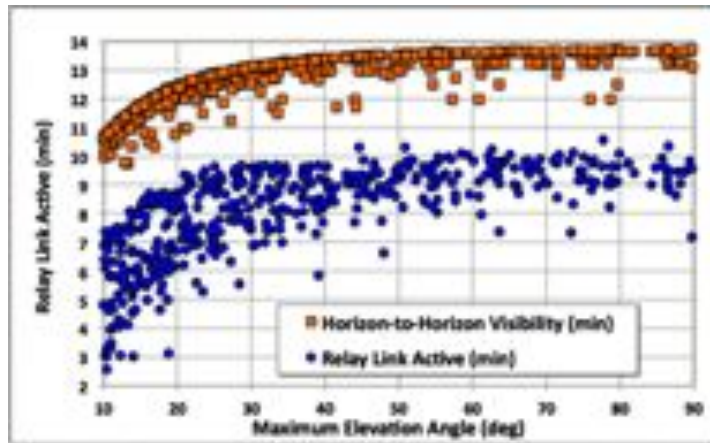


**Figure 7-4.** Low altitude (100–200 km) orbiter uplink RF power requirements, assuming coherent BPSK, (7,12) convolutional coding. Expected range of operation is shown in green/blue boundary (both vertical and horizontal axis (Graph from: N. Lay, et al., “Developing Low Power Transceiver Technologies for In-Situ Communications Applications”, JPL IPN Progress Report 42-147, Nov. 15, 2001).

7.2.1.2 Returned Data Volume

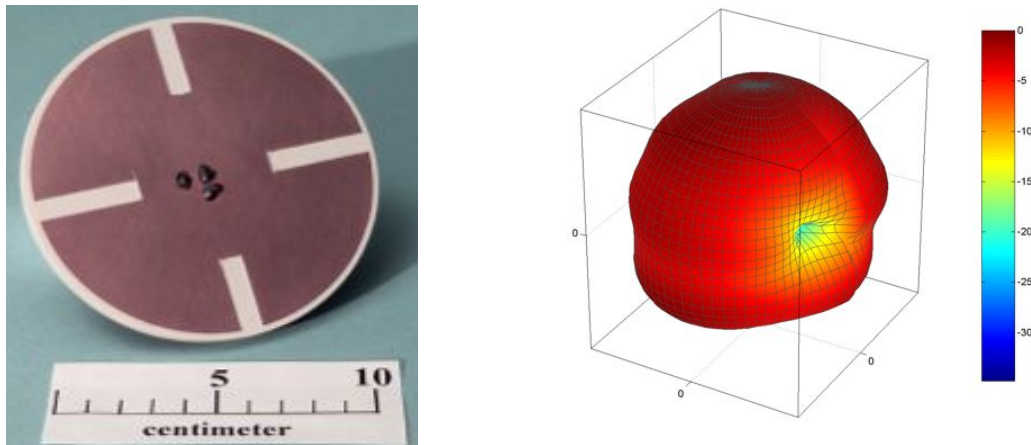
Figure 7-5 shows typical link duration for MSL to MRO passes. For the 2D lander, if operated with a minimum elevation angle of 30°, we can expect a pass duration of about 5 minutes. Assuming the higher capability antenna, and a transmit power of 10 mW, the configuration discussed earlier can return 4.8 Mbits of data. With the lower quality, lower mass antenna, the returned data volume will be as low as 100 kbits. In Phase II we will examine the required returned data volume, pass durations and achievable rates, which will lead to the number of passes/sol required.

**Figure 7-5** Typical pass duration for the case of a Mars orbiter, shown as active link (in minutes) vs. elevation angle during the link



7.2.1.3 Example of UHF Patch Antenna

Figure 7-6 shows an example of a nearly isotropic radiation pattern when using an electrically small ground plane. This antenna weighs 0.25 kg, and supports dual frequencies of 402.5 MHz and 437.1 MHz.

