Exploration Architecture with Quantum Inertial Gravimetry and In-situ ChipSat Sensors

NIAC Phase I Final Report

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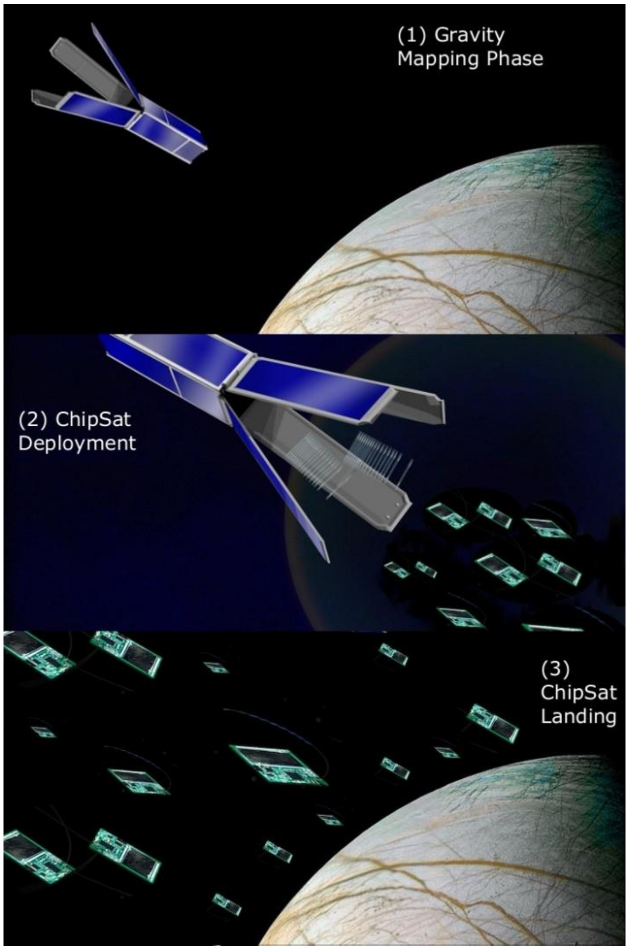

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Executive Summary

The Dual Exploration Architecture is a mission concept that combines remote sensing and in-situ observations into a single mission to answer planetary science questions that can only be answered with both types of data. Adoption of dual exploration architectures may short circuit the long, slow cycle of missions to inaccessible bodies by eliminating the need for separate precursor and follow-up missions. Additionally, the dual architecture possesses inherent flexibility that enables the design of adaptive, event-driven missions that are very different from traditional, largely pre-planned missions. Five key observations about the state and trends of planetary science exploration lead us to the dual architecture: increasing complexity of observations, scarcity of future mission opportunities, desire to capture transitory events, continued miniaturization of spacecraft components, and the Mars exploration cycle. Our goal in this study is to explore missions that can only happen using the dual architecture concept and find technology development needs that must be filled for those missions to compete.

A survey of historical and current missions finds that opportunities for exploration are becoming less frequent, causing the flexibility and dual-nature elements of each mission to become more common. The dual exploration architecture takes these trends to their far conclusion, attempting to eliminate precursor and follow-up missions while still returning more scientific payoff. A study of the future of planetary science goals through the decadal survey reveals broad applicability of dual missions to solve mysteries that cannot be answered with a traditional mission architecture. These missions fall into three broad classes: choosing a local target from a global survey, dynamic/reactive science, and global in-situ networks. Two example missions of each class are notionally described.

A deeper look at these dual architecture classes reveals four technology development needs that must be addressed for wide adoption of dual missions: passive landers, guided atmospheric probes, robust sensing packages, and small, precise orbital instruments. This study pursues a specific focus on two examples of such enabling technologies: the ChipSat and cold atom gravimetry. The ChipSat is a fully functional spacecraft-on-a-chip system that has broad versatility in the dual architecture mission space. Initial studies show that ChipSats could survive as passive impactor landers on bodies up to the size of Europa. Furthermore, COTS components could provide an in-situ senor suite that readily answers a number of pressing planetary science questions. Cold atom gravimetry uses inertial sensors based on light-pulse atom interferometry in a small form factor to map the gravity field of a body to precision equaling what would normally require two full spacecraft to achieve. The cold atom gravimeter provides an example of how advanced remote sensing capability can enable dual missions by providing greater returns in a significantly smaller package.

Using the above two technologies, we study an example dual architecture mission to both characterize and sample the subsurface oceans at Europa. The greatest scientific return in terms of detecting extraterrestrial life is in those regions where Europa’s ice crust is thin. The

identification of regions with thin ice should therefore precede the selection of surface targets and dispatch of probes to those targets. This two-step process, if accomplished by separate flagship-scale missions, might take decades. As a result, a combined mission to both identify thin areas of Europa's ice and follow up with surface observations at those regions is a good candidate for the dual exploration architecture. This example mission consists of an orbiter spacecraft carrying a cold atom gravimeter capable of sensing or inferring the ice thickness on regional to local scales, along with a number of ChipSat probes capable of landing on the moon. The small size and weight of the ChipSats allows large numbers of them to be carried, ensuring that enough can be dropped to ensure survival of a minimum number of probes and potentially allowing for the in-situ sampling of multiple locations on the moon.

The example missions and Europa case study show that amazing scientific return can obtained from dual exploration architecture missions with a single launch by breaking the long timescales of planetary exploration and providing the flexibility to capturing transitory events and collect data across the local, regional, and global scales.

1 Introduction and Motivation

The Dual Exploration Architecture is a mission concept that combines remote sensing and in-situ observations to answer planetary science questions that can only be answered with both types of data. The combination produces a mission with the ability to examine details shortly after identifying them. As such, the dual exploration architecture also can short circuit the long, slow cycle of missions to inaccessible bodies by eliminating the need for separate precursor and follow-up missions. Additionally, the dual architecture possesses inherent flexibility that enables the design of adaptive, event-driven missions that are very different from traditional, largely pre-planned missions

Five key observations about the state and trends of planetary science exploration lead us to the dual architecture:

1. **Increasing complexity of observations:** as solar system exploration matures, the data sets required to answer new questions naturally become more complex. A single observation becomes less and less likely to fully solve an open question as we return to bodies or classes of bodies that we have visited before. Increasingly, combinations of remote sensing and ground truth data or body-wide, coordinated in-situ measurements are required. Complex questions need to be examined on local, regional, and global scales to gain full understanding.
2. **Increasing scarcity of mission opportunities:** as further described below in Sec. 2.1, opportunities to visit bodies of interest have become scarcer in recent decades, and that trend is projected to continue. As such, any mission needs to return significantly more science payoff if we want to push planetary science forward at a comparable speed to today.
3. **Desire to capture transitory events:** as we continue to visit solar system bodies, their static qualities (such as mass, baseline composition, etc.) become better known and we need to start capturing dynamic and transitory events (such as jets/volcanoes, trace gas concentrations, weather patterns, etc.) to fully understand them. Some events whose timing cannot be predicted far beforehand drive important processes. Studying such events is hard to do with current exploration paradigms
4. **Miniaturization of spacecraft components:** as with most industries, spacecraft components continue to become smaller and more capable over time. Although launch vehicle capabilities have not significantly increased, the miniaturization of components and systems allows for more capability within the same launch mass. This miniaturization needs to be exploited to increase scientific returns multiplicatively rather than additively.
5. **The Mars cycle and its failure beyond Mars:** Mars exploration tends to work in cycles of remote survey and in-situ sensing. Mars Global Survey and Mars Odyssey did planet-wide studies. With this global data, interesting sites could be selected for the Mars Exploration Rovers. With new, more-detailed information from the Mars Reconnaissance Orbiter, a new interesting landing site for the Mars Science Laboratory was chosen. For Mars exploration, this cycle works well, as there are launch windows every two years and travel time can be

measured in months rather than years. Resources, enthusiasm, interest, and expertise do not have time to significantly diminish between missions. For more inaccessible targets, the cycle of remote followed by in-situ does not always close. For example, the Galileo mission made many exciting and unexpected discoveries at Europa, resulting in an almost universal desire to revisit the moon with an in-situ probe. However, due to resource and time constraints, such a probe has been often proposed but never built. As the delay between visits to Europa widens, expertise and enthusiasm brought on by Galileo slowly wanes, making it ever harder to close the exploration cycle.

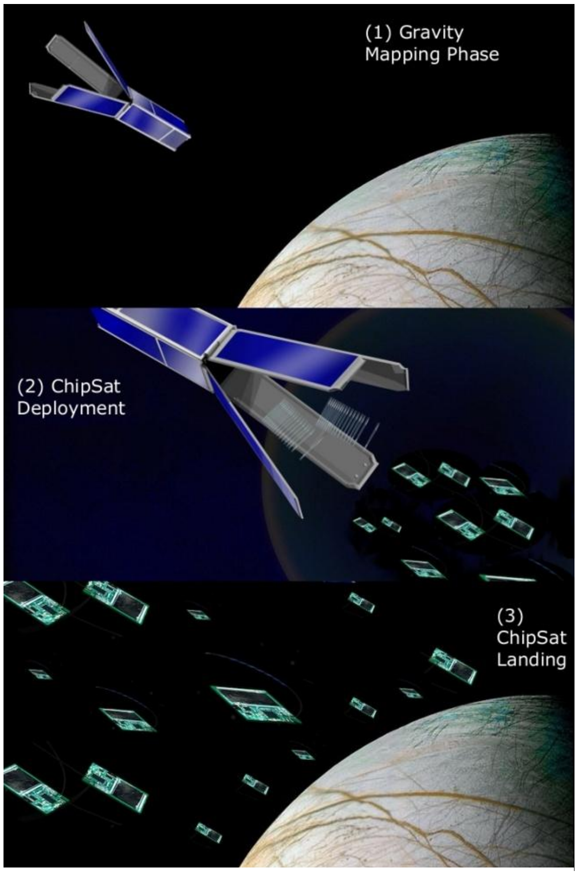

Figure 1. Conceptual stage of a Europa dual exploration architecture

Our goal in this study is to explore missions that can only happen using the dual architecture concept and find technology development needs that must be filled for those missions to compete. In Section 2, we expand upon the above drivers that justify the dual exploration architecture by both looking backwards at past trends in planetary science and looking forward with the planetary sciences decadal survey. This allows us in Section 3 to broadly classify dual missions, generate dual mission concepts, and explore the technologies that enable them. We have a specific focus on two examples of such enabling technologies: the ChipSat and cold atom gravimetry. The ChipSat is a fully functional spacecraft-on-a-chip system that has broad versatility in the dual architecture mission space. Cold atom gravimetry uses inertial sensors based on light-pulse atom interferometry in a small form factor to map the gravity field of body to precision equaling what would normally require two full spacecraft to achieve. Using these two technologies we develop a dual exploration mission case study in Section 4. In this example mission we explore both fully mapping the ice crust thickness at Europa and then obtaining an in-situ sampling of ocean material within a single mission.

2 Background and Significance

2.1 Historical Perspective

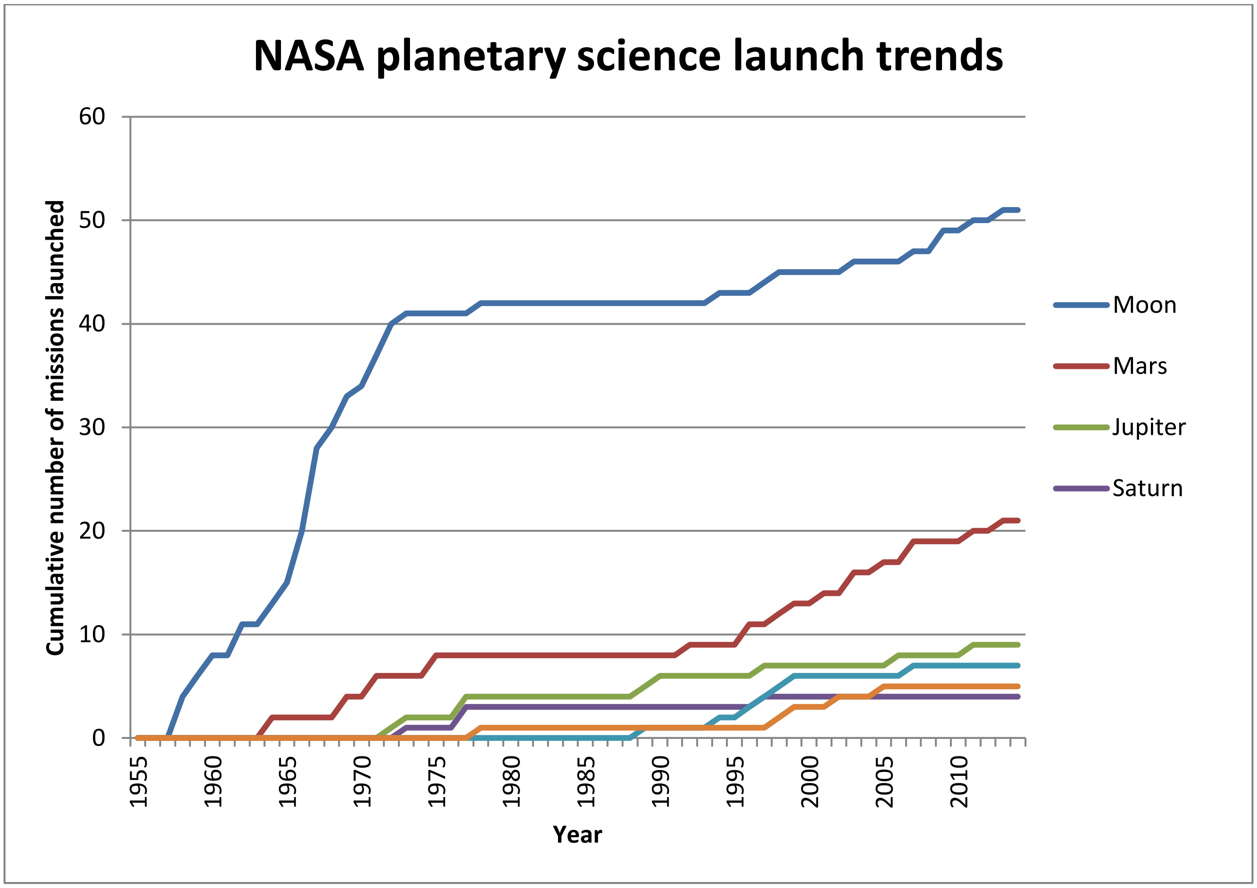

Figure 2. Cumulative number of NASA missions launched to several different solar system bodies versus launch date. Human, robotic, successful, and unsuccessful missions are all included.

Figure 2 shows the cumulative number of NASA missions launched to various planetary science targets as a function of launch date. Both manned and unmanned missions are included, as well as both successful and unsuccessful missions. A list of the specific missions counted as raw data for this plot appears in Appendix 5.1. Three features are evident from this figure. First, the number of spacecraft launched to the Moon ramped up dramatically in support of the Apollo human exploration program. Science missions to other solar system bodies, especially the outer planets, did not begin until later. Second, there is a period around the 1980s in which a hiatus of almost all planetary science launches occurs. Third, after the hiatus the cadence of launches to many solar system bodies is lower than before the pause (with the exceptions of launches to Mars, which coincide with the familiar two-year launch window both before and after the hiatus, and asteroid/cometary exploration, which did not pick up until the 1990s). In fact, the cadence of lunar launches is 80% lower between the hiatus and present than it was between the first lunar launch and the 1980s. Jupiter exploration launches happen 50% less frequently after the hiatus than before the hiatus.

From Figure 2, we draw the conclusion that launches to various solar system exploration targets are happening at a generally decreasing cadence over time. Indeed, the number of NASA missions projected to launch in the future is smaller still: before 2030, InSIGHT and Mars 2020 may launch to Mars, Europa Clipper to Jupiter, and OSIRIS-REx and a potential human mission to asteroids. Few other programs, if any, have started. (Of course, future smaller-scale missions such as Discovery-class missions may not be predicable this far in advance.) The drop in launch cadence is likely due to a number of factors, several of which revolve around the Apollo program. Not only did the Space Race result in sustained high funding levels for NASA, but NASA maintained a steady focus on lunar exploration to support the eventual human landing. It is not until the end of the Apollo program in 1972 that NASA launched any missions to the outer solar system at all. After the pause in the 1980s, NASA began to split its attention between a larger number of science targets than before – with a smaller bank of funds to divide between them.

With science and exploration missions launching at a slower pace as time passes, it will be imperative to formulate missions that maximize science returns. A natural reaction to this drive would be to pack as much functionality as possible into each individual mission to a given exploration target. However, it is likely that the data from such a mission will raise even more questions, leaving the scientific community without fresh data for ever-longer periods of time. In such an environment, there may be great value to exploration architectures capable of responding to scientific targets of opportunity.

2.2 Other Missions with Dual Features

A number of other missions have included elements of the dual-mode responsive exploration architecture. However, despite some commonalities, these past missions fall short of achieving the revolutionary objectives of the proposed approach. Table 1 lists a number of historical missions, indicating which include the three key elements of the architecture: remote survey measurements (such as from an orbiter), in-situ science (for example, from a lander or penetrator), and whether or not the remote science data informed the choice of in-situ science target. We view this last point to be crucial to the dual exploration architecture: that the mission responds to scientific targets of opportunity that may not have been known to the mission definition team.

Table 1. Other missions with dual exploration architecture-like features.

