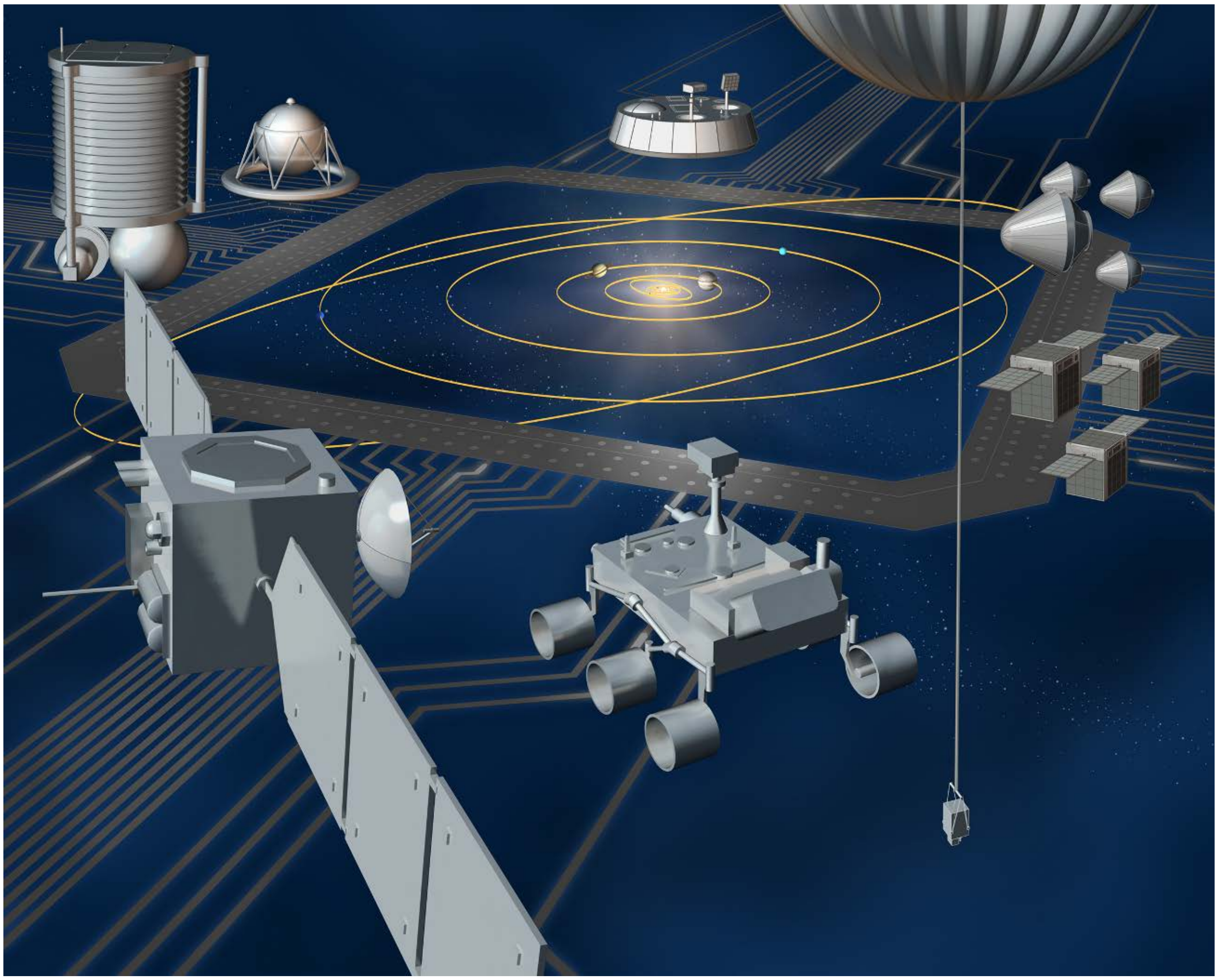
NASA Planetary Science Division

Technology Plan



December 20, 2015

Prepared under the JPL Planetary Science Program Support task, this report was developed by Pat Beauchamp and Jim Cutts with support from a JPL team and inputs from the following NASA Centers and institutions: APL, ARC, GRC, GSFC, LaRC, and MSFC. Special thanks to Young Lee for the development of the databases, website (with Tricia Talbert), and detailed editing and to Richard Barkus for the cover art. This report is for the use of the Planetary Science Division staff only, and further dissemination of elements of this report is to be determined by the PSD POC for this task.

CONTENTS

FIGURES

TABLES

1 Executive Summary

This document describes the technology planning undertaken to date by the Planetary Science Division (PSD) in the Science Mission Directorate (SMD) with assistance from the Jet Propulsion Laboratory's (JPL's) Planetary Science Program Support (PSPS) task. This document provides the background, agreed upon timeline and methodology and output of the plan. In order to make this document succinct, the details of the analyses, which are the heart of the undertaking, are provided in Appendices. Although not immediately obvious, it is important to note that the changing face of NASA PSD missions and mission planning warrants an *active* Technology Plan (TP). In turn, a dynamic process, rather than static one, for developing and maintaining the plan is required. Thus, we have updated the plan quarterly and in response to requests by the PSD management. Much of the current output has been used by SMD in their planning process with Space Technology Mission Directorate (STMD) and we are already being asked for updates. The work described in this document has been presented and discussed with PSD management and many program managers and scientists over the last 18 months. The plan is updated quarterly and aside from that the remaining tasks are to provide rough order of magnitude (ROM) costs for the technology plan elements and provide detailed assessments of the Technology Readiness Level (TRL) of each task. The former is not easily accomplished, but estimates *can* be provided to assist in making decisions and one method is described in Appendix 7. This will be provided in the next Technology Plan update.

2 Background

The PSD has been without a published Technology Plan (TP) for many years, although Gordon Johnston had compiled an excellent draft document, entitled Planetary Science Division Relevant Technologies. This draft document provided a concise but thorough description of PSD's technology needs. In addition, it contained a definition of the technologies important to achieving PSD's strategic goals in 2011, prior to the last Decadal Survey. He recognized the need for updating this draft document after the latest Decadal Survey and that a PSD TP was needed to formulate and address the technologies for the missions in the Planetary Science Decadal Survey (PSDS) document, *Visions and Voyages*. This PSDS document stated, *"The committee unequivocally recommends that a substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources. This program should be consistently funded at approximately 6 to 8 percent of the total NASA Planetary Science Division budget."* In addition, *"the committee recommends that the Planetary Science Division's technology program should accept the responsibility, and assign the required funds, to continue the development of the most important technology items through TRL 6."*

The intent of this effort is to assist PSD leadership in guiding technology efforts after *Visions and Voyages* by developing a TP that can be used to communicate PSD's technology needs to the broader scientific and technical community as well as to the STMD. Pete Panetta contacted JPL to support the preparation of a PSD TP during his tenure in PSD. JPL has carried out a Technology Planning function for the PSD for a number of years under its long-standing PSPS task. This task has included performing technology assessments, which are widely disseminated, conducting technology needs assessments in support of NASA's Assessment Groups (AGs), working closely with NASA's Office of the Chief Technologist and STMD to align their programs with PSD needs[†]. Initially, the scope of work for the TP was to culminate in a few months of effort, but after Pete Panetta left PSD, JPL was asked to continue the work. Due to the dynamic nature of PSD Technology Planning, some additional items were incorporated and the timeline extended.

JPL was asked to develop a specific investment plan for technology, initially based on the Master Plan that Pete had developed. The original scope of work, as agreed upon, was defined in a document written in January 31, 2014. Subsequently, it was updated March 11, 2014 and it is reproduced in Appendix 1.

3 PSD Technology Planning Process

Here we describe the PSD Technology Planning process in three stages: the initial planning process, the overall methodology and an evaluation of the current PSD Technology efforts with respect to the Decadal Survey recommendations.

3.1 Initial Planning Process

The original Master Plan (shown in Appendix 2) was developed with input from David Schurr and Jim Green as well as other members of the PSD staff. The goal of this Master Plan is to provide upcoming planetary science missions, as prioritized in *Visions and Voyages*, with the technologies required to successfully implement them (preferably, at lower cost and higher efficiency). It was decided to look at the technologies needed for near- and far-term missions and for competed (i.e., multimission technologies) and assigned (or core) missions. A number of other considerations also informed the initial planning process:

3.1.1 Technology Program Balance

The PSDS recommended that technology spending should amount to 6 to 8% of the PSD's overall budget[1]. The Planetary Science Technology Review (PSTR) panel recommended 8% of budget to be spent on technology (2011). Both the PSDS and the PSTR also laid down targets for the allocation of this funding between different types of technology in the case of PSDS and different maturity levels of technology in the case of PSTR. There are also other metrics that could be applied including the allocation between preparing for competitive missions and strategic missions. The plan should, therefore, contain a mechanism for determining and evaluating these metrics.

[†] The PSD is comfortable with JPL performing these tasks because as an FFRDC (from the FAR 35.017), in order to discharge its responsibilities to NASA, JPL has access, beyond that which is common to the normal contractual relationship, to Government and supplier data, including sensitive and proprietary data, and to employees and installations equipment and real property. An FFRDC is required to conduct its business in a manner befitting its special relationship with the Government, to operate in the public interest with objectivity and independence, to be free from organizational conflicts of interest, and to have full disclosure of its affairs to the sponsoring agency.

3.1.2 Portfolio Content and Analysis

One of the primary goals for the Master Plan was to diversify the technology developments and ensure PSD readied all technologies for upcoming and future missions. To that end the questions posed at the outset by the PSD were:

1. How can we improve Portfolio diversification?
   - Where we currently are making investments vs. where we want to be making them
2. What technologies are missing from the portfolio?
3. What and how much will PSD and others, e.g., STMD provide for technology development?
4. What are the longer-term (5/10 year) mission needs and the technology priorities to satisfy them?
5. How do we maintain current capabilities? We needed to determine what we exercise and at what frequency.
6. Who do we partner with to augment the funding required to develop PSD technology?
   - STMD, Human Exploration and Operations Mission Directorate (HEOMD), Air Force (AF), Defense Advanced Research Projects Agency (DARPA), etc.

3.1.3 Importance of STMD Technologies

STMD was not in existence when either the PSDS or the PSTR made their recommendation and Office of the Chief Technologist (OCT) was just being formed and roadmaps initiated. However, since the DS committee was aware of the plans, they did address it in *Visions and Voyages* by pointing out that "*Given the unique needs of planetary science,* ***it is therefore essential that the Planetary Science Division develop its own balanced technology program,*** *including plans both to encourage innovation and to resolve the existing mid-TRL crisis."*

While the plan still must respond to PSDS and PSTR recommendations, it is also necessary to interpret the goals, the planning process and the technology plan itself in light of the formation of STMD. In particular, PSD directed us to monitor, evaluate and work with STMD to define and fund critical PSD mission technologies. To this end, we have worked closely with STMD, particularly the Game-Changing Development (GCD) Program because this is the program that moves relevant technologies through the 'valley of death' to reach a level of maturity that allows PSD to infuse them into missions. We have devised a process to evaluate current technology developments and monitor future investments based on interactions with the GCD program and evaluations conducted quarterly. The Technology Demonstration Missions (TDMs) do not change as frequently as the GCD projects do, and currently there are only a small number of TDMs proposed for FY16; hence, we set goals for PSD to influence STMD to adopt two GCD projects and one TDM project that would be beneficial to PSD missions. To do this, we support the SMD Chief Technologist, when requested, who interfaces with STMD management in advocating for specific technology developments. PSD management also realized that with limited funds, PSD has to focus on technologies that are required by missions and leave the funding of 'Push' technologies to STMD and other sources. While STMD is the most important technology source external to PSD, PSD also needs to track work in HEOMD and in some cases external agencies.

3.1.4 Current Status of the Planning Effort

Over the course of the last ~18 months, we addressed the above questions, and this document reflects the progress made to date. There are still tasks to be done: determining ROM costs for the needed technologies, assessment of technology readiness and vetting the output that PSD management requested with the broader PSD staff. The current output evolved into a list of technology gaps aimed at near- and mid-term future missions that PSD management could fund, if and when funding became available. The list is organized into categories to allow flexibility in choosing the tasks to fund depending on changing priorities within PSD. JPL met with PSD management and staff approximately every three months or more and specific deliverables (e.g., Technologies for Europa Lander and for New Frontiers) were added during the year to accommodate changing PSD priorities, reflecting the dynamic nature of PSD's TP. The flow plan followed for developing the TP, which was agreed with PSD management, is shown in Figure 1.

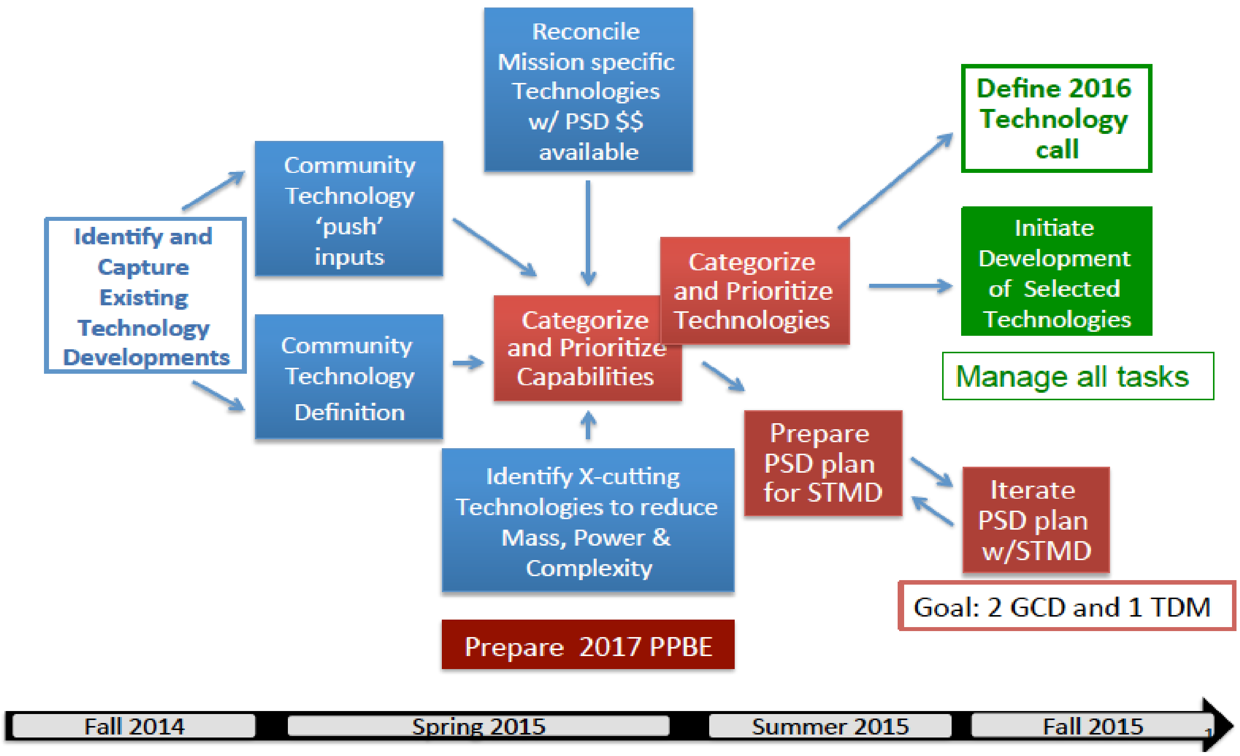


Figure 1: 2015 PSD technology plan flow.

3.2 Planning Methodology and Capability Gap Analysis

The overarching methodology, agreed upon with PSD and captured in Figure 2, describes how the TP was developed to define a diverse set of technologies that could be funded from various sources. The focus is on enabling missions and modernizing spacecraft and instruments and inherently involves a capability gap analysis. While the details of this analysis are described in the Appendices, an outline of the process is given here. Note that all the documents evaluated are provided by the community, either from scientists or technologists, and are vetted, most commonly by National Research Council (NRC) panels.

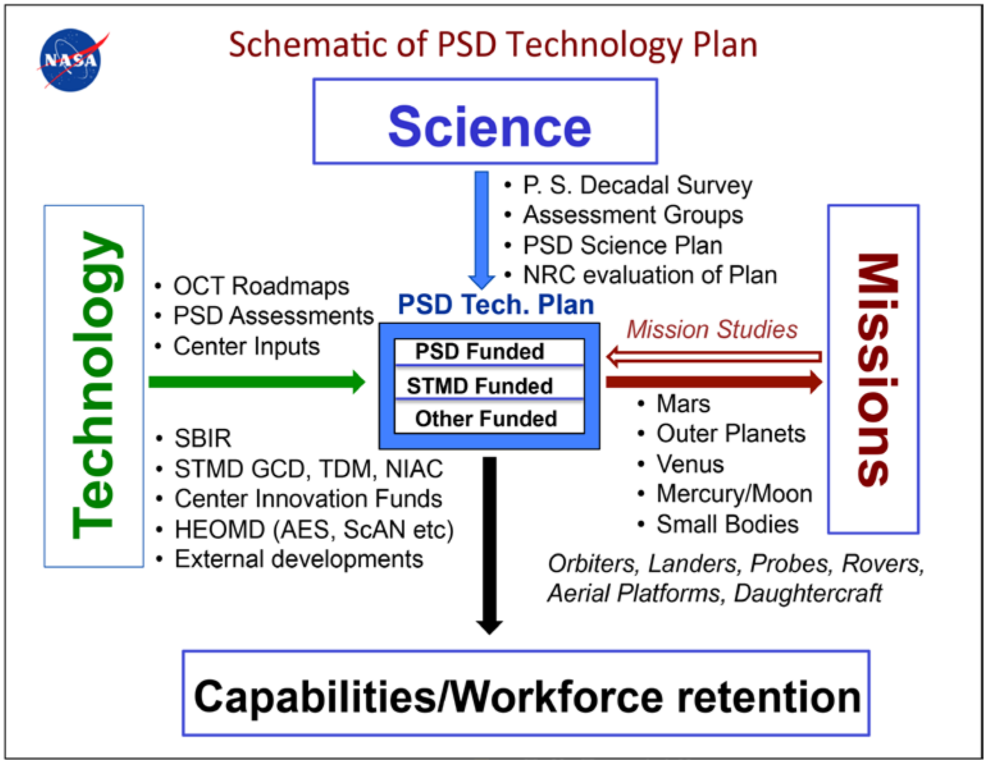


Figure 2: Process for developing the PSD Technology Plan (PSD-TP).

3.2.1 Technology Needs and Technology Maturity Assessment

The science requirements for the missions and technologies are well captured in *Visions and Voyages*, with the technology recommendations primarily listed in Chapter 11 of the document. However, additional inputs come from the AGs, which keep up with new science results and, deriving from those, provide community inputs to the PSD in the form of their Technology Plans (which build on *Visions and Voyages*). In addition, we analyzed the PSD portion of the NASA Science Plan and the NRC evaluation of that plan. These are all discussed in more detail in Appendix 3, Section 2. Additional requirements also come from specific mission studies and as these studies occur, technology needs are identified and incorporated into the Plan.

The technology inputs from the community to the TP come in two flavors: planning and assessments documents prepared by technologists and the actual technology development work that is being conducted in a range of different programs (PSD, STMD and HEOMD).

Technology Assessments: The general assessment documents include the NASA OCT Technology roadmap and Technology 'Push' documents, which cover all technologies at NASA and was updated in July 2015. The Small Business Innovation Research (SBIR) program continues to develop early stage technologies relevant to NASA, including planetary, and those were evaluated too but most were deemed too low in TRL to be ready for infusion by the PSD, however, they must be continually tracked for progress toward possible infusion. Finally, as part of this general data gathering and assessment process we screened TechPort (the OCT technology database) for relevant technologies. TechPort is an integrated, agency-wide software system designed to capture, track, and manage NASA's portfolio of technology investments in order to provide detailed information on individual technology programs and projects throughout NASA. More specific assessments, often undertaken by the PSPS under direction of the PSD, have also been conducted on technologies that are relevant to planetary missions, e.g., Energy Storage, Planetary Protection, Extreme Environment Technologies for Future Space Science Missions and Guidance Navigation and Control and these were gathered, analyzed and are provided in the references. They can also be found on http://solarsystem.nasa.gov/missions/techreports. The other inputs to the plan are from mission studies. High-fidelity studies driven by science input from the community were by far the best data source; however, there are smaller studies, sometimes technology-related and sometimes science-focused, that yielded technology inputs that were considered.

3.2.2 Current Technology Programs

Among the current technology development programs considered were those funded by PSD, which are described in detail in Section 3.3 below as well as in the Appendix 3, Section 3. However, as discussed previously, a number of other NASA programs are relevant including those in the STMD and the HEOMD and the details of the assessments are also provided in Appendix 3, Section 3. In addition, we also consider the technologies that would lower PSD mission costs by modernizing spacecraft (S/C) infrastructure and update old subsystems, e.g., moving from the RAD750 computer flown on most missions to high-performance computing (currently funded by STMD, SMD and AF). PSD also relies on autonomous subsystems for a variety of mission functions, which is another critical capability that the entire Agency is interested in addressing and which is not clearly spelled out in the OCT roadmaps. At the early stages, these may not show up in any particular *science or mission* document, but are well understood by the mission Centers and some have been studied in the past by the PSPS program to determine their suitability for challenging outer planet missions.

3.2.3 Capability Gap Analysis

The primary output of this process is a gap analysis for all the mission types that are under consideration. Capability gaps were derived from analyzing the individual mission types and then looking for common capabilities needed across the missions and determining what was missing. The color-coding in Table 1 indicates the maturity level given the current technology programs described in Section 3.3.

The technology gaps represent a menu of possibilities for PSD to examine as it formulates its own technology program and advocates funding by other directorates. There are far more programs than there are resources to support them. In addition to the factors discussed earlier, PSD considers the following factors in making choices:

1) Is this enabling or enhancing for a PSDS mission?
2) Is it applicable to multiple missions?
3) Will this technology save PSD costs in the short- or long-term?
4) What are the resource requirements?
5) What is the probability of success?
6) Can it be completed in time for the mission?
7) Are there partnership possibilities?