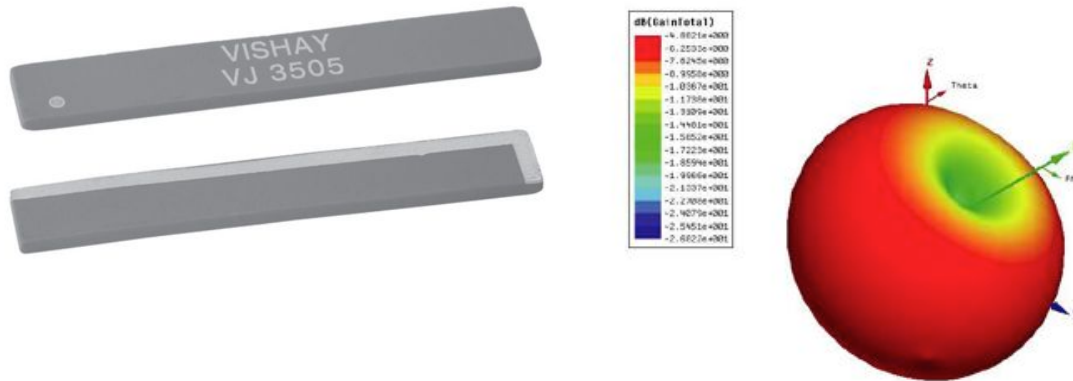


**Figure 7-6.** Example of a candidate UHF patch/flat antenna (left) for communications and its performance characteristics (right). This antenna, located on the 2D lander will communicate with conventional Electra receiver on the orbiter. The zero point on the color chart (on the right) corresponds to +5 dBi on boresight.

Figure 7-7 shows another example of a COTS UHF ceramic antenna for a 2D lander. In this configuration the 2D lander antenna element usage combines antenna printed wiring board (PWB) into lander structure elements to conserve structural mass. In that case, mass will be extremely low (~5 g), which is traded against its low gain (-10 dBi). The



lower temperature bound of this antenna is at  $-40^{\circ}\text{C}$ .



**Figure 7-7.** COTS UHF antenna example. The antenna itself is shown on the left (top figure shows the front, bottom figure shows the back). Nearly omnidirectional radiation pattern performance is shown for the antenna (right).

#### 7.2.1.4 Telecom DC Power Estimation for UHF Links

Table 7-3 summarizes the preliminary power consumption estimates for the telecom portion of the lander.

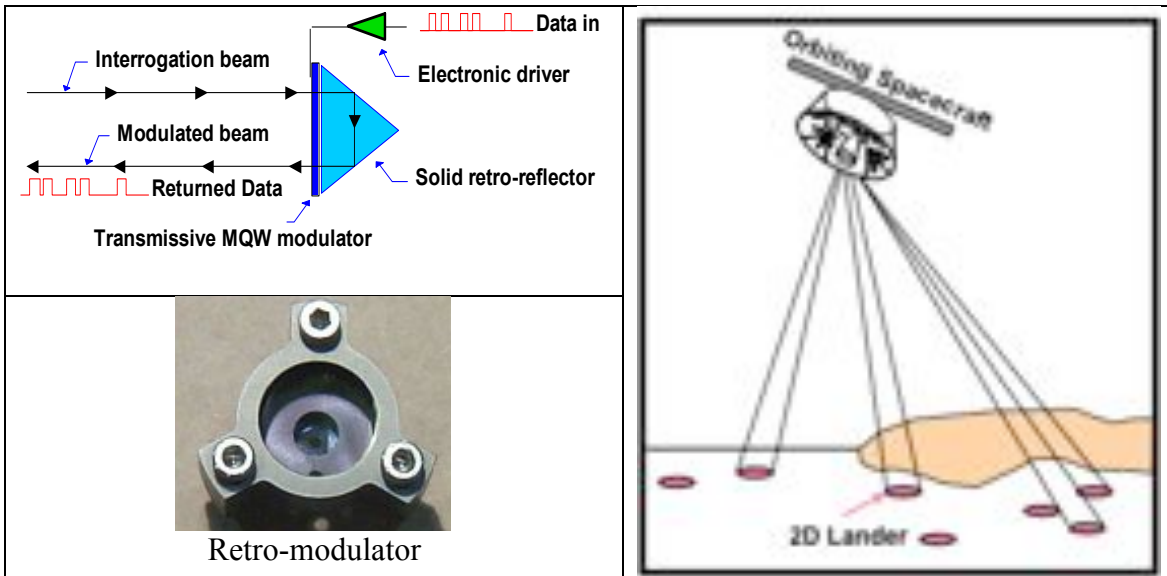
**Table 7-3.** Estimates of DC power usage for 2D lander’s telecom assembly

Component /Assembly	Power Consumption (W)
AD9361 (half-duplex operation assumed, UHF band)	
Transmit power (+7 dBm output RF)	0.50
Receive power	0.25
Cortex M3 at 48 MHz	
Transmit power	0.25
Receive power	0.25
Transmit power amplifier (+20 dBm output RF power at ~20% efficiency) - DC power	0.50
Receive low-noise amplifier	0.25
Total DC power transmit	~1.25 W*
Total DC power receive	~0.6 W*

\* Numbers do not include DC-DC power converter efficiencies

#### 7.2.2 Telecom with Lander via Optical Modulating Retro-Reflector Links

A modulating retro-reflector, in principle, works like a supermarket barcode reader. Except that in this case, the barcode is variable (with data) and is embedded into a retro-reflector so that the modulated laser beam (carrying the data) returns to where the laser source was originated. An advantage of this approach is extremely low power (10’s of mW) at the lander. Disadvantages are requirement for a high power ( $>10\text{ W}$ ) laser at the orbiter, and modest data-rate due to  $1/R^4$  nature of signal loss. Figure 7-8 schematically illustrates the concept.