Launch year	Mission	Remote science?	In-situ science?	Choose target from survey?	Notes
1975	Viking Orbiter + Lander	**Yes**	**Yes**	No*	* Mission operators re-targeted Viking 2 Lander based on Orbiter images
1995	Galileo + Probe	**Yes**	**Yes**	No	
1996	NEAR-Shoemaker	**Yes**	No*	**Yes**	* Landed on asteroid at end of mission as a demonstration
1997	Cassini + Huygens	**Yes**	**Yes**	No	
2004	Rosetta + Philae	**Yes**	**Yes**	**Yes**	Closest to this exploration concept!
2005	Deep Impact + Smart Impactor	**Yes**	No*	No	*Impactor not designed to survive and record measurements
1999	Stardust-NEXT	**Yes**	No	No*	*Mission re-targeted to respond to Deep Impact mission science needs
2016	OSIRIS-REx	**Yes**	**Yes***	**Yes**	*Sample return; no in-situ science performed on board

Some of the most obvious comparisons of historical missions to the dual exploration architecture are the Galileo mission to Jupiter and the Cassini-Huygens mission to Saturn. In both cases, the mission consisted of an orbiter spacecraft and a lander or probe, and so each might seem similar to the dual exploration concept. However, both the Galileo Probe and Huygens lander separated from their mother spacecraft before any science return was available from the orbiters. Neither in-situ probe was designed to target a site identified from remote sensing data. In effect, the probes' missions were independent of the orbiter mission.

In several cases, a mission deviated from its initial definition in a way that aligned with the dual exploration architecture. The earliest such example is Viking 2, which consisted of the Viking 2 Orbiter and Lander. Mission planners selected a landing site for the Lander in advance, but upon review of images returned from the Orbiter, they decided to re-target the Lander. In some sense, then, the Lander mission responded to remote sensing data. Another prominent example is the NEAR-Shoemaker mission, which launched as a mission to survey an asteroid from orbit. As a demonstration, the spacecraft ended its mission life by touching down on the asteroid surface, at a point selected from available science data. Finally, some missions include attempts to visit more than one target, sometimes responsively: after the Deep Impact mission, operators re-tasked the Stardust spacecraft to perform follow-up studies of Comet Tempel 1.

The European Space Agency's Rosetta and Philae spacecraft represent the closest match of any past or present mission to the dual exploration architecture proposed in this study. The mission consisted of an orbiter and a lander spacecraft, with the orbiter performing a survey of the target comet 67P/Churyumov–Gerasimenko before deploying the lander. The team scientists selected the landing site from remote sensing results. Furthermore, the Rosetta science team did not know what to expect at the comet. Rather than sending two different missions, though, with Philae as a follow-up to Rosetta, the two spacecraft were launched together with the intention that the lander would immediately follow on the science from the orbiter.

In a sense, there is already a trend towards the dual-phase exploration architectures this study suggests. The need to maximize science return from less frequent missions, combined with increasing experience with autonomous landers and proximity operations, is evident in the progression from Galileo and Cassini-type missions to more recent mission concepts such as Rosetta and OSIRIS-REx. Rather than sending multiple missions to perform initial survey and then follow-on studies of a target, these missions combine both efforts. The exploration architecture put forward in this study embraces and encourages this trend.

2.3 Survey of Decadal Survey Topics

The planetary sciences decadal survey is the guiding document for NASA's planetary science agenda for the next decade.[1] In addition to prioritizing objectives and missions, the decadal survey gives a concise summary of lines of research for planetary science in the form of a large number of unanswered questions about our solar system. This set of questions provides a rich set of data for us to examine what types of missions and data sets are required to advance planetary science in the near-term, mid-term, and far-term periods.

We have parsed these questions to determine what kind of mission is needed for an answer, and they fall into three distinct categories:

1. **Remote observation or in-situ observation only questions**: these are questions which we both know how to ask and how to answer. We know where to go and what to look for. These questions are the "low hanging fruit," so to speak, which we could answer in 5-10 years (given the resources). This category represents 84 of 161 questions (52%) asked within the decadal survey. However, this category is likely overrepresented as these are the types of decade-scale questions that the survey is prioritizing. One example of this category is "How does the atmosphere of Venus respond to solar-cycle variations?" This is a pure remote observation question that can be answered with a spacecraft very similar to the MAVEN mission to Mars. We know where to go and what to do when we get there. An example of an in-situ only question is "How do the compositions of presolar grains and organic molecules vary among different comets?" Again, we know what data we need, we just have to go get it.
2. **Dual Architecture questions**: the "high-hanging fruit" requiring both In-situ and Remote observations. We know how to answer these but they push the boundaries of

traditional mission architectures and have a 10-20 year horizon. These are the questions that seem to fall within the NIAC charter and are what we focus on in this report. With traditional single mission architectures, two separate missions or spacecraft would be needed to answer these questions, potentially pushing the final answer out several decades for hard to reach targets. This category represents 19% of the explicitly asked questions. An example from the decadal survey is "What can the significant differences among ring systems teach us about the differing origins, histories, or current states of these giant planet systems?" We need both a planetary-scale view to see the overall ring structure and an in-situ view to get to resolve the fine detail within the rings to answer such a question. This begs for a dual architecture mission that can fully satisfy the question in a single mission rather than two missions likely separated by decades. A second dual architecture example question from the decadal survey is "What is the four-dimensional wind structure of the Martian atmosphere from the surface boundary layer to the upper atmosphere?" This question, and several others that are meteorological in nature, requires global atmospheric data, coupled with a global network of in-situ sensors, something that can only be accomplished using a dual architecture.

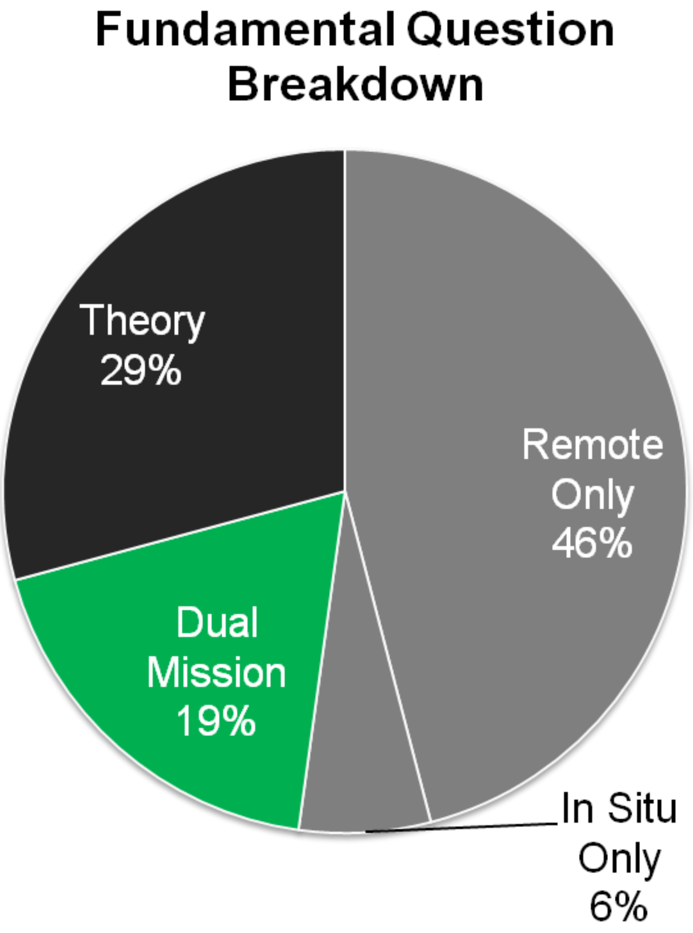

Figure 3. Breakdown of decadal survey question types

3. **Theoretical questions**: This group of inquiries is looking for deeper answers. These are generally questions we do not know how to ask precisely enough to properly answer, and, thus, they have very long time horizons. Often such questions would require precursor missions. We posit that the inherent flexibility of dual architecture missions could effectively short circuit the long timeline by providing better precursor data, or by providing the opportunity for an immediate response to precursor data. Theory questions represent 29% of questions. An example of such a deep question is “Can evidence of life be found on Mars?” We have to agree on what evidence of life would look like before we can design a mission to find it, but a dual mission that searched for hotspots of certain compounds from orbit before deploying a lander could provide a faster answer. A second example is “What do the crater populations on the satellites reveal about the satellites’ histories and subsurface structure and about the populations of projectiles in the outer solar system and the evolution thereof?” This is much more of a modeling question, but will require lots of data from around the solar system to corroborate the model.

All of the decadal survey questions and classifications are shown in Section 5.2.

Pursuing dual architecture missions allows us to skip ahead, so to speak, on the second and third categories, using designed-in flexibility to greatly reduce the need for precursor missions or repeated visits to planetary bodies.

3 Dual Mission Classes and Technology Needs

3.1 Dual Mission Classes and Examples

Looking deeper at the Dual Exploration Architecture questions posed by the Decadal Survey, we create dual mission scenarios to answer these questions with a single mission instead of multiple visits. Upon completing this exercise, three broad classes of Dual Architecture mission are evident:

1. **Global Survey Chooses Local Site**: The first dual mission class involves choosing the right landing or sampling location after mapping a quantity of interest remotely. This class is appropriate when we know there is a spot of particular interest on a planet or body, but we can’t know exactly where it is until we arrive. An example is our case study, *Example Mission 1* in Table 2*:* Gravimetry of an icy body to determine the locations of thinnest ice or most likely spot to gain access to subsurface material, followed by landing small in-situ sampling probes at the most promising location. This mission allows us to determine both the ice thickness and subsurface ocean composition with the same mission, something that would likely take decades otherwise. Another, different example is *Example Mission 2*, which explores Saturn's (or other body's) rings from both a global and local perspective to achieve understanding of their structure at all

scales. Such a mission would include both survey-class instruments and small probes that actually enter the ring system.

2. **Dynamic/Reactive Science**: The second class of dual architectures involves capturing transitory events on other bodies. Certain events are ephemeral, with hard to predict start and end times. A dual mission can operate with the flexibility to wait for these events to occur. An example of this type of mission is *Example Mission 3*: a reactive orbiter that waits for active volcanoes and then releases probes to fly through the plume. We know these events are occurring at a body, but we cannot predict ahead of time where and when we need to be to capture them. Thus, instead of a traditional mission that will follow a prescribed trajectory and timeline; we need an orbital platform that watches and waits for the transitory event and then releases a separate probe to capture it. A second example of this class, *Example Mission 4*, is a global weather satellite that monitors for new storms on a giant planet and then sends a probe into the eye of the storm.
3. **Global In-situ Networks**: The third class of dual mission involves deploying and communicating with global sensor networks. Many measurements of interest require a global network of in-situ samples. Generally a global asset is required to both deploy and communicate with the distributed network. Our first example of this class, *Example Mission 5*, is a seismic network at a small body. A global “mothership” deploys a network of seismic sensors to map internal composition of asteroids or KBOs. A second example of this class, *Example Mission 6*, is a global Martian LIDAR wind measurement network with reserved nodes deployed into active large scale dust storms detected from orbit.

Table 2 gives presents these six example missions and gives further description of the questions asked in the decadal survey to inspire each mission. Figure 4 show a breakdown of the dual mission classes, their examples, and the technology development needs for each example mission.

Table 2. Example dual-phase missions to answer questions posed in the Decadal Survey.

Example Mission	Mission Idea(s)	Decadal Survey Question	Decadal Chapter	Class	Technology Development Needs
1	Gravimetry of an icy body to determine the locations of thinnest ice or most likely spot to gain access to subsurface material followed by landing small in-situ sampling probes at the most promising location	Are volatiles present at the surface or in the ice shell of Europa that are indicative of internal processing or resurfacing? And many other Europa questions	Ch8	1	Small scale gravimeter, Passive landers (impactors)
2	Explore Saturn's (or other body's) ring from both a global and local perspective to achieve understanding of their structure at all scales. Include small probes that actually enter the ring system	What is the mechanical process of accretion up to and through the formation of meter-size bodies? Plus other ring related questions	Ch4, Ch7	1	Small, cheap, disposable camera/sensing package

3	Reactive orbiter that waits for active volcanoes and then releases probes to fly through the plume	What are the inventories and distributions of volatile elements and compounds (species abundances and isotopic compositions) in the mantles and crusts of the inner planets? Plus other volcanism questions	Ch5, Ch8	2	Guided atmospheric probes, remote eruption sensor
4	Global 'weather' satellite that monitors for new storms on a giant planet and then sends a probe into a the eye of the storm	What are the natures of periodic outbursts such as the global upheaval on Jupiter and the infrequent great white spots on Saturn?	Ch7	2	Guided atmospheric probes, storm sensor
5	Seismic networks at small bodies. A global 'mothership' deploys a network of seismic sensors to map internal composition	What are the internal structures of Trojans and KBOs?	Ch4	3	Passive landers (small body), Seismic sensor
6	Global Martian LIDAR wind measurement networks with reserved nodes deployed into active large scale dust storms detected from orbit	What are the processes controlling the variability of the present-day climate? What is the four-dimensional wind structure of the Martian atmosphere from the surface boundary layer to the upper atmosphere? What are the primary causes behind the occurrence of global dust events? What are the processes coupling the CO2, dust and water cycles?	Ch6	3	Weather sensors, Passive landers (atmospheric)

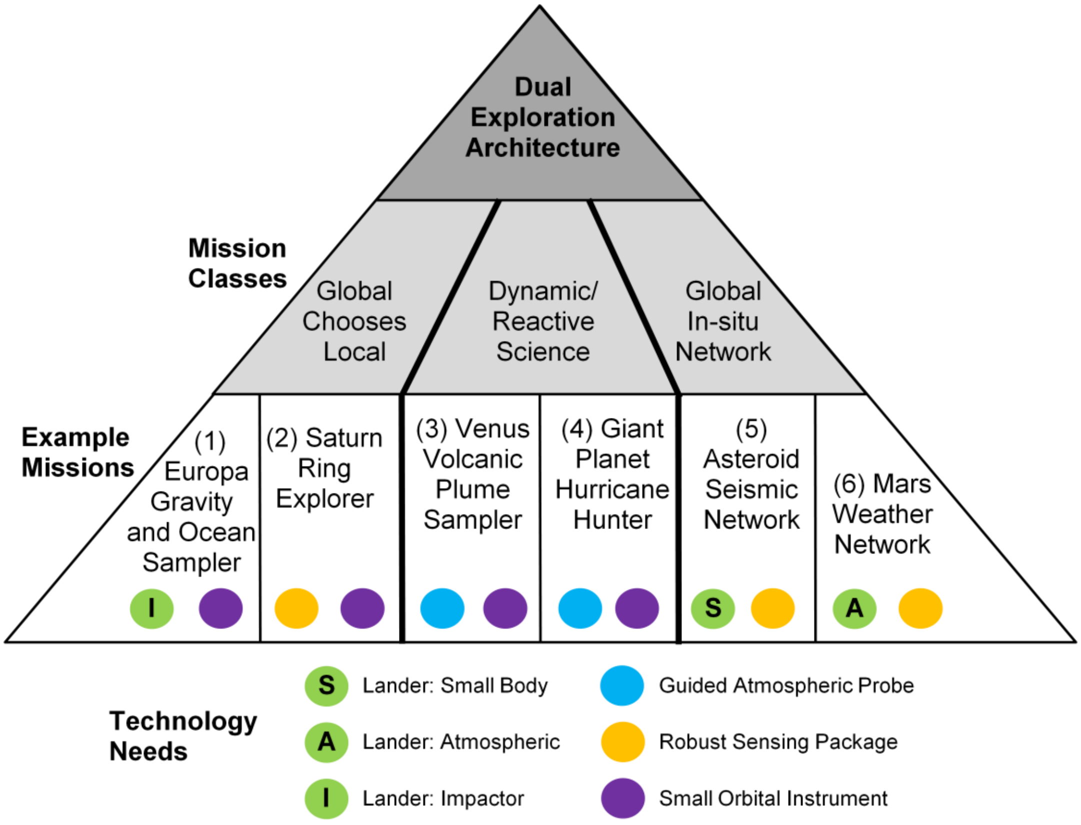

Figure 4. Dual exploration classes, mission examples, and technology needs

3.2 Technology Needs for Dual Missions

From the three classes of dual architecture mission and their examples listed in Table 2, four major technology categories appear that need more development to make these mission possible:

1. **Passive Landers:** Needed for getting from orbit to the in-situ environment with minimal packaging. These landing technologies must be robust enough to ensure mission success. However, an importation distinction between traditional mission architectures and many of our example missions is robustness through numbers: single in-situ sensors are unimportant as long as enough survive to complete the mission. Three distinct versions of landers are needed:
   a. Small body, for asteroids/comets. These impact with very low speeds, but must remain on the body (i.e. not bounce back off), which can be the most challenging aspect of design as the Rosetta mission demonstrated.
   b. Atmospheric, for large bodies with significant atmospheres. The presence of atmosphere can help with passive landing, especially for very small probes. At the extreme some designs with very low area-to-mass ratios can survive with no heat protection at all [2]
   c. Impactors, for moons and other significant bodies without atmosphere. As bodies grow larger without an atmosphere, passive landers must survive larger and larger impact velocities, bringing in new design challenges. A sufficient number must survive the impact such that the mission still succeeds.
2. **Guided Atmospheric Probes:** Needed for sampling specific places in an atmosphere or landing on specific surface spots. Passive landers are designed to land where they may, but many missions require passage through or landing on a specific spot. These missions tend to occur on atmospheric bodies, with goal of sampling things like volcanic plumes, storm regions, or areas with a higher concentration of a gas species of interest.
3. **Robust Sensing Packages:** Needed for reliably operating away from a mothership in highly challenging environments (rings, high radiation zones, etc.). These sensing units are thought of as somewhat disposable with perhaps even planned destruction. They go to places where a main spacecraft asset cannot and must reliably capture and return data before succumbing to the environment. By acting away from the main orbital asset, they protect the overall mission.
4. **Small, Precise Orbital Instruments:** The ideal dual mission provides the benefits of both modes of exploration in the same scale package. In addition to the in-situ technologies listed above, this requires the continued miniaturization and improvement of remote sensing units.