Table 1: Maturity of technology capabilities for implementing planetary science missions. This information is reproduced from a Planetary Science Technology Plan update, April 9, 2015[2].

	Technology Information	Near-Term Missions						Mid-Term Missions						Far Term-Missions				
	Capability/Functionality	Small Bodies	Outer Planets	Venus	Mars	Moon	Common-ality	Small Bodies	Outer Planets	Venus	Mars	Moon	Common-ality	Small Bodies	Outer Planets	Venus	Mars	Common-ality
System Technologies	**In Space Propulsion**						MOD						MOD					MOD
	Aerocapture/Aeroassist	NA		Aerobrake			LOW	NA					TBD	NA				MOD
	Entry including at Earth		⬆	⬆		Earth	HIGH		⬆	⬆			HIGH					MOD
	Descent and Deployment			Plains			MOD			Tessera			MOD					MOD
	Landing at target object				⬆		LOW						MOD					MOD
	Aerial Platforms			Balloon	Rotorcraft		LOW		Balloon	Balloon			MOD			Balloon		LOW
	Landers - Short Duration						NA											LOW
	Landers - Long Duration						NA											LOW
	Mobile platform- surface near surface				⬆		NA											
	Ascent Vehicle						NA						LOW					LOW
	Sample Return						NA						LOW					LOW
	Planetary Protection		⬆				HIGH						MOD					MOD
Subsystem Technologies	Energy Storage- Batteries						HIGH						MOD					LOW
	Energy Generation - Solar																	MOD
	Energy Generation - Radioisotope Power											?	LOW					MOD
	Thermal Control - Passive						LOW						LOW					LOW
	Thermal Control - Active																	
	Rad Hard Electronics						LOW						LOW					
	Extreme temperature mechanisms						LOW						LOW					LOW
	Extreme temperature electronics						LOW						LOW					LOW
	Communications						HIGH	Optical	Optical	Optical	Optical		HIGH	Optical	Optical	RF-HT		HIGH
	Autonomous Operations						HIGH						HIGH					
	Guidance, Navigation and Control				⬆		HIGH						HIGH					HIGH
Insutrument	Remote Sensing - Active		⬆				MOD						LOW					HIGH
	Remote Sensing - Passive		⬆				HIGH						HIGH					HIGH
	Probe - Aerial Platform						LOW						MOD					LOW
	In Situ - Space Physics																	
	In Situ Surface - Geophysical												LOW					LOW
	Sampling						LOW						LOW					HIGH
	In Situ Surface - Long Duration - Mobile						LOW						LOW					LOW

TRL Maturity Legend	
	Very High. Ready for flight. Same as TRL 6
⬆	High. Funding is in place to advance to Very High in one to four years
	High. Limited development and testing still needed
	Moderate. Major R&D effort needed.
	Low. Major R&D effort needed with notable technical challenges

3.3 Assessment of the Current Technology Programs Relevant to PSD

Prior to developing the PSD TP, it was agreed that we must first determine the status of the PSD technology effort as currently understood as well as technology programs relevant to PSD carried out elsewhere in NASA. This information was compiled and is now available on PSD's internal technology website (https://inside.nasa.gov/planetaryscience/technology/psd-tech-planning). An overview appears below. More details appear on the website and in Appendices to this document. The original Master Plan called for a PSD Technology website. A "Technology" tab has been created for the PSD internal website and has been populated with data on PSD-funded technologies as well as technology relevant to PSD but funded by other NASA and non-NASA organizations. FY14 quad charts were obtained from most of the programs and posted on the internal PSD website. FY15 quad charts have yet to be posted. The website has been updated periodically, and the site was down for several months while it underwent restructuring, but it is now available for PSD use.

3.3.1 PSD Technology Investments FY14 and FY15

Table 2 summarizes the funding and content of the programs for FY14 and FY15. A more detailed description of the contents of each of the program and project elements appears in Appendix 3.

Table 2: Summary of PSD technology in technology programs and projects. The data was updated through end of FY15.

Acronym	Description	Total Program ($M)		Technology Only ($M)		Comments
		FY14	FY15	FY14	FY15	
Technology Program						
ISPT	In-Space Propulsion Technology	$3.7	$1.5	$2.4	$1.5	NEXT Funded FY14. Program terminated
RPS	Radioistope Power Systems	$42.0	$25.2	$32.5	$15.4	
DOE	Plutonium and Pu Infrastructure	$66.0	$74.4	$0.0	$0.0	PSTR recommended this was not Tech.
AMMOS	Adv Multi Miss Ops System	$33.7	$35.6	$1.0	$1.8	Historically funded under Technology
R&A	Research and Analysis	$26.7	$24.9	$26.7	$24.9	Primarily science instrument programs
	Subtotal	$172.1	$161.6	$62.6	$43.6	
Projects						
MEP	Mars Exploration Program	$4.0	$5.6	$3.7	$4.3	
NEOO	Near Earth Object Observations	$0.5	$0.9	$0.5	$0.9	
Europa	Europa Project	$15.0	$18.0	$15.0	$17.8	
Disc	Discovery Program	$40.0	$24.9	$35.1	$2.4	
NF	New Frontiers Program	$0.0	$0.0	$0.0	$0.0	Homesteader funding in F16
	Subtotal	$59.5	$49.3	$54.3	$25.4	
PSD Technology Support						
PSPS	PSPS Technology Planning	$0.9	$0.9	$0.0	$0.0	
	Subtotal	$0.9	$0.9	$0.0	$0.0	
	Totals	$232.5	$211.8	$116.9	$69.0	

Determining the funding that PSD spends on technology is not a straightforward task. Some programs that are within the technology program funding line, such as AMMOS, are primarily involved in operations, although it does have a small technology element. The radioisotope power system (RPS) program has also been involved in the development of Pu-238 capability with the Department of Energy (DOE) and how much of that is considered technology versus infrastructure and capability maintenance can be debated. The PSTR panel suggests "the procurement of Pu-238 to supply radioisotope power for planetary missions should **not** be considered technology and it should not be funded with technology resources." Therefore, it was not included as technology.

On the other hand, flight programs and projects are sometimes involved in technology development, e.g., the Discovery program funds some technology efforts. The estimate of technology work is based on discussions with the project and program managers but involves some judgment on what is technology and what is management or engineering.

3.3.2 Non-PSD Technology Assessment

In addition to technology development sponsored by PSD, other Directorates at NASA and particularly the STMD and the HEOMD conduct technology development (SCaN and AES). In order to formulate a technology plan, it is necessary to know what work relevant to PSD is being conducted in those organizations and how it is progressing. We spent significant amount of time becoming familiar with how STMD works, who to talk to and how to get data. The GCD program is the most fluid. We attend each quarterly review to update the analysis and now have access to all the resource data including funding for the individual GCD programs. This topic is covered in detail in Appendix 3, Section 3.

In addition, we track the HEOMD programs. Table 3 shows an overview of the PSD relevant technology, their total funding as well as an assignment of PSD applicable funding. This latter amount was calculated using weighting factors described in detail Appendix 3, Section 3.2.3. The methodology chosen, which is described in Appendix 3.2.3, is as follows:

1. Assess the relevance of the general area of technology to PSD and place it in one of five categories. Very High, High, Moderate, Low, and Not Applicable.
2. Assess the *relevance* of the specific task to PSD using the same scale. A PSD Relevance weighting factor was then applied to the budget data with Very High (designated 1.0), High (designated 0.2); all other categories rated zero.
3. The *uniqueness* of this technology to PSD applications is evaluated on a scale of High, Medium, Low, and Not Applicable. PSD Uniqueness weighting factors of 1.0, 0.3 0.1 and 0 were applied to these designations. Through application of this weighting factor, technologies that are unique to PSD were fully credited as PSD-relevant investments. However, technologies that are important to PSD but also relevant in other Divisions or Directorates were discounted with the expectation that those organizations would contribute to funding them.

Other weighting factors could be considered but we felt this was a reasonable approach. If alternative weighting factors are preferred, the PSD applicable dollars can easily be recalculated from the database.

Table 3: PSD relevant technology funded by other NASA directorates in FY15.

Acronym	Description	FY15 ($M)		Comments
		Total Program	PSD Applicable	
STMD GCD Technology Program				
LMAM	Lightweight Materials and Advanced Manufacturing	$15.1	$0.2	
FPES	Future Propulsion and Energy Systems	$9.5	$0.3	
ADSI	Affordable Destination Systems and Instruments	$18.3	$5.4	
AEDL	Advanced Entry, Descent, and Landing	$26.8	$3.8	EDL Technology is very high priority
RRAS	Revolutionary Robotics and Autonomous Systems	$36.6	$0.0	
	Subtotal	**$106.3**	**$9.7**	
STMD TDM Technology Program				
LDSD	Low Density Supersonic Decelerator	$38.0	$11.4	
LCRD	Laser Communication Relay Demonstration	$37.0	$0.0	
SEP	Solar Electric Propulsion	$35.9	$0.0	
GPIM	Green Propellant Infusion Mission	$16.1	$0.0	
eCryo	Evolvable Cryogenics	$12.9	$0.0	
CEUS	Composites for Exploration Upper Stage	$6.9	$0.0	
DSAC	Deep Space Atomic Clock	$4.5	$1.3	
	Subtotal	**$151.3**	**$12.7**	
HEOMD AES Technology Program				
CMS	Crew Mobility Systems Domain	$1.7	$0.0	
DSHS	Deep Space Habitation Systems Domain	$52.7	$0.0	
VS	Vehicle Systems Domain	$25.5	$0.0	
FS	Foundational Systems Domain	$15.1	$2.8	
RP	Robotic Precursors Domain	$37.3	$1.5	
NSB	NextSTEP BAA	$0.0	$0.0	
	Subtotal	**$132.2**	**$4.3**	
HEOMD SCaN Technology Program				
DSOC	Deep Space Optical Comm	$1.2	$0.4	
DSAC	Deep Space Atomic Clock	$7.6	$2.3	
	Subtotal	**$8.8**	**$2.6**	
	Total NASA Non PSD Technology Totals	$247.3	$16.7	

3.4 Planning the Future of PSD Technology

With knowledge of the "as is" state of technology funding within PSD and the other NASA directorates, we could plan the future technologies needed by PSD and how they would get funded. There were three aspects to this:

3.4.1 Science and Mission Needs

As discussed earlier, the PSD TP relied on reading and identifying all the technology needs in the science and technology documents and interacting with the community to make sure we understood the requirements. All of these documents were analyzed with respect to missions expected to launch in the next 10 to 20 years although some technologies would benefit Mars2020. See Appendix 3, Section 2 for details. Further, we encouraged all the planetary AGs to update their documents to reflect the latest science goals and objectives as well as their technology plans. This has or is happening for all the AGs, except for the Lunar Exploration Analysis Group (LEAG), who are planning to do a Technology Plan. We have been involved in many of those updates, either being responsible for them or participating in them.

3.4.2 NASA Center Inputs

Although the documents cited above had involved all the NASA Centers, we wanted to ensure we had not missed something that they did not put into one of these planning and assessment documents. To accomplish that we captured technologies that Centers consider vital for the future of planetary science and we invited Centers and Johns Hopkins University (JHU) Applied Physics Laboratory (APL) to submit their technology needs ('push' or 'pull') or technology developments they felt were important for planetary missions. This data gathering was done privately to facilitate Centers to communicate potentially confidential information safely, and examples of these are shown in Appendix 3, Section 3.7. Encouragingly, there were very few 'new' technologies that we had not already considered from all the community documents, which confirmed we had captured nearly all the requirements. Progress in technology development carried out in external organizations is also important. However, for this Plan we did not conduct a separate assessment but relied on inputs coming from the NASA Centers. All Centers undertaking planetary missions and/or technology development were polled for their input to the Technology Plan, to make sure there were no omissions. They were asked to provide

- Technologies your Center has identified for future Discovery and New Frontiers (NF) (through the next decade or so)
- Technologies you have at your Center (or you know some other Center has) that could be applicable to future planetary missions.
- Anything else you would like to bring up for the PSD to pay attention to as far as technology planning goes.

3.4.3 Disruptive Technology

To round out the information we needed to formulate technology gaps, we conducted an assessment of disruptive technologies. These are technologies that would not necessarily show up in earlier documents or in a needs assessment and might not be a major part of existing technology programs but could radically change the way in which we conduct planetary exploration and potentially create totally new ways of exploring planets. The main focus of this assessment was miniaturization and, in particular, the impact of CubeSat technologies and applications to planetary exploration and the future needs of SmallSats (100–200 kg capable of planetary exploration, either as daughter-ships or launched with planetary missions as stand-alone spacecraft or landed elements). This is covered in Appendix 4.

4 Technology Plan Assessment

In this section, we present a preview of how the community and the NRC would assess the current PSD TP. For planning and assessment purposes, the plan is considered to include the PSD-funded technology tasks and those parts of the STMD and HEOMD technology programs (Appendix 3, Section 3) that are considered directly relevant to PSD. Relevance was considered to be if a technology could significantly enhance or enable a future mission. This was used to track how the portfolio relates to the technology funding guidelines set out by the Decadal Survey.

4.1 Comparison of Technology Funding with Decadal Survey Goals

A comparison between PSD-relevant technology funding and goals set by the Decadal survey appears in Table 4.

Table 4: Comparison of technology funding with Planetary Science Directorate Decadal Survey goals.

Acronym	Technology Funding Elements	Funding ($M)	Funding (% of total)	PSDS Guidelines
		FY15	FY15	
Breakdown by Funding Organization				
PSD	Planetary Science Division	$69.0	**70.1%**	NA
STMD	Space Tech Missions Directorate	$22.4	**22.8%**	NA
HEOMD	Human Expl. Opts Missions Directorate	$7.0	**7.1%**	NA
	Total	**$98.4**	**100.0%**	
Breakdown by Application - PSD				
SI	Science Instruments	$33.8	**34.4%**	35.0%
EE	Extreme Environments	$8.9	**9.0%**	15% **
ISE	*In Situ* Exploration*	$0.9	**0.9%**	25.0%
SACT	Space Access and Core Technologies	$54.8	**55.7%**	25.0%
	Total	**$98.4**	**100.0%**	
% of Overall PSD Budget		**$1,438.0**		
PSD	Planetary Science Division	$69.0	**4.8%**	6 to 8%
STMD	Space Tech Missions Directorate	$22.4	**1.6%**	NA
HEOMD	Human Expl. Opts Missions Directorate	$7.0	**0.5%**	NA
	All PSD Technology Funding	**$98.4**	**6.8%**	NA

* $'s assigned to Extreme Environment over *In Situ*, when technology applies to icy body landers

** Percentage assigned prior to direction from Congress to support Europa Lander

4.2 Program Size

In the Executive Summary of *Visions and Voyages*, the report of the PSDS (Page 7) stated, "*The future of planetary science depends on a well-conceived, robust, stable, technology investment program. The committee unequivocally recommends that a substantial program of Planetary Exploration Technology*

Development should be reconstituted and protected against all incursions that would deplete its resources. The program should be consistently funded at approximately 6 to 8% of the total Planetary Science Division budget."

In FY15, the PSD funded technology *alone* is well below the 6–8% goal set by the Decadal Survey (a total of $69M out of a PSD budget of $1.44B = 4.8%). However, if the PSD relevant technology funding in STMD and HEOMD (AES and SCaN) is credited to PSD, the total funding relevant to PSD is $98.4M or 6.8% of total PSD program funding—meeting the 6–8% goals. Of course, this is dependent on the weighting factors used, so these need to be vetted and agreed upon by PSD.

Table 5: Summary of NASA technology programs as a percentage of the PSD FY15 budget.

Funding Source	Total FY15 Technology Funding Applied to PSD	% FY15 of PSD Budget ($1,438M)	Cumulative % of FY15 PSD Budget
PSD	$69.0	**4.8%**	4.8%
STMD	$22.4	**1.6%**	6.4%
HEOMD	$7.0	**0.5%**	6.8%

4.3 Program Balance

As discussed earlier, in the chapter on Technology Development of the PSDS there is also a call for balance in the technology development program. The targets that are laid out be the PSDS are as follows:

- Science Instruments (35%)
- Extreme Environments (15%)
- In Situ Exploration (24%)
- Space Access and Core Technologies (25%)

A composite figure arrived at after the allocation of funding between each of these categories has been determined for each of funding sources. This assessment effort involves a great deal of judgment, particularly because there is significant overlap among the categories. Where an activity has elements of two or more categories, a weighting factor has been used to determine the allocation. The funding per category for Science Instruments and Space Access is approximately as specified in the PSDS, but the funding for Extreme Environments together with In Situ Exploration is only 10%, which is far lower than the recommended 39%.

4.4 Technology Infusions

The PSDS recommended (p305) "that the Planetary Science Division should accept the responsibility and assign the required funds to continue the development of the most important technology items through TRL 6." With the decrease in budget that PSD experienced as soon as the PSDS was published, this was not immediately practical but with the FY 16 increase to $1.62B and the $25M allotted to icy satellites surface technology this can now be achieved. The latter should also improve the amount targeted for Extreme Environments and In Situ Exploration.

4.5 Progress against These Goals

Progress against these goals will continue to be measured against metrics established by the Decadal Survey. This has already been done for FY15 in Table 4 and will be carried out in a similar fashion for future years.

5 PSD Technology Dynamic Portfolio

The primary purpose of this section of the PSD TP at this time is to provide PSD management with guidance on opportunities for the most effect investment of PSD funds and on the advocacy for new programs in STMD and other NASA directorates. The portfolio identifies those technologies that are currently funded as well as candidate technologies for future investment. The goal is to provide sufficient information on the candidate technologies to permit informed prioritization. The plan evolves as new information becomes available and as different levels of detail are developed. Lacking new technology program initiatives, the PSD opportunities primarily arise through funding wedges in the ongoing competitive programs and through new mission initiatives. The interests of PSD should inform the STMD opportunities and co-funded opportunities are particularly attractive.

5.1 Initial Technology List (June 2015)—Version 1

The list, developed in response to a request from David Schurr for a list of priority technologies for PSD, appears in Appendix 5. The list consists of technologies that are needed for competitive missions (both New Frontiers and Discovery), directed missions (Mars, Europa Lander, Neptune, Uranus) as well as a list of priority science instruments. In addition, a list of existing or potential areas of collaboration was included. The rationale for the selection of items in the list was described in a PowerPoint presentation to David Schurr[3].

5.2 Updated Technology List (December 2015)—Version 2

Using the initial list of June 2015 as a starting point, an updated technology list was assembled by December 2015 and appears in Appendix 6. For each item in the updated list the following information was included in tabular form:

- The level of funding characterized at three levels -full funding, partial funding or no funding
- The source of funding—typically PSD, STMD or HEOMD or non-NASA
- NASA Technology Roadmap—WBS entry

The listing has been reorganized to group competitive missions separately from directed missions and to include science instruments as a separate category to reflect the distinctive acquisition process that NASA used for instruments. Ongoing collaborative activities with other directorates and agencies are included as well as opportunities for new ones.

5.3 Upcoming Technology List (June 2016)—Version 3

The goals for this planned product is a list with the information:

- Specific TRLs for technology developments—current and planned
- ROM costs for each of the technology items (see Appendix 7)

- Generated Technology Snap Shots for technology items that are not in the NASA Technology Roadmap of 2015
- External sources of funding, e.g., DARPA, Department of Defense (DOD), etc.

5.4 Complete Technology List (Dec 2016)—Version 4

The detailed specifications for this are still to be defined but the goal is to format the information with additions such as

- Prioritization scheme
- Infusion history
- SBIR elements—process to be defined
- Detailed costs for selected high-priority items
- Links to trade studies

The portfolio will then be updated at least annually or as needed to reflect any major changes in requirements, program content or structure.

6 Vetting of Product

The plan for vetting the TP is to review the Plan with Len Dudzinski and Tibor Kremic first and then present it internally within PSD in a discussion session with the PSD staff as agreed upon at the October 29 meeting with David Schurr.

7 Summary

The PSD Technology Plan has been developed in close collaboration with PSD management and based on documents generated by the community and NASA Centers. Hence, the TP is inherently responsive to the community and the needs of PSD. Due to the dynamic nature of PSD, continual evaluation and assessment of the changes in the TP are necessary and planned. Disruptive technologies also come along, which have to be taken into account as soon as practical. Details of the assessments and evaluations are found in Appendix 3. The remaining tasks are to vet the Plan as discussed with PSD management, flesh out the costs and revise/iterate the plan on an ongoing basis as discussed above. Continual evaluation and assessment of the changes in the Technology task will be performed and documented in future years and the internal PSD website will continue to be updated with the current data.