**Figure 7-8.** Modulating corner-cube devices and description of its use and operation. These devices may be viewed as a “dynamic barcode”.

### 7.2.3 2D Lander Telecom Challenges

**Extreme Temperature Range:** Current hardware designed down to  $-40^{\circ}\text{C}$  but environment expected to be much lower. This issue will be addressed in Phase II

**Radiation environment:** That portion of the hardware assumed here that is in COTS form (e.g., the Vishat patch antenna) is not tested for radiation environment (TID/SEE, etc.). This issue will also be addressed in Phase II.

### 7.2.4 Future Trades for Telecom Assembly

- Telecom pass duration – does the lander only transmit at higher elevation angles to operate at a higher data rate (since for a shorter time link, the lander saves power)? The required returned data volume given that assumption has to be estimated?
- How often do we conduct an active link pass (daily or weekly)?
- How do we schedule a pass?
  - Wake the lander up with a tone from an orbiter or have a controller on-board that has an accurate clock and can be commanded to turn on its transmitter
- Do we operate with a data protocol or just transmit blindly to the orbiter?
- Consider other antenna options that provide better performance within the mass and volume constraints.
- How much data do the science instruments and other sensors generate?

## 8 Science Instruments for 2D Landers

Table 8-1 summarizes science investigations and the corresponding measurements to be achieved by planetary landed assets.

**Table 8-1.** Traceability of measurement objectives to science.

	Mineralogy	Noble gases	Volatiles	Isotopic Ratios	Geophysics	Morphology
Origins	X	X	X	X	X	X
Evolution	X			X	X	X
Habitability	X		X	X	X	X
Human Exploration	X		X		X	

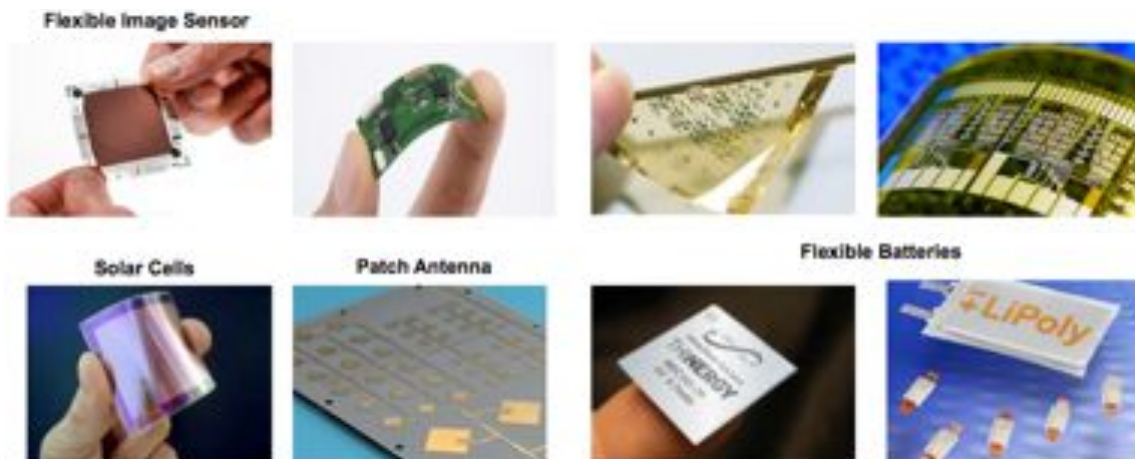
Spectrometers of all kinds are the key instruments for identifying:

- Geochemical characteristics,
- Atmospheric constituents, and
- Possible biological activity.

Gas analysis, helps determine the presence of

- Methane, a signature for biological activity,
- Carbon compounds, and
- Noble gases.

Past decades and an ongoing flurry of technological advancements in low-profile sensors and avionics will be instrumental in enabling 2D landers to collect scientific data and transmit them to ground via relay spacecraft. Figure 8-1 shows examples of such devices that are now in use, but require flight qualification for space flight. Table 8-2 lists science payloads in recent past Mars rovers, and envisioned science instruments onboard the 2D landers.