Development in the above categories improves the overall TRL of all of our example missions. However, given the inherent flexibility designed into the dual exploration architecture, these technologies have wide ranging uses and applications. For space exploration, each could serve as either the focal point of a small mission or a hosted payload/instrument on a large mission. The technology set also have many applications terrestrially, some of which are noted in Table 3.

Table 3. Potential Earth Applications of the Dual Mission Technology Needs

Technology Class		Potential Earth Applications
Passive Landers	Small Body	Sensor deployment from a low altitude, low velocity UAV
		Sensors able to land on a moving vehicle
	Atmospheric	Deployment of widely dispersed sensor networks from orbit
		Sampling of mesosphere and atmospheric layers unreachable by balloons or traditional spacecraft
		Measuring radiation environment in near space and within auroras
	Impactor	Development of electronics robust to extreme g-loading, e.g. gun-launched sensors
		Gun-launched spacecraft for inexpensive, high-cadence suborbital (or, perhaps, orbital) access
		Other gun-launched devices? E.g. law enforcement launch a GPS tag at a getaway car
		Sensors to monitor road and rail condition subject to vehicles driving over them
Guided Atmospheric Probes		Return of small sample capsules from LEO
		Return of data from LEO in physical form factor ('thumb drive from space')
		Sampling of volcanic plumes
		Gather in situ data from hurricanes
		Oceanic sensor networks with individuals that hold station in ocean currents (to listen for airliner "black box" pings, track subsurface oil spills, monitor climate variables like dissolved CO2)
		Sea-floor probes that target a particular landing site (deep-sea vents, wreckage, coral reef, search-and-rescue sites)
Robust Sensing Packages		Sensor networks covering glaciers or ice caps
		Sensor networks for high radiation environments
		Sensor networks for high pressure environments
		Sensor networks for other dangerous environs (high temperature, toxic, etc.)
Small, Precise Orbital Instruments		Move instruments that used to require large spacecraft into CubeSats

3.3 Technology Example: ChipSats

The ChipSat architecture represents a core that can be adapted to meet many of the technology needs discussed in the previous section. Designed as extremely small standalone spacecraft, they readily fill the role of robust sensing packages and can readily be used as small body and impactor landers. With small aerodynamic surfaces attached, ChipSats can become the core of atmospheric landers as well.[2]

A revolutionary characteristic of ChipSats is that they are both very small and relatively inexpensive to produce in volume. Because of these unique features, a modest-size primary satellite (even a smallsat, less than 180 kg) can store and deploy hundreds to thousands of ChipSats in a single launch. Their sheer numbers enable mission planning to be based on a high-confidence statistical model of success, very different from the probabilistic reliability models used for single spacecraft.

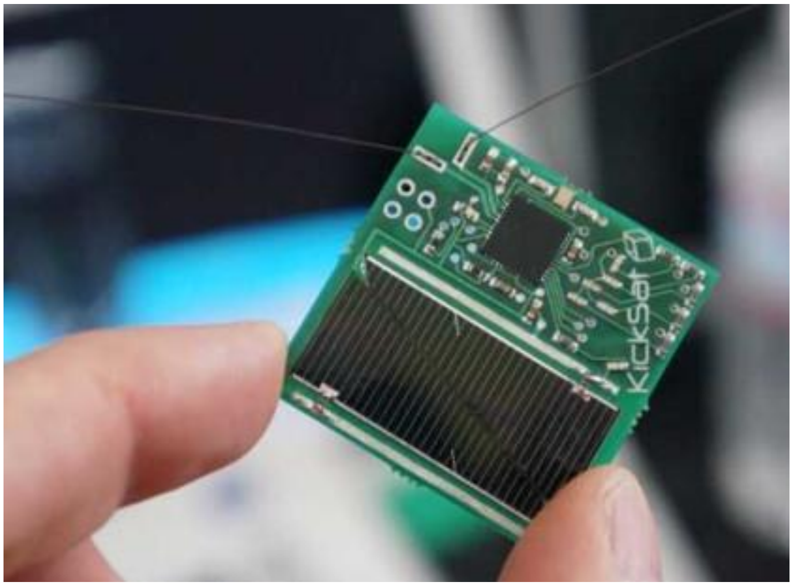

Figure 5. A Sprite spacecraft

ChipSats have several target applications and more will surely follow as the technology matures. One of the target missions is in-situ detection. ChipSats can be equipped with temperature, pressure, magnetic, and other sensors to measure phenomena on a planetary surface. Another scientific objective for ChipSats would be testing for the presence of particular chemistry, specifically those related to organic compounds and life.

The Sprite spacecraft is the first instance of a ChipSat, motivated originally by a 2006 NIAC study. Each weighs approximately 5 g. 1000 of them would represent a 5 kg payload. Each contains solar cells (on both sides), a radio transceiver, and a microcontroller. In 2011 three prototypes flew on the MISSE-8 experiment. They survived three years in LEO and continue to function today. In April 2014, 104 Sprites ware launched from a 3U CubeSat satellite bus called KickSat. These two technology-demonstration missions establish the feasibility of communicating across large distances with low power—10 mW reaches over 1000 km with suitable forward-error correction, requiring only a laptop and a hand-held antenna. Increasing this range requires only trivial changes, primarily an increase in the length of the pseudorandom-noise sequence that represents a single bit transmitted from the Sprite. We are confident that lightweighting the current design can result in a roughly 1 g Sprite equivalent, and advancing this technology may reduce the mass to below 100 mg. The roadmap for doing so is based on exploiting thin-film solar-array technologies, custom ASICs, and antenna structures mounted or printed on a thin-film Kapton substrate.

The communications architecture enables simultaneous reception of a large number of signals, one from each Sprite, with a guarantee that the source of the signal (i.e. the identity of a single Sprite) is unambiguous. So, the data can be correlated spatially and temporally to suit the mission needs. Furthermore, the communications hardware on the spacecraft side can be quite simple. These important objectives are accomplished with a Code-Division Multiple Access (CDMA) strategy that was demonstrated in 2011. It has since been flown on Sprite prototypes on ISS, where the technology successfully survived three years on the MISSE-8 experiment, exposed to the space environment. An additional communications technology, forward error correction, increases the signal-processing gain at the expense of data bandwidth, allowing the mission architecture to accommodate an optimal combination of data rate and signal-to-noise (SNR), analogous to gain.

Each Sprite communicates a single data bit via a unique pseudorandom-noise (PRN) sequence. This PRN is in fact a so-called gold code, mathematically orthogonal to that of every other Sprite. Matched filtering essentially allows the energy in the entire PRN code to be summed and treated as a single data bit, providing an increase in SNR equal to the code length. For the 2014 KickSat mission, a family of PRN codes 640 chips long is being used, providing a “code gain” of about 28 dB for a very robust link margin. Aside from improving SNR, matched filtering also makes possible CDMA. By assigning each Sprite a different PRN, the receiver can “tune” to a particular spacecraft’s signal by correlating against its unique code. This allows all the Sprites on a particular mission to share the same allocated frequency, simplifying receiver hardware and eliminating the need for clock synchronization that would otherwise be required for the Sprites to alternate transmitting on the same frequency. CDMA has been used for many years in the cellular telephone industry and the global positioning system. It has proven in practice to be the most efficient channel access method when a large number of users must be accommodated. We conclude that the Sprite technology enables a wide range of survey tasks that require spatial and/or temporal distribution of in-situ sensors.

For this study, we adapt this proven design to the science needs of a dual-mission architecture. Chief among these adaptations is the sensor technology. Sprite spacecraft will have to be outfitted with suitable small-scale sensors. The size of the spacecraft restricts the kinds of sensors that are appropriate for this technology concept, as does the available power. This study considers state-of-the-art, COTS components to establish feasibility. With this existence proof in place, we argue that extending the capability or further reducing mass is entirely feasible. Companies such as Systron Donner Inertial, Colibrys, ST Microelectronics, Bosch, and Texas Instruments have developed entire product lines of microelectromechanical systems (MEMS) sensors that fit Sprite’s design parameters. Inevitable advancement in sensing technology will represent additional design margin or further opportunities for NASA missions in the longer term.

Sprites may be able to reveal information about the gravitational field and composition of the celestial body by measuring their inertial behaviors in orbit and as they impact the surface. A combination of MEMS gyroscopes and accelerometers can achieve this goal. They can be used as two independent sensors or together. Some COTS IMUs combine the two products into one small MEMS unit. Advancements in MEMS technology have enabled these gyros to provide suitable performance, including low noise, miniature size, wide bandwidth and temperature ranges, and high reliability, as shown in Tables 1 through 3.

Table 4: Systron Donner Inertial Gyroscopes

Product Name	Size [mm]	Input voltage [V]	Input current [mA]	Standard range [°/sec]	Scale factor	Bandwidth [Hz]	Noise [°/sec/√Hz]
QRS11	Ø 37.9 x 13.46	± 5	< 80	± 100	< 1% of value	> 60	< 0.01
QRS116	Ø 37.9 x 13.46	± 5	< 20	± 100	< 1% of value	> 60	< 0.002
SDG1400	40.6 x 35.6	± 10 to 16	< 15	± 200	0.025 VDC/°/sec	50 ± 10	< 0.0017
SDG500	32.5 x 32.5	± 10 to 15	< 20	± 100	0.050 VDC/°/sec	60 ± 15	< 0.005
QRS14	53.1 x 25.7 x 25.7	9 to 18, ± 9 to 18	< 20, < 25	± 50, 100, 200, 500	± 2% of value	> 50	< 0.05, < 0.02
HZ1	58.3 x 25.3 x 25.3	8 to 15	< 20	± 90, 100	< 2% of value	> 18, > 60	< 0.025

Table 5: Colibrys inertial sensors

Product Name	Size [mm]	Full-scale [g]	Scale factor [mV/g]	One year bias stability [mg]	One year SF stability [ppm]	Bandwidth [Hz @ -3dB]	Noise [μV/√Hz]
MS8002.D	14.2 x 14.2	± 2	1000	1.5	300	> 200	18
MS8010.D	14.2 x 14.2	± 10	200	7.5	300	> 200	18
MS8030.D	14.2 x 14.2	± 30	66.6	22	300	> 200	18
MS8100.D	14.2 x 14.2	± 100	20	75	300	> 200	18
MS9001.D	8.9 x 8.9	± 1	2000	< 1	300	> 100	18
MS9002.D	8.9 x 8.9	± 2	1000	1.5	300	> 100	18
MS9005.D	8.9 x 8.9	± 5	400	3.75	300	> 100	18

MS9010.D	8.9 x 8.9	± 10	200	7.5	300	> 100	18
MS9030.D	8.9 x 8.9	± 30	66.6	22	300	> 100	18
MS9050.D	8.9 x 8.9	± 50	40	37.5	300	> 100	18
MS9100.D	8.9 x 8.9	± 100	20	75	300	> 100	18
MS9200.D	8.9 x 8.9	± 200	10	150	300	> 100	18

Note: The sensors operate from a single power supply voltage (between 2.5 V and 5.5 V) with low current consumption (< 0.5 mA at 5 V). The output is a radiometric analog voltage that varies between 0.5 V and 4.5 V for the full-scale acceleration range at a voltage supply of 5 V. They operate over temperature range of -55 °C to 125 °C and can withstand shocks up to 6000 g.

Table 6: Colibrys tilt sensors

Product Name	Size [mm]	Full-scale [g]	Scale factor [mV/g]	One year bias stability [mg]	One year SF stability [ppm]	Bandwidth [Hz @ -3dB]	Noise [µV/√Hz]
RS9002.B	8.9 x 8.9	± 2	1000	10	< 300	> 200	30
MS9001	8.9 x 8.9	± 1	2000	0.75	300	> 100	18
MS9002	8.9 x 8.9	± 2	1000	1.5	300	> 100	18
MS9005	8.9 x 8.9	± 5	400	3.75	300	> 100	18
MS9010	8.9 x 8.9	± 10	200	7.5	300	> 100	18
MS9030	8.9 x 8.9	± 30	66.6	22	300	> 100	18
MS9050	8.9 x 8.9	± 50	40	37.5	300	> 100	18
MS9100	8.9 x 8.9	± 100	20	75	300	> 100	18
MS9200	8.9 x 8.9	± 200	10	150	300	> 100	18

Note: The sensors operate from a single power supply voltage (between 2.5 V and 5.5 V) with low current consumption (< 0.5 mA at 5 V). The output is a radiometric analog voltage that varies between 0.5 V and 4.5 V for the full-scale acceleration range at a voltage supply of 5 V. They operate over temperature range of -55 °C to 125 °C and can withstand shocks up to 6000 g.

Conceivable surface measurements include tectonic activity and magnetic fields, and potentially weather on the few bodies with atmospheres. There are a number of MEMS options that can be outfitted on the Sprites for these purposes including seismic, geomagnetic, humidity, pressure, and temperature sensors. Once again, there are also some units that integrate the multiple weather sensors into one small product. Vibration sensors with a low noise, high resolution, and large dynamic range offer a solution to seismic monitoring. They are designed to detect natural movements that are characterized by low amplitude signals. Geomagnetic sensors measure external magnetic fields in three axes and can be integrated with a three-axis accelerometer to detect the planet-fixed direction of the magnetic field by compensating for the sensor's tilt. For general weather measurements, e.g. on surface of Titan, a combination of humidity, pressure, and temperature sensors can be used on the Sprites. These would also be useful from a science perspective and for monitoring spacecraft health.

Table 7: Colibrys vibration sensors

Product Name	Size [mm]	Full-scale [g]	Scale factor [mV/g]	Bandwidth [Hz @ -5%]	Bandwidth [Hz @ -3dB]	One year stability [mg]	Noise [µV/√Hz]
VS9002.D	8.9 x 8.9	± 2	1000	> 250	> 800	1.5	25
VS9005.D	8.9 x 8.9	± 5	400	> 700	>1700	3.75	25
VS9010.D	8.9 x 8.9	± 10	200	> 1000	> 3000	7.5	25
VS9030.D	8.9 x 8.9	± 30	66.6	> 1000	> 3000	22	25
VS9050.D	8.9 x 8.9	± 50	40	> 1000	> 3000	37.5	25
VS9100.D	8.9 x 8.9	± 100	20	> 1000	> 3000	75	25
VS9200.D	8.9 x 8.9	± 200	10	> 1000	> 3000	150	25
MS9100	Ø 15.55 x 3.9	± 2	10	n/a	800	2	7
MS9200	8.9 x 8.9	± 10	50	n/a	650	10	7

Note: The VS series sensors operate from a single power supply voltage (between 2.5 V and 5.5 V) with low current consumption (< 0.5 mA at 5 V). The output is a radiometric analog voltage that varies between 0.5 V and 4.5 V for the full-scale acceleration range at a voltage supply of 5 V. They operate over temperature range of -55 °C to 125 °C and can withstand shocks up to 6000 g. The MS series sensors operate from a single power supply voltage (between 2.5 V and 5.5 V) with low current consumption (< 0.2 mA at 3 V). The output is a radiometric analog voltage that varies between 0.5 V and 2.5 V for the full-scale acceleration range at a voltage supply of 3 V. They operate over temperature range of -40 °C to 125 °C and can withstand shocks up to 6000 g.

After impacting the surface, the detection of organic compounds and gases is one of the principal goals. MEMS sensor technology in this field has not progressed as rapidly as others, but there are a few technologies that fit the Sprite design requirements and the dual-mission concept. For a Solar System body that has even a thin atmosphere, a gas chemical sensor can be used to measure the composition. Electrochemical sensors can only detect and measure a specific gas, so the type of sensor would have to be determined before the ChipSats are built and launched. The target gasses include nitrogen dioxide, ammonia, hydrogen, and volatile organic compounds, among others. Water quality (e.g. on Europa) can even be monitored by measuring the pH, or the concentration of hydrogen ions in solution. Conversely, non-dispersive infrared (NDIR) sensors are not confined to a specific gas and are able to make various measurements, but they also require more hardware to operate as a complete system.

The simplest ChipSats are designed to be impactors, in that they do not have a method of slowing their descent. The size of the planetary body and the presence of an atmosphere greatly affect the landing conditions of the Sprites. The gravity on larger bodies causes the satellites to approach at very high velocities, likely incurring fatal damage upon impact. Heavy atmospheres can cause the satellites to burn up upon entry unless their mass is below 100 mg, where aerothermal heating is never sufficient to cause demise. With no active landing system, these two factors constrain the target bodies to minor planets, certain moons, and asteroids/comets. Nevertheless, this wide range of applicability enables future mission architectures based on an in-situ site survey.