8 Acronyms and Abbreviations

ADEPT	Adaptable, Deployable Entry Placement Technology
AES	(HEOMD) Advanced Exploration Systems (Division)
AF	Air Force
AG	Assessment Group
APL	Applied Physics Laboratory

ARC	Ames Research Center
ASRG	advanced Stirling radioisotope generator
BAA	Broad Agency Announcement
C&DH	command and data handling
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DOE	Department of Energy
DRM	Design Reference Mission
DSAC	Deep Space Atomic Clock
DSN	Deep Space Network
DSOC	Deep Space Optical Communications
EM	exploration mission
eMMRTG	enhanced MMRTG
GCD	(STMD) Game-Changing Development (Program)
GN&C	guidance, navigation, and control
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HEEET	High-Energy Entry Environment Technology
HEOMD	(NASA) Human Exploration and Operations Mission Directorate
IMU	inertial measurement unit
iROC	Integrated Radio and Optical Communication
InSight	Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport
INSPIRE	Interplanetary NanoSpacecraft Pathfinder In Relevant Environment
ISE	In-Space Engine
JAXA	Japanese Space Agency
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
KISS	Keck Institute for Space Studies
LaRC	Langley Research Center
LCRD	Laser Communication Relay Demonstration
LEAG	Lunar Exploration Analysis Group
LEO	low Earth orbit
LIDAR	light detection and ranging
LILT	low-light-intensity and low-temperature
MarCO	Mars Cube One
MASCOT	Mobile Asteroid Surface Scout
MAV	Mars ascent vehicle

MEP	Mars Exploration Program
MINERVA	Micro/Nano Experimental Robot Vehicle for Asteroid
MMRTG	multimission radioisotope thermoelectric generator
MRO	Mars Reconnaissance Orbiter
MSFC	Marshall Space Flight Center
MTD	Mars Technology Development
MUSES	Mu Space Engineering Spacecraft
NEA Scout	Near-Earth Asteroid Scout
NEPA	National Environmental Protection Act
NF	New Frontiers
NIAC	NASA Innovative Advanced Concepts
NRC	National Research Council
NRO	National Reconnaissance Office
OCT	Office of the Chief Technologist (NASA)
OPAG	Outer Planets Assessment Group
OWET	Ocean Worlds Exploration Technologies
PPBE	Planning, Programming, Budgeting, and Execution
PPU	power processing unit
PROCYON	Proximate Object Close Flyby with Optical Navigation
PSD	Planetary Science Division
PSDS	Planetary Science Decadal Survey
PSPS	Planetary Science Program Support
PSTR	Planetary Science Technology Review
RADAR	radio detection and ranging
RHU	radioisotope heater unit
ROM	rough order of magnitude
RPS	radioisotope power system
SBAG	Small Bodies Assessment Group
SBIR	Small Business Innovation Research
SCaN	(HEOMD) Space Communications and Navigations (Division)
SEP	solar electric propulsion
SKG	Strategic Knowledge Gap
SLS	Space Launch System
SMD	(NASA) Science Mission Directorate
SSB	Space Studies Board
STB	SCaN Testbed
STIP	Strategic Technology Investment Plan

STMD	(NASA) Space Technology Mission Directorate
TDM	(STMD) Technology Demonstration Missions (Program)
TP	Technology Plan (PSD)
TRL	Technology Readiness Level
USAF	United States Air Force
VEXAG	Venus Exploration Analysis Group
VISE	Venus In Situ Explorer

Appendix 1: Scope of Work for PSD Technology Plan

A1.1 Background

PSD has been without a Technology Plan for many years. Under the PSPS Task Plan, the PSD Chief Technologist, Len Dudzinski, has requested a Technology Plan by May 1. This culminates in an investment plan for Technology to be presented to David Schurr and a Planning, Programming, Budgeting, and Execution 17 (PPBE17) submission to PSD/SMD (This was later revised by PSD Management).

A1.2 Scope

Under the PSPS task plan, JPL will evaluate all the technologies (including power and propulsion) required for future missions (competed and strategic) for the PSD. This technology evaluation will result in a phased Technology Plan to be undertaken over the next five to ten years. It will encompass the technologies required for Outer Planets, Venus, and Small Bodies missions, including Mars missions. An estimate of the cost will be provided for the out-years but a realistic (negotiated) amount will be proposed for FY15 to PSD. The current FY14 budget is $143M, including AMMOS, but not including funding under the missions and R&A lines. We will also evaluate the AMMOS costs and recommend an approach to modernizing AMMOS and reducing costs in the out years.

The technologies will be parsed between the PSD, STMD, HEOMD and other applicable agencies. In the latter three cases, the PSD will need to advocate for these technologies with those Divisions. JPL will assist the PSD in making the connections to the other Divisions and encourage proposers from around the Agency to submit technology proposals that fit within the PSD Technology Plan.

In addition to working with Peter Panetta to prepare the plan, JPL will assist the PSD in making appropriate connections to the various Assessment Groups and the PSS to encourage the support of the scientific community. We will ensure that the ‘message’ is appropriate and consistent by reviewing the presentations and helping target the charts for individual audiences.

Deliverables:

1. High-level Technology Plan by May 1, 2014 with approximate cost phasing for 5–10 years
2. Charts for PPBE development by May 1, 2014
3. Technology Plan expanded to include further details by July 1, 2014. Deliverable is a Word document plan.

Appendix 2: Original Master Plan

Planetary Science Division Integrated Technology Portfolio

Peter Panetta
03/19/14 Update

Framing the Problem

The following key questions need to be answered:

1. *Portfolio diversification*
   - Where we currently are making investments vs. where we want to be making them
2. *How much PSD funding do we devote to technology development*?
   - Decadal Survey suggested 6-8%
   - PS Technology Review Panel suggested 8%
3. *What technologies are missing from the portfolio*?
4. *What are the longer term (5/10 yr) mission needs and the technology priorities to satisfy them? Do not lose current capabilities – need to determine what we exercise and at what frequency.*
5. *Who do we partner with to augment the funding required to develop PSD technology?*
   - *STMD, HEOMD, AF, DARPA, etc.*

The Master Plan

- Approach the development of an integrated PSD technology portfolio plan in 3 phases
- <u>Phase 1</u>: Identify all technology components currently under development with FY14 funding
  - NOT to include technology as part of approved missions in development (e.g. Mars 2020, InSight, O-Rex)
  - Enter all of these activities into some form of technology database
    - *Preferred near term solution*: Technology tab on the PSD website
      - Modeled after ESTO Website
      - Simple in design, only requires quad charts
    - *Alternate near term solution*: IMPaCT (JPL Technology & Mission Info)
    - *Longer term activity*: Migration to TechPort (OCT)
      - What OCT eventually wants all of SMD to use to list their technology data
      - A more complex platform to enter data and use for quick reference
- <u>Phase 2</u>: Integrate longer term technology development strategies into the plan and prioritize these activities
  - Obtain strategies from:
    - ❑ Discussions with Lead PE's
    - ❑ Program Line Technology Plans
    - ❑ Assessment Group Reports (SBAG, OPAG)
    - ❑ Planetary Science Decadal Survey
    - ❑ What else?
  - Prioritize in order of need
    - ❑ Include TRL development schedules and cost projections where available
      - ❖ Ideally produce a Quad Chart
- <u>Phase 3</u>: Map the plan with PPBE16 process to determine technology investments
  - Identify which items get funded, which fall below the line
  - Use priority list from phase 2 to fund additional activities if more funding were to become available

Appendix 3: PSD Technology Assessment

A3 Overview

This Appendix describes the process of creating a set of candidate tasks for inclusion in the PSD TP. The process has been subdivided into three steps, which have been outlined in the main body of the text and are described in more detail in the following three sections of this Appendix.

A3.1 Technology Needs and Maturity Assessment

The steps in the technology planning process involved the following elements:

- **NRC Planetary Science Decadal Survey (PSDS)-2011:** Reviewed the finding and recommendations respect to technology.
- **PSD Technology Assessment Team**: Reviewed the findings and recommendations of the PSD Technology Assessment Group.
- **Technology Capability Maturity Assessment:** Performed a detailed analysis of the maturity of technology capabilities by target object(s) defined by the scope of NASA's AGs. The maturity of capabilities for each target object category was assessed and this information synthesized to provide a complete picture for all of planetary science. This activity incorporated inputs from the AGs and the Mars Program.
- **Technology Commonality:** Determined the degree of commonality in the some of the technologies required in each of the capability categories.
- **Technology Gaps**: Defined the technology tasks needed to raise the current capabilities from their current level of maturity to flight readiness. Here we relied heavily on the content of the NASA OCT Technology Plan, which is now updated and includes a series of snapshots for all tasks important to NASA. Where gaps still existed, they were identified.

A3.2 NRC Planetary Science Decadal Survey, 2011

The PSDS document *Vision and Voyages* includes a section on the role of technology development in planetary exploration[4]. The findings are summarized in a set of three tables that are reproduced here (Table A3-1, Table A3-2, and Table A3-3).

The PSDS formed five subpanels to formulate scientific objectives, identify mission candidates and, where needed, identify technology needs. These subpanels were Primitive Bodies (including asteroids, comets and Kuiper belt objects), The Inner Planets (Mercury, Venus and the Moon), Mars, the Giant Planets (Jupiter, Saturn, Uranus and Neptune) and Satellites (the major satellites of the outer planets, namely, those large enough to have acquired a roughly spherical shape. A summary of the technology development needs identified by those panels appears in Table A3-1.

Using this information as input, but supplementing it with information from separate briefings on the state of planetary science technology, the PSDS then formulated a set of mission types that would be important in the period 2023 to 2033 and identified a corresponding set of technology requirements. Their focus was on developing a technology investment plan for the 2013 to 2022 decade that would impact missions in the subsequent decade. That summary, which appears in Table A3-2, emphasizes capabilities and not specific technical solutions.

Finally, the PSPS panel formulated a set of investment goals for planetary technology. It specified a target of 6–8% of the Planetary Science budget for technology development and outlined a possible investment profile for technology development (Table A3-3).

Table A3-1: Key technological findings by the subpanels of the PSDS. (Reproduced from Table 11.1 in *Visions and Voyages*)

	Chapter 4 The Primitive Bodies	Chapter 5 The Inner Planets	Chapter 6 Mars	Chapter 7 The Giant Planets	Chapter 8 Satellites
Technology development	Continue technology developments in several areas including ASRG and thruster packaging and lifetime, thermal protection systems, remote sampling and coring devices, methods of determining that a sample contains ices and organic matter and of preserving it at low temperatures, and electric thrusters mated to advanced power systems. Develop a program to bridge the TRL 4-6 development gap for flight instruments.	Continue current initiatives. Possibly expand incentives to include capabilities for surface access and survivability for challenging environments such as Venus's surface and frigid polar craters on the Moon.	Key technologies necessary to accomplish Mars Sample Return are Mars ascent vehicle, rendezvous and capture of orbiting sample return container, and planetary protection technologies.	Continue developments in ASRGs, thermal protection for atmospheric probes, aerocapture and/ or nuclear-electric propulsion, and robust deep-space communications capabilities.	Develop the technology necessary to enable Jupiter Europa Orbiter. Address technical readiness of orbital and in situ elements of Titan Saturn System Mission including balloon system, low-mass/low-power instruments, and cryogenic surface sampling systems.

Table A3-2: Summary of types of missions that may be flown in the period 2023–2033 and their potential technology requirements (from *Vision and Voyages* Table 11.2).

Objective: 2023-2032	Mission Architecture	Key Capabilities
Inner Planets		
Venus climate history	Atmospheric platform Sample return	High-temperature survival Atmospheric mobility Advanced chemical propulsion Sample handling
Venus/Mercury interior	Seismic networks	Advanced chemical propulsion Long-duration high-temperature subsystems
Lunar volatile inventory	Dark crater rover	Autonomy and mobility Cryogenic sampling and instruments
Mars		
Habitability, geochemistry, and geologic evolution	Sample return	Ascent propulsion Autonomy, precision landing In situ instruments Planetary protection
Giant Planets and Their Satellites		
Titan chemistry and evolution	Coordinated platforms: orbiter, surface and/or lake landers, balloon	Atmospheric mobility Remote sensing instruments In situ instruments-cryogenic Aerocapture
Uranus and Neptune/Triton	Orbiter, probe	Aerocapture Advanced power/propulsion High-performance telecommuications Thermal protection/entry
Primitive Bodies		
Trojan and Kuiper belt object composition	Rendezvous	Advanced power/propulsion
Comet/asteroid origin and evolution	Sample return Cryogenic sample return	Advanced thermal protection Sampling systems Verification of samples—ices, organics Cryogenic sample preservation Thermal control during entry, descent, and landing

Table A3-3: Example of a possible technology investment profile that would be appropriately balanced for the future of planetary exploration (from *Visions and Voyages* Table 11.3).

Technology Element	Percentage Allocation	Key Capabilities
Science instruments	35	Environmental adaptation Radiation tolerance In situ sample analysis and age dating Planetary protection
Extreme environments	15	Survivability under high temperature and pressure Radiation tolerance (subsystems) Survival and mobility in cryogenic conditions
In situ exploration	25	Sample acquisition and handling Descent and ascent propulsion systems Thermal protection for entry and descent Impactor and penetrator systems Precision landing Mobility on surfaces and in atmospheres Planetary protection
Solar system access and core technologies	25	Reduced spacecraft mass and power Improved interplanetary propulsion Low-power, high-rate communications Enhanced autonomy and computing Aerocapture Improved power sources Innovative mission and trajectory design

A3.3 Planetary Science Technology Review (PSTR) Panel

The PSTR Panel was commissioned by the PSD to provide recommendations on how to efficiently and effectively develop the new technologies that can increase science discoveries lower mission costs or both. This committee, which functioned in parallel with the PSDS, issued its report in July 2011[5], after coordinating with the authors on the PSDS.

The panel report included recommendations in four areas: strategy, process structure, resources and culture/communications. Some of the recommendations of the PSTR panel have influenced the way this planning process was approached including ensuring that scientists, technologists, and mission planners have understandable and easily accessible information so that technology developments are directly traceable to PSD science goals.

A3.4 Technology Capability Maturity Assessment

The needs identified by the PSDS and the Planetary Science Review Panel are specified at a high level and, for planning purposes, we need to have more detail and an assessment of the current state of those capabilities. For this purpose, we worked with the PSD's AGs, the Mars Program and, in some cases, conducted independent analyses.

The PSD sponsors five AGs, which provide science input and planning and prioritizing of exploration and technology for planetary exploration. The five AGs break down the solar system in a slightly different way than did the PSDS panels, as follows:

- The PSDS Mars panel was almost identical in scope to the Mars Exploration Assessment Group (MEPAG).

- The PSDS Primitive Bodies panel corresponds closely to the Small Bodies Assessment Group (SBAG).
- The topics covered by the PSDS Giant Planets and Satellites groups are consolidated within one AG—the Outer Planets Assessment Group (OPAG)
- The topics covered by the PSDS Inner Planets panel (Venus, Mercury and the Moon) have been subdivided as follows: Venus is covered by the Venus Exploration Assessment Group (VEXAG), the Moon by the Lunar Exploration Assessment Group (LEAG) while Mercury, which received no strong endorsement from the PSDS for future missions other than those currently planned, has no assessment group.

Following the publication of Vision and Voyages in 2011, some of the AGs have conducted assessments of the state of the technology for their missions of interest. Relative to the PSDS assessment discussed in Section A3.3, these assessments described not just the capabilities that are important but also the state of maturity of these capabilities. Since VEXAG did the most recent Technology Plan, the format developed there was followed to describe the other science areas.

A3.4.1 Venus

The example missions used for Venus were derived from the VEXAG Roadmap of May 2014[6]. They were divided into Near-Term, Mid-Term and Far-term. The Venus Technology Capabilities Assessment (see Table A3-4) is based primarily on the assessment in the VEXAG Technology Plan of May 2014[7]. The legend for this table appears below Table A3-4 in Figure A3-1. There have been some limited updates based on progress made in technology programs and also include more recent technology analyses and workshops[8].

Table A3-4: Venus capabilities assessment, based on findings in the VEXAG Technology Plan of 2014.

		Near-Term Missions							Mid Term Missions				Far Term Missions				
	Applicable Technology	Radar Orbiter	Remote Sensing Orbiter	Aerial Platform Sustained	Deep Probe	Multiple Shallow Probes	Multiple Shallow Sondes	Lander - Smooth Terrain	Lander Rough Terrain	Lander Long Duration	Multiple Deep Probe	Mutli Deep Sondes	Lander Network	Mobile Surface	Mobile Near Surface	Sample Return Clouds	Sample Return Surface
System Technologies	Aerocapture																
	Aerobraking																
	Entry			↑	↑	↑		↑			↑						
	Descent and Deployment																
	Landing																
	Aerial Platforms											↑					
	Landers - Short Durations																
	Landers Long Duration - Geophysica																
	Mobile Platform - Surface or near surface																
	Ascent Vehicle																
Subsysystem Technologies	Energy Storage- Batteries																
	Energy Generation - Solar																
	Energy Generation - Radioisotope Power																
	Thermal Control - Passive																
	Thermal Control - Active																
	High temperature mechanisms																
	High temperature electronics																
	Communications																
	Guidance, Navigation and Control																
Insutrument	Remote Sensing - Active																
	Remote Sensing - Passive																
	Probe - Aerial Platform																
	In Situ Surface - Short Duration																
	IN Situ Surface - Long Duration - Geophysical																
	In Situ Surface - Long Duration - Mobile Lab																

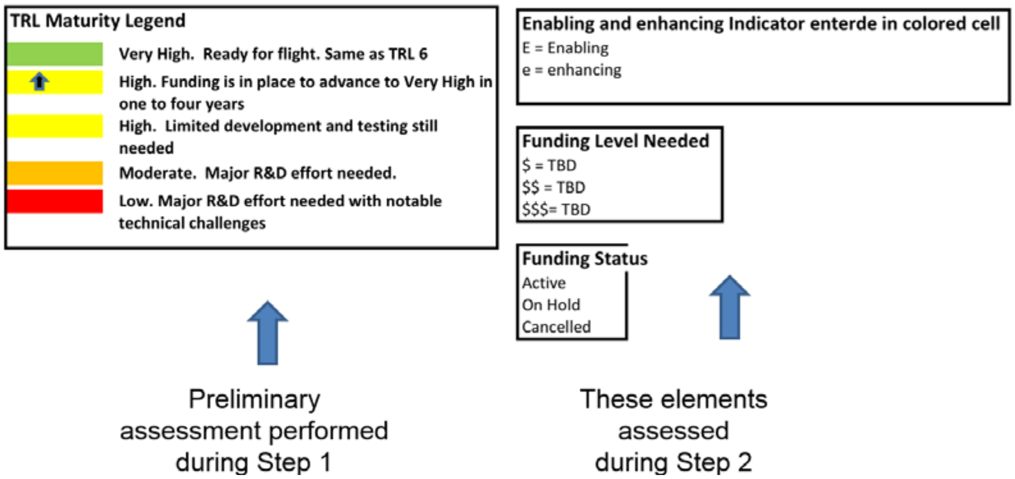


Figure A3-1: Legend for colors and other symbols in the capabilities assessment conducted during Phase 1. This legend also indicates the symbols to be used during the Phase 2 assessment. This will only be conducted for a subset of the capabilities examined during Phase 1.

A3.4.2 Outer Planets

The example missions used for the Outer Planets Technology Capabilities Assessment (Table A3-5) were based on the PSDS recommendations. These were grouped into the same three categories used for Venus: near-term, mid-term and far-term. The technology assessment drew on many of the analyses in the Outer Planet Roadmap of 2009[9], which will be updated in the near future as soon as the OPAG updated Science Goals and Objectives document is finalized. The capabilities taxonomy used for Venus was adapted to cover outer planets.

Many of these missions have different implementation approaches with different implications for capabilities. Detailed trade studies are needed to better characterize the options with the most current assessment of technology. Two examples of this are particularly important:

- Radioisotope power vs solar: Solar powered missions can now operate farther and farther out in the solar system as the performance of solar panels improves and larger arrays can be constructed at a competitive cost.
- Aeroassist vs. propulsion approaches: For fast orbital missions to Uranus and Neptune, these are both options. A trade study is needed to determine the range of trip times for which aerocapture is superior. Since aerocapture technology had not been evaluated for over 8 years, we held an A-team study at JPL with Langley Research Center (LaRC) and Ames Research Center (ARC) in order to determine the state of the art and the projected needs for missions, including Gas Giants. A report from this will be supplied independent of this assessment.

Table A3-5: Outer planets technology capability assessment, based on OPAG white paper but updated with PSDS information.

	Technology Information	Near-Term Missions				Mid Term Missions				Far Term Missions		
	Capability/Functionality	Europa Clipper	Europa Clipper Lander	Titan Lander Discovery	Saturn Probe (NF-4)	Uranus Orbiter & Probe	Titan Saturn System Mission	Europa Advanced Lander	Io Observer (NF5)	Enceladus Plume	Pluto Orbiter & Lander	Neptune Orbiter and Probe
System Technologies	**In Space Propulsion**											
	Aerocapture/Aeroassist					?						
	Entry											
	Descent and Deployment											
	Landing											
	Aerial Platforms											
	Landers - Short Duration											
	Landers - Long Duration											
	Mobile platform- surface near surface											
	Planetary Protection											
Subsystem Technologies	Energy Storage- Batteries		?									
	Energy Generation - Solar											
	Energy Generation - Radioisotope Power											
	Thermal Control - Passive											
	Thermal Control - Active											
	Rad Hard Electronics											
	Cold temperature mechanisms											
	Cold temperature electronics											
	Communications											
	Autonomous Operations		?									
	Guidance, Navigation and Control											
Insutrument	Remote Sensing - Active											
	Remote Sensing - Passive											
	Probe - Aerial Platform											
	In Situ Surface - Short Duration											
	IN Situ Surface - Long Duration -											
	Sampling											
	In Situ Surface - Long Duration - Mobile											

A3.4.3 Small Bodies

The example missions used for the Small Bodies Technology Capabilities Assessment (Table A3-6) were based on the selections at the PSDS subpanel for Primitive bodies. As with the other targets, they have been classified into near-, mid- and far-term. The capabilities assessment drew on work done by the SBAG[10], which completed an assessment of technology two years ago. The SBAG is interested in targets ranging from asteroids and comets to bodies in the outer solar system; e.g., Pluto, Charon, and other Kuiper belt objects that lack significant atmospheres, which has an important implication because Aerocapture technology is not an option for fast orbital missions to a body with little or no atmosphere.

Table A3-6: Small bodies technology capability assessment based on analysis by the SBAG.