**Figure 8-1.** Recent technologies are potential candidates for 2D landers.



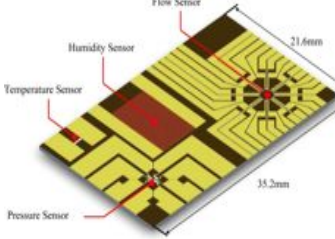

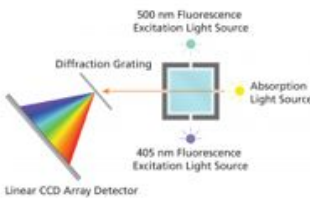
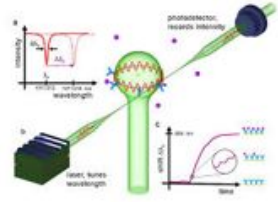

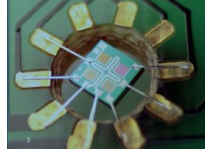

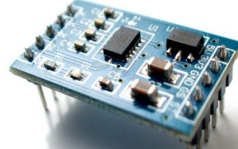
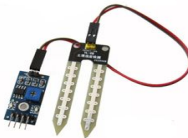
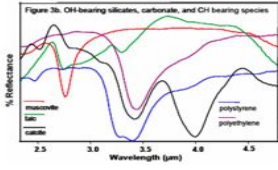
**Table 8-2.** Summary of science instruments onboard past Mars landed assets compared with the expected payload capability of the 2D lander

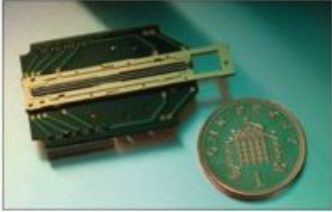
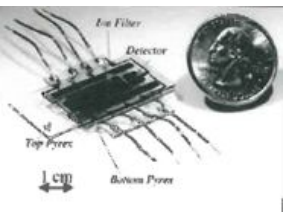

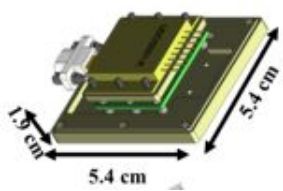
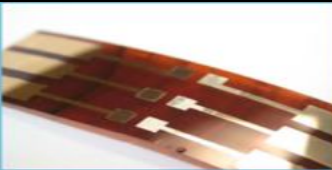



Lander/Rover: Instrument	MER	MSL	Phoenix	InSight	2D Lander (envisioned)
<b>Cameras</b>	<b>Panoramic</b>	<b>Mast</b>	<b>Surface stereoscopic</b>	<b>120° and 3D video</b>	<b>Panoramic and 3D video</b>
Microscopic imager	Included	Included	Included		Included
Descent imager		Included	Included		Included
<b>Spectrometers and analyzers</b>	Miniature thermal emission	Chemistry and camera	Thermal, evolved gas analyzer		Thermal and gas analyzers. Laser fluorescence and laser spectrometer included
	Mössbauer	Chemistry and mineralogy x-ray diff.	Electrochemistry and conductivity		Miniaturization for low-profile required
	Alpha particle X-ray	Alpha particle X-ray			No miniature solution now (although very small already)
		Mass spectrometer			Included
		Gas chromatograph			No miniature solution now
		Tunable laser spectroscopy			A version included
		Sample and gas processor			Gas processor included
<b>Radiation detector</b>		Radiation assessment			Included
		Neutron dynamic albedo			TBD
<b>Grinder/drill</b>	Included	Included		Included	No miniature solution now
<b>Landing radar</b>	Included	Included	Included		Not required. 10s M\$
<b>Environmental sensors</b>		Monitoring station		Included	Included
<b>Atmospheric sensor</b>		Entry health monitor.			Included
<b>Meteorological stat.</b>	Included	Included	Included		Included
<b>Seismometer</b>	X	X	X	Included	Included
<b>Radio science</b>	X	X	Included	Included	Included
<b>Robotic arm</b>		Yes	Yes		No miniature solution now

Table 8-3 shows examples of a variety of potential science instrument payload that can address the above science investigations, in many instances with capability akin to the

large science instruments that are being flown today to deep space.