Impacting a body the size of Europa or Earth's moon is only barely survivable—on the order of 1% of impacting ChipSats remain functional, as discussed below. For smaller bodies, the survival rate can be much higher, approaching 100% for impact velocities on the order of 1 m/s or lower. These speeds correspond to a large number of bodies in the solar system, as shown in Figure 6. These velocities are based on cases with no atmospheric drag, which is representative of virtually every body under consideration, and the minimum impact velocity is equal to the escape velocity. However, 20% additional velocity appears in these results, in order to account for variations in the deployment from the spacecraft and unmodeled orbital perturbations. The figure is a histogram showing the impact velocities for over 250 planetary bodies in the Solar System (note the varying scale on the x-axis). The impact velocities of Earth, Mars, the Moon, Europa, and Itokawa are 9,493, 4,266, 2,017, 1,719, and 0.10 m/s, respectively.

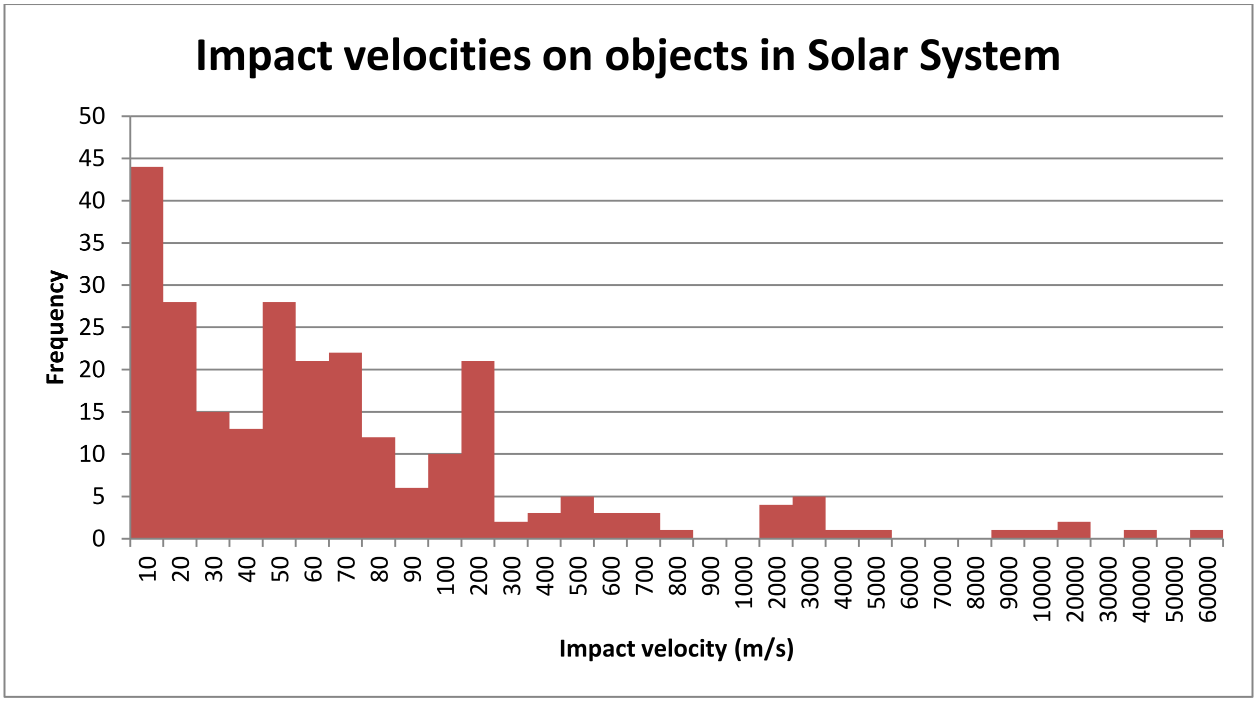

Figure 6. Impact velocities for various Solar System objects

The significant savings in technology-development effort by omitting explicit Entry, Descent, and Landing (EDL) hardware, as well as the versatility that this ChipSat concept offers, make it a valuable element of the dual-mission architecture.

3.4 Technology Example: Cold Atom Gravimeter and Gravity Gradiometer

Atom interferometry is a powerful tool for precision metrology [see, e.g., 3, 4, 5, 6, 7], and represents an example of the small, precise orbital instrument category of technology that enables dual exploration architectures. Light pulse atom interferometry (LPAI) has been successfully used to measure gravity [8] and gravity gradients [9, 10] at high precision. To realize its technological potential outside the laboratory, methods must be developed for operating atom interferometers in adversely dynamic environments and within constraints of reduced size, weight, and power (SWaP) [11, 12, 13, 14]. We have carried out a design study for a LPAI-based gravity gradiometer for space science applications, with an eye towards gravitational survey of Jovian moons. The proposed gradiometer will exploit Raman LPAI beamsplitter technology intended for use in dynamic environments and in physically compact sensors: specifically, LPAI at short interrogation times using large momentum transfer (LMT) technology [15,16].

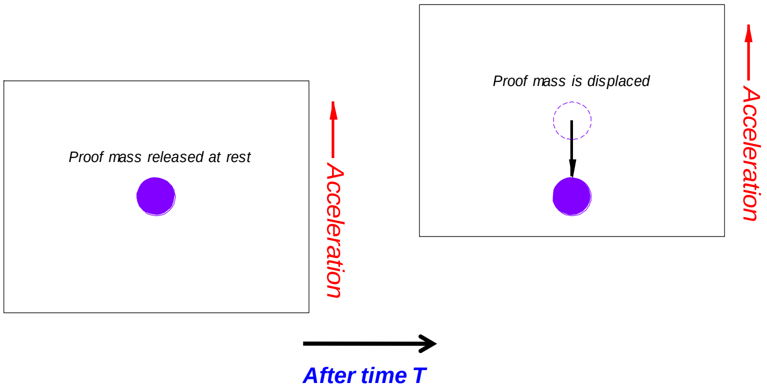

Figure 7. Acceleration sensing with free particles. A proof mass is released from rest in the reference frame of the sensor. Measurement of the particle displacement during a known time interval will enable determination of the average acceleration.

Figure 7 illustrates the method for measuring acceleration using free particles. LPAI uses this scheme, with atoms as proof masses. The use of particular atoms (in this case, alkali) allows for application of laser cooling and trapping for creation of a proof mass, and LPAI as a means for measuring proof mass displacements with very high precision. LPAI exploits laser beams as highly precise “rulers” to measure non-uniform motion of free particles in a sensor reference frame. The Gaussian mode structure of the laser beams can be thought of as a “transducer” between frequency and distance: the frequency-stabilized lasers provide

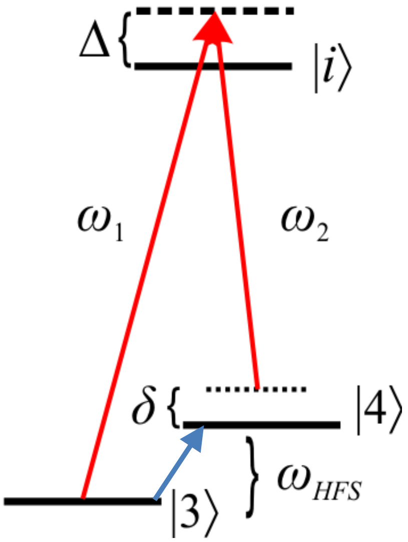

Figure 8. Two-photon transfer between ground states.

exquisitely precise and accurate position references.

An LPAI accelerometer (or gravimeter) uses a pair of oppositely directed, phase-coherent laser beams, prepared such that the difference in the laser frequencies coincides with the energy level splitting of an alkali atom [17]. The laser beam pair induces the atom to simultaneously change its internal state while absorbing a 2-photon momentum "kick" from the light (Figure 8). The result is a so-called entangled state in which the atom is a coherent superposition of conflated internal and center of mass momentum states [18,19]. The atom is thus "split" into two wavepackets that tend to separate along the laser beam direction.

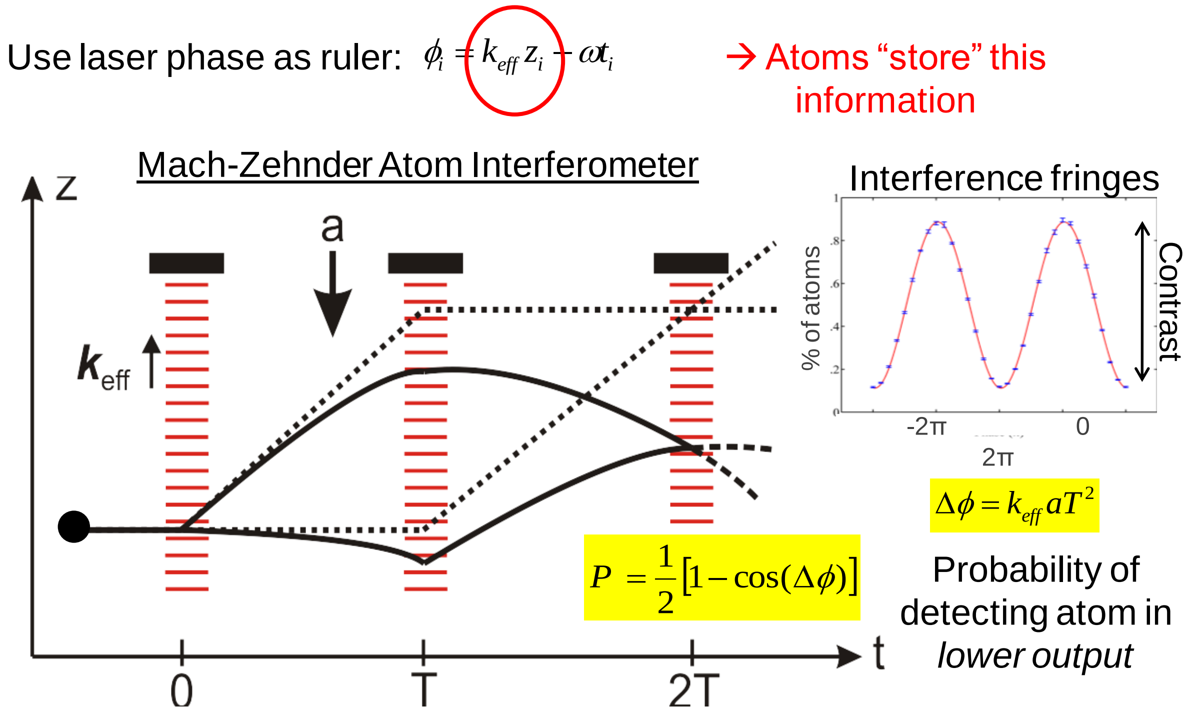

Figure 9. Acceleration measurement with atom interferometry. Three pulses are applied to an atom that is initially stationary in the sensor reference plane. Under acceleration (solid line), the fractional population of the ground states varies sinusoidally; the period of the sinusoid decreases with increasing time T between pulses, because the inertially induced deflection of the atom increases.

A series of laser pulses can be applied in order to carry out inertial sensing. A three pulse sequence from a single laser beam pair can be used to measure acceleration: Figure 9 depicts the motion of atomic wavepackets during the three pulse sequence (a so-called Mach-Zehnder interferometer). The difference of optical phases of the two lasers is imprinted on the atomic wavefunction during each pulse. The result is a sinusoidal variation in the probability of occupation of the two ground states at the end of the measurement sequence (interferogram), which depends on the applied acceleration. The interferometer phase is defined as the relative phase of the interferogram with the interferogram measured with zero inertial input.

It is possible to carry out a measurement of gravity gradient by applying a single pair of laser beams to two atom clouds prepared at a known separation, as depicted in Figure 10. A difference in the phase registered by the two interferometers then is a measure of the difference in acceleration at the sites of the two atom clouds. This method has the advantage that many sources of noise are common to the two measurements; thus, when the difference is taken, there is a significant reduction in the net noise signal, as compared to the individual acceleration measurements.

Table 8. Gravity gradiometer design parameters and performance goals

Quantity	Value	Description/Discussion
b	1 meter	Baseline separation between accelerometers
Δb	70 μm	Maximum variation in gradiometer baseline
T	50 msec	Measurement time
N	3	LMT index (12 “augmentation” pulses: [16])
$(2N+1)k_{eff}T^2$	2.58e5 sec^2/m	Individual interferometer scale factor (factor to convert acceleration to phase shift)
C	0.10	Individual accelerometer contrast
T_a	1.2 μK	Atom cloud temperature
$SNR_{1\text{ shot}}$	600	Per shot SNR
f_{rep}	8 Hz	Rate of accelerometer measurements
$\frac{C^{-1}\cdot SNR_{1\text{ shot}}^{-1}}{(2N+1)k_{eff}T^2\sqrt{f_{rep}}}$	2.3 nano-g /sqrt(Hz)	Individual accelerometer noise density
ε_{com}	0.1	Common mode noise rejection factor
$\frac{\varepsilon_{com}\delta a_{1\text{ sec}}}{b}$	2.3 E /sqrt(Hz)	Gradiometer noise density

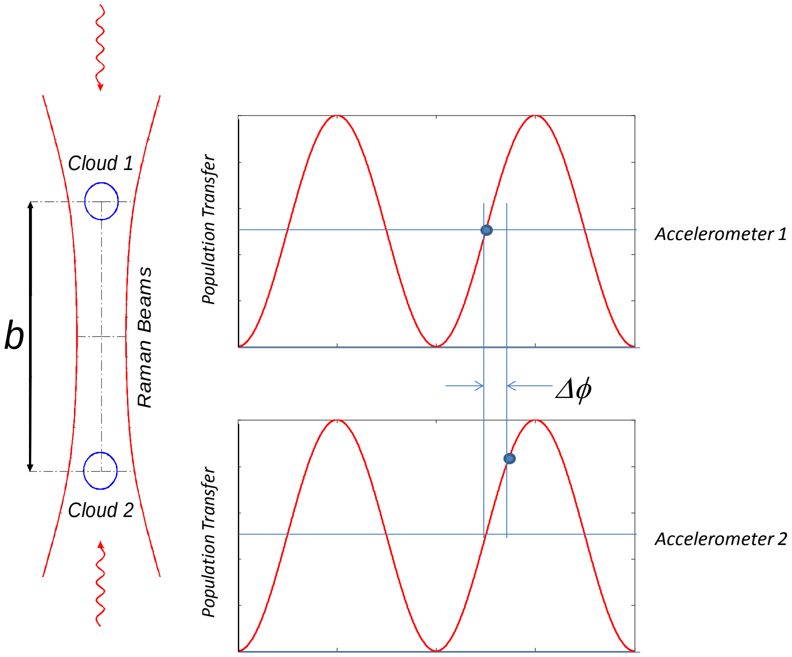

Figure 10. Gravity gradiometry. A difference in the gravitational acceleration (along the beam axis) at sites separated by baseline *b* induces an interferometer phase difference *Δϕ*. Common mode noise processes cause simultaneous phase variations in the two interferograms, leaving *Δϕ* unaffected.

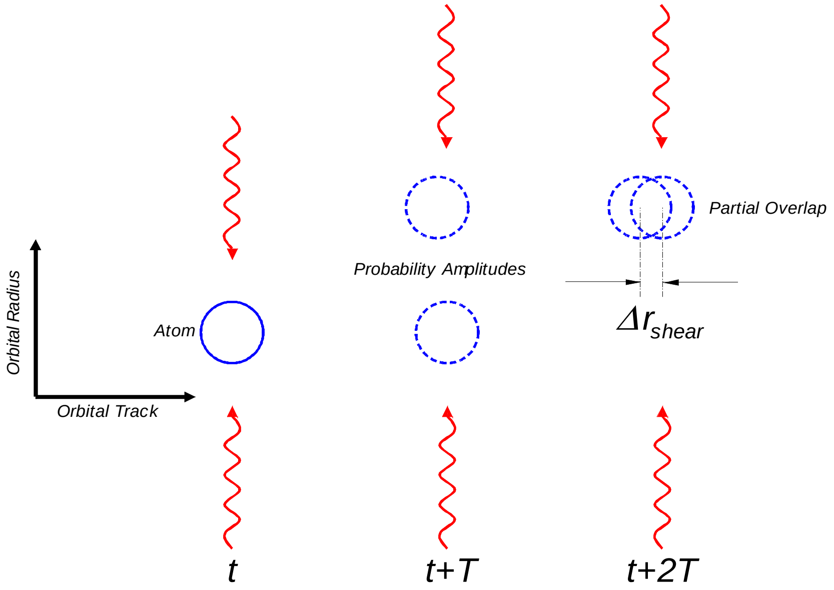

Figure 11. Raman interferometry in orbit. Raman pulse interferometry operates by splitting individual atoms into spatially separated wavepackets. If the wavepackets are separated along the radial direction, they orbit at slightly different altitudes during the measurement and thus slightly different speeds. When the wavepackets are recombined, they no longer overlap perfectly and the atomic interference is reduced. Spatial coherence length for atoms at 10 micro-K are of order 50 nm. The wavepacket separation increases with T as $\Delta r_{shear} \propto T^2$.

We propose to apply our dynamic environment sensing modality (high repetition rate with LMT interferometry) to achieve a highly robust, noise-immune gradiometer with sensitivity adequate to perform important science goals.

