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Robotic Access to Planetary Surfaces

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Robotic Access to Planetary Surfaces
Technology Capability Synopsis

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1 General Portfolio Overview

1.1 Technology Capability Description

This Robotic Access to Planetary Surfaces (RAPS) technology capability portfolio (TCP) addresses the capabilities for missions that need to land, fly, rove, and dig/drill on the surfaces or in the atmospheres of large bodies in our solar system, such as the Moon, Mars, Venus, Titan, Europa, Jupiter, and Neptune, as well as capabilities to support sample returns to Earth. Due to the significant overlap in required functionality, this portfolio also includes aerocapture.

The systems outlined here have the job of delivering instruments to an atmosphere or surface, and/or delivering samples to the instruments. The instruments themselves are covered by the Science Instrument and Sensors Technology Capability Portfolio.

Per Agency direction, this technology capability portfolio does not cover operations at small bodies, i.e., asteroids or comets. It also does not cover robotic assistants for human missions, or robotic resource collection, e.g. mining, for in situ resource unitization (ISRU). These topics are covered by the Autonomous Systems and Robotics, Human Exploration Systems and Mobility and In Situ Resource Utilization Capability Roadmap teams (RAPS relationship with these teams is defined in Section 3.4). In addition, many of the required RAPS atmospheric transit capabilities overlap directly with analogous capabilities required