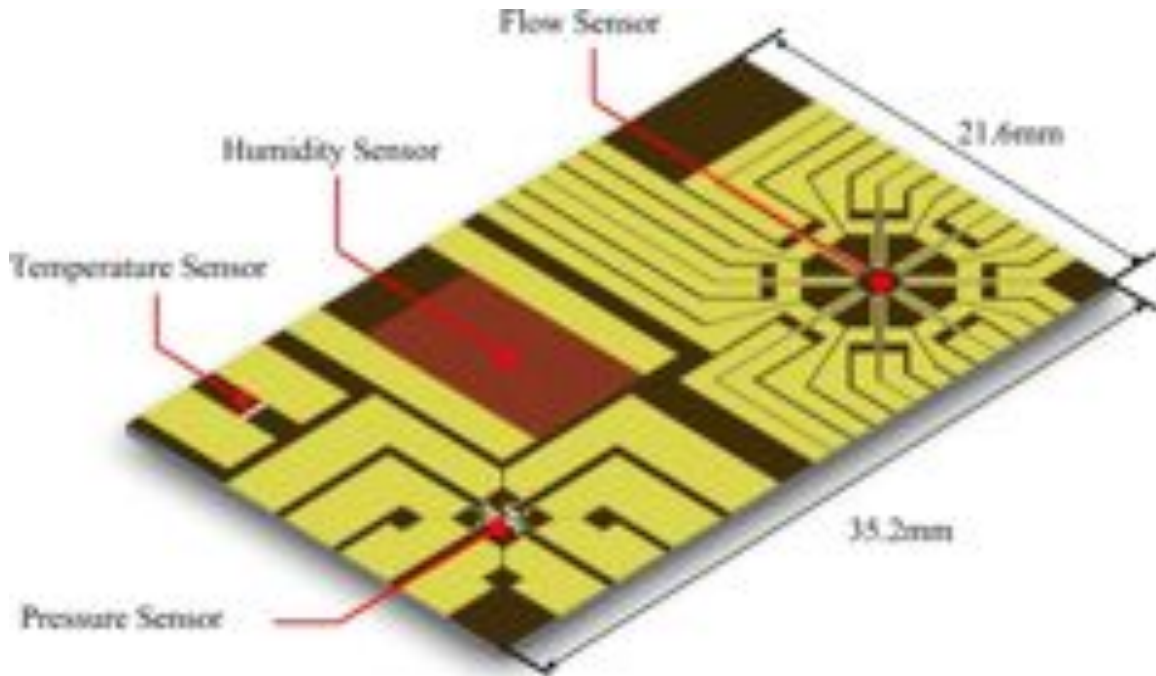
**Table 8-3.** Examples of highly capable science instruments that can fit within the 2D lander concept.

Instrument	Measurements	Example 1	Example 2
<b>Imaging cameras</b>	<b>2D and 3D imaging Wide-field-of-view imaging</b>	 <b>3mm Diameter Camera</b>	 <b>Array Camera for 3D Video</b>
<b>Environment Monitoring (MEMS-based)</b>	<b>Wind-Speed &amp; Direction, Humidity, Temperature, Altitude, Pressure, Temperature</b>	 	 
<b>Spectrometer</b>	<b>Atmospheric constituents Prebiotic chemistry Astrobiology Water</b>	 <b>UV LED Fluorescence</b>	 <b>Whispering Gallery Resonator</b>
<b>Gas sensing films</b>	<b>CO, CO<sub>2</sub>, NH<sub>3</sub>, NO<sub>x</sub>, C<sub>x</sub>H<sub>y</sub>, H<sub>2</sub>, H<sub>2</sub>S, SO<sub>2</sub>, volatile organic compounds (VOCs) – ppb sensitivity</b>	 <b>Carbon Nanotube Sensors</b>	 <b>Semiconductor Sensor Array</b>
<b>3-axis accelerometer 3-axis gyroscope, Magnetic-field sensor</b>	<b>Seismometry Magnetometry</b>	 <b>Accelerometer &amp; Gyroscope</b>	 <b>Magnetic Field Sensor</b>
<b>Soil Moisture</b>	<b>Proof of existence and amount of water in soil</b>	 <b>Soil Hygrometer</b>	 <b>LED-based Soil Probe</b>

<p><b>Mass spectrometer</b></p>	<p><b>Analysis of atmospheric gas constituents, and given a scooping mechanism, soil constituent analysis</b></p>	 <p>By: Microsaic Systems</p>	 <p>By: Draper Laboratories</p>
<p><b>Radiation Monitoring</b></p>	<p><b>Gamma, Alpha and Neutron spectroscopy)</b></p>		 <p><a href="http://www.nrl.navy.mil/ssd/branches/7650/MARS">http://www.nrl.navy.mil/ssd/branches/7650/MARS</a></p>
<p><b>PH, Humidity</b></p>	<p><b>Measurements of humidity and PH</b></p>	 <p><b>PH Sensor Array</b></p>	 <p><b>Humidity Sensor</b></p>
<p><b>Ground Penetrating Radar</b></p>	<p><b>Mapping subsurface Stratigraphy (50m depth, 15m resolution)</b></p>	 <p><b>S. S. Kim et al. (JPL)</b> 10cmx5cmx1cm, 1W, 45g</p>	
<p><b>Particle/Dust Analyzer</b></p>	<p><b>Dust particle counting</b></p>	 <p><b>Miniature, Laser-Based</b></p>	