A serious challenge to high precision atom interferometry in an orbital environment is “orbital shear” (Figure 11), wherein atomic wavepackets separated in a radial direction (with respect to the body being orbited) will effectively orbit at different speeds in the sensor reference frame, when the sensor is rotating to maintain a fixed orientation to the orbital radius. Maintaining a fixed orientation with respect to the radial direction would be important in a gradient survey campaign; the “shear” is a pseudo-force arising from operation in the rotating frame. Table 8 summarizes the design goals of a cold atom gravity gradiometer designed for gradient surveys of Jovian moons.

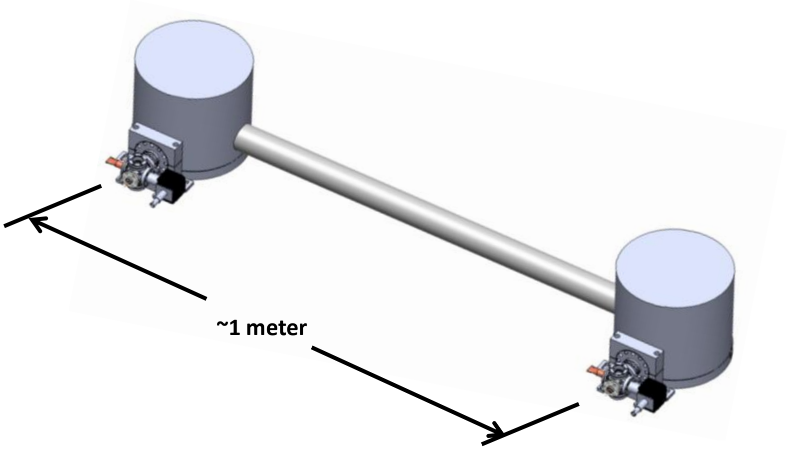

Figure 12. Design concept for flight capable interferometer. Each accelerometer unit is magnetically shielded, as is the vacuum drift tube connecting them.

Figure 12 depicts a possible physics package for a Jovian moon gradiometer system. The gradiometer comprises a pair of LPAI accelerometers connected by a magnetically shielded, evacuated drift tube that would provide optical access for a single Raman laser beam pair to excite both atom clouds (Figure 10). We note that a layer of magnetic shielding surrounding the gradiometer will likely be necessary. Of particular importance for a Jovian moon orbital operation is the fact that Raman LPAI sensors are intrinsically radiation hard: the proof masses (clouds of atoms) are totally impervious to ionizing radiation. The bulk of the apparatus would require little or no additional radiation shielding beyond that provided by magnetic shields. Only sensitive electronics and lasers would need to be shielded. These components would occupy but a small volume, reducing the mass needed for radiation shielding. Draper has carried out radiation effects testing on typical LPAI-capable DFB lasers, and shown that with suitable shielding, they would be capable of sustained operation in Europa’s orbit for weeks or months with little performance degradation [20].

Table 9. Gravity gradiometer phase shifts in a Europa orbital environment

Phase Shift	Value (mrad: N = 3)	Fractional Size	Description
$k_{eff}\Delta r_{shear,mean}$	380	-6.01	"Gravity shear" mean phase for the two accelerometers (strongly common mode—see entry below)
$(2N+1)k_{eff}b\frac{dg_z}{dz}T^2$	-63.2	1	Mean gradiometer phase difference
$(2N+1)k_{eff}b\Omega_y{}^2T^2$	31.6	-0.5	Gradiometer phase due to "centrifugal force" induced by rotation
$2(2N+1)k_{eff}\Delta v_x\Omega_yT^2$	0.723	-0.011	Error arising from rotation-induced displacement from discrepant initial cloud velocities in x-direction
$k_{eff}\left(\underset{50\text{ km}+1\text{ meter}}{\Delta r_{shear}} - \underset{50\text{ km}}{\Delta r_{shear}}\right)$	2.37e-4	-3.75e-6	"Gravity shear" (rotation-induced) phase difference between the two radially separated accelerometers: gravity shear errors are common mode to 1e-6 fractional level
$-3(2N+1)k_{eff}\Delta v_z\Omega_y{}^2T^3$	-1.90e-5	3.00e-7	"Centrifugal force" error arising from discrepant initial cloud velocities in z-direction
$-(2N+1)k_{eff}\frac{dg_z}{dz}\Delta v_zT^3$	1.26e-5	-2.00e-7	Phase difference between two accelerometers induced by discrepant initial cloud velocities in z-direction coupling to the z-comp. of the gravity gradient
$\frac{7}{6}(2N+1)k_{eff}b\frac{dg_z}{dz}\Omega_y{}^2T^4$	-2.26e-8	3.57e-10	"Centrifugal force" error arising from difference in gravitational acceleration of the two clouds in z-direction
$\frac{7}{12}(2N+1)k_{eff}b\left(\frac{dg_z}{dz}\right)^2T^4$	1.13e-8	-1.79e-10	Phase difference between two accelerometers induced by discrepant velocities in z-direction induced by gravity gradient, coupling to the z-comp. of the gravity gradient
Notes: • Phase shift values are computed assuming an orbit 50 km above the Europa surface. Orbital frequency is approximately $\Omega_y = 2\pi\left(7.18\times10^3\text{ sec}\right)^{-1}$, and the gradiometer is rotated synchronously to maintain radial orientation. Note that when radial orientation is maintained, $\Omega_y{}^2 = \frac{1}{2}\left\|\frac{dg_z}{dz}\right\|$. If the gradiometer is oriented normal to the orbital track and the orbital radius, $\Omega_y \cong 0$. • The accelerometers are separated by $b =$ 1 meter. The mean gravity gradient			

$\frac{dg_z}{dz} = -1532\ \text{E}$ is the value at the mean orbital altitude.

- Velocity differences $\Delta v_z, \Delta v_x$ are estimated differences in release velocities from the atom traps of the two accelerometers, i.e., mean velocities of the respective atom clouds.
- “Orbital shear” displacement phase and phase difference are estimated assuming the formula below for the final cloud separation Δr_{slip}
- $\Delta r_{slip} = 3\Omega_y \frac{\hbar k_{eff}}{2m_{Cs}}(2N+1)T^2$
- Parameter values: $T = 20$ msec; $\Omega_y = \frac{2\pi}{7.18\times10^3\ \text{sec}}$; $N = 3$; $\Delta v_z = \Delta v_x = 0.001$ cm/sec
- Adapted from D.M.S. Johnson, “Long Baseline Atom Interferometry”, p. 31, Ph.D. thesis, Stanford (2011)

We have made a preliminary assessment of systematic gradiometer errors that would be realized in a Europa orbital environment; a tabular summary of those errors is displayed in Table 9. These errors serve to guide the definition of performance requirements and resultant design for a flight gradiometer. It is interesting to note that the largest phase signature (for radial gradiometer orientation) is a so-called separation phase arising from the “gravity shear” error mechanism, arising from orbital rotation, described earlier. This phase is highly common-mode and should be rejected to a few parts per million. We also note that the mean gradiometer phase difference (that would be produced by a perfectly spherical Europa) is exactly twice the magnitude and of opposite sign to a centrifugal force error arising from gradiometer rotation when radial orientation is preserved. This can be interpreted as a net reduction to this gradient background, but does require control (or at least measurement) of the gradiometer rotation rate at the 0.01°/hr level of accuracy in order to correctly account for rotation in determining the net gradient signature. The last major error mechanism arises from rotation induced displacement occurring when the atoms are inadvertently released with different initial velocities. For a velocity discrepancy of 10 mm/sec, an error of roughly 15 E occurs in a radial gradiometer orientation; the degree to which this error can be controlled will probably determine if radial gradiometer orientation will permit high accuracy operation (1 E or below). The remaining errors are all at or below the desired long term stability (0.1 E).

We can contrast the single axis gravity gradiometer of Figure 12 with the hardware suites comprising high performance systems like those used in GRACE [21] or GOCE [22]. GRACE derives gravitational information by highly precise measurement of the relative positions of a leader-follower pair of nearly identical satellites in a polar near-earth orbit, in conjunction with careful accounting for the effects of non-inertial motional effects through use of exquisitely sensitive ONERA Star accelerometers [23]. GOCE was a single spacecraft mission that exploited an array of six ONERA accelerometers in a configuration to enable measurement of all components of the gravity gradient tensor; the accelerometer signals were also used to control thrusters for achievement of drag-free operation. The ONERA electrostatically suspends a parallelepiped-shaped titanium proof mass, and the measured electrostatic restoring forces provide the inertial input signal. A single ONERA sensor measures acceleration and rotation along all three axes. GRACE and GOCE provided highly accurate, global, and homogeneous measurements of the Earth's geoid to very high precision, over a period of years and at a cost enumerated in hundreds of millions of dollars. The satellites used had mass on order of a metric ton.

Such systems possibly could, and perhaps should, ultimately be deployed for study of the Jovian moons, but cost considerations would demand a comprehensive justification—framed by compelling preliminary data that could be provided by a "first look" survey carried out by a relatively low-cost, low mass, relatively simple cold atom gradiometer operating from a ChipSat launch platform. The proposed cold atom gradiometer is a cost/performance compromise vis-à-vis an ONERA-based gradiometer system. The cold atom gradiometer has no moving parts and a minimum of critical mechanical alignments; has sensitivity roughly comparable to a pair of ONERA Star accelerometers; could reasonably be guessed to be order 10X lower cost and mass than an ONERA accelerometer pair; could have ~30X higher bandwidth; but can only sense a single component of the gravity gradient tensor at a time, whereas a pair of ONERAs could simultaneously sense three tensor components (out of five independent components). We believe that a cold atom gravity gradiometer has the simplicity, robustness, and level of performance needed to observe key phenomena that could motivate a more comprehensive subsequent exploration. Applications of the design to the study of Europa are summarized in Section 4.2.

4 Europa Case Study

4.1 Mission Goals and Science

Jupiter's icy moon Europa is an enticing target for planetary exploration, due to the potential habitability of its subsurface ocean.[24] Perhaps the greatest challenge facing a mission to determine whether any kind of life actually exists on Europa is the limited access to the ocean. The ice shell, which completely covers the moon, has an unknown thickness. Some researchers estimate that the ice may be on the order of a few kilometers thick[25] while other groups suggest that the crust could have a thickness of tens of kilometers.[26] The ice thickness has implications not only for habitability but also for what engineering solutions might be necessary to penetrate through to liquid water. Without new data since the Galileo mission, the ice crust thickness is an open question in the scientific community. Fortunately, Europa has surface features that planetary scientists interpret as marking thin ice or even direct exposure of the ocean to space.[27] These locations might even be habitable.[24]

Clearly, the greatest scientific return in terms of detecting extraterrestrial life is in those regions where Europa's ice crust is thin. The identification of regions with thin ice should therefore precede the selection of surface targets and dispatch of probes to those targets. This two-step process, if accomplished by separate flagship-scale missions, might take decades. As a result, a combined mission to both identify thin areas of Europa's ice and follow up with surface observations at those regions is a good candidate for our dual-phase exploration architecture.

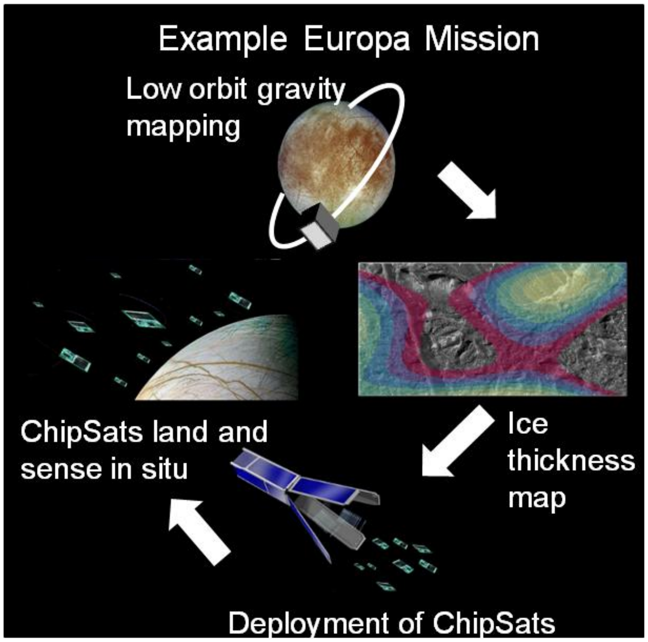

Figure 13. Basic steps for Europa example mission

Such a mission would consist of an orbiter spacecraft carrying instruments capable of sensing or inferring the ice thickness on regional to local scales, along with a number of probes capable of landing on the moon. A sensitive gravimeter is a potential instrument for determining the ice thickness; cold-atom interferometers provide the required sensitivity with a relatively small baseline suitable for packaging as a spacecraft instrument. For the surface probes, we suggest taking advantage of the enabling technology of ChipSats to send a very large number – perhaps thousands – of small vehicles with our notional mission. A particular advantage of sending such a large number of surface probes is that they can be deployed to many locations on Europa, allowing the mission to repeat landing events rather than banking on the success (in terms of both the probe itself and the target selection) of a single vehicle. Each ChipSat is a centimeter-scale, self-contained spacecraft including power, computation, communication, and science subsystems. The science instruments on a ChipSat may be only a lab-on-chip device designed to detect a single chemical biomarker, and the communication need only be one way from the ChipSat back to the orbiter.

The concept of operations of this mission to detect life on Europa, after its arrival in the Jovian system, would be as follows:

1. The main spacecraft inserts into a mapping orbit around Europa.
2. The cold-atom interferometer commences gravimetry of Europa. The mission downlinks science data to Earth for analysis.
3. Based on the gravity map of the moon, correlated to image or other data, scientists identify regions of interest corresponding to locations where the ice crust may be thin or the subsurface ocean may be exposed.

4. The orbiter deploys a large number of ChipSats to a target region. The deployment time, altitude, and other parameters are selected to scatter the ChipSats across a landing zone with some known statistics.
5. ChipSats impact the surface of Europa in the landing area. Some fraction of the ChipSats will be destroyed on impact; the number of ChipSats in the initial deployment is selected to achieve a desirable survivability rate for science return.
6. The ChipSats' science instruments collect data.
7. ChipSats signal the orbiter spacecraft with the results from their science packages.
8. The orbiter collects all the science data and relays it to Earth.
9. Steps 4 through 8 may be repeated for other targets of interest.

On Earth, the collection of signals from all the ChipSats forms the basis for the scientific return of the mission. In this example, suppose the orbiter deploys a population of 2000 ChipSats, each of which signal "1" to indicate the detection of a biomarker and "0" to indicate non-detection. If the survival rate of the ChipSats after impact is 1%, and half of the survivors are positioned in an attitude to power their instrument and communicate back to the orbiter, then scientists will receive 10 data points as to whether the biomarker is at the landing site. The number of "1"s in the data set will contribute to scientists' confidence that the biomarker is present at the target site. Every additional 2000 ChipSats deployed to the same site will provide, on average, 10 more data points.

The following sections describe the enabling technologies for this mission with greater specificity.

4.2 Gravity Mapping Phase

The performance characteristics of the gravity gradiometer concept described in Sec. 3.4 are based on the requirements for addressing key science questions pertaining to a gravitational field survey of Europa. In this section we outline analyses of some key elements of a gravity survey.

To define the types of accelerometer accuracies a cold-atom gradiometer would need to explore some of the more compelling science questions surrounding icy moons such as Europa, a series of numerical experiments were done by researchers at Georgia Tech [28].

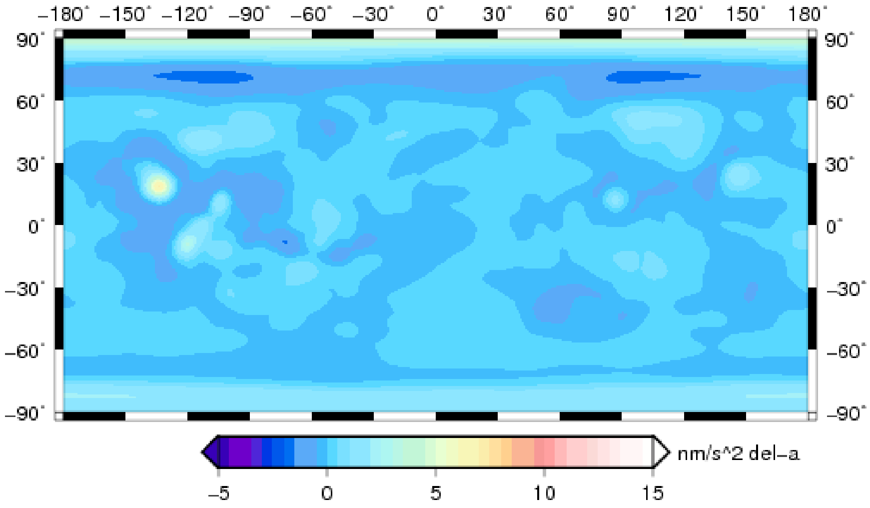

Figure 14. Simulated gravity gradients from possible sea floor topography, as observed from a 100 km orbital altitude.

For Europa, the combination of a sub-surface ocean, along with variations in the sea-floor topography and potential density variations in the external ice shell (currently estimated to be 30-100km thick), makes for a very complex and dynamic gravitational field. The largest gravitational features of interest, besides the central body terms, would be those of the ice shell and sub-surface ocean.

To explore potential sea-floor variations, Figure 14 shows the gravity gradient from the same accelerometer pair (1m radial at 100km altitude) for features that lie 100km below the ice shell. Since no information exists on Europa's sub-shell topography, a Mars gravity field was used as a proxy, scaled down to the size of Europa. As expected, the gravity variations are smaller, but still in the 1-5 E (eötvös, where 1 E = 1×10^{-9} s^{-1} = 1.02×10^{-10} g/m) range.