	Technology Information	Ongoing and Near-Term Missions					Mid Term Missions			Far Term Missions		
	Capability/Functionality	Dawn /Vesta Ceres[1]	New Horizons Pluto[1]	OSIRIS REX[1]	Comet Nucleus SR	Trojan Tour Rendezvou	Asteroid Interior Composition	Comet Cryogenic SR	Chiron Orbiter	Pluto Orbiter	Trojan or Centaur Lander	Kuiper Belt Orbiter or Lander
	Status/Mission Type	in flight Discov.	In Flight NF-1	In Build NF-3	Candidate NF 4	Candidate NF 4	Decadal Panel Study	Decadal Panel Study	Decadal Panel Study	Concept	Concept	Concept
System Technologies	**In Space Propulsion**											
	Aerocapture/Aeroassist											
	Entry including at Earth											
	Descent and Deployment											
	Landing at target object											
	Aerial Platforms											
	Landers - Short Duration											
	Landers - Long Duration											
	Mobile platform- surface near surface											
	Sample Return											
	Planetary Protection											
Subsystem Technologies	Energy Storage- Batteries											
	Energy Generation - Solar											
	Energy Generation - Radioisotope Power											
	Thermal Control - Passive											
	Thermal Control - Active											
	Rad Hard Electronics											
	Cold temperature mechanisms											
	Cold temperature electronics											
	Communications											
	Autonomous Operations											
	Guidance, Navigation and Control									?		
Insutrument	Remote Sensing - Active											
	Remote Sensing - Passive											
	Probe - Aerial Platform											
	In Situ - Space Physics											
	In Situ Surface - Geophysical											
	Sampling											
	In Situ Surface - Long Duration - Mobile											

A3.4.4 Mars

The Example Missions were based on guidance from the Mars Program. Because this is predominantly a planned rather than a competitive program, we have a smaller mission set than any of the other three groups. Correspondingly, the Mars Technology Capabilities Assessment (Table A3-7) is focused on fewer technologies. Most of the capabilities needed have been extensively studied and well-defined technology solutions have been formulated.

Two of the key assumptions that were made in putting together this chart are

- Delays in the schedule for sample return will likely mean a greater reliance on human involvement—for capture of the sample in Mars orbit or by an earth or lunar orbiter.
- 2022 or 2024 mission will likely to be a high-resolution imager on an orbiter with electric propulsion and optical communication.

Again, since this is a dynamic environment, these assumptions may well be changed and will be reviewed when this assessment is updated next year.

Table A3-7: Mars technology capability assessment based on Mars Program evaluation.

		Outer Planets - Icy Moons					
	Technology Information	Near-Term Missions	Mid-Term Missions			Far-Term Missions	
	Capability/Functionality	Mars 2020	MSR Orbiter Mission	MSR Lander Mission	MSR Handling Facility	Robotic Precursor Missions	Human-Robotic Missions
System Technologies	Propulsion						
	Aerocapture/Aeroassist						
	Entry						
	Descent and Deployment						
	Landing						
	Mobility						
	Planetary Protection (BACK-PP/Containment Assurance)						
	Rendezvous and Sample Capture						
	Earth Entry Vehicle (EEV)						
	Mars Returned Sample Handling						
	Mars Ascent Vehicle (MAV)						
	In-Situ Resource Utilization (large scale)						
	Automated Landing of Surface Infrastructure Elements						
	Habitats						
	Surface Transportation Elements						
Subsystem Technologies	Reducing Control Electronics Volume and Mass						
	Stationary Power						
	Extreme temperature electronics and actuators						
	Thermal Control - Passive						
	Thermal Control - Active						
	Rad Hard Electronics						
	Cold temperature mechanisms						
	Cold temperature electronics						
	Communications						
	Autonomous Operations						
	Guidance, Navigation and Control						
Insutrument	Dual Wavelength Raman/Fluorescence Spectrometer						
	NIR Spectrometer						
	Smapling Acquisition and Caching						
	In-Situ Utilization (small scale)						
	Miniatruized Science Instruments						
	In Situ Surface - Short Duration						
	IN Situ Surface - Long Duration - Geophysical						
	In Situ Surface - Long Duration - Mobile Lab						

A3.4.5 Moon

Since lunar science is only called out for New Frontier missions, and LEAG has not created a Technology Plan, the only assessments that can be performed at this time are related to the mission (Lunar South Polar Aitken Basin Sample Return mission). They have been identified in the NF mission technologies in the main body of the document.

A3.4.6 Integrated Technology Capabilities Assessment

Information is summarized for the domains of interest for all five AGs. Again, this is a snapshot based on current missions and science planning and has to be revisited annually. The near-term missions in the assessment refer to mission recommended for this decade by the PSDS as modified in response to budget shortfalls and minor adjustments by the AGs. The mid-term missions correspond approximately to the mission categories that the PSDS specified in Table A3-2 as drivers for the technology priorities they identified in the plan described in Table A3-7.

Not unexpectedly, most of the technologies for the near term missions have high maturity with many ready for flight and others that can be brought to flight readiness in less than four years. The 'up' arrow indicates where those developments are currently funded. For the mid- and long-term missions, very few technologies are ready and many of those are at a moderate or low level of maturity. At present, we do not have estimates of either the time or the resources needed to bring these capabilities to maturity although we can expect to see a great deal of variability.

A3.5 Technology Commonality

Some of the capabilities depicted in Table A3-8 only apply to a small number of missions but many of them apply to 10 or more missions. What the chart does not show is what *degree* of commonality exists between the requirements for the different missions.

Differences in requirements may arise from a number of factors. Different target objects may mean quite different environments to contend with and this may mean that the capability has to be tailored to these environmental conditions. Solutions for *in situ* operations at Venus will be very different from Saturn's moon Enceladus. Different requirements may also result from differences in the mission modality. The power capabilities needed for a large orbiter would be very different from those needed by a small probe or lander, for example.

Figure A3-2 depicts the commonality and breadth of application of various technology capabilities that are important in planetary exploration. Breadth of application corresponds to the number of mission applications that appear in each horizontal set of boxes in Table A3-8. The commonality axis represents the commonality among those capabilities. Other things being equal, capabilities with a high degree of commonality will require a less complex and costly technology program.

Table A3-8: Maturity of technology capabilities for implementing planetary science missions. This information is reproduced from a Planetary Science Technology Plan update of April 9, 2015.

	Technology Information	Near-Term Missions						Mid-Term Missions						Far Term-Missions				
	Capability/Functionality	Small Bodies	Outer Planets	Venus	Mars	Moon	Common-ality	Small Bodies	Outer Planets	Venus	Mars	Moon	Common-ality	Small Bodies	Outer Planets	Venus	Mars	Common-ality
System Technologies	**In Space Propulsion**						MOD						MOD					MOD
	Aerocapture/Aeroassist	NA		Aerobrake			LOW	NA					TBD	NA				MOD
	Entry including at Earth		↑	↑		Earth	HIGH		↑	↑			HIGH					MOD
	Descent and Deployment			Plains			MOD			Tessera			MOD					MOD
	Landing at target object				↑		LOW						MOD					MOD
	Aerial Platforms			Balloon	Rotorcraft		LOW		Balloon	Balloon			MOD			Balloon		LOW
	Landers - Short Duration						NA											LOW
	Landers - Long Duration						NA											LOW
	Mobile platform- surface near surface				↑		NA											
	Ascent Vehicle						NA						LOW					LOW
	Sample Return						NA						LOW					LOW
	Planetary Protection		↑				HIGH						MOD					MOD
Subsystem Technologies	Energy Storage- Batteries						HIGH						MOD					LOW
	Energy Generation - Solar																	MOD
	Energy Generation - Radioisotope Power											?	LOW					MOD
	Thermal Control - Passive						LOW						LOW					LOW
	Thermal Control - Active																	
	Rad Hard Electronics						LOW						LOW					
	Extreme temperature mechanisms						LOW						LOW					LOW
	Extreme temperature electronics						LOW						LOW					LOW
	Communications						HIGH	Optical	Optical	Optical	Optical		HIGH	Optical	Optical	RF-HT		HIGH
	Autonomous Operations						HIGH						HIGH					
	Guidance, Navigation and Control				↑		HIGH						HIGH					HIGH
Instrument	Remote Sensing - Active		↑				MOD						LOW					HIGH
	Remote Sensing - Passive		↑				HIGH						HIGH					HIGH
	Probe - Aerial Platform						LOW						MOD					LOW
	In Situ - Space Physics																	
	In Situ Surface - Geophysical												LOW					LOW
	Sampling						LOW						LOW					HIGH
	In Situ Surface - Long Duration - Mobile						LOW						LOW					LOW

TRL Maturity Legend	
	Very High. Ready for flight. Same as TRL 6
↑	**High. Funding is in place to advance to Very High in one to four years**
	High. Limited development and testing still needed
	Moderate. Major R&D effort needed.
	Low. Major R&D effort needed with notable technical challenges

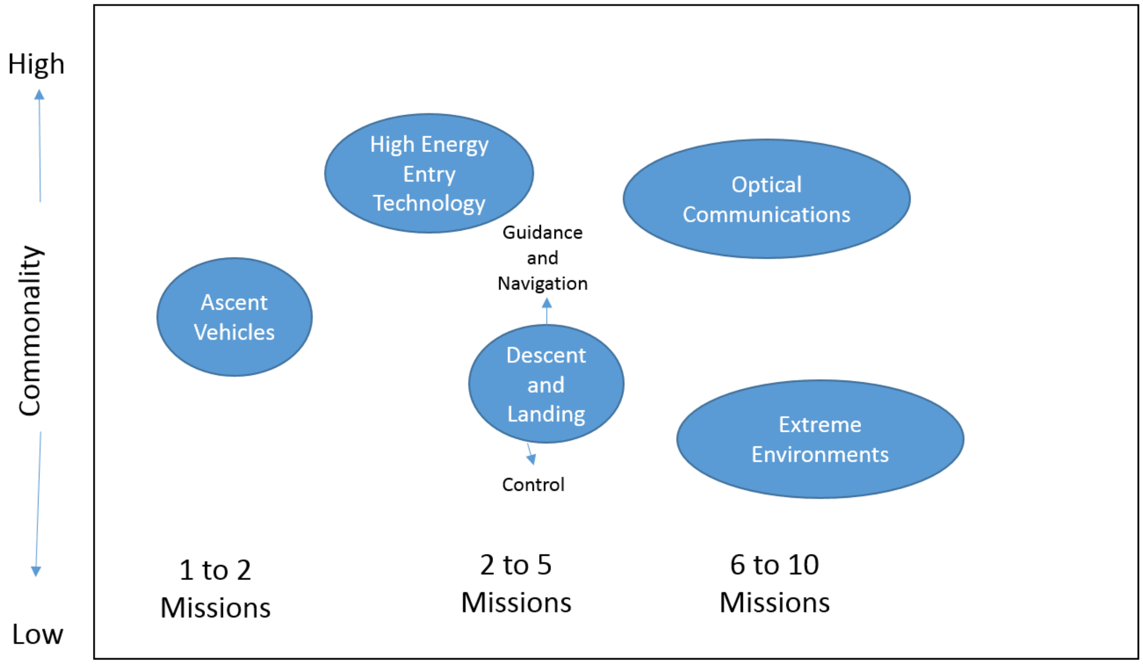


Figure A3-2: Breadth of mission applications and commonality of various technology capabilities important to planetary explorations.

Ascent Vehicles: These have a very limited breadth of applicability and low commonality. The technology for lunar ascent vehicles is mature, Mars is currently the major challenge and Venus is so far in the future that it will have very little influence on a design effort.

High-Energy-Entry Technology: The technical challenges for entry of robotic vehicles at Mars and Titan are now well understood. The main challenges are now the higher energy entry environments at Venus, the Outer Planets and for Sample Return to Earth. With the development of the High-Energy Entry Environment Technology (HEEET), which is now underway, there appear to be solutions, which have a great deal in common for all of these targets.

Descent and Landing: This technology capability has moderate to broad applicability as indicated in Figure A3-2 and moderate commonality. On the one hand, the guidance techniques such as terrain-relative navigation can be adapted to many different targets and so this displays high commonality. On the other hand, the control functions will be different for airless bodies and for bodies with atmosphere, where they are influenced by the density of the atmosphere and therefore will be quite different for Mars, Venus and Titan, which puts commonality on the low side.

Optical Communications Technologies: These technology capabilities have broad applicability to the mid- and far-term missions identified in Table A3-8, since they are generally implemented from an orbital spacecraft where the environment can be more easily controlled whatever the location in the solar system, the technical solutions have a high degree of commonality.

Extreme Environment technologies: These capabilities also have broad applicability to mid- and far-term mission. However, since they generally apply to *in situ* missions where coping with the environment is much more challenging, commonality is moderate to low degree. Technologies required in a hot surface environment such as Venus will be very different than for an icy satellite. Nevertheless, within the group of icy satellites, there will be a fair degree of commonality with satellites further from the sun, in general, posing the greater thermal and power challenges.

A3.6 Inputs from NASA Centers and APL

Inputs were sought from NASA Centers involved in planetary exploration and technology development as well as APL. APL, ARC, GRC, GSFC, JPL, LaRC and MSFC all responded although MSFC identified only a specific instrument and thus is not included here. (Note: George Tahu identified that the hot fire test of the In-Space Engine (ISE-100) Divert Attitude Control System (DACS) thruster that MSFC was working on with industry is still needed). The inputs are all reproduced below in Tables A3-9 through A3-13. There was substantial confirmation of the needs identified described in Section A3.5 that were received from other sources. There were a few new items, some of which are still being evaluated, but in general, the overlap with existing documents was excellent and very few new technologies were identified.

Table A3-9: Technology needs for planetary science identified by Goddard Space Flight Center.

Power

- *Radioistotope-based*: more efficient, lower mass and volume than MMRTG, e.g. some ASRG derivative to deal with limited plutonium.
- *Solar*: The next generation advanced Solar panels and solar panel concentrators for deep space missions and SEP missions when RPS is unavailable or unaffordable.

Propulsion

- Small advanced SEP systems.

Communications

- Laser communication.

Proximity Operations Systems

- Accurate low cost laser-based prox ops systems that are better than today's options and can provide the needed accuracy and flexibility without the size and cost of radar or existing systems

Sample acquisition and storage systems

- Next generation of sample acquisition and storage systems for colder storage, stratigraphy, high or low temperature targets
- Volatiles sample storage and monitoring – need for a large set of sample targets.

Entry, probes and landing

- Lower mass, more flexible entry systems for needed in situ missions – need lower mass, more angle range etc.
- Lower cost lander and probe systems for those missions.

Instruments

- Super high res mass specs – next gen - not TOF or current high TRL version. GSFC works a lot on this.
- Low cost Planetary capable microsats – power, thermal, comm, propulsion capabilities in a small package.
- Near and far IR instruments for 1-2U form factor.
- Low mass focal plane cooling.
- Low mass LIDARS for either Earth applications or deep space exploration. – GSFC works a lot on this

Extreme Environments

- Electronics for extreme conditions (including very high radiation).
- High temperature survivability for small landers and probes
- High temperature power and sensors for Venus and other targets like active volcano sites.

Table A3-10: Technology input from JHU Applied Physics Laboratory.

Power:

- Stirling radioisotope power system
- Higher efficiency solar arrays for LILT missions
- Non-radioisotope power systems (Advanced metal-combustion engines)

Propulsion:

- NeXT ion engine system

Navigation:

- TRANSIT-like system for planetary Nav

Attitude Control:

- Low mass, lower power optical sensors
- Low mass, lower power IMU

Sampling:

- Cryo. sample storage system that preserves volatiles

Entry Vehicles and Probes:

- Multi-mission entry vehicle (Earth, Mars, Lunar, Atmospheric probes) - currently not available as a commodity – big need here

Instruments:

- Miniature instruments for Micro/NanoSats
- Mass spectrometer inlet systems

Materials:

- Lighter weight TPS
- Robust TPS to replace Carbon Phenolic

Software/Embedded systems:

- Big investments needed here (cross system) as technology moves forward as being software driven vs. hardware driven

19

Table A3-11: Technology inputs from JPL.

Entry and Probes

- Aeroentry thermal protection systems for extreme environments (Venus, giant planets, ice giants) e.g. HEEET and ADEPT.
- Aerocapture (Titan, Uranus, Neptune). Atmosphere definition needed for latter two.
- High-g survivable surface impactors/penetrators
- Long-life planetary aeromobility systems (balloons, helicopters, planes)

Power

- Higher efficiency LILT solar cells enabling solar operation deeper into the solar system
- Higher specific power RPS
- CubeSat to SmallSat scale RPS
- RPS systems that can work at T ranging from -180° C to 450° C

Surfaces

- Venus surface access and survivability: safe landing, sampling and coring, power/thermal management (very high temperature and pressure)
- Icy moon safe landing
- Cryogenic surface sampling and coring for primitive bodies and Icy moons
- Components for extreme environments (low temp, high temp, , high P, shock)
- Planetary protection technologies/methods for sample return from habitable zones

Miniaturization

- Low mass, low power flight elements and subsystems
- Miniature, low mass and power, high performance instruments

Table A3-12: Technology input from NASA Langley Research Center.

- **Integrated Radio/Optical Deep Space Comm. (iROC, SCaN):**
  - Eliminates the need for an optical beacon uplink to establish pointing
  - Provides a more robust solution tolerant of intermittent clouds at the ground station (current TRL is 3)
- **Superconducting Quantum Interference Filter (SQIF,SCaN/ GCD)**
  - Provides for detection of downlink signal at near the quantum limit
  - Would deploy on a 7 meter class space antenna and relay signal to ground
- **Large Deployable Antenna (SCaN)**
  - 7 meter class antenna development now under way
  - 5 meter class has been demonstrated with 50% efficiency up to 50 GHz
- **Gimbals (SCaN)**
  - Pursued as part of iROC project
  - Driver is minimizing mass for iROC (current TRL is 2-3)
- **Propulsion**
  - Solar Sails

Table A3-13: Technology inputs from Ames Research Center. This is a summary of the inputs; the original also contains a detailed description of the ARC TPS and instrument capabilities.

- **Thermal Protection Systems**
  - Low Ballistic Coefficient Drag and Lift Modulating Systems
  - Multifunctional integrated TPS
  - Sample Return from outer planets
  - Non Propulsive spacecraft deorbit technology
- **Small Satellites/CubeSats for Deep Space Missions**
  - Robust designs for longer lifetimes
  - Radiation tolerance
  - Advanced board and box-level designs
- **Modular Reusable Spacecraft**
  - Focus on low cost missions
  - Diverse applications
  - Broad range of component technologies in common with larger missions
- **Instruments**
  - In situ instruments
  - Remote sensing instruments
  - Sample handling
  - Cubesat compatible instruments

A3.7 NASA Technology Programs Supporting Planetary Science

A key part of formulating the work that is funded by PSD in planetary science is to have a comprehensive understanding of technology work that is funded by PSD, elsewhere within NASA, elsewhere within the government, by foreign space agencies and by industry. With this knowledge, duplication can be avoided and opportunities for productive partnerships can be identified. This section describes how this is being approached by the PSD.

A3.7.1 Assessment of the Current PSD Technology Program

A detailed graphical depiction of the funding information that appears in Table 2 (Section 3.3.1 of the main TP document) is presented in Figure A3-3 and Figure A3-4. This depiction illustrates the funding categories and the breakdown of real technology work and management/other support functions. The key provides a breakdown of technologies within the Technology Funding line (yellow) and those supported under other programs.

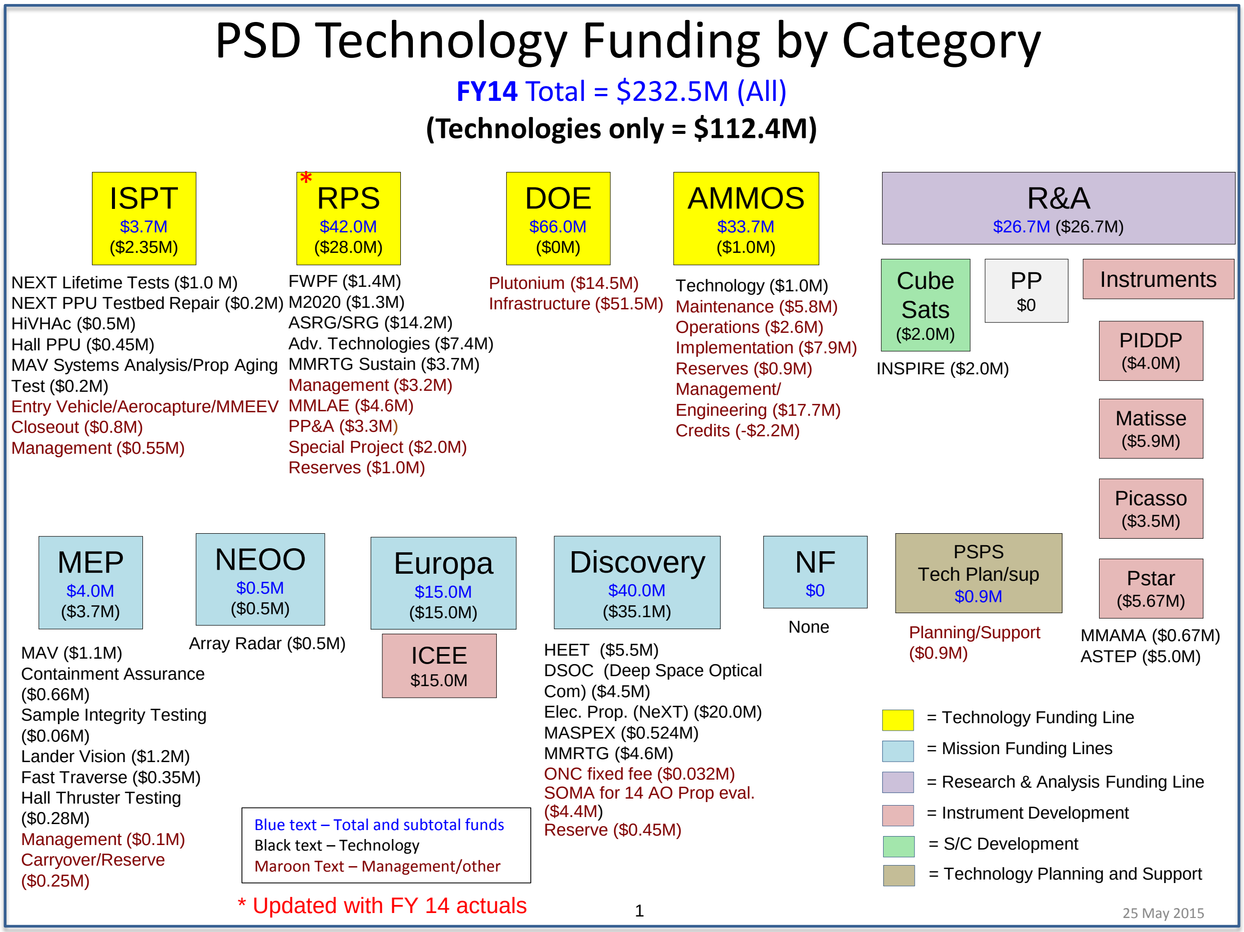


Figure A3-3: Funding for PSD Technology tasks in FY14 (actuals).