**Example: A MEMS-based multi-sensor**

The sensor suit shown in Figure 8-2 incorporates four highly capable sensors into an overall small area – made possible by Micro-electromechanical (MEMS) technology.



**Figure 8-2.** Close up view of one of the instruments described in Table 8-3, showing four highly capable sensors packed into a small area. Reference:  
[http://openi.nlm.nih.gov/detailedresult.php?img=3231589\\_sensors-11-02715f2a&req=4](http://openi.nlm.nih.gov/detailedresult.php?img=3231589_sensors-11-02715f2a&req=4)

Developments of versions of the following instrument will increase science data gathering capability of the 2D Lander

- Miniature Mössbauer spectrometer
- Miniature gas chromatograph
- Miniature X-ray diffraction instrument
- Drills and penetrators that can be deployed from the flat landers.

## ***Spinoffs and Collaborations***

### **Spinoffs:**

- Proposal to DARPA on dropped sensor
- Proposal to multiple branches of Navy for ocean surface sensing

### **Collaborations:**

- **Pelican Imaging Corporation: Miniature array camera for 3D** video
- University of Idaho students – acquiring students
- MIT students – acquiring students
- Discussions and monitoring progress of following NIAC-funded tasks:
  - Printable Spacecraft, Super Ball Bot, and Transformers-for-Extreme-Environments

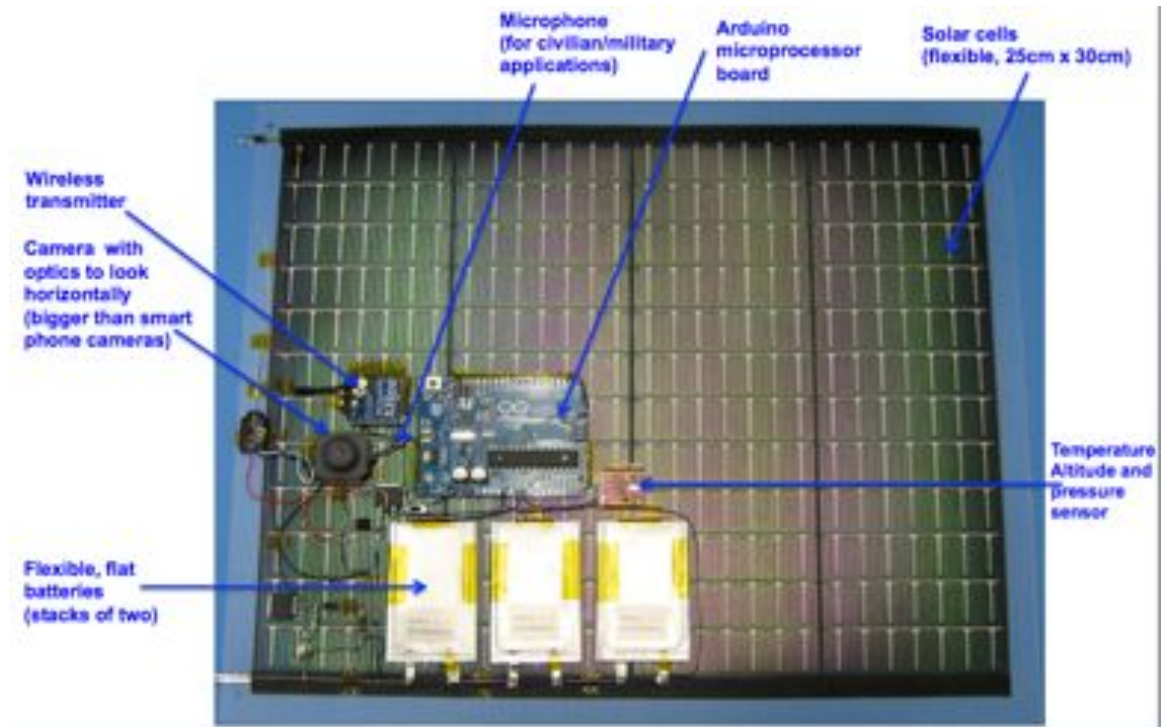
### **Publications:**

- Submitted conference paper to 11th International Planetary Probe Workshop – accepted. To be presented: 16–20 June 2014, Pasadena, California.