To address potential variations in ice shell density, specifically the existence of water pockets, a simple "slab" geometry was numerically analyzed comprising a square volume of 100 x 100 x 5 km with a density ~8% that of water (corresponding to a water pocket surrounded by ice). Figure 15 shows gravity gradients for the same 1m separated accelerometers at an altitude of 50km, flying directly over the center of the slab. Sensing the presence of such a water pocket would require sensitivity at the level of a few E in the radial direction.

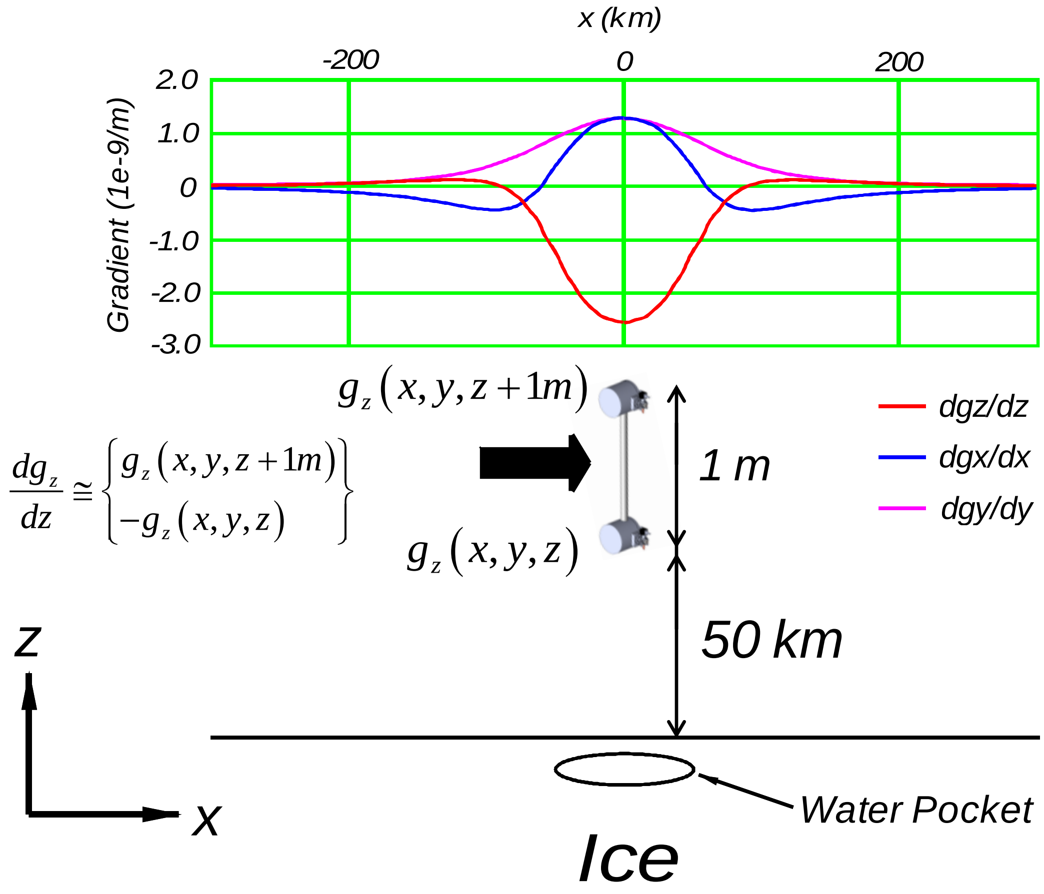

Figure 15. Gradiometer oriented along orbital radius, overflying the center of a water pocket at an altitude of 50 km. The gradient is the difference in gravitational acceleration sensed by the two component gravimeters. Three components of the gravity gradient are plotted as a function of gradiometer position relative to the water pocket.

We conclude that the proposed gravity gradiometer technology would be capable of addressing important Europa science questions and would comprise a critical component of the dual mission architecture.

4.3 In-situ Sampling Phase

ChipSats offer a unique opportunity in the context of a dual-mission architecture: they can land on the surface of a small-enough celestial object with a certain statistical guarantee of survival, despite not having an explicit entry, descent, and landing (EDL) technology on board. Deploying a sufficient number toward the surface offers confidence in this statistical survival of impact with the surface. This unusual approach is well-suited to the dual-mission concept because it enables operators to decide where and how to send ChipSats without needing to implement EDL hardware and software before launch. The result is a flexible science architecture suitable for a wide range of celestial bodies, from the smallest asteroids to moons the size of Europa.

This principle has been verified through simulations of ChipSat landings at Europa, for a ChipSat architecture that closely resembles the TRL 7 design launched on KickSat in 2014. A key difference is that the mechanical substrate is not FR-4 (the common fiberglass circuit-board material) but Kevlar, a tough material that custom board-fabrication service providers use today, although very infrequently. Also, these ChipSats are lightweighted to 3 g (a 40% reduction from the current baseline), are 2 cm square, and 1.57 mm thick. These specifications represent an adaptation of the current Sprite platform, but nothing of sufficient technology-development risk to contribute to the risk associated with the broader objectives of this NIAC study.

A key factor for ChipSat swarm mission success is how the swarm’s orbit mechanics evolve in time, after deployment from a spacecraft. This numerical simulation represents the trajectory propagation of a swarm released with some probabilistic distribution in position and velocity around a nominal initial condition. The simulation models an arbitrarily large number of ChipSats near small or irregular bodies. It uses available spherical harmonic gravity coefficients to calculate accelerations in spherical coordinates and integrates for extended trajectories. The integration stops when the trajectory has intersected the sphere circumscribing the object, or when it has exited an approximate Hill sphere. The surface contact velocity and incident angles are then analyzed for survival statistics. The regolith or ice on the surface is assumed to be half as stiff as the Kevlar. So, about 80% of the impact energy is absorbed in the planetary surface.

A mission to Europa is a stressing case, with impact velocities above 1 km/s. For this case, we simulate a direct approach at 1.2 times escape velocity, and initialize at varying altitudes with the same distribution about the nominal trajectory. The figures show varying landing zones, spread in impact velocities, and incident angles. The incident angle accounts for the fact the surface is rotating, and is banded because of numerical round-off.

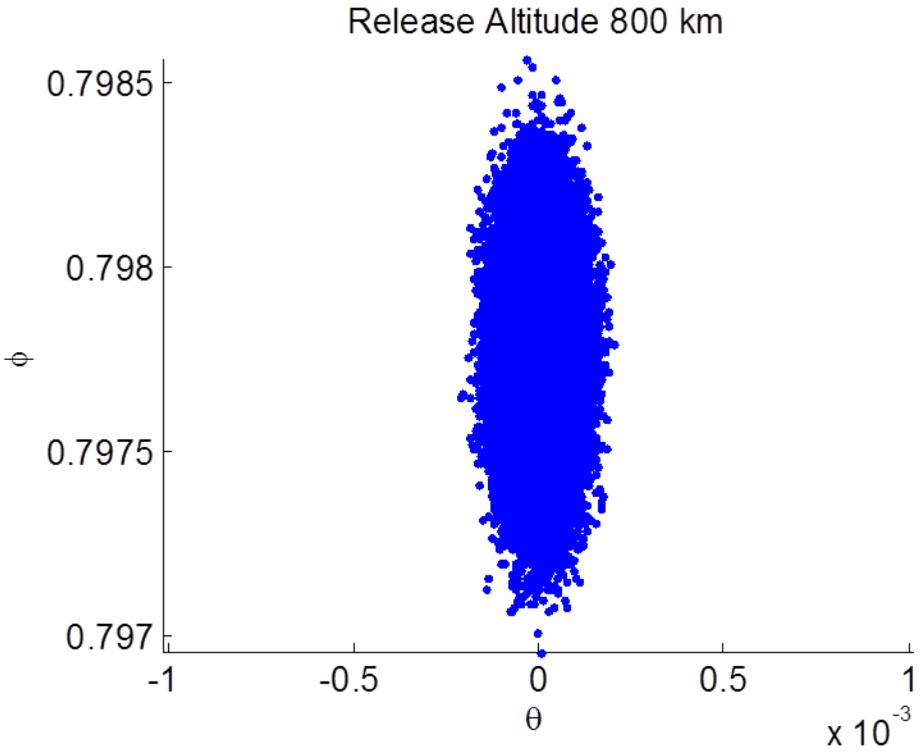

Figure 16. Impact attitude distribution

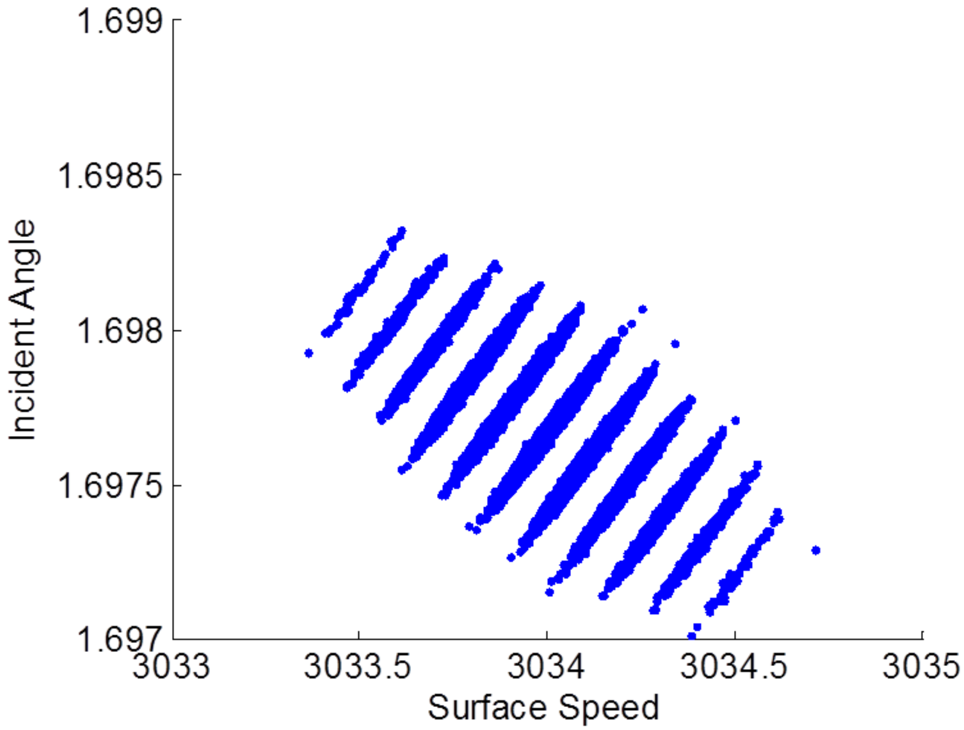

Figure 17. Total incident angle and speed relative to surface for high-speed impact

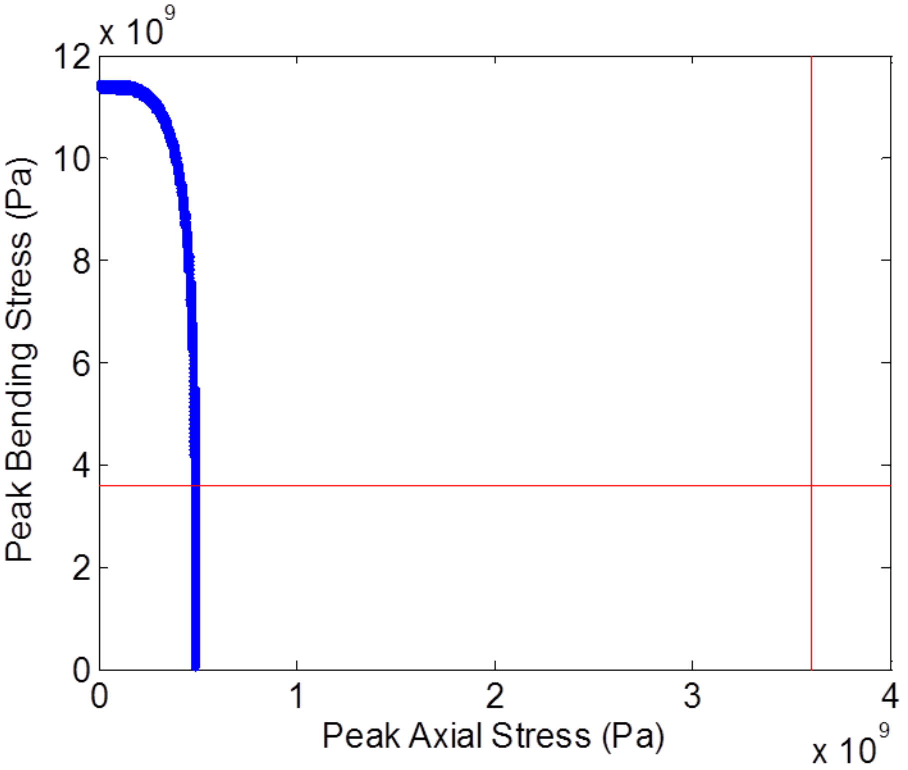

Figure 18. Statistical distribution of impact stress in Kevlar material

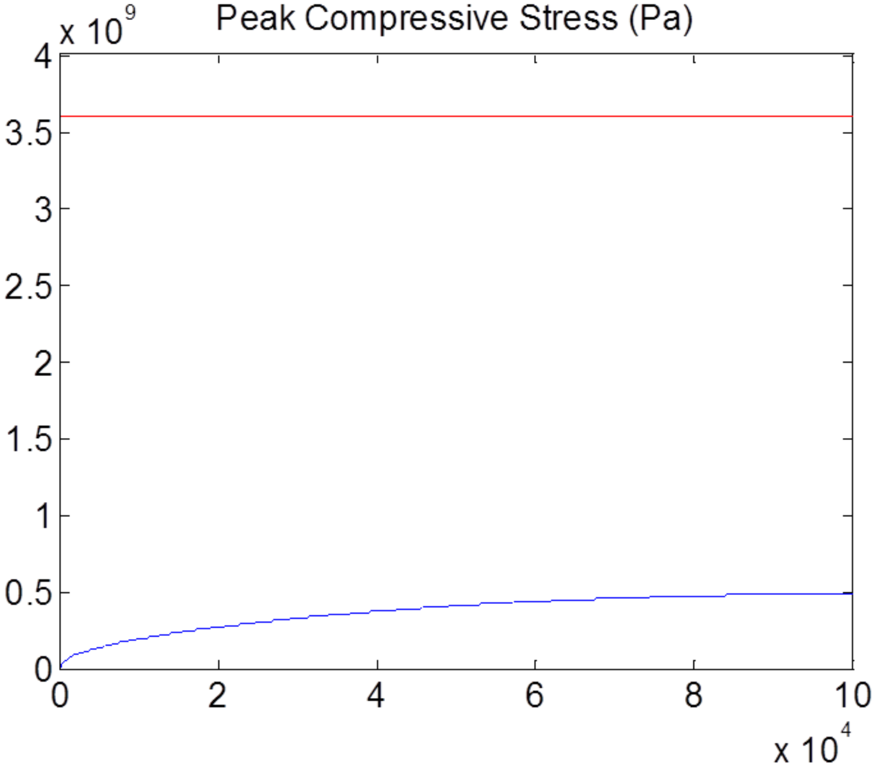

Figure 19. Statistical distribution of impact stress in Kevlar material

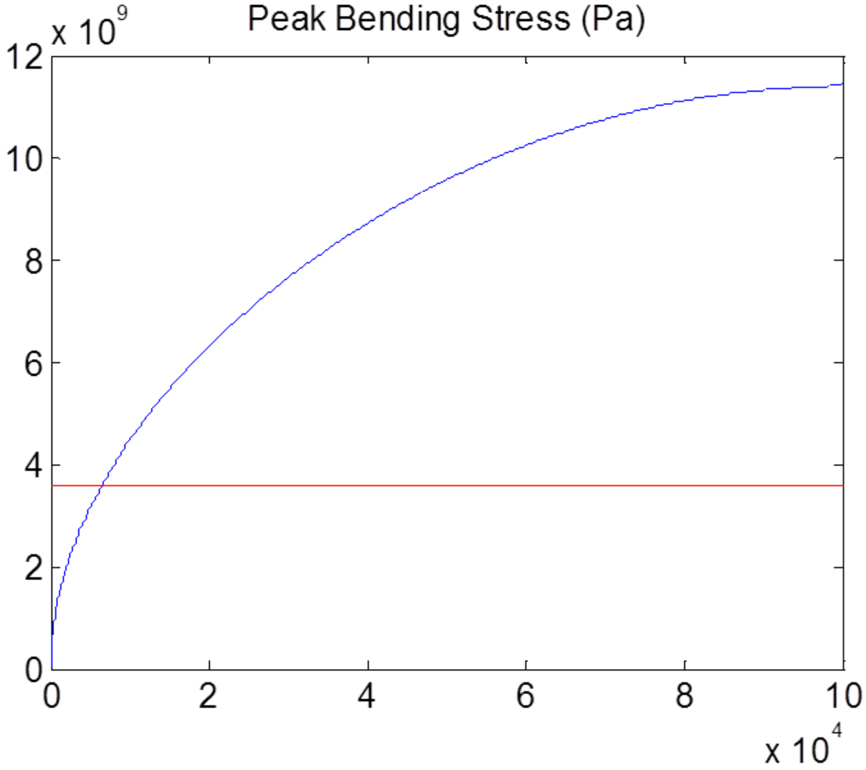

Figure 20. Statistical distribution of impact stress in Kevlar material

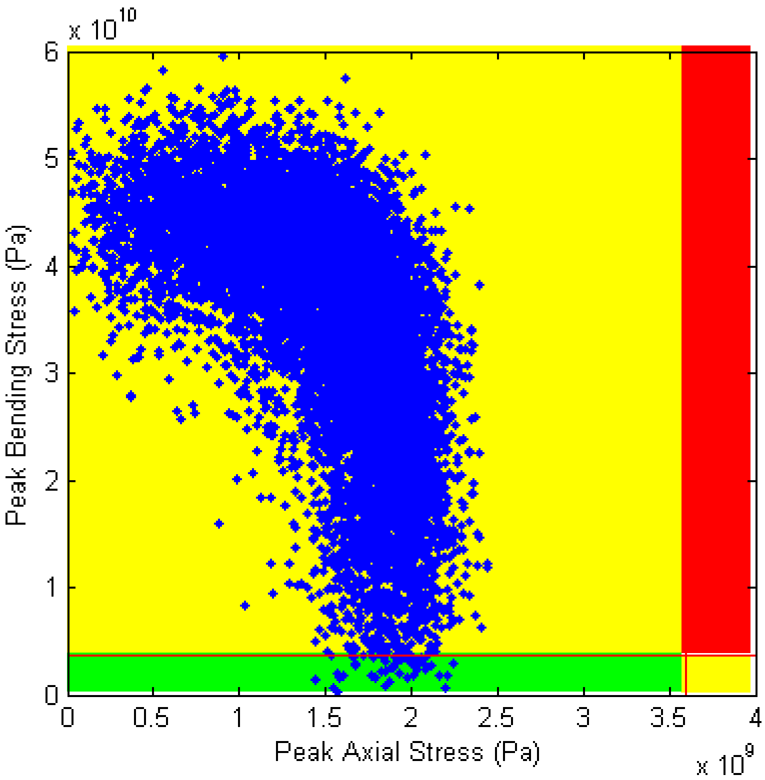

Figure 21. Summary of survivability: green region indicates survival

For the extreme case of Europa impact, approximately 1% of the incident ChipSats survive. This small fraction nevertheless may represent tens of individual sensors with various scientific and technological uses.