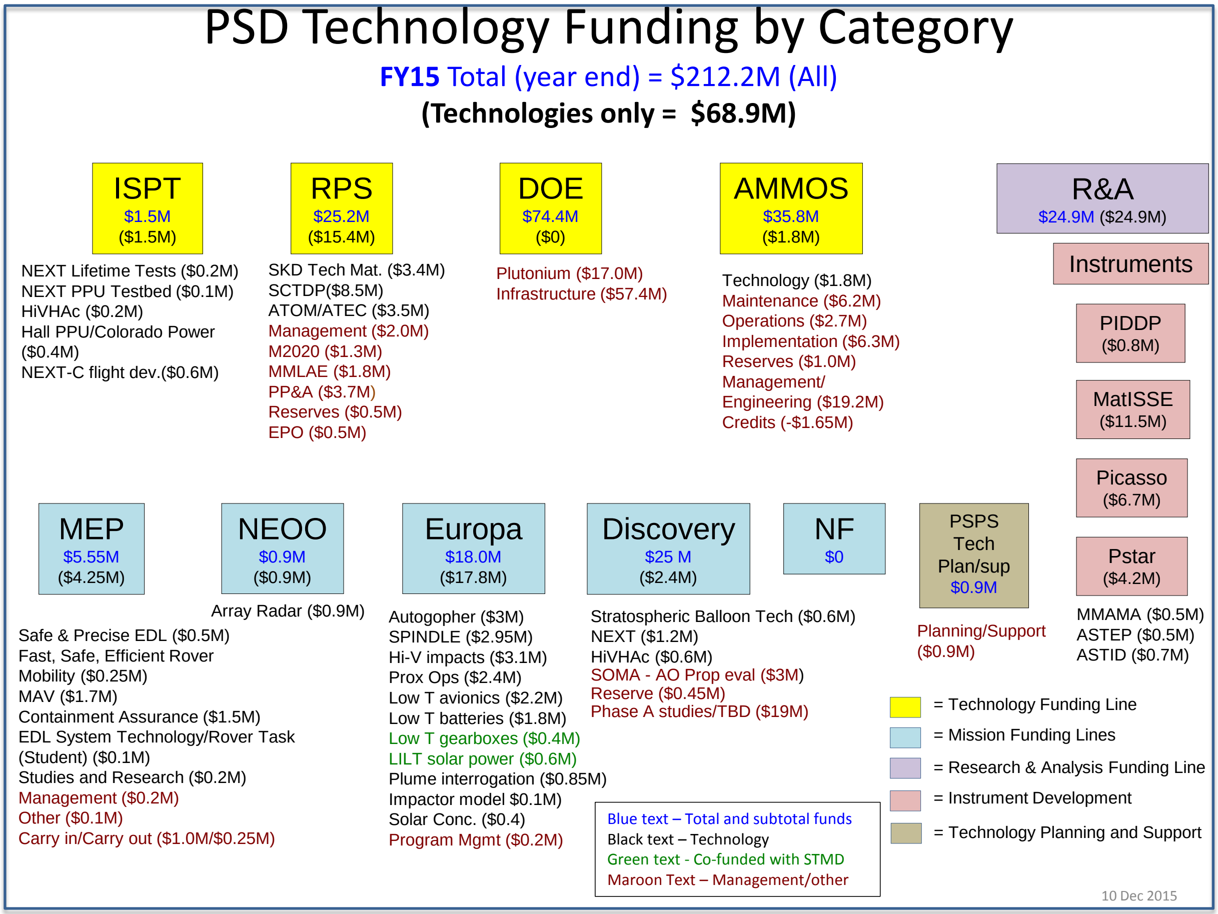


Figure A3-4: Funding for PSD Technology tasks in FY15 (actuals).

Flight programs and projects are often involved in technology development; e.g., the Discovery is based on discussions with the project and program managers. The RPS program is currently not identified as technology development, but rather infrastructure development. Note that the PSD-funded technologies are well below the guidelines set by the Decadal Survey:

Table A3-14: PSD Technology Funding Summary for 2015
(Note that this is the same table as in Chapter 3 of the main TP document).

Funding Source	Total FY15 Technology Funding Applied to PSD	% FY15 of PSD Budget ($1,438M)	Cumulative % of FY15 PSD Budget
PSD	$69.0	**4.8%**	4.8%
STMD	$22.4	**1.6%**	6.4%
HEOMD	$7.0	**0.5%**	6.8%

A3.8 Space Technology Mission Directorate (STMD)

The STMD was formed in 2012 with the goal of rapidly developing, demonstrating and infusing revolutionary, high-payoff technologies into space applications. When the PSDS formulated its technology recommendations in Vision and Voyage, STMD did not exist, and it was necessary to determine the extent to which the STMD projects and task supplied useful technologies to the PSD. This was evaluated and quantified.

A3.8.1 Relevance of STMD Programs to PSD

In the first year, the STMD program was formulated in response to new concepts emerging from NASA Centers. This initial assessment focused on the goals of the tasks in two programs: Game-Changing Development (GCD), which focuses on moving technology from TRL 4 to 6, and Technology Demonstration Missions (TDMs) which focused on flight validation of technology. The conclusions of this assessment were that there was a great deal of work that was potentially of interest in both of these STMD program. A summary of that initial assessment for the GCD program appears in Table A3-15. Technologies where more information was needed to complete an assessment are described in Table A3-16.

Table A3-15: Assessment of Game-Changing Development technologies and PSD needs, January 2015.

Thematic Projects	Start FY	Finish FY	Approved Budget ($M)					PSD Relevance		Technical Progress	Benefits to PSD
			PY11	PY12	PY13	PY14	Total	Area	Project		
A. Lightweight Materials and Advanced Manufacturing (LMAM)			$7.79	$17.07	$12.08	$14.79	**$51.73**				
Composite Cryotank Technologies and Demonstration (CCTD)	FY11	FY14	$7.79	$17.07	$9.62	$4.91	$39.39				
Advanced Manufacturing					$1.52	$5.82	$7.34				
Nanotechnology					$0.94	$4.06	$5.00				Needs analysis
B. Future Propulsion and Energy Systems (FPES)			$7.79	$17.07	$12.08	$14.79	**$51.73**				
Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS)	*FY12*	*FY14*		*$2.69*	*$4.10*	*$4.83*	$11.62			Canceled	
ISS SPHERES Fluid Slosh Experiment	*FY11*	*FY14*	*$0.15*	*$1.53*	*$0.04*	*$0.07*	$1.79				
Electro-Dynamic Debris Eliminator (EDDE) - Clean Space	*FY12*	*FY14*		*$2.87*	*$0.06*	*$0.00*	$2.93				
Nuclear Systems				$4.61	$3.38	$3.51	$11.50				
Advanced In Space Propulsion (AISP)					*$3.27*	*$2.22*	$5.49				Needs analysis
Advanced Space Power Systems				*$6.14*	*$6.06*	*$3.57*	$15.77				
C. Affordable Destination Systems and Instruments			$2.09	$16.33	$18.01	$18.80	**$55.24**				
High Performance Spaceflight Computing (HPSC)	*FY12*	*FY14*		$1.36	$0.95	$0.20	$2.51				
Deep Space Optical Communications (DSOC)	*FY11*	*FY17*	$1.60	$3.72	$1.48	$0.10	$6.90				
Fast Light Optical Gyroscopes for Precision Inertial Navigation (FLOG)	*FY13*	*FY14*			$0.60	$0.10	$0.70				Need analysis
Station Explorer for X-Ray Timing and Navigation Technology (SEXTANT)	*FY11*	*FY18*	$0.49	$1.88	$3.88	$4.86	$11.11				
AFTA Coronagraph Technology Development	*FY14*	*FY17*				$2.00	$2.00				
Space Synthetic Biology (SSB)	*FY12*	*FY19*		$1.99	$1.68	$1.53	$5.20				
Adjustable Grazing X-Ray Optics	*FY12*	*FY14*		$0.00	$0.43	$0.03	$0.46				
Thermal Systems						$1.04	$1.04				Need analysis
Advanced Radiation Protection (ARP)				$1.29	$1.37	$1.08	$3.74				
In-Situ Resource Utilization (ISRU)					$0.14	$1.52	$1.66				
Next Genration Life Support (NGLS)				$6.09	$7.49	$6.35	$19.93				
D. Advanced Entry, Descent, and Landing			$8.70	$20.02	$18.37	$22.70	$69.80				
Entry Systems Modeling (ESM)	*FY13*	*FY19*			$3.48	$6.71	$10.19				
Thermal Protection Systems Materials				$2.20	$3.59	$2.89	$8.69				
Hypersonic Inflatable Aerodynamic Decelerator (HIAD)	*FY11*	*FY14*	$8.70	$14.66	$7.08	$5.92	$36.36				
Adaptive Deployable Entry and Placement Technology (ADEPT)	*FY12*	*FY16*		$3.16	$2.84	$2.32	$8.31				Needs analysis
Propulsive Descent Technologies (PDT)	*FY13*	*FY16*			$1.38	$4.87	$6.25				
E. Revolutionary Robotics and Autonomous Systems			$5.00	$29.67	$24.44	$13.70	$72.81				
Multi-level Autonomous Piloting System (MAPS)	*FY13*	*FY14*			$0.35	$0.43	$0.78				
Re-Entry Vehicle Adaptive Controls (ReVAC) Experiment	*FY14*	*FY14*				$0.43	$0.43				
Programmable Ultra Lightweight System Adaptable Radio (PULSAR)	*FY13*	*FY14*			$0.29	$0.29	$0.58				
Habitat Automation	*FY12*	*FY14*		$3.16	$3.54	$1.80	$8.50				
Autonomous Cryogenic Loading Operations	*FY12*	*FY14*		$4.55	$2.08	$1.15	$7.78				
Human Robotics Systems (HRS)			$5.00	$21.96	$18.18	$9.61	$54.75				Needs Analysis
Total			**$31.37**	**$100.16**	**$84.99**	**$84.79**	**$301.31**				
		V. High		High		Mod		Low		Not app	

Table A3-16: GCD tasks where further study was needed to establish relevance to PSD.

Theme	Activity	Further PSPS Study Needed
Lightweight Materials and Advanced Manufacturing	High conductivity CNT nanowires	Will projected CNT performance meet needs for planetary applications?
Future Propulsion and Energy Systems	Solar Electric Propulsion	What are propulsion requirements for planetary CubeSats and Small Sats?
Future Propulsion and Energy Systems	Batteries for extreme environments	Can requirement be met through non NASA programs (e.g. ARPA-E)?
Affordable Destination Systems and instruments	Fast optical light gyro (FLOG)	What PSD applications (e.g. in situ exploration) would the FLOG have?
Affordable Destination Systems and instruments	20K and 2W refrigerator	What benefits would this technology have for outer planet orbiters?
Advanced Entry Descent and Landing	Adaptive Deployable Entry and Placement (ADEPT)	What applications does ADEPT have to Venus and Outer planet exploration?
Revolutionary Robotics and Autonomy	Robotics	What are highest priority technologies for robots sent to explore beyond the reach of human missions?
Revolutionary Robotics and Autonomy	Autonomy	What are synergies between PSD needs (AMMOS) and human program needs?

In some cases, not enough information was available to determine relevance to PSD needs or more information would allow a better assessment of whether the technical goals could be achieved. For these cases, the note "Needs Analysis" appears in the last column of Table A3-15. For these cases, the specific questions are identified in Table A3-16. Several of these questions are being addressed through the PSPS task and will be detailed in upcoming reports.

A3.8.2 Assessment of Progress in STMD Programs Relevant to PSD

In the second and third year, the nature of the assessment of the STMD program evolved. For the ongoing tasks, the emphasis changed from assessing relevance of the entire programs to looking in more detail on those activities that were of most relevance to PSD. JPL attends the quarterly reviews of the program and provides feedback not only to PSD but also to STMD management when they need to understand if a technology can be infused into a planetary mission.

An example of such a report made in January 2015 appears in Table A3-15. This table lists all of the Game-Changing Development activities active at that time with their funding levels and indicated the relevance to the PSD of the general area and the specific project. In those cases, where the activity is relevant to PSD, the chart indicated the technical progress.

One of the goals of the PSD TP is to affect the STMD formulation process by identifying technologies that would be appropriate for STMD to fund. Information that is incorporated in the plan is already being used by the SMD Chief Technologist to help guide the selection of new areas of work. Having a credible infusion plan is critical to the STMD mission and PSD offers a set of challenging missions for infusing technology and at the same time enabling new science.

A3.8.3 STMD Technology Funding Relevant to PSD Programs

The PSDS established a goal for planetary science funding of 6 to 8% of the total spending on planetary science by NASA (see Section A3.3). It also defined a recommended allocation of those funds. When those targets were set, the PSDS did not realize that NASA's Planetary Science budget was going to be cut as severely as it was in the years beginning in FY13. Neither did it anticipate that STMD would come into being and play such a prominent role.

STMD addresses the needs of a broad range of customers but does not systematically characterize the prime beneficiaries for its work. Accordingly, we have attempted here to assess the portion of the funding that is applicable to planetary science. We have used the following approach to assess this for both the GCD and HEOMD's Advanced Exploration Systems (AES) program discussed in Section A3.10

1. Assess the relevance of the general area of technology to PSD and place it in one of five categories. Very High, High, Moderate, Low, and Not Applicable.
2. Assess the relevance of the specific task to PSD using the same scale. A PSD Relevance weighting factor was then applied to the budget data with Very High (designated 1.0), High (designated 0.2), all other categories rated zero.
3. The uniqueness of this technology to PSD applications on a scale of High, Medium, Low, and Not Applicable. PSD Uniqueness weighting factors of 1.0, 0.3 0.1 and 0 were applied to these designations.

The results of this assessment appear in Table A3-17a and Table A3-17b for GCD and TDM projects, respectively. The PSD relevant funding for FY14 and FY15 reflects application of these weighting factors. FY16 funding is not available yet. Funding of a technology task rated very high need coupled with high uniqueness to PSD (in other word not applicable to HEOMD, other divisions of SMD, for example) would be fully credited to PSD relevance. Other combinations would be discounted by various amounts. Clearly, the relevance data here are sensitive to the choice of a weighting factor and the Excel workbook has been constructed so these sensitivities can easily be evaluated.

A3.9 Human Exploration and Operations Missions Directorate (HEOMD)

The Human Exploration element of HEOMD is focused on the needs of the human exploration program and not surprisingly a much smaller portion of the work is relevant to PSD. However, the Operations activity is of great relevance to Planetary Science and there is important work in telecommunications that is being conducted there.

A3.9.1 HEOMD Advanced Exploration Systems program (AES)

A summary of HEOMD's AES projects and their applicability appears in Table A3-18. Because of resource limitations, this work is not monitored to the same depth as STMD GCD but key developments are noted**.** There is little relevance to PSD in the tasks in the first three "domains": Crew Mobility, Deep Space Habitation, and Vehicle Systems. The potential areas of commonality are the three domains with application to robotic systems or low-TRL technologies: Foundational Systems, Robotic Precursors, and Next-Step Broad Agency Announcement (BAA).

Table A3-17a: STMD GCD technologies with applicability to PSD missions.

STMD GCD Thematic Projects/Elements	FY15 Status	Start FY	Finish FY	Approved Budget ($M) FY14	FY15	FY16	PSD Relevance Area	Cat	Unique	Relevance Weighting	Uniqness Weighting	PSD Applicable Funding ($M) FY14	FY15	FY16	Technical Progress
A. Lightweight Materials and Advanced Manufacturing (LMAM)				$14.27	$15.07							$0.14	$0.16		
Minimalistic Advanced SoftGoods Hatch (MASH)	Impl	FY14	FY16	$2.02	$3.61			5	H	0.00	1.00	$0.00	$0.00		
Advanced Manufacturing technologies (AMT)		FY14	FY18	$6.75	$4.90			3	L	0.00	0.10	$0.00	$0.00		
Nanotechnology (NT)		FY13	FY17	$3.50	$2.96			2	L	0.25	0.10	$0.09	$0.07		
Light-Weight Materials and Structures		FY13	FY18	$2.00	$3.60			2	L	0.25	0.10	$0.05	$0.09		
B. Future Propulsion and Energy Systems (FPES)				$13.40	$9.50							$0.40	$0.27		
Affordable Vehicle Avionics (AVA)	Impl	FY15	FY16	$1.62	$0.85			4	L	0.00	0.10	$0.00	$0.00		
Nuclear Systems (NS)		FY12	FY18	$3.51	$4.72			3	L	0.00	0.10	$0.00	$0.00		
Advanced In-Space Propulsion (AISP)		FY13	FY17	$3.95	$2.72			1	L	1.00	0.10	$0.40	$0.27		
Advanced Space Power Systems (ASPS)		FY12	FY20	$4.32	$1.22			3	L	0.00	0.10	$0.00	$0.00		
Extreme Environments Solar Power (EESP)	Impl	FY16	FY20					1	L	1.00	0.10				
C. Affordable Destination Systems and Instruments (ADSI)				$18.21	$18.27							$2.88	$5.40		
High Performance Spaceflight Computing (HPSC)*	Impl	FY12	FY20	$0.39	$0.15	$1.01		1	L	1.00	0.10	$0.04	$0.02		
Deep Space Optical Communications (DSOC)**	Impl	FY12	FY17	$2.80	$5.32	$7.50		1	H	1.00	1.00	$2.80	$5.32		
Station Explorer for X-ray Timing and Navigation Technology (SEXTANT)	Impl	FY11	FY18	$5.06	$3.46			4	NA	0.00	0.00	$0.00	$0.00		
AFTA-WFIRST Coronagraph Technology Development (ACT)	Form	FY14	FY17	$2.19	$0.95			3	NA	0.00	0.00	$0.00	$0.00		
Space Synthetic Biology (SSB)		FY12	FY17	$1.57	$1.86			5	NA	0.00	0.00	$0.00	$0.00		
Thermal Systems (TS)		FY14	FY18	$1.71	$2.57			2	L	0.25	0.10	$0.04	$0.06		
Advanced Radiation Protection (ARP) Thick GCR Shield	Impl	FY14	FY18	$1.10	$1.57			4	L	0.00	0.10	$0.00	$0.00		
In-Situ Resource Utilization (ISRU)		FY15	FY20		$6.60			4	L	0.00	0.10	$0.00	$0.00		
Next Genration Life Support (NGLS)		FY12	FY17	$6.68	$4.70			5	L	0.00	0.10	$0.00	$0.00		
High Dynamic Range Stereo X (HiDyRS-X)	Impl	FY15	FY16		$0.21			5	NA	0.00	0.00		$0.00		
D. Advanced Entry, Descent, and Landing (AEDL)				$23.48	$26.80							$1.90	$3.85		
Propulsive Descent Technologies (PDT)	Impl	FY14	FY16	$4.85	$2.80			3	M	0.00	0.30	$0.00	$0.00		
Adaptive Deployable Entry and Placement Technology (ADEPT)	Impl	FY12	FY18	$2.32	$2.17			2	M	0.25	0.30	$0.17	$0.16		
Entry Systems Modeling (ESM)		FY13	FY18	$13.45	$10.93			2	M	0.25	0.30	$1.01	$0.82		
Thermal Protection Systems - Materials (TPS-M)		FY13	FY17	$2.87	$8.16			2	H	0.25	1.00	$0.72	$2.04		
MSL Entry Descent & Landing Instrument (MEDLI) 2***	Impl	FY15	FY21		$2.74	$3.72		1	M	1.00	0.30		$0.82		
Ocean Worlds Europa Tech		FY16	FY17			$3.10		1	H	1.00	1.00				
E. Revolutionary Robotics and Autonomous Systems (RRAS)				$23.30	$36.64							$0.00	$0.00		
In-Space Robotic Servicing (ISRS)	Impl	FY11	FY20	$10.00	$10.00			3	L	0.00	0.10	$0.00	$0.00		
Autonomous Systems (AS)		FY12	FY17	$4.30	$2.10			3	L	0.00	0.10	$0.00	$0.00		
Human Robotics Systems (HRS)		FY12	FY17	$9.00	$14.11			3	L	0.00	0.10	$0.00	$0.00		
Human Exploration Robotics 2 (HET 2)		FY14	FY17		$9.59			3	L	0.00	0.10		$0.00		
Integrated Display & Environmental Awareness System (IDEAS)	Impl	FY15	FY16		$0.84			5	L	0.00	0.10				
Po-up Flat Folding Explorer Robots (PUFFER)	Impl	FY16	FY17					1	M	1.00	0.30				
Total				$92.66	$106.28							$5.31	$9.68		

LEGEND: Applicability to PSD
- Cat 1 – Very High
- Cat 2 – High
- Cat 3 – Moderate
- Cat 4 - Low
- Cat 5 - N/A

Table A3-17b: STMD TDM technologies with applicability to PSD missions.