## 9 First Hardware Prototype Based on Off-the-Shelf Components

Functional prototype: received images, sound, altitude, pressure, and temperature data nearly 200m away.



## 10 Benefits Summary

- Significantly reduces development time.
- Obviates the most complicated, most expensive, and highest-risk phase of landing
- The flat nature and low mass of these landers allows dozens to be stacked for transport and distributed en masse to the surface.
  - Simplicity of system testing and validation on Earth.
- Redundant landers; the mission is not dependent on the success of any particular lander.
- Even at a high attrition rate of 50% would still provide invaluable data and images that currently cannot be obtained in any other way.
- Enables certain types of missions such as seismic probing or weather monitoring for which distributed landers are required.
- Dual-use benefits civilian and DOD applications.
  - Land, ocean, glacier, or forest where it may be difficult to land.

## 11 Phase II Planned Activities

- Reference mission selected.
- Complete EDL analysis and approach identification for selected mission.
- Complete thermal analysis for descent and upon landing.
- Complete telecom link analysis and hardware specification.
- Complete mass, power, size determination for the given mission.
- Specific point-design. Thorough performance description.
  - Lander's area and mass, power-generation capability.
  - EDL approach.
  - Thermal management.
  - Science gathering capability / performance.
  - Telecomm capability and concepts of operation.
  - Estimates of cost and lifetime.
- Manufacturing partner identified.
- Development and testing of a larger size and more capable prototype.

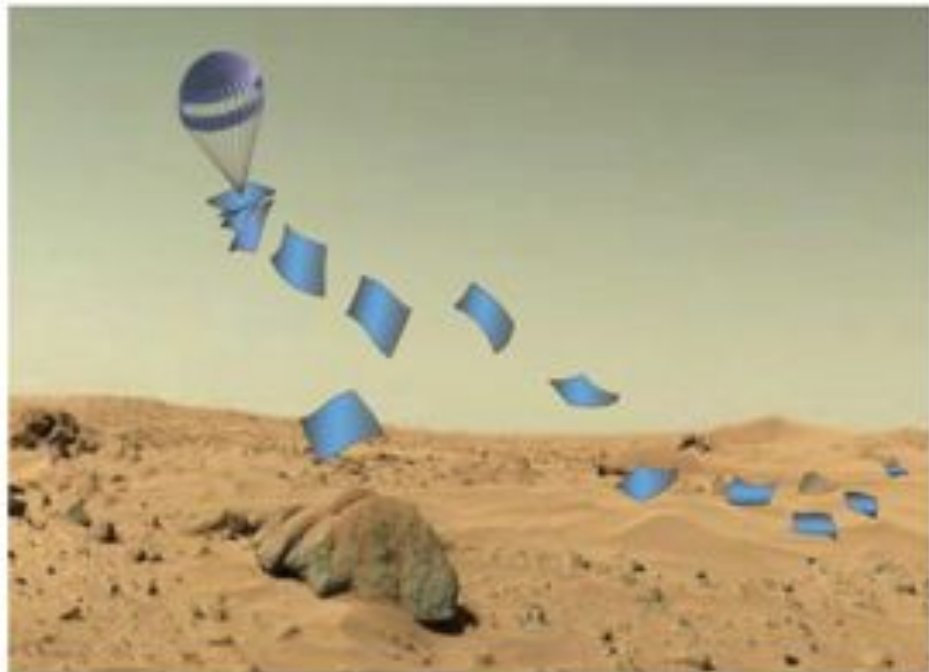
## Appendix. Public Relations and Publications



# Incredible Technology: How Fleets of 'Flat Landers' Could Explore Other Planets

By Mike Wall, Senior Writer | March 10, 2014 08:00am ET

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Future space missions may send dozens of rug-like robots fluttering down to the surface of alien worlds, taking much of the risk out of planetary exploration.  
Credit: Hamid Hemmati  
[View full size image](#)

**Editor's Note:** *In this weekly series, SPACE.com explores how [technology](#) drives space exploration and discovery.*

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# Popular Mechanics

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Homepage / Science / Space / Deep Space / Cosmic Concept: Exploring the Solar System With a Fleet of Flat Landers

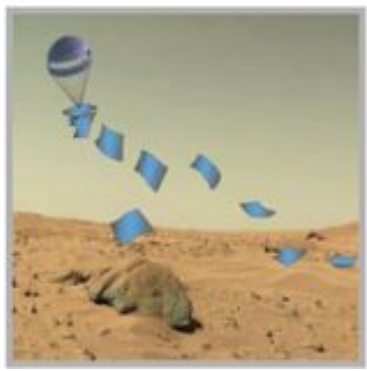
## Cosmic Concept: Exploring the Solar System With a Fleet of Flat Landers

Tiny two-dimensional rovers could be the key to exploring the most exciting places in our solar system.