A compelling example of an in-situ sensor is a microfluidic lab-on-chip system that determines the chirality of amino acids. Virtually all life that we understand forms chiral compounds as one or another enantiomer. Enantiomers are isomers for which the left- and right-handed forms are mechanically identical but react differently with other chiral molecules. In contrast, for most chemical processes that do not take place within an organism, left- and right-handed molecules form in equal amounts because chirality is random. Odds are that unless some special chiral reagent is present, this randomness produces just as many right- as left-handed compounds. On Earth, all amino acids in biologically produced proteins are of the same chirality, so-called "L." All of the sugars in nucleic acids happen to have the opposite spatial relationship and are designated "D". Assuming that this principal extends to all life, a survey of the chirality of organic compounds can point to the presence of life as the source of a chirality bias in these and other compounds.

In 2011, Nagl, Schulze, and others [29] reported the development of a microfluidic sensor for determining chirality. Figure 22 shows the results from a technology demonstration,

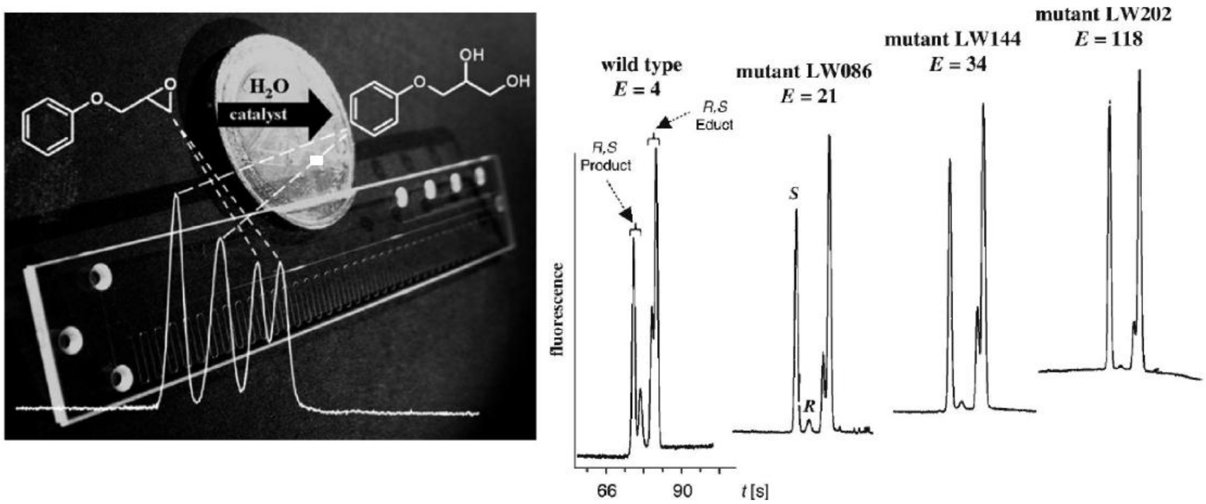

Figure 22. Left: synthesis and analysis chip for enzyme screening and chiral separation. Right: Electropherograms after on-chip separation for determination of mutant biocatalyst enantioselectivity. Enantioselectivity is expressed vie the E value. Adapted from [30]

This technology, implemented on board a ChipSat, may represent a means to perform an in-situ detection of biomarkers on a surface with organic matter. In Europa’s case, the ChipSat would need sufficient power to melt a very small (micrograms) sample, ingest it into the microfluidic chirality sensor by wicking the liquid water along thin-polymer fibers extending from the Sprite, and transmit the binary result. This prospect in an exciting example of what can be done at the small scale, leveraging a dual mission architecture to answer a high-priority planetary-science decadal question.

Overall, the Europa mission shows the power of using next generation technologies and a dual exploration architecture to produce amazing scientific results without the decades-long wait between visits to this exciting moon. At its heart, the dual architecture concept is designed to speed the progress of planetary science by operating in leaps and answering questions with a single mission that would require multiple missions under traditional architectures.

5 Appendices

5.1 Historical Mission Data

5.1.1 Missions launched to the Moon

Name	Launch date
Pioneer 0	17 August 1958
Pioneer 1	11 October 1958
Pioneer 2	8 November 1958
Pioneer 3	6 December 1958
Pioneer 4	3 March 1959
Pioneer P-3	26 November 1959
Pioneer P-30	25 September 1960
Pioneer P-31	15 December 1960
Ranger 3	26 January 1962
Ranger 4	23 April 1962
Ranger 5	18 October 1962
Ranger 6	30 January 1964
Ranger 7	28 July 1964
Ranger 8	17 February 1965
Ranger 9	21 March 1965
Surveyor 1	30 May 1966
Explorer 33	1 July 1966
Lunar Orbiter 1	10 August 1966
Surveyor 2	20 September 1966
Lunar Orbiter 2	6 November 1966
Lunar Orbiter 3	5 February 1967
Surveyor 3	17 April 1967
Lunar Orbiter 4	4 May 1967
Surveyor 4	14 July 1967
Explorer 35	19 July 1967
Lunar Orbiter 5	1 August 1967
Surveyor 5	8 September 1967
Surveyor 6	7 November 1967
Surveyor 7	7 January 1968
Apollo 8	21 December 1968
Apollo 10	18 May 1969
Apollo 11	16 July 1969
Apollo 12	14 November 1969
Apollo 13	11 April 1970
Apollo 14	31 January 1971
Apollo 15	26 July 1971
PFS-1	26 July 1971

Apollo 16	16 April 1972
PFS-2	16 April 1972
Apollo 17	December 1972
Explorer 49	10 June 1973
ISEE-3	12 August 1978
Clementine	25 January 1994
PAS-22	24 December 1997
Lunar Prospector	7 January 1998
SMART-1	27 September 2003
ARTEMIS	17 February 2007
SELENE	14 September 2007
Lunar Reconnaissance Orbiter	18 June 2009
LCROSS	18 June 2009
GRAIL	10 September 2011
LADEE	7 September 2013

5.1.2 Missions launched to Mars

Name	**Launch date**
Mariner 3	5 November 1964
Mariner 4	28 November 1964
Mariner 6	25 February 1969
Mariner 7	27 March 1969
Mariner 8	9 May 1971
Mariner 9	30 May 1971
Viking 1	20 August 1975
Viking 2	9 September 1975
Mars Observer	25 September 1992
Mars Global Surveyor	7 November 1996
Mars Pathfinder	4 December 1996
Mars Climate Orbiter	11 December 1998
Mars Polar Lander	3 January 1999
Deep Space 2	3 January 1999
Mars Odyssey	7 April 2001
Spirit rover	10 June 2003
Opportunity rover	8 July 2003
Mars Reconnaissance Orbiter	12 August 2005
Phoenix	4 August 2007
Dawn	27 September 2007
Curiosity rover	26 November 2011
MAVEN	18 November 2013

5.1.3 Missions launched to Jupiter

Name	Launch date
Pioneer 10	March 72
Pioneer 11	April 73
Voyager 1	September 77
Voyager 2	August 77
Ulysses	October 89
Galileo	October 90
Cassini	October 97
New Horizons	January 06
Juno	August 11

5.1.4 Missions launched to Saturn

Name	Launch date
Pioneer 11	April 73
Voyager 1	September 77
Voyager 2	August77
Cassini	October 97

5.1.5 Missions launched to asteroids

Name	Launch date
Galileo	October 89
Clementine	January 94
NEAR Shoemaker	February 96
Cassini	October 97
Deep Space 1	October 98
Stardust	February 99
Dawn	September 07

5.1.6 Missions launched to comets

Name	Launch date
ICE	August 78
Deep Space 1	October 98
Stardust	February 99
CONTOUR	July 02
Deep Impact	January 05

5.2 Decadal Survey Question Classifications

All question copied from Visions and Voyages[1]

5.2.1 Chapter 4 –Primitive Bodies

Important Questions:	Remote Component	In-situ Component	Both	Theory
Chapter 4 - Proto bodies				
How do the presolar solids found in chondrites relate to astronomical observations of solids disposed around young stars?	0	0	1	0
How abundant are presolar silicates and oxides? Most of the presolar grains recognized so far are carbon (diamond, graphite) phases or carbides.	0	1	0	0
How do the compositions of presolar grains and organic molecules vary among different comets?	0	1	0	0
How much time elapsed between the formation of the various chondrite components, and what do those differences mean?	0	1	0	0
Did evaporation and condensation of solids from hot gas occur only in localized areas of the nebula, or was that widespread?	0	0	0	1
What are the isotopic compositions of the important elements in the Sun?	0	0	1	0
Which classes of meteorites come from which classes of asteroids, and how diverse were the components from which asteroids were assembled?	0	0	0	1
How variable are comet compositions, and how heterogeneous are individual comets?	0	0	1	0
What are the abundances and distributions of different classes of asteroids, comets, and KBO?	1	0	0	0
How do the compositions of Oort cloud comets differ from those derived from the Kuiper belt?	1	0	0	0
To what degree have comets been affected by thermal and aqueous alteration processes?	0	0	1	0
How well can we read the nebular record in extraterrestrial samples through the haze of secondary processes?	0	0	0	1
What is the relationship between large and small KBOs? Is the small population derived by impact disruption of the large one?	1	0	0	0
How do the impact histories of asteroids compare to those of comets and KBOs?	1	0	0	0
How do physical secondary processes such as spin-up result from non-gravitational forces, the creation and destruction of binary objects, and space weathering?	0	0	0	1
Did asteroid differentiation involve near-complete melting to form magma oceans, or modest partial melting?	0	1	0	0
How did differentiation vary on bodies with large proportions of metal or ices?	1	0	0	0
Were there radial or planetesimal-size limits on differentiation, and were KBOs and comets formed too late to have included significant amounts of live 26Al as a heat source?	1	0	0	0

What are the internal structures of Trojans and KBOs?	0	0	1	0
What are the chemical routes leading to organic molecule complexity in regions of star and planet formation?	0	0	0	1
What was the proportion of surviving presolar organic matter in the solar nebula, relative to the organic compounds produced locally?	0	0	0	1
What roles did secondary processes and mineral interactions play in the formation of organic molecules?	0	0	0	1
How stable are organic molecules in different space environments?	0	0	1	0
What caused the depletions in volatile elements, relative to chondrites, observed in differentiated asteroids and planets?	0	0	0	1
What kinds of surface evolution, radiation chemistry, and surface-atmosphere interactions occur on distant icy primitive bodies?	0	0	1	0
How is the surface composition of comets modified by thermal radiation and impact processes?	1	0	0	0
Are there systematic chemical or isotopic gradients in the solar system, and if so, what do they reveal about accretion?	0	0	0	1
Do we have meteoritic samples of the objects that formed the dominant feeding zones for the innermost planets?	0	0	0	1
How did Earth get its water and other volatiles? What role did icy objects play in the accretion of various planets?	0	0	0	1
What is the mechanical process of accretion up to and through the formation of meter-size bodies?	0	0	1	0
Which classes of asteroids participated in the late heavy bombardment of the inner planets and the Moon, and how did the current population of asteroids evolve in time and space?	0	0	0	1
What are the sources of asteroid groups (Trojans and Centaurs) that remain to be explored by spacecraft?	0	0	0	1
How are objects delivered from the Kuiper belt to the inner solar system? Specifically, by what mechanisms are Jupiter family comets resupplied to the inner solar system?	0	0	0	1

5.2.2 Chapter 5 – Inner Solar System

Important Questions:	Remote Component	In-situ Component	Both	Theory
Chapter 5 -Inner Solar System				
What are the proportions and compositions of the major components (e.g., crust, mantle, core, atmosphere/exosphere) of the inner planets?	1	0	0	0

What are the volatile budgets in the interiors, surfaces and atmospheres of the inner planets?	1	0	0	0
How did nebular and accretionary processes affect the bulk compositions of the inner planets?	0	0	0	1
How do the structure and composition of each planetary body vary with respect to location, depth, and time?	0	0	1	0
What are the major heat-loss mechanisms and associated dynamics of their cores and mantles?	1	0	0	0
How does differentiation occur (initiation and mechanisms) and over what timescales?	0	0	0	1
What are the major surface features and modification processes on each of the inner planets?	0	0	1	0
What were the sources and timing of the early and recent impact flux of the inner solar system?	1	0	0	0
What are the distribution and timescale of volcanism on the inner planets?	1	0	0	0
What are the compositions, distributions, and sources of planetary polar deposits?	0	0	1	0
How are volatile elements and compounds distributed, transported, and sequestered in nearsurface environments on the surfaces of the Moon and Mercury? What fractions of volatiles were outgassed from those planets' interiors, and what fractions represent late meteoritic and cometary infall?	0	0	1	0
What are the chemical and isotopic compositions of hydrogen-rich (possibly water ice) near the Moon's surface?	0	1	0	0
What are the inventories and distributions of volatile elements and compounds (species abundances and isotopic compositions) in the mantles and crusts of the inner planets?	0	0	1	0
What are the elemental and isotopic compositions of species in Venus's atmosphere, especially the noble gases and nitrogen-, hydrogen-, carbon- and sulfur-bearing species? What was Venus's original volatile inventory and how has this inventory been modified during Venus's evolution? How and to what degree are volatiles exchanged between Venus's atmosphere and its solid surface?	0	0	1	0
Are Venus's highlands and tesserae made of materials suggestive of abundant magmatic water (and possibly liquid water on the surface)?	0	0	1	0
What are the timescales of volcanism and tectonism on the inner planets?	0	0	0	1
Is there evidence of environments that once were habitable on Venus?	0	1	0	0
How are planetary magnetic fields initiated and maintained?	0	0	0	1
What are the mechanisms by which volatile species are lost from terrestrial planets, with and without substantial atmospheres (i.e., Venus versus the Moon), and with and without significant magnetic fields (i.e., Mercury versus the Moon)? Do other loss mechanisms or physics become important in periods of high solar activity?	1	0	0	0

What are the proportions of impactors of different chemical compositions (including volatile contents) as functions of time and place in the solar system?	0	0	0	1
What causes changes in the flux and intensities of meteoroid impacts onto terrestrial planets, and how do these changes affect the origin and evolution of life? What are the environmental effects of large impacts onto terrestrial planets?	0	0	0	1
What are the influences of clouds on radiative balances of planetary atmospheres, including cloud properties: microphysics, morphology, dynamics and coverage?	1	0	0	0
How does the current rate of volcanic outgassing affect climate?	1	0	0	0
How do the global atmospheric circulation patterns of Venus differ from those of Earth and Mars?	1	0	0	0
What are the key processes, reactions and chemical cycles controlling the chemistry of the middle, upper and lower atmosphere of Venus?	1	0	0	0
How does the atmosphere of Venus respond to solar-cycle variations?	1	0	0	0
What is the history of the runaway greenhouse on Venus and is this a possible future for Earth’s climate?	0	0	0	1
What is the relative role of water on the terrestrial planets in determining climate, surface geology, chemistry, tectonics, interior dynamics, structure, and habitability?	0	0	1	0
What is the history of volcanism and its relationship to interior composition, structure and evolution (e.g., outgassing history and composition, volcanic aerosols and climate forcing)?	0	0	0	1
How has the impact history of the inner solar system influenced the climates of the terrestrial planets?	0	0	0	1
What are the critical processes involved in atmospheric escape of volatiles from the inner planets?	0	0	0	1
Do volatiles on Mercury and the Moon constrain ancient atmospheric origins, sources and loss processes?	0	0	0	1
How similar or diverse were the original states of the atmospheres and the coupled evolution of interiors and atmospheres on Venus, Earth, and Mars?	0	0	0	1
How did early extreme ultraviolet flux and solar wind influence atmospheric escape in the early solar system?	0	0	0	1