STMD TDM Projects	Approved Budget ($M) FY15 Cost	FY16 Plan	PSD Relevance Area	Task Cat	PSD Unique	Relevance Weighting	Uniqness Weighting	PSD Applicable Funding ($M) FY15	FY16	Technical Progress
Low Density Supersonic Decelerator (LDSD)	$38.00			1	M	1.00	0.30	$11.40		
Laser Communication Relay Demonstration (LCRD)	$37.00			5	M	0.00	0.30	$0.00		
Solar Electric Propulsion (SEP)	$35.90			5	M	0.00	0.30	$0.00		
Green Propellant Infusion Mission (GPIM)	$16.10			3	M	0.00	0.30	$0.00		
Evolvable Cryogenics (eCryo)	$12.90			4	L	0.00	0.10	$0.00		
Composites for Exploration Upper Stage (CEUS)	$6.90			4	L	0.00	0.10	$0.00		
Deep Space Atomic Clock (DSAC)	$4.48			1	M	1.00	0.30	$1.34		
Inactive TDM Projects and Program Support	$10.10			5	NA	0.00	0.00	$0.00		
TDM Total	$161.38							$12.74		

LEGEND: Applicability to PSD
- Cat 1 – Very High
- Cat 2 – High
- Cat 3 – Moderate
- Cat 4 - Low
- Cat 5 - N/A

The funding relevant to PSD applications has been determined with the same approach used for GCD and with the same weighting factors and appears in the columns to the right of the table. The FY14 data were not available for this analysis but the FY15 data were.

A3.9.2 HEOMD Space Communications and Navigation (SCaN) Program

HEOMD's SCaN program plays a vital role in supporting and developing infrastructure that is important to planetary exploration. For example, (1) STMD TDM and SCaN are funding the development of the Deep Space Atomic Clock (DSAC) and (2) STMD GCD, SMD and SCaN are funding Deep Space Optical Communications (DSOC). SCaN has also been funding the Integrated Radio and Optical Communication system (iROC--hybrid RF-Optical Flight system) at GRC (see Table A3-19). However, much of SCaN's "technology" funding is going toward the SCaN Testbed (STB) and the Laser Communication Relay Demonstration (LCRD) with STMD, which tend to be near-Earth technologies although some small percentage might be extensible to deeper space.

Table A3-18: HEOMD AES technologies with applicability to PSD missions.

HEOMD AES Thematic Domain/Projects	Approved Budget ($M)		PSD Relevance		PSD	Relevance	Uniquess	Applicable Funding		Technical
	FY15 Cost	FY16 Plan	Area	Task Cat	Unique	Weighting	Weighting	FY15 $M	FY16 $M	Progress
A. Crew Mobility Systems Domain	**$1.65**	**$19.39**						**$0.00**	**$0.00**	
Advanced EVA - PLSS and Z-2 Space Suit	$1.65	$19.39		4	L	0.00	0.10	$0.00	$0.00	
B. Deep Space Habitation Systems Domain	**$52.74**	**$47.50**						**$0.00**	**$0.00**	
Exploration Augmentation Module (EAM)	$7.00			5	NA	0.00	0.00	$0.00	$0.00	
Bigelow Expandable Activity Module (BEAM)	$3.94	$1.68		5	NA	0.00	0.00	$0.00	$0.00	
Life Support Systems (LSS)	$15.39	$16.34		4	L	0.00	0.10	$0.00	$0.00	
Radiation Protection	$9.90	$9.35		5	NA	0.00	0.00	$0.00	$0.00	
Logistics Reduction	$4.70	$7.59		5	NA	0.00	0.00	$0.00	$0.00	
In-Space Manufacturing	$3.60	$3.09		5	NA	0.00	0.00	$0.00	$0.00	
Spacecraft Fire Safety	$8.20	$9.46		5	NA	0.00	0.00	$0.00	$0.00	
C. Vehicle Systems Domain	**$25.50**	**$14.16**						**$0.00**	**$0.00**	
AES Modular Power Systems (AMPS)	$4.50	$3.97		5	NA	0.00	0.00	$0.00	$0.00	
Lander Technology - Lunar CATALYST, RP Lander and ALHAT infusion	$11.30	$10.20		3	M	0.00	0.30	$0.00	$0.00	
Nuclear Cryogenic Propulsion Stage	$9.10	$0.00		5	NA	0.00	0.00	$0.00	$0.00	
Fiber Optic Sensors	$0.60			5	NA	0.00	0.00	$0.00	$0.00	
D. Foundational Systems Domain	**$15.10**	**$13.02**						**$2.80**	**$2.54**	
Autonomous Systems and Operations (ASO)	$7.30	$5.56		4	L	0.00	0.10	$0.00	$0.00	
Avionics and Software (Core Flight Software)	$4.10	$3.89		3	L	0.00	0.10	$0.00	$0.00	
Disruption Tolerant Networking (DTN)	$2.80	$2.54		1	H	1.00	1.00	$2.80	$2.54	
Ka-Band Objects Observation Monitoring (KaBOOM)	$0.90	$1.03		5	NA	0.00	0.00	$0.00	$0.00	
E. Robotic Precursors Domain	**$37.26**	**$46.93**						**$1.54**	**$1.49**	
Resource Prospector	$15.20	$13.20		4	L	0.00	0.10	$0.00	$0.00	
EM-1 Secondary Payloads	$9.35	$20.19		3	M	0.00	0.30	$0.24	$0.55	
Lunar Flashlight	$3.20	$5.72		4	L	0.00	0.10	$0.00	$0.00	
Bio-Sentinel	*$3.01*	*$7.16*		5	NA	0.00	0.00	$0.00	$0.00	
Near Earth Asteroid (NEA) Scout	*$3.14*	*$7.31*		2	M	0.25	0.30	$0.24	$0.55	
Solar System Exploration Research Virtual Institute (SSERVI)/LMMP*	$5.17	$4.14		5	NA	0.00	0.00	$0.00	$0.00	
Radiation Assessment Detector (RAD)	$2.00	$0.79		4	L	0.00	0.10	$0.00	$0.00	
Mars 2020 Payloads	*$5.54*	*$8.61*		4	L	0.00	0.10	$1.30	$0.95	
Mars Oxygen In Situ Resource Utilization Experiment (MOXIE)	$2.80	$6.90		5	NA	0.00	0.00	$0.00	$0.00	
Mars Environmental Dynamics Analyzer (MEDA)	*$1.44*	*$0.76*		5	NA	0.00	0.00	$0.00	$0.00	
MSL Entry Descent & Landing Instrument 2 (MEDLI-2)	*$1.30*	*$0.95*		1	H	1.00	1.00	$1.30	$0.95	
F. NextSTEP BAA	*$0.00*	*$13.75*		3	L	0.00	0.10	$0.00	$0.00	
Three Advanced Propulsion Systems Awards				2	M	0.25	0.30			
Ad Astra Rocket Co for a VASIMR Rocket Core Testing										
Aerojet Rocketdyne for Ops demo of 100 kW EP										
MSNW LLC for flexible high power electric Propulsion										
Two BAA Small Satellite Awards				4	M	0.00	0.30			
6U Lunar IceCube by Morehead State University										
Skyfire 6U CubeSat by Lockheed Martin										
Seven Habitation Awards				5	NA	0.00	0.00			
Total	$132.25	$154.75						$4.34	$4.03	

LEGEND: Applicability to PSD

- Cat 1 – Very High
- Cat 2 – High
- Cat 3 – Moderate
- Cat 4 - Low
- Cat 5 - N/A

Table A3-19: HEOMD SCaN technologies with applicability to PSD missions.

HEOMD SCaN Projects	Approved Budget ($M) FY15 Cost	PSD Relevance Area	PSD Relevance Task Cat	PSD-Unique	Relevance Weighting	Uniqness Weighting	PSD Applicable Funding FY15	Technical Progress
Deep Space Optical Comm (DSOC)	$1.24		1	M	1.00	0.30	$0.37	
Deep Space Atomic Clock (DSAC)	$7.58		1	M	1.00	0.30	$2.27	
TDM Total	**$8.82**						**$2.64**	

LEGEND: Applicability to PSD

Cat 1 – Very High
Cat 2 – High
Cat 3 – Moderate
Cat 4 - Low
Cat 5 - N/A

A3.10 Identifying and Filling Technology Gaps

Along with the mission and science ‘pull’, the planning process involves the development of technology roadmaps to take capabilities from where they are today to where they need to be to meet the needs of PSD mission. Of course, not all such roadmaps can be executed for resource reasons but roadmaps are a key resource for selecting technologies and for formulating credible plans to bring them to fruition.

A3.10.1 PSD Technology Roadmaps

Over the years, the PSPS task has developed a number of roadmaps and technology assessments for power technologies, extreme environments, planetary protection and guidance and control designed specifically to address the needs of Planetary Science over the last decade. These assessments can be downloaded from the NASA Solar System website[11]. For topics that are covered, they remain an important resource and one that is most focused on the specific needs of planetary science. Currently, two outdated roadmaps, solar power and energy storage, are in the process of being updated and will be published in spring of 2016.

A3.10.2 NASA Technology Roadmaps

In 2010, NASA’s Office of the Chief Technology initiated the development of roadmaps to guide the development of technology across the agency. The 2015 NASA Technology Roadmaps expanded and update the original 2010 roadmaps, providing details about anticipated NASA mission capabilities and associated technology development needs. The 2015 Technology Roadmaps were released to the public in July 2015[12]. A list of the fifteen technology roadmaps appears in Table A3-19,

The roadmaps are viewed as a cornerstone of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing technologies essential to the pursuit of NASA’s mission and achievement of National goals. The STIP will prioritize the technology candidates within the roadmaps and provides guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA’s technology prioritization. The STIP is currently in draft format.

Prior to publication of the Roadmap in July 2015, we were asked to review the content from the vantage point of the PSD. The assessment was completed and forwarded to the SMD Chief Technologist in early 2015. This task was conducted within one month and involved review of documents with more than

2,000 pages[13]. Since we had such a short time to do this, we reviewed the content primarily for omissions. Because not all the changes got into the next revisions, we also input changes during the public comment period.

Each Roadmap contains the four-level technology taxonomy with the actionable tasks consisting of a Technology Snapshot at the lowest level of the taxonomy. In order to identify omissions of PSD-relevant technologies in the NASA Technology Roadmap, we used Technology Elements defined in the PSDS survey Vision and Voyages document, already reproduced earlier in this document as Table A3-3, and prepared an overall assessment (Table A3-20). This shows that some sections of the document, notably TA02 In-Space Propulsion Technologies, TA03 Space Power and Energy Storage, TA05 Communications and Navigation and TA09 Entry Descent and Landing Systems, do an excellent job of describing technologies of actual or potential importance to PSD. Some technologies of importance to planetary science, such as Planetary Protection, are not well covered with respect to the needs of *robotic* missions. There was also little emphasis on technologies (other than instruments) for the extreme environments that exist in the outer solar system and on the surface of Venus.

Table A3-20: Fifteen individual technology roadmaps comprise the NASA Technology Roadmap with TA00 addressing cross-cutting technologies.

Code	Technology Capability	Code	Technology Capability
TA01	Launch Propulsion Systems	TA09	Entry, Descent, and Landing Systems
TA02	In-Space Propulsion Technologies	TA10	Nanotechnology
TA03	Space Power and Energy Storage	TA11	Modeling, Simulation, Information Technology, and Processing
TA04	Robotics and Autonomous Systems	TA12	Materials, Structures, Mechanical Systems, and Manufacturing
TA05	Communications, Navigation, Orbital Debris Tracking and Characterization Systems	TA13	Ground and Launch Systems
TA06	Human Health, Life Support, and Habitation Systems	TA14	Thermal Management Systems
TA07	Human Exploration Destination Systems	TA15	Aeronautics
TA08	Science Instruments, Observatories, and Sensor Systems		

Table A3-21: Assessment of how well PSD relevant technologies are covered in the 2015 NASA Technology Roadmap.

Technology Element (from PSPS Vision and Voyages)	NASA Roadmap Coverage	Rating (A,B,C,D, F)
Science Instrument		
Environmental Tolerance	Not explicit in one section but adequately addressed in TA03, TA04 and TA08	B
In Situ Sample analysis	*In situ* analysis is mentioned in TA03.3.3 but limited set of instruments described.	B
Age Dating	No snapshot on this topic.	F
Planetary Protection	In section on human exploration but only limited reference in TA08.3	C
Extreme Environments		
Survivability under high temperature and pressure	Completely absent from the document.	F
Radiation tolerance (subsystems)	Almost nothing on this topic. Radiation issues are limited to effects on humans	D
Survivability and mobility in cryogenic conditions	Limited discussion of the topic in TA4. Nothing in TA9	D
In Situ exploration		
Sample Acquisition and Handling	Detailed treatment in several sections (4. Robotics and 8 Science Instruments)	A+
Descent and ascent propulsion systems	The basic technology is covered in TA2 and Landing in TA9. No mention of skyhook.	B
Thermal protection for entry (and descent)	TA14 has a comprehensive description of what is needed.	A+
Impactor and penetrator systems	Only reference is as an aid to securing conventional landers	D
Precision Landing	Addressed in TA04, TA05 and TA09. Very well covered.	A+
Mobility on planetary surfaces	TA9. Very complete with material on sensing, mobility, systems and components.	A+
Mobility in atmospheres	Incomplete. Only two snapshots on this topic and they are not up to date.	D
Planetary Protection	Included in section on human exploration with no reference to robotic exploration	C
Solar System Access and Core Technologies		
Reduced spacecraft mass and power	Distributed through many sections	B
Improved interplanetary propulsion	Well described in TA02.	A
Low power high rate communications	Well described in TA05.	A
Enhanced autonomy	Well described in TA04	A
Enhanced computing	High performance computing described in TA11.1.1. Also covered as Avionics topic.	B
Aerocapture	Well described in TA09 (TA09.1.3 Rigid aeroshell). Need to extend to TA09.1.3 Deplo	B
Improved power sources	Well described in TA03 Some refinement still needed.	A
Innovative mission and trajectory design	Well described in TAO5 (TA05.4.2)	F

Key: Rating describes how well the NASA Technology roadmaps address PSD needs technology needs.

A+ = Excellent	A= Very Good	B= Good	C= Poor	D= Inadequate	F= Omitted

The set of Design Reference Missions (DRMs) specified was almost entirely limited to missions that were defined as near-term. Where time frames go beyond near-term, it is for competitive missions, which are largely unspecified.

Some of the errors and omissions in the technology (Table A3-15) were corrected for the final version of the Roadmap. However, there was no provision for incorporating Snapshots that were omitted in the final stage of review. This was discussed with Mike Seablom and he has been working with OCT (Faith Chandler) on plans to update the Roadmaps on a continuing basis.

A3.11 NASA Technology Roadmap Applicability

The NASA OCT Technology Roadmap is an important resource for the PSD in developing its detailed technology implementation plan. However, since there was a limited set of DRMs considered, this leads to some PSD technologies not being identified as relevant. PSD needs to continue its own efforts to ensure that work on technologies that are of broad applicability across the agency are adequately focused on PSD needs and development of technologies that are a unique interest of PSD are funded (e.g., *in situ* instruments and extreme environments technologies). More specifically:

1. It appears impractical to include the range of planetary missions that are discussed in this document in the NASA OCT Technology Plan. Hence, PSD needs to independently evaluate the breadth of application and commonality of technologies as discussed earlier in Section A3.6, particularly in Table A3-8.

2. The NASA OCT Technology plan can realistically only be updated every five years to prescribe the technologies that are important. For the rapidly evolving and complex fields or planetary science instrumentation, it appears impractical to encompass all of the instrument techniques that are evolving and will potentially become available in the near term.
3. The NASA OCT Technology Roadmap will be particularly valuable if used as a resource for judging the context and importance of innovations, particularly for instruments. However, inclusion in the Roadmap should not be viewed as a prerequisite for funding by NASA.

The OCT Technology Snapshot format for road-mapping future technology developments has been adopted for describing technologies that are important to PSD but were omitted from the July 2015 NASA Technology Roadmap update. These snapshots will be compiled in the remainder of in FY16.

A3.12 PSD Technology Roadmap

The PSD Technology Roadmap builds upon the NASA Technology Roadmap in the following way.

1. Include all relevant PSD missions in the manner that we have described in Appendix 3, Section A3.5.
2. Include references to the NASA Technology Roadmap where applicable material exists
3. Generate Technology Snapshots in the general format specified for the Roadmap where those technologies are omitted.
4. Supplement the high-level information provided in the roadmap with more detailed technology assessments and trade studies to refine knowledge of performance data.

Appendix 4: Disruptive Technologies Relevant to PSD

A4.1 Disruptive Technologies—CubeSats and SmallSats

The Planetary Science Decadal Survey[1] discussed the continuing importance of small satellites in the context of the Discovery program and the importance of miniaturization in relation to instruments. However, there is no mention of microsats, nanosats or CubeSats in the document. Since 2011, there has been a surge of interest in CubeSats with many Earth orbital flights conducted and the potential and realization for applications to deep space planetary missions. The Planetary Science Program Support Task has continued to monitor the development of this field and to provide guidance to the Planetary Science Division on possible applications to Planetary Science.

A4.1.1 CubeSat

A CubeSat is a type of miniaturized spacecraft that was conceived in 1999 at Cal Poly University and Stanford University. The original CubeSat was established as a standard 10 cm cube (referred to as 1U), a mass of about 1.5 kg and using commercial off-the-shelf electronic components (Figure A4-1). To date, hundreds of CubeSats have been launched and currently NASA launches about 30 a year to low Earth orbit (LEO). Some are in the minimal 1U configuration but most have been built with multiple cubes described as 2U, 3U up to 12U, for example.

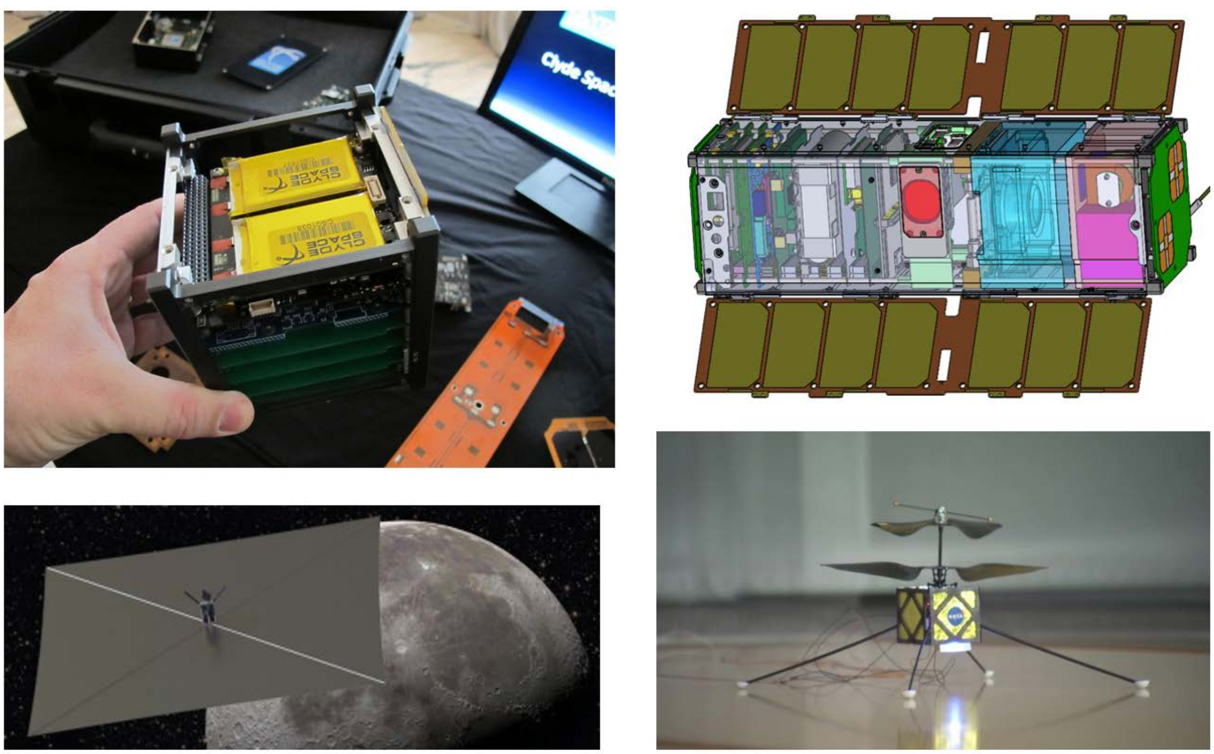


Figure A4-1: CubeSat technologies and potential for planetary explorations:
(upper left) CubeSat structure compared with the size of the human hand;
(upper right) INSPIRE, the first CubeSat designed specifically for Deep Space, uses a 3U configuration;
(lower left) Lunar Flashlight mission shows a CubeSat with a large deployed solar sail;
(lower right) Mars Helicopter is under development for possible flight on the Mars 2020 mission.

CubeSats beyond Earth orbit are an obvious next step but present challenges because they will be outside the protection of the Earth's magnetosphere, are exposed to solar and galactic cosmic rays and have to operate for months to years if they are going to be useful. However, subsystems and components are rapidly being developed and deep space CubeSats are being built; for example, Interplanetary NanoSpacecraft Pathfinder In Relevant Environment (INSPIRE) and Mars Cube One (MarCO).

A4.1.2 INSPIRE

In 2012, with partial support from the PSPS task, JPL began the development of the *INSPIRE* with the objective of demonstrating the deep space capability of CubeSat technology[14]. Prior to any inclusion on larger planetary missions, CubeSats must demonstrate that they can be operated, communicated, and navigated far from Earth—these are the primary objectives of INSPIRE. Key spacecraft components for this include a Deep Space Network (DSN)–compatible X-band radio, and the robust watchdog system will provide the basis for future high-capability, lower-cost-risk missions beyond Earth. It also includes a miniature helium magnetometer capable of conducting sensitive scientific measurements. INSPIRE was selected for flight via the NASA CubeSat Launch Initiative (CLI). Two INSPIRE 3U CubeSats were completed in 2014 (the 3U configuration is shown in Figure A4-1) and are now awaiting a flight opportunity.