By John Wenz

1   2   3   4   5   6   7   8   9   10   11   12

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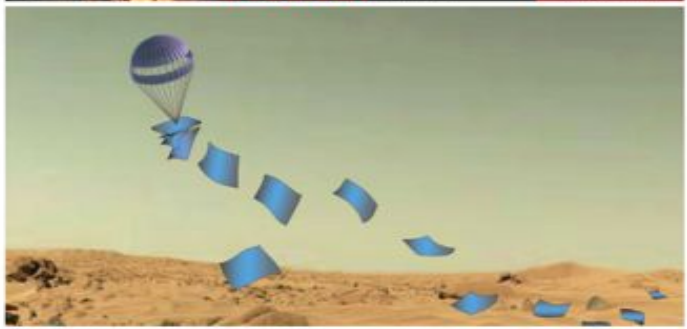
May 23, 2014 3:15 PM   TEXT SIZE: A . A . A

If all goes according to plan, Hamid Hemmati's plan will fall flat.

Hemmati is the project lead on the [Two Dimensional Planetary Surface Landers](#), a NASA Innovative Advanced Concepts (NIAC) project that is in the planning stages. These flat probes would resemble solar panels, but with a flexible electronic body. Each lander would be less than a half inch thick and just over three feet on each side—small enough you could stack 10 to an orbiter. Sensors on board the probe would scan the terrain of a moon or planet below, giving insight into places no NASA lander has dared go. And then these two-dimensional explorers could

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### MAGIC CARPETS: HOW RUG-LIKE LANDERS COULD EXPLORE ALIEN PLANETS

BY LINDY PIRCE ON MARCH 13, 2014

The search for a terrestrial explorer that wouldn't break the bank - or one of its wheels - continues with NASA's new "flat lander" design. The new design is for "sailor-lander" sheets that could be easily dumped off a space craft over a wide area of a planet and beam information back to surrounding satellites. The simple delivery system is the real key here, eliminating the need for the kind of complicated landing strategies necessary for rovers like Curiosity and Opportunity.

The sheets, which give a whole new meaning to the term "space blanket", would be about 3'x3' and about 0.4 inches thick. Once deployed from a spacecraft, the flat landers could drift softly down to the surface of a planet without any sort of complicated and accident-prone landing gear like the *sky crane* used to drop out

WHAT'S NEW   WHAT'S TRENDING



The header for the NewScientist Space website. It features the 'NewScientist' logo in a blue box and the word 'Space' in a large, bold, black font. To the right is a search bar with the text 'search New Scientist'. Below the logo and title is a navigation menu with links: Home, News, In-Depth Articles, Opinion, CultureLab, Galleries, Topic Guides, and Last Week. A secondary navigation bar contains categories: SPACE, TECH, ENVIRONMENT, HEALTH, LIFE, PHYSICS&MATH, and SCIENCE IN SOCIETY.

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## 2D planet lander and suspended animation get NASA cash



The Yahoo! Voices search bar. It includes the 'YAHOO! VOICES' logo, a search input field, a 'Voices' dropdown menu, and a 'Search' button. Below the search bar is a purple navigation bar with links for: Entertainment, Auto, Business, Creative Writing, Health, Home Improvement, Lifestyle, News, and Sports. A secondary bar below that contains links for: Science, Tech Tutorials, and Video Games.

## NASA Funds 'Two-Dimensional Planetary Surface Landers' Project

Landing with a Flutter Rather a Roar and a Bump



The header for the ABC Science website. It features the 'ABC Science' logo and a background image of a hand. Below the logo is a navigation menu with 'Explore by topic' and sub-categories: News in Science, In Depth, Dr Karl, and Ask an Expert. Further down are links for: Latest News in Science, News Analysis, StarStuff, and News Arch. The main headline reads: 'Flat landers get NASA's tick of approval'.

### ***Acknowledgements***

The work described here was conducted at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

The investigation team is indebted to:

- Vachik Garkanian for thermal analysis and study of materials;
- Carlos Esproles for developing functioning prototypes of the 2D lander;
- William Farr for providing ideas on different implementation approaches;
- Kendra Short for sharing information on her Printable Spacecraft, another project funder by the NIAC Program.

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