5.2.3 Chapter 6 – Mars

Important Questions:	Remote Component	In-situ Component	Both	Theory
Chapter 6 - Mars				

Which accessible sites on Mars offer the greatest potential for having supported life in the past? How did the major factors that determine habitability—duration and activity of liquid water, energy availability, physicochemical factors (temperature, pH, Eh, fluid chemistry), and availability of biogenic elements—vary among environments, and how did they influence the habitability of different sites?	1	0	0	0
Which accessible sites favor preservation of any evidence of past habitable environments and life? How did the major factors that affect preservation of such evidence—for example aqueous sedimentation and mineralization, oxidation, radiation—vary among these sites?	1	0	0	0
How have the factors and processes that give rise to habitable conditions at planetary and local scales changed over the long term in concert with planetary and stellar evolution?	0	0	1	0
Can evidence of past (or present) life in the form of organic compounds, aqueous minerals, cellular morphologies, biosedimentary structures, or patterns of elemental and mineralogical abundance be found at sites that have been carefully selected for high habitability and preservation potential?	0	0	0	1
Do habitable environments exist today that may be identified by atmospheric gases, exhumed subsurface materials, or geophysical observations of the subsurface? Does life exist today, as evidenced by biosignatures, atmospheric gases, or other indicators of extant metabolism?	0	0	1	0
What are the processes controlling the variability of the present-day climate? What is the four-dimensional wind structure of the martian atmosphere from the surface boundary layer to the upper atmosphere? What are the primary causes behind the occurrence of global dust events? What are the processes coupling the CO2, dust and water cycles?	0	0	1	0
What is the distribution of chemical species in the atmosphere and what are their sources and sinks? Do unexpected short-lived trace gases indicate a subsurface activity or even the presence of life, currently or in the past? What was the role of volcanic gases and aerosols in controlling the atmospheric composition? What is the role of photochemical reactions? Are we missing key chemical or physical processes in our models?	1	0	0	0
Is there an observable change in martian climate on the 10- to 1,000- years timescale? If so what causes it? Which processes control the evolution and stability of the residual carbon dioxide ice cap?	1	0	0	0
How do the climate and especially the water cycle vary with orbital and obliquity variations? What is the global history of ice on Mars? How and when did the polar layered deposits form? What is the origin of the latitude-dependant ice mantle?	1	0	0	0

What was the nature of the early martian climate? Were the conditions suitable for liquid water episodic or stable on longer time scales? What processes enabled such conditions?	0	0	0	1
How and why did the atmosphere evolve? Which process did and still do control the escape and the outgassing of the atmosphere?	0	0	0	1
How, when, and why did environments vary through Mars's history and were these environments habitable? What was the origin and nature of the diverse sedimentary units and inferred aqueous environments, what are their ages, and how did significant accumulations of layered sediments form? What is the mineralogy of the regolith and how did it form?	0	0	1	0
Are reduced carbon compounds preserved and, if so, in what geologic environments? What is the origin of the reported methane? What is is the martian carbon cycle?	0	0	0	1
What is the petrogenesis and character of the igneous rocks, how old are they, and what does this tell us about martian crustal and mantle processes and formation of the core? How do martian meteorites relate to the martian surface?	0	0	0	1
What is the geologic record of climate change? How do the polar layered deposits and layered sedimentary rocks record the present-day and past climate and the volcanic and orbital history of Mars?	0	1	0	0
What is the interior structure of Mars? How are core separation and differentiation processes related to the initiation and/or failure of plate tectonic processes on Mars?	0	0	1	0
When did these major interior events occur, and how did they affect the magnetic field and internal structure? What is the history of the martian dynamo? What were the major heat flow mechanisms that operated on Early Mars?	0	0	0	1
What is Mars's tectonic, seismic, and volcanic activity today? How, when, and why did the crustal dichotomy form? What is the present lithospheric structure? What are the martian bulk, mantle and core ompositions? How has Mars's internal structure affected its magmatism, atmosphere, and habitability?	1	0	0	0

5.2.4 Chapter 7 – Giant Planets

Important Questions:	Remote Component	In-situ Component	Both	Theory
Chapter 7 GIant Planets				
What is the energy budget and heat balance of the ice giants, and what role do water and moist convection play?	1	0	0	0
What fraction of incident sunlight do Uranus and Neptune absorb and how much thermal energy do they emit?	1	0	0	0
What is the source of energy for the hot coronas/upper atmospheres of all four giant planets?	1	0	0	0
What mechanism has prolonged Saturn's thermal evolution?	0	0	0	1

Does helium rain play a role in reducing the H/He in Saturn’s molecular envelope?	0	0	0	1
Why and how does the atmospheric temperature and cloud composition vary with depth and location on the planet?	1	0	0	0
Which processes influence the atmospheric thermal profile, and how do these vary with location?	0	0	1	0
How did the giant planet atmospheres form and evolve to their present state?	0	0	0	1
What are the current pressure-temperature profiles for these planets?	0	0	1	0
What is the atmospheric composition of the ice giants?	0	0	1	0
What are the pole precession rates for giant planets?	0	0	0	1
How much do they constrain models of the internal structure of the giant planets?	0	0	0	1
How do giant planets respond to extreme heat balance scenarios, both in terms of thermal structure and global dynamic state?	1	0	0	0
How is energy dissipated within giant planets?	1	0	0	0
What is the nature of the displaced and tilted magnetospheres of Uranus and Neptune, and how do conditions vary with the pronounced seasonal changes on each planet?	1	0	0	0
What is the detailed plasma composition in any of these systems, particularly for ice giants?	0	0	1	0
What causes the enormous differences in the ion to neutral ratios in these systems?	0	0	0	1
What can our understanding of the giant planet magnetospheres tell us about the conditions to be expected at extra-solar giant planets?	0	0	0	1
What can the significant differences among ring systems teach us about the differing origins, histories, or current states of these giant planet systems?	0	0	1	0
Can the highly structured forms of the Uranus and Neptune ring systems be maintained for billions of years, or are they “young”? Are their dark surfaces an extreme example of space weathering?	0	0	1	0
What drives orbital evolution of embedded moonlets; how do they interact with their disks?	0	0	1	0
What drives mass accretion in a ring system?	0	0	1	0
How and why do elemental and isotopic abundances vary as a function of distance from the Sun?	0	0	0	1
How and why do the abundances of the heavy elements and their isotopes, the D/H ratio, the H/He ratio and noble gases differ between the two classes of giant planets represented in the solar system?	1	0	0	0
What is the current impact rate on Jupiter?	1	0	0	0
To what extent can Jupiter’s current atmospheric composition be utilized as a record of the impact history?	0	0	0	1

What are the characteristics of bolides and large airbursts on Jupiter, and how do they compare with known bolides and airbursts on Earth?	1	0	0	0
What are the flux, size distribution, and chemical composition of the various populations of impactors, from late-stage planetesimals 4 billion years ago to present-day interplanetary dust?	0	0	0	1
What are the surface modification mechanisms for low-temperature smaller icy targets?	0	0	0	1
What processes drive the visible atmospheric flow and how do they couple to the interior structure and deep circulation?	0	0	1	0
What are the sources of vertically propagating waves that drive upper atmosphere oscillations and do they play a role on all planets?	0	0	0	1
Are there similar processes on Uranus and Neptune, and how do all these compare with Earth's own stratospheric wind, temperature and related abundance (ozone, water) variations?	1	0	0	0
How does moist convection shape tropospheric stratification?	0	0	0	1
What are the natures of periodic outbursts such as the global upheaval on Jupiter and the infrequent great white spots on Saturn?	0	0	1	0
How far have the various satellites evolved outwards from their sites of formation?	0	0	0	1
To what extent do the observed eccentricities and inclinations of satellites reflect this evolution?	0	0	0	1
How do magnetospheres interact with the solar wind?	0	0	0	1
How is surface material modified exogenically (e.g., processes such as magnetospheric interactions and impacts) versus being pristine or relatively unmodified?	0	0	1	0

5.2.5 Chapter 8 – Moons

Important Questions:	Remote Component	In-situ Component	Both	Theory
Chapter 8 - Moons				
Why are Titan and Callisto apparently imperfectly differentiated whereas Ganymede underwent complete differentiation?	1	0	0	0
Why did Ganymede form an iron-rich core capable of sustaining a magnetic dynamo?	1	0	0	0
What aspects of formation conditions governed the bulk composition and subsequent evolution of Io and Europa?	0	0	0	1
In what ways did the formation conditions of the saturnian satellites differ from the conditions for the jovian satellites?	0	0	0	1
Can we discern any evidence in the uranian satellites of a very different origin scenario (a giant impact on Uranus for example) or is this satellite system also the outcome of a process analogous to the other giant planet satellite origins?	1	0	0	0
What features of Triton are indicative of its origin?	1	0	0	0

In what ways do the highly volatile constituents differ between Callisto and Ganymede?	1	0	0	0
Are volatiles present at the surface or in the ice shell of Europa that are indicative of internal processing or resurfacing?	0	0	1	0
How, and to what extent, have volatiles been lost from Io?	1	0	0	0
What does the plume material from Enceladus tell us about the volatile inventory of that body?	0	0	0	0
Why does Titan uniquely have an exceptionally thick atmosphere?	0	0	0	1
What does the volatile inventory of Titan tell us about its history? In particular, how is the methane resupplied, given its rapid photochemical destruction in the upper atmosphere?	1	0	0	0
What is the history of the resonances responsible for the tidal heating and how is this heating accomplished?	0	0	0	1
How does this heat escape to the surface?	0	0	0	1
How is this heat transfer related to the internal structure (thickness of an outer solid shell, or composition of the interior) and formation?	0	0	0	1
How hydrostatic are the satellites?	0	0	0	1
Does Io have a magma ocean and what is the compositional range of its magmas?	1	0	0	0
What is the origin of the topography of Io?	1	0	0	0
What is the magnitude and spatial distribution of Io’s total heat flow?	1	0	0	0
What are the thickness of Europa’s outer ice shell and the depth of its ocean?	1	0	0	0
What is the magnitude of Europa’s tidal dissipation, and how is it partitioned between the silicate interior and the ice shell?	0	0	0	1
What is the relationship between Titan’s surface morphology and internal processes, particularly for the history of the methane budget and lakes or seas and possible replenishment of methane from the interior or subsurface?	1	0	0	0
Does Titan have an internal liquid water ocean?	1	0	0	0
What is the spatial distribution of Enceladus’s heat output, and how has it varied with time?	1	0	0	0
Does Enceladus have an ocean or some other means of providing large tidal dissipation, and to what extent is its behavior dictated by its formation conditions (e.g., presence or absence of a differentiated core?)	1	0	0	0
What does the diversity of the uranian moons tell us about the evolution of small to mediumsized icy satellites? What drove such dramatic endogenic activity on Miranda and Ariel?	0	0	0	1
What powers past or possible ongoing activity on Triton, which currently has negligible tidal heating?	0	0	0	1
One of the key missing pieces in our understanding of satellite surface geology is adequate knowledge of the cratering record in the outer solar system.21 What are the impactor populations in the outer solar system, and how have they changed over time, and what is the role of secondary cratering?	0	0	0	1

What are the origins of tectonic patterns on Europa, including the ubiquitous double ridges (Figure 8.4) and chaos regions?	1	0	0	0
How much non-synchronous rotation has Europa’s ice shell undergone, and how have the resulting stresses manifested at the surface?	1	0	0	0
How is contraction accommodated on Europa?	1	0	0	0
Has material from a subsurface Europa ocean been transported to the surface, and if so, how?	0	0	1	0
What caused Ganymede’s surface to be partially disrupted to form grooved terrain, and is the grooved terrain purely tectonic or partly cryovolcanic in origin?	1	0	0	0
Did Ganymede suffer a late heavy bombardment that affected its appearance and internal evolution?	1	0	0	0
What is the age of Titan’s surface, and have cryovolcanism and tectonism been important processes? Have there been secular changes in the surface methane inventory?	0	0	1	0
Why is Enceladus’s geology so spatially variable, and how has activity varied with time?	0	0	0	1
What geological processes have created the surfaces of the diverse uranian moons, particularly the dramatic tectonics of Miranda and Ariel?	0	0	0	1
Has viscous extrusive cryovolcanism occurred on icy satellites, as suggested by features on Ariel and Titan?	1	0	0	0
What geological processes operate on Triton’s unique surface, how old is that activity, and what do its surface features reveal about whether it is captured?	1	0	0	0
What mechanisms drive and sustain Enceladus’s plumes and active tiger stripe tectonics?	1	0	0	0
What are the magnitude, spatial distribution, temporal variability, and dissipation mechanisms of tidal heating within Io, Europa, and Enceladus?				
Is there active cryovolcanism on Titan?	1	0	0	0
What are the eruption mechanisms for Io’s lavas and plumes and their implications for volcanic processes on early and modern Earth?	1	0	0	0
What is the temporal and spatial variability of the density and composition of Io’s atmosphere, how is it controlled, and how is it affected by changes in volcanic activity?	1	0	0	0
What are the relative roles of sublimation, molecular transport, sputtering and active venting in generating tenuous satellite atmospheres?	1	0	0	0
Do the large organic molecules detected by Cassini in Titan’s haze contain amino acids, nucleotides and other pre-biotic molecules?	0	0	1	0
What processes control Titan’s weather?	1	0	0	0
What processes control the exchange of methane between Titan’s surface and the atmosphere?	1	0	0	0
Are Titan’s lakes fed primarily by rain or by underground methane-ethane “aquifers”?	0	0	1	0

How do Titan's clouds originate and evolve?	1	0	0	0
What is the temperature and opacity structure of Titan's polar atmosphere, and what is its role in Titan's general circulation?	1	0	0	0
What is Triton's surface distribution of molecular nitrogen and methane, and how does it interact with the atmospheric composition and dynamics?	1	0	0	0
Is Io's intense magnetospheric interaction responsible for its volatile depletion?	0	0	0	1
How is the strong ionosphere of Triton generated?	0	0	0	1
How do exogenic processes control the distribution of chemical species on satellite surfaces?	0	0	0	1
How are potential Europa surface biomarkers from the ocean/surface exchange degraded by the radiation environment?	0	1	0	0
What do the crater populations on the satellites reveal about the satellites' histories and subsurface structure and about the populations of projectiles in the outer solar system and the evolution thereof?	0	0	0	1
Why is Jupiter's magnetosphere dominated by charged particles whereas Saturn's magnetosphere is dominated by neutral species?	0	0	0	1
What fraction of the material in Jupiter's magnetosphere originates from Europa and other icy satellites?	1	0	0	0
Is the reconnection in Ganymede's magnetosphere steady or patchy and bursty?	1	0	0	0
How rapidly does Saturn's magnetosphere react to the temporal variability of Enceladus's plume?	1	0	0	0
Do other saturnian icy satellites such as Dione and Rhea contribute measurable amount of neutrals or plasma to Saturn's magnetosphere?	1	0	0	0
What is the nature of Triton's inferred dense neutral torus?	1	0	0	0
What are the depths below the surface, thickness and conductivities of the subsurface oceans of the Galilean satellites? The depth of the ocean beneath the surface is important because it controls the rate of heat loss from the ocean, and the probability of material exchange with the surface. The thickness indicates the likely ocean lifetime, and for Ganymede and Callisto constrains the ocean temperature.	1	0	0	0
Which satellites elsewhere in the solar system possess long-lived subsurface bodies of liquid water? Titan and Enceladus are obvious candidates, but other mid-sized icy satellites, including those of Uranus and Neptune, could in theory have retained internal oceans to the present day.43 Triton in particular, with its geologically young surface and current geysering, is another interesting candidate.	1	0	0	0
For all satellites, what is the lifetime of potential oceans? Ocean lifetime is a key to habitability. If Enceladus is only intermittently active, for instance, as suggested by several lines of evidence, and thus only intermittently supports liquid water, it is less attractive as a potential habitat.44	0	0	0	1

What is the nature of the atmospheric processes on Titan that convert the small organic gasphase molecules observed in the upper atmosphere (such as benzene) into large macromolecules and ultimately into solid haze particles?	0	0	0	1
What is the fate of organics on the surface of Titan and their interaction with the seasonally varying lakes of liquid hydrocarbons?	0	0	0	1
Are organics present on the surface of Europa, and if so, what is their provenance?	0	1	0	0
What is the source of the organic material in the plume of Enceladus?	0	0	1	0
What is the nature of any biologically relevant energy sources on Europa?	0	0	0	1
What are the energy sources that drive the plume on Enceladus? These may lead to understanding the possibilities for biologically relevant energy sources.	0	0	0	1
On Titan, how is chemical energy delivered to the surface?	0	0	0	1
Does (or did) life exist below the surface of Europa or Enceladus?	0	1	0	0
Is hydrocarbon-based life possible on Titan?	0	0	0	1

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