A4.1.3 MarCO

Two 6U CubeSats MarCO are also being built to travel with the next Discovery mission, InSight (Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport), which will be launched to Mars and will be an integral part of communications as the spacecraft enters the martian atmosphere. During InSight's entry, descent, and landing (EDL) operations, the lander will transmit information in the ultrahigh-frequency (UHF) radio band to NASA's Mars Reconnaissance Orbiter (MRO) flying overhead. MRO will forward EDL information to Earth using the X-band radio frequency. The orbiter could receive confirmation of a successful landing more than an hour before it is relayed to Earth, but MarCO will transmit in real time back to Earth.

A4.1.4 CubeSats and exploration of Europa

In March 2014, Jim Green was asked by the Office of Science and Technology Policy (OSTP) to determine the role of CubeSat technology in the exploration of Europa. In a report prepared under the PSPS Technology Planning task[15], it was determined that a CubeSat alone could not explore Europa from Earth because

- Propellant needed to reach Jupiter, and then Europa, is unreasonable to expect from a CubeSat
- Power generation from solar arrays at Jupiter distances are too little from a CubeSat solar array
- A large antennas is needed to achieve acceptable data rates
- The mass needed to provide shielding from radiation is far in excess of what a CubeSat can support

However, the possibility existed that CubeSats, deployed by the mission then known as Europa Clipper, could

- Carry out technology demonstrations and scientific investigations with modest objectives

- Address certain science questions provided they could be implemented in a few days
- Survive for a limited lifetime because of reduced shielding and radiation tolerance

Subsequently, in October 2014, JPL selected 10 CubeSat concepts from 10 universities around the nation for feasibility studies. These are all daughtercraft that would be delivered by the Europa spacecraft.

A4.1.5 Lunar and Asteroid Exploration

While outer planet exploration is infeasible with freestanding CubeSats, exploration of targets in the inner solar system is another matter. There are several CubeSats, e.g., Lunar Flashlight (MSFC/JPL) that have been selected to fly on the first Space Launch System (SLS) Exploration Mission (EM)-1 launch in 2018 (Figure A4-1). HEOMD is using CubeSats to undertake the science identified in Strategic Knowledge Gaps (SKG). One such CubeSat is Near-Earth Asteroid Scout (NEA Scout) (MSFC/JPL), which is an exciting new mission that was recently selected by NASA's Advanced Exploration Systems (AES). This innovative, low-cost concept will map an asteroid and demonstrate several technological firsts, including being the first CubeSat to reach an asteroid.

A4.1.6 NRC Space Studies Board (SSB) Symposium

So numerous are the concepts for this CubeSat platform that the NRC SSB held a symposium in Irvine in early September 2015 "to ascertain the feasibility of obtaining high-priority science data using CubeSats." Many of the posters and discussions were centered on planetary objects. Instruments are being developed (even radar and hyper-spectral instruments) which can be housed on 1U and 2U S/C, so significant science can be accomplished in these smaller volumes. A report from the committee will be forthcoming in spring 2016, but it is clear that this is a disruptive technology that could change the way planetary science is done, particularly, if a number of high-quality, miniaturized instruments are demonstrated to have the same performance as existing instruments.

A4.1.7 Small Satellites for Outer Planet Exploration

In May 2015, JPL studied the feasibility of a Pluto Orbiter mission in response to a request from the PSD. While the study did not directly address the application of small satellites, it did illuminate the potential benefits of spacecraft in the 100- to 200-kg class for planetary exploration. The key results of the study are as follows:

- The mission is only feasible using chemical propulsion for Pluto orbit insertion if the Earth-Pluto trip times are much longer than those of New Horizons.
- Use of electric propulsion for orbit insertion is practical provided an advanced RPS is developed with specific power approximately 50% higher than multimission radioisotope thermoelectric generator (MMRTG) technology.
- Although the study did not determine the optimal mass for a Pluto Orbiter SmallSat, it appears that a vehicle in the mass range 100 to 300 kg could enable fast flight times with credible science.

A4.1.8 Application to In Situ Exploration

Microminiature vehicles for *in situ* (aerial and surface) exploration have a significant track record although there have been few unqualified successes to date.

- Two balloon missions flown to Venus by the Soviet Union in 1984. The total mass of the floating system was 21 kg, while the gondola containing power, communications and science instruments weighed only 6.7 kg. Each balloon operated for 48 hours and was tracked from Earth by the Russian and European antennas as well as the DSN. The data rate was about 2 bps.
- Micro/Nano Experimental Robot Vehicle for Asteroid (MINERVA) deployed to the asteroid Itokawa by the Japanese spacecraft Hayabusa 1 in May 2005. MINERVA weighed only 591 g and was approximately 10 cm tall by 12 cm in diameter. An error during deployment at the asteroid resulted in the craft's failure.
- Mu Space Engineering Spacecraft (third in a series—NASA, MUSES-CN), a 1.7-kg nanorover that was developed by NASA and would have also been deployed on asteroid Itokawa by Hayabusa 1, but NASA canceled MUSES-CN in 1999.

Recent technology developments including CubeSat development as well as the advances in guidance and control technology incorporated in the development of drones can be leveraged for future more capable, robust, or low-cost vehicles

- Mobile Asteroid Surface Scout (MASCOT) is built by the same team that developed Philae but it is an order of magnitude smaller and includes a hopping capability for surface mobility
- Mars Helicopter[16], under development at JPL for possible flight on Mars 2020, is a solar powered rotorcraft with sensors and electronics enclosed in a cube although not in the traditional CubeSat configuration.
- Subsurface vehicles—a variety of vehicles for subsurface exploration, which are being pursued in Europe and the US for subsurface exploration of both rocky and icy bodies.

A4.1.9. Future Prospects for CubeSats and SmallSats

While future work is needed to characterize the capabilities of CubeSats and SmallSats as a function of mass, a few general conclusions can already be drawn:

- The development of CubeSats and other kinds of miniature spacecraft creates new possibilities for planetary science. Industry is leading the way with support from NASA Centers that are experienced with deep space environments and radiation testing.
- Larger CubeSats (3U and 6U) are already being developed for technology demonstrations and even science missions to the Moon and inner planets. While the science they can do and the data rate at which they can return will be much less than conventional spacecraft, they can play a niche role.
- CubeSats are too limited in capability to serve as the primary spacecraft in an outer planet mission. However, they can serve in scientific and technical roles when carried by a larger spacecraft and then deployed near the target. One role of a CubeSat could be as a probe to profile the atmosphere of an outer planet prior to the arrival of the parent craft.
- Size is important for achieving the power and the communications capability needed for missions beyond 5 AU. While CubeSats are too small to serve as the primary spacecraft, for certain applications spacecraft in the 100- to 200-kg mass range (SmallSats) may be optimal from both a performance and cost point of view.

- While most attention is currently focused on deep space applications of CubeSats as flyby and orbiter spacecraft, they can also play a key role for *in situ* exploration where the inherent proximity to the target object can overcome some of the scientific limitations of very small vehicles.

The University of Tokyo/ Japan Aerospace Exploration Agency (JAXA) with Proximate Object Close Flyby with Optical Navigation (PROCYON), a 65-kg deep-space microspacecraft with a 10-kg payload, has already demonstrated that a deep-space SmallSat can produce scientific data. It was designed and built in 18 months and launched with Hayabusa 2 as a piggyback launch. The Mission Outline was as follows:

- Demonstration of microspacecraft bus system for deep space exploration including communication system and attitude and orbit control system. (Achieved)
- Demonstrate various deep space exploration technologies including asteroid close flyby observation. (Achieved the Heliophysics experiment but did not achieve trajectory maneuver to the asteroid)

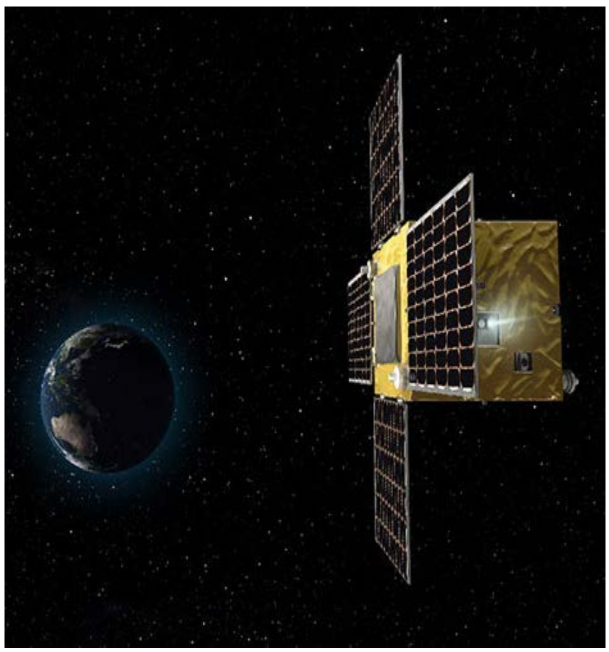


Figure A4-2: PROCYON, a 65-kg deep-space microspacecraft with a 10-kg payload and dimensions h 630 cm × w 550 cm × d 550 cm.

Appendix 5: PSD Technology Portfolio—Priority List (June 2015)

A5.1 Overview

This list of technologies requiring funding for PSD missions was originally submitted to PSD in June 2015. It includes technologies for directed missions, instruments and for competitive missions in the Discovery and New Frontiers class. It also specified some areas for advocacy to other organizations.

A5.2 Icy Bodies

A5.2.1 Landing

Intelligent Landing systems are common across the bodies. Technologies needed:

- Terrain-relative navigation
- Hazard avoidance
- Robust landing
- Science targeting
- Control methods:
  - Europa—entirely propulsive needed because no atmosphere
  - Titan—guided entry plus parafoil for targeted landing because of the dense atmosphere (same as Venus)

A5.2.2 Surface Operations and sample return

- Cryogenic surface sampling, coring and melt probes
- Components and mechanisms for extreme environments (low temp, high temp, high P, shock)
- Low-temperature-capable electronics and batteries for landing on icy bodies
- Autonomous operations
- Higher-specific-power RPS for when solar is not available
- Small-scale RPS
- Miniaturized, low-power instruments to reduce the landed mass
- Communications with buried probes and probes in rough terrain
- Long-life planetary aeromobility systems (balloons, helicopters, planes)
- Planetary protection technologies/methods for sample return from habitable zones
- Cryogenic sample storage system that preserves volatiles

A5.3 Outer Planets (e.g., Uranus and Neptune)

- Long-life, reliable RPS
- Technologies will emerge as a result of mission studies underway

A5.4 Instruments—General

Miniature and low-power instruments of all kinds, especially *in situ* instruments, e.g.,

- Super-high-resolution mass spectrometers
- Passively cooled, miniature high-resolution spectrometers
- High-resolution ultraviolet (UV) spectrometers
- Low-mass, miniaturized LIDARs and RADARs

- Advanced, miniature sub-mm spectrometers
- Novel Life detection instruments
- Outer planet probe instruments

A5.5 Mars

A5.5.1 Mars Sample Return

- Sample acquisition and caching
- Mars ascent vehicle
- On-orbit rendezvous and capture
- Planetary protection/assured containment

A5.5.2 In Situ Exploration

- Extreme terrain access
- Miniaturized science instruments

A5.5.3 Cross-Cutting Needs

- Improved EDL Capability (increased landed mass, reduced landing dispersion)
- Enhanced rover mobility
- High-bandwidth communications (direct-to-Earth and relay)
- High-performance/low-power computing
- Extreme temperature electronics and actuators

A5.6 New Frontiers Specific

A5.6.1 Applicable to Several Missions

- Low-mass subsystem technologies (appears consistently in Discovery lists)
- Low-power subsystem technologies (appears consistently in Discovery lists)
- Low-temperature batteries
- High-performing solar arrays under low-light-intensity and low-temperature (LILT) conditions (will need solar cell development)

A5.6.2 Comet Surface Sample Return–Specific—Enabling

- Autonomous operations (proximity)
- Guidance and control—including landing sensors
- Sample acquisition and transfer
- Sample preservation

A5.6.3 Venus Specific—Enabling

- Sampling technology—including ingesting material into the lander
- Remote and contact analysis instruments and methods
- High-temperature batteries
- High-temperature mechanisms—required for sampling

A5.6.4 Venus Specific—Enhancing

- High-resolution mass spectrometers—enhance the science
- Balloon technologies for atmospheric objectives.
- Thermal control—for extended lifetime
- High-temperature electronics
- Long-life power sources and thermal management that work at the high temperature, pressure

A5.7 Discovery Class

A5.7.1 Cross-Cutting Technologies That Can Benefit ALL Missions

Developing robust miniature, modernized S/C will reduce costs and enable a plethora of missions for small bodies and outer planetary systems. Subsystem technologies needed for small spacecraft deep space missions ($\geq$10 AU, 100–200 kg dry mass, 130 W_e, $\geq$15 years lifetime):

- Propulsion
  - Small advanced propulsion systems, e.g., ~500 W_e Hall thrusters with power processing unit (PPU)
- Low-mass/power guidance, navigation, and control (GN&C) sensors and actuators
  - Leverage recent advancements in CubeSat GN&C technologies
  - Low-mass, lower-power optical sensors
  - Low-mass, lower-power inertial measurement unit (IMU)
- Next-generation high-efficiency solar cells (~38% efficiency)
- Low-power, integrated command and data handling (C&DH) subsystem
- Multifunctional structures and thermal management techniques
  - Integrated, 3-D printed structures
- Wireless S/C technologies
- Technologies for autonomous operations
- Advanced solar power technologies, including batteries and LILT solar cell and array development
- High-performance computing (STMD funding) and expanded memory systems
- Novel wireless sensor systems, e.g., fuel sensor system
- Astrodynamics
- Autonomous GN&C systems technologies including algorithms and associated capabilities

A5.8 Advocating to Other NASA Organizations

A5.8.1 Telecommunication (SCaN/STMD)

- Ka-band communications small spacecraft
- Optical communications
- Deep Space Atomic Clock

A5.8.2 TPS Materials and Methods (STMD)

- HEEET—solutions currently under development within STMD sufficient
- Adaptable, Deployable Entry Placement Technology (ADEPT)—for possible use at Uranus

A5.8.3 Outer Planets (HEOMD)

- SLS
- High-power solar electric propulsion (SEP)

Appendix 6: PSD Technology Portfolio—Updated Priorities (December 2015)

A6.1 Overview

This appendix provides a summary of the technology developments needed for PSD missions based on the analyses described earlier. It updates the list provided to PSD in June 2015 by providing more information on each of the technologies and including a few more related technologies. Since the PSD Technology plan also incorporates the advocacy and co-funding of PSD relevant technologies for programs in STMD and HEOMD, we include the funding sources, both current and potential (if known at this time). The plan presents a set of technologies that are needed for both competitive missions and directed missions: the competitive missions are Discovery and New Frontiers while the directed missions are Mars, Ocean Worlds Exploration, Ice Giants and Venus. It also provides guidance for potential projects that PSD could request from STMD. For completion, the last column indicates the NASA roadmap designation.

A6.2 PSD Competitive Programs

We have addressed the needs for two competitive mission program here: Discovery and New Frontiers. In each case, the focus is primarily on cross-cutting technologies applicable to many mission types but for New Frontiers some mission specific technologies are identified.

A6.2.1 Discovery Programs

The Discovery Program is a Principal Investigator (PI) led program with few constraints on the mission except a requirement that it addresses PSD's science goals. It does so with a mission that complies with the Discovery cost cap currently at $425M. Technologies that are applicable to Discovery missions appear in Table A6-1. Potential funding sources are STMD, HEOMD (either SCaN or AES) and PSD, with occasional external collaborators such as the USAF.

In the past, Discovery missions have been conducted to the Moon, Mercury and Mars as well as multiple missions to small bodies in the solar system. In the current round of Discovery programs, two Venus missions are also included. The Discovery missions undertaken so far include flybys, orbiters, landers, probes, impactors, and two sample-return missions. Given the diversity of targets and exploration methods, the technology plan emphasizes technologies with a great deal of commonality. In particular, developing robust miniature, modernized S/C will reduce costs and enable a plethora of missions for small bodies, landers and outer planetary systems. Subsystem technologies are needed for small spacecraft deep space missions ($\geq$10 AU, 100–200 kg dry mass, 130 W_e, $\geq$15 years lifetime). Investments in technologies that are specific to *particular* Discovery concepts are also needed but these could be funded on a competitive basis where the concept that they apply to is an integral part of the evaluation.

Table A6-1: Cross-cutting technologies applicable to Discovery missions.

Category/Specific Technologies	Funding Status	Current Funding Source	NASA Roadmap
Propulsion			
Small advanced propulsion systems	◒	STMD	TA02, TA10
Miniaturized electric propulsion systems	◒	STMD	TA02, TA10
Structural/Thermal			
High-energy-entry TPS	●	STMD/PSD	TA09, TA14
Multifunctional structures and thermal mgmt		STMD	TA12, TA14
GN&C/C&DH			
Low-mass, lower-power trackers and IMUs	◒		TA12
Low-power integrated C&DH	◒		TA04
High-performance computing and memories	◒	STMD/PSD/AF	TA11
Autonomous GN&C systems technologies, including algorithms and associated capabilities	○		TA04
Power			
High-efficiency solar cells	◒	STMD (call out)	TA03
High-specific-power LILT arrays	◒	STMD/PSD	TA03
High-specific-energy batteries	○		TA03
Communications/Autonomy			
Optical communications (tech experiment)	●	STMD/PSD/SCaN	TA05
Technologies for autonomous S/C operations	◒	STMD/AES	TA04
S/C wireless technologies, including sensor systems	○		TA05, TA08

● Fully funded or mature, ◒ Partial funding, ○ No funding

A6.3 New Frontiers Technologies

While New Frontiers (NF) is also a competitive program, it includes a mission set with specific science objectives that was updated by the Planetary Science Decadal Survey in 2011. Five missions were selected for the NF4 call (Venus In Situ Explorer, Comet Surface Sample Return, Lunar Aitken Basin Sample Return, Saturn Probe, and Trojan Tour and Rendezvous) and these would be supplemented with an additional two missions—an Io Orbiter and a Lunar Geophysical Network for NF5 call. A list of technologies relevant to NF missions appears in Table A6-2.

While the science goals are specific, NASA plans to leave considerable flexibility in implementing those goals. Nevertheless, it is possible to be more specific than with Discovery in the mission specific technologies. The list of technologies that were identified here primarily include cross-cutting technologies similar to those identified for Discovery but also some more specific technology gaps that would be applicable to specific missions (Table A6-2). They are not comprehensive but rather include the top few developments required by these potential missions. Technologies that are supported by the Homesteader program in FY16 are designated as PSD-HS in Table A6-2.

Table A6-2: Technologies applicable to New Frontiers missions.

Category/Specific Technologies		Funding Status	Current Funding Source	NASA Roadmap
Applicable to Several Missions				
	High-energy-entry technologies	●	STMD	TA04, TA09
	Optical communications	●	STMD/SCaN/PSD	TA05
	Low-mass subsystem technologies	◒	STMD	TA12
	Electronics—low temperature	●	PSD	TA08
	Batteries—low-temperature operation	●	PSD	TA03
	Solar arrays for LILT operation	◒	STMD & PSD-HS	TA03
Comet Surface Sample Return–Specific—Enabling				
	Autonomous operations (proximity sensors)	◒	PSD	TA04, TA08
	Guidance and control—including landing	◒	PSD-HS	TA04, TA09
	Sample acquisition and transfer	◒	PSD-HS	TA04
	Sample preservation	◒	PSD-HS	TA04
Venus Specific—Enabling				
	Sampling technology for *in situ* analysis	◒	PSD-HS	TA04
	Remote and contact analysis techniques	●	PSD	TA08*
	High-temperature batteries	○		TA03*
	High-temperature mechanisms—sampling	◒	SBIR	TA04*
Venus Specific—Enhancing				
	High-resolution mass spectrometers	◒	PSD	TA08*
	Balloon technologies	○		TA04
	Thermal control—for extended lifetime	○		TA14
	High-temperature electronics	○		TA08
	Long-life power sources	○		TA03*

● Fully funded or mature, ◒ Partial funding, ○ No funding, * Should be added to this OCT Roadmap
HS = Homesteader funding in FY16

In May 2015, NASA issued the Homesteader call inviting proposals for all seven missions. The call specified proposals for two years of technology development, which would overlap the planned issuance of the New Frontiers Announcement of Opportunity (AO). The call was targeted at technologies that with the assistance of Homesteader could be brought to TRL 6 by Preliminary Design Review (PDR) of the flight mission. NASA selected 84 proposals to proceed to Step 2 of which 8 were ultimately awarded in September 2015. Eight selections include three instrument developments and the remainder advance specific S/C elements:

- Sample Acquisition, Containment, and Thermal Control Technology for Comet Surface Sample Return
- Venus Entry Probe Prototype
- An Advanced Pointing Imaging Camera
- Navigation Doppler LIDAR Sensor for Reliable and Precise Vector Velocity and Altitude Measurements, an entry, descent and landing technology study
- A "small, low-cost hopping lander for asteroid exploration"
- The Atmospheric Constituent Explorer System for Planetary Probe Missions

- Active-Tracking Microelectromechanical System Microconcentrator for Low-Intensity, Low-Temperature Missions
- Tunable Laser Spectrometer Risk Reduction for Saturn Probe and Venus in Situ Explorer NF Missions

A6.4 Directed Programs

In this section, we cover technologies that are needed for directed programs. This includes ongoing activities in the Mars Exploration Program as well as emerging applications to other targets. The Mars Program Office provided the information.

A6.4.1 Mars Exploration Program

Planning technology for the exploration of Mars is much more straightforward and specific than for the competitive programs because it involves an agreed upon sequence of missions and technical approaches that can be openly discussed in public forums. The list of technologies appears in Table A6-3.

Mars Exploration technology capabilities have been grouped into three broad categories: Mars sample-return missions, *in situ* missions or cross-cutting technologies that address both. Some orbiter technologies (telecommunications) are also included in the cross cutting category. The sample return technologies address acquisition and caching of the sample, transferring it to Mars orbit and capturing the sample canister in Mars orbit. The planetary protection technologies are needed to protect against back contamination of earth and in particular for assuring ultra-reliable containment of the sample that is delivered to Earth.

Table A6-3: Technology capabilities for Mars exploration.

Category and Specific Technology		Funding Status FY15	Current Funding Source	NASA Roadmap
Mars Sample Return				
	Sample acquisition and caching	●	M2020	TA04
	Mars ascent vehicle	◒	MEP-MTD	TA01
	On-orbit rendezvous and capture	○		TA04
	Planetary protection/assured containment	◒	MEP-MTD	TA12
In Situ Exploration				
	Extreme terrain access	○		TA08
	Miniaturized science instruments	◒	PSD	TA08
Cross-Cutting Needs				
	Improved EDL capability	◒	MEP-MTD	TA09
	Enhanced rover mobility	◒	MEP-MTD	TA04
	High-bandwidth communications	◒	STMD	TA05
	High-performance/low-power computing	◒	STMD/SMD/AF	TA11
	Extreme temp. electronics & actuators	◒	STMD—Gearboxes	TA12

● Fully funded or mature, ◒ Partial funding, ○ No funding
MEP-MTD: Mars Exploration Program—Mars Technology Development

The unique *in situ* exploration challenge is for technologies that enable access to extreme terrains and special regions. These include terrains with steep slopes and large numbers of boulders, which cannot be traversed by the current generation of rovers and/or require sterilization of the vehicle exploring the special regions. Further miniaturization of sensors is needed for compatibility with what are likely to be small vehicles, such as helicopters and 'daughter' rovers.

Cross-cutting technologies apply to both sample return and *in situ* missions. They include EDL technologies that can increase landing mass and extend the available altitude range of landing sites as well as methods for reducing landing errors and ensuring safe landing. An alternative approach to precision landing is rovers with enhanced mobility and faster travel times. Autonomous operation is key to more efficient operations and some of those technologies are beginning to be developed for Mars 2020. Improving telecommunications continues to be important both for the trunk line to Earth which should be able to benefit from optical communication in coming decades and the relay link between orbiters and surface assets. Enhanced on board computing is needed for both EDL and rover mobility and cold electronics are needed so that electronics can be placed near the actuators and motors that they drive and avoid the complexity and mass of complex cabling. The latter can also be achieved with wireless technologies within the vehicle.

Mars Technology Development tasks carry out targeted technology development efforts in a number of topic areas with the goal of enabling future Mars exploration mission concepts, reducing their cost, and/or enhancing their science return. Specific areas of investment include

- Mars sample return–focused technologies
  - Sample handling & caching
  - Containment assurance (*highest priority*)
  - Mars ascent vehicle (MAV) (*highest priority*)
  - Orbiting sample rendezvous & capture
  - Earth entry vehicle
- Mission-enabling base technologies (*highest priority*)
  - Alternative exploration platforms and vehicles
  - Increased EDL capabilities—higher mass, higher landing elevation, greater precision
  - Improved exploration capabilities—longer range, more extreme terrain, access to new environments

The tasks designated above as highest-priority (e.g., MAV focused fundamental[§], containment assurance focused fundamental) are receiving MTD funding in FY14-17. Adjustments in task scope, funding, and duration will be made as program objectives evolve.

In FY15, four tasks were conducted under MTD funding:

1) Safe Rover Mobility: This effort sought to improve rover mobility (speed and safety) through the use of advanced vision processing algorithms installed on an onboard computing element. This task concluded in FY15 with a successful Mars Yard testbed demonstration and has since been infused into the Mars 2020 rover mission.

[§] In this context, "fundamental" means that the technology development is focused toward a specific mission (e.g., MSR) without necessarily assuming any specific configuration for the flight system solution.

2) Safe and Precise EDL: This task sought to improve landed system accuracy and safety through the application of terrain-relative navigation algorithms installed on an onboard computing element. (Coincidentally, the same onboard computing element for the fast traverse task described above may be utilized for this activity, since these operations would be performed serially in a landed mission.) This task concluded in FY15 and is currently awaiting an infusion decision by the Mars 2020 rover mission.
3) Mars Ascent Vehicle (MAV) Focused Fundamental Technology: This task seeks to increase maturity of a portfolio of relevant technologies to a Mars Sample Return (MSR) MAV system. In FY15, activity included solid rocket motor design, pump-fed liquid engine technology development, and hybrid motor fuel design and testing. This task continues in FY16 with additional development focusing on hybrid and liquid rocket technologies.
4) Containment Assurance/Break-the-Chain Fundamental Focused Technology: This task seeks to mature a portfolio of technologies related to containment assurance of a Mars sample for Earth return. In FY15, activity included sealing technology development, orbital particle dispersion analysis, and end-to-end BTC concept development. This task continues in FY16 with additional development focusing on sealing, sterilization, and encapsulation technologies, along with risk analysis and 'Break the chain' concept maturation.

A6.5 Ocean Worlds Exploration

Although not a formal program at this stage, NASA has embarked on an effort to develop the capabilities that are needed to pursue the exploration of the icy bodies in the outer solar system including Europa, Enceladus, Titan and Triton as well as Ceres in the asteroid belt. The scope of the technology that was defined for this effort is covered in Table A6-4 first formulated in the spring of FY15.

Shown in parentheses are those technologies that are already being supported by the Ocean Worlds Exploration Technologies (OWET) initiative, a joint PSD/STMD effort. Technologies are placed in two categories: Entry Descent and Landing technologies needed to descend to the surfaces of these bodies and In Situ Operations technologies for operations above, on or under the surface.

Entry, Descent, and Landing: Only Titan among the targets of interest has a significant atmosphere and the density and vertical extent of that atmosphere assures benign entry conditions such that there are no special entry challenges. Descent and landing on airless bodies or those with a thin exo-atmosphere are much more challenging. It will be necessary to adopt the terrain-relative navigation and hazard-avoidance techniques developed for Mars and the Moon to the particular conditions of these icy bodies, which can present very different kinds of hazards. Finally, features of interest are expected to be small and highly localized on these bodies including deposits of freshly formed ice and potential vents and likely to be detectable only in the late stages of descent and so the ability to carry out science targeting will be an important additional capability. These capabilities are now being funded as the *Intelligent Landing Systems* task under the OWET program with a focus on an early landed mission to Europa but with an application to other icy bodies. While chemical propulsion will be adequate for control at bodies without atmospheres, other techniques will be needed for intelligent landing (targeted landing in small error ellipses) at Titan and this remains the most conspicuous gap in the funded program.

Table A6-4: Technologies for the exploration of icy bodies.

Category and Specific Capability or Technology		Funding Status	Current Funding Source	NASA Roadmap
Entry, Descent, and Landing				
	Terrain-relative navigation	●	PSD	TA04, TA09
	Hazard avoidance	●	PSD	TA04, TA09
	Robust landing	◒	PSD	TA09
	Science targeting	●	PSD	TA09
	Target-dependent control methods (Titan)	○		TA09
In Situ Operations				
	Cold-temperature electronics	●	PSD	TA08
	Cold-temperature batteries	●	PSD	TA03
	Surface mobility (rovers and hoppers)	●	STMD	TA04
	Aerial mobility (balloons, blimps, rotorcraft for Titan)	○		TA04
	Subsurface mobility	◒	PSD	TA04*, TA07
	Navigation of surface aerial and subsurface systems	○		TA05*
	Power for surface, aerial, and subsurface systems	○		TA03*
	Cryogenic surface sampling and coring	◒	PSD	TA04
	Cryogenic returned sample storage that preserves volatiles	◒	PSD	TA04
	Planetary protection—forward protection	◒	PSD	TA07

● Fully funded or mature, ◒ Partial funding, ○ No funding, *Should be added to this OCT Roadmap

In Situ Operations: Once on the target of interest, new technologies will be needed for *in situ* operations. Because the Europa mission is currently a solar mission, the initial focus is on vehicles that use stored energy that do not use radioisotope heater units (RHUs) because added costs would be incurred with National Environmental Protection Act (NEPA) compliance. Thus cold electronics and low-temperature batteries are needed for extending the operational lifetime of these vehicles. This work is currently funded by OWET.

Mobility is a key element in exploring icy bodies. STMD GCD Robotics is supporting surface mobility and PSD is supporting subsurface icy penetrator. There is also active ice probe research in both Germany and the United Kingdom. Despite the stated priority to develop these technologies in *Visions and Voyages* for a future Titan Flagship mission, work on Titan aerial mobility is currently confined to an early TRL rotorcraft study in STMD's NASA Innovative Advanced Concepts (NIAC) program. Advances in Autonomy, GN&C and Power are key technologies required for all mobility systems on distant bodies.

Sampling in cryogenic environments presents particular challenges for both *in situ* and sample return missions. In the time frame of interest for planned technology developments, sample return from ocean worlds will be limited to those samples obtained on a flyby trajectory. As with cryogenic sample collection the key issue is ensuring cryogenic storage for the return leg of the mission.

A6.6 Ice Giants

Defining the technology needs for Ice Giant missions to Neptune and Uranus suffers from the lack of detailed mission studies. Fortunately this situation is being rectified with studies that are currently underway and will be completed by the summer of 2016. Accordingly, we have divided information in this list into items that can be defined now and items that will be contingent on what is learned from the studies.

While the trade space is wide with both orbiter and flyby options under consideration, advanced thermoelectric power systems can be expected to benefit all conceivable mission options. Similarly, optical communications, which can enhance data return by an order of magnitude or reduce the use of on board power and ground assets, is also a positive benefit. However, more development work needs to be done to accomplish optical communication from those distances. For the probe, the continued development of a high-energy thermal protection system is vital although the entry conditions are not expected to be any more severe than at Saturn which is the current HEEET development target.

The benefits of the other technologies will hinge on the selection of the preferred design for this mission and the readiness and maturity of those technologies will be a factor in evaluating architectural options. Aerocapture and advanced chemical techniques are enabling for a fast orbiter mission but could also drive the development costs. A recent aerocapture study showed that no major technological challenges remain in order to consider it in the study trade space. SEP can be beneficial for some classes of mission both very large missions and those with very small spacecraft. For those missions with very small spacecraft, the development of technologies that will enable vehicles half the size of New Horizons is of great interest. The benefits of such a capability first surfaced in a recent study of a Pluto orbiter completed in June 2015[17]. Finally the potential benefits of miniaturizing deep space technologies tested on CubeSats need to be evaluated. One possible application is a miniature Pathfinder SmallSat or CubeSat, which could be used to assess the Ice Giant atmosphere to ensure the refinement of the trajectory for deployment of a probe and aerocapture of an orbiter.

Table A6-5: Candidate technologies for an Ice Giants mission.

Category/ Specific Technology	Funding Status	Current Funding Source	NASA Roadmap
Orbital or Flyby Missions			
Adv. thermoelectric power (eMMRTGs, advanced RTGs)	●	PSD	TA03
Optical communications	●	STMD/PSD	TA05
Small spacecraft technology	◒	STMD	TA12
Lox H_2 propulsion systems	◒	STMD	TA01
Outer planet aerocapture technology	◒	PSD	TA04
CubeSat atmospheric pathfinder vehicle	◒	PSD/STMD	TA09
Solar electric propulsion—large system	●	STMD	TA02, TA03
Entry Probe			
High-energy thermal protection systems	●	STMD	TA09, TA14
Probe instrumentation	◒	PSD	TA08*

● Fully funded or mature, ◒ Partial funding, ○ No funding, *Should be added to this OCT Roadmap

A6.7 Venus Technologies

Defining the technologies for investment for Venus also presents challenges. After more than two decades without a Venus mission, prospects for a Discovery mission have improved significantly with the two Venus mission Step 1 selections in 2015. The Venus In Situ Explorer (VISE) is also one of five New Frontiers (NF-4) candidate missions that *could* be selected in about two years and NASA and the Russian Federal Space Agency have formed a joint Science Definition Team to define the science objectives of Venera D, a mission with a broadly similar concept to VISE. Finally, the Planetary Science Decadal Survey of 2011 prioritized the Venus Climate Mission (VCM), a flagship mission, and the VEXAG in October 2015 endorsed the importance of a flagship but advocated a new mission study that would reflect the many scientific, technical and programmatic developments in the last five years.

The Venus technology plan identified here looks beyond VISE in view of the pending NF-4 AO and the selections of technologies already made through the Homesteader call. As with the Ice Giants plan, it identifies technologies that can be defined now and those that are subject to change based on the outcome of the study. The plan also includes investment in technologies relevant to long lifetime surface and near surface vehicles on Venus, which could be demonstrated on the next major mission but will require a decade or more to bring to full maturity. For a more complete analysis of technologies required, see Appendix 3.

Orbital Platform: While developments in a number of technologies could enhance the performance of an orbital platform, optical communications, which is currently under development and requires both advances in spacecraft technologies and ground-based technologies and infrastructure for special attention. In addition, we can expect a growing role for autonomous analysis of multisensory data on board the spacecraft for the detection of events such as lighting, seismic events and meteors.

Table A6-6: Candidate technologies for Venus missions.

Category/Specific Technology		Funding Status	Current Funding Source	NASA Roadmap
Orbital Platform				
	Optical communications	●	STMD/PSD	TA05
	Autonomous event detection	◒	PSD	TA04
Aerial Platforms				
	Descent and deployment	○		TA09
	Superpressure balloons	○		TA04
	Altitude control balloons	○		TA04
	Balloon sensors—magnetic/electromag.	○		TA08
Descent Probe				
	Deep probes	●	PSD/HS	TA08*
	Sondes and gliders	○		TA08*
Landed Platforms				
	Terrain-relative navigation	◒	PSD-OWET	TA04, TA09
	Hazard avoidance	◒	PSD-OWET	TA04, TA09
	Rough landing	◒	PSD-OWET	TA09*
	Aerodynamic controlled descent	○		TA09*
	Passive thermal-control systems	○		TA14
	Surface and near-surface mobility	○		TA04*
Cross Cutting				
	High-energy entry system	●	STMD	TA09, TA14
	Physics of supercritical fluids at Venus	◒	JPL internal	
	Experimental studies of Venus environments	◒	GRC internal	
	High-temperature power systems	○		TA03*
	High-temperature electronics	○		TA08*
	High-temperature sensors	○		TA08*
	GN&C	○		TA04

● Fully funded or mature, ◒ Partial funding, ○ No funding, *Should be added to this OCT Roadmap
HS = Homesteader funding in FY16; OWET = Ocean Worlds Exploration Technologies

Landed Systems: While many of the system principles involved in safe and precise landing that apply to Mars and ocean worlds also apply here, there are differences in the sensing and control methodologies that can be applied, although these will have commonalities with Titan. Passive thermal control systems do have the potential for extending lifetimes on the surface. Ultimately, improved technologies to extend lifetimes at the surface as well as near-surface mobility will be needed.

High-Temperature/Pressure Technologies: Technological advancements are needed in developing power, electronics and sensors that can work in the Venus surface environment especially as the mission lifetimes increase.

A6.8 Science Instruments

Science Instruments are competitively selected, so we do not elaborate on specific types of instruments. Suffice it to say that the general need is for miniature, low-mass and low-power instruments of all kinds, especially *in situ* instruments, e.g.,

- Super-high-resolution mass spectrometers
- Passively cooled, miniature high-resolution spectrometers
- High-resolution UV spectrometers
- Low-mass, miniaturized LIDARs and RADARs
- Advanced, miniature sub-mm spectrometers
- Novel life-detection instruments

Instruments that have low mass and power and occupy small volumes enable significantly more scientific data to be obtained and thereby can decrease costs and/or increase the overall scientific value of any mission, especially if the entire spacecraft can be reduced in size, mass, and volume too. This applies not only to *in situ* applications, but also to remote sensing.

A6.9 Opportunities for Collaboration with Other NASA Directorates

This list was provided to PSD in June of 2015, but has been updated to reflect additional areas of interest to PSD. In several cases, PSD is supporting the technologies but in other cases, advocacy enhances the likelihood of other directorates funding the technologies. For a complete list see the above tables.

A6.9.1 Space Technology Missions Directorate (STMD)

- HEEET—Range of entry applications for Venus and OP.
- ADEPT or HEEET—potential aerocapture at Uranus or Neptune
- Deep Space Atomic Clock—broad applications (joint with SCaN and USAF)
- Optical communications—broad applications
- Ocean worlds technologies
- Miniature propulsion technologies
- High-power SEP—potential outer planet applications
- High-performance computing (with HEOMD, AF, and NRO)

A6.9.2 HEOMD/Space Communications and Navigation (SCaN) Program

- Ka-Band Communications for Small Spacecraft
- Optical Communications

A6.9.3 HEOMD/Advanced Exploration System Program

- Disruption-Tolerant Networks

Upcoming areas of *potential* collaboration are in autonomous systems and novel intra-spacecraft communication methods for sensors and data transfer.

Appendix 7: Plan for Costing the Vetted Technology List

Costing these technology efforts is extremely difficult. We did that for the Outer Planet Decadal Survey Technology White Paper and there were many caveats. We are in the process of attempting to do that again for the PSD technologies so that PSD can have some estimate of cost and time mature the technologies. Some costs, we understand fairly well, e.g., the High-Performance Computing Task currently jointly funded by STMD, PSD, AF, and potentially NRO; others we will have to estimate and phase them in a generic way. As an example, for the previously cited White Paper, the caveat was:

ROM Costs for OPAG Technology White Paper Recommendations
2-7-2010

This document is intended to provide a top-level assessment of the topic described. All technical and cost analyses are preliminary. The data contained in this document may not be modified in any way. This document does not constitute a commitment on the part of JPL or Caltech.

Cost estimates described or summarized in this document were generated as part of a preliminary, first-order cost class identification. These costs are not validated for budgetary planning purposes. Estimate totals and cost reserve allocations would be revised as requested in future more-detailed studies as appropriate for the specific cost-risks for a given mission application.

***Example* costs from that paper for Recommendation 1 are:**

Recommendation 1 (Power): OPAG strongly recommends that NASA work with the relevant agencies to ensure that Pu-238 production provides enough material for future OP missions, and fully support the validation of the ASRG system for OP applications, including the development of small (milli-/multiwatt) radioisotope power generators for sensor networks. In addition, NASA should adapt and complement industry-developed advanced solar cell and array technology program, advanced battery technology, and advanced power conversion and distribution technologies program for OP missions.

1. NASA should work with the relevant agencies to ensure that Pu-238 production is restarted and provides enough material for future outer planet missions. In particular, NASA should flight-qualify ASRG power systems.

Advanced radioisotope power systems (Currently funded at $50–60M per year)

1. High-efficiency and long-life ASRG: ~$ 150 M
2. Long-life and high-efficiency advanced radioisotope thermoelectric generator: ~$ 150 M
3. Pu^{238} production: ~ $150M (costs per year depend on DOE schedule)

Advanced Solar Array Technology:

- LILT solar cells and arrays: ~$10M over 5 years ($2M, $2M, $3M, $3M, $1M)
- High-efficiency solar cells (>40%): ~$10M over 5 years ($2M, $2M, $3M, $3M, $1M)

Cryogenic Power Electronics: $15M over 6 years ($2M, $3M, $3M, $3M, $3M, $1M)

Advanced Battery Technology:

- High-energy-density and low-temperature primary batteries (<-100°C): ~$15M over 6 years ($2M, $3M, $3M, $3M, $3M, $1M)

- High-energy-density, long-life, and low-temperature rechargeable batteries (<-60°C): ~$20M over 7 years ($2M, $3M, $3M, $3M, $3M, $3M, $3M)

We will revisit these estimates in the next few months and ascertain which are still valid and which are not and undertake a costing exercise for the Technologies in the Technology Plan.

Appendix 8: References

1. Planetary Science Decadal Survey, section on Technology, National Research Council, 2011
2. Planetary Science Technology Plan Update, by Pat Beauchamp and Jim Cutts, briefing to David Schurr, April 9, 2015
3. PSD Technology Plan Status presentation to David Schurr by Pat Beauchamp and Jim Cutts, June 2015
4. Planetary Science Decadal Survey—Vision and Voyages Chapter 11: The Role of Technology Development in Planetary Exploration. National Research Council 2011
5. Planetary Science Technology Review Panel. Final Report July29, 2011
6. Venus Exploration Roadmap, published by VEXAG, May 2014
7. Venus Technology Plan, published by VEXAG, May 2014
8. Probing the Interior Structure of Venus report on a Keck Institute for Space Studies (KISS) workshop, April 1 2015
9. Outer Planet Technology Roadmap, White Paper submitted 2009 to Planetary Science Decadal Survey Panels.
10. Small Bodies Technology Assessment, 2011 by John Dankanich et al.
11. Technology Assessment reports for Planetary Science http://solarsystem.nasa.gov/missions/techreports
12. NASA Technology Roadmaps issued August 2015 can be downloaded from http://www.nasa.gov/offices/oct/home/roadmaps/index.html
13. NASA Technology Roadmaps: Assessment for Planetary Science Division, Jim Cutts and Young Lee, August 3, 2015
14. Interplanetary NanoSpacecraft Pathfinder In Relevant Environment (INSPIRE) http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2992&context=smallsat
15. CubeSats, SmallSats and the Exploration of Europa, report prepared for Jim Green, March 31, 2014
16. Mars Helicopter https://www.nasa.gov/jpl/helicopter-could-be-scout-for-mars-rovers
17. Aerocapture Technology Assessment performed by JPL’s A-Team, Dec 2015.
18. Pluto Orbiter Mission Study, briefing to Dr. James L. Green ad NASA HQ July 3, 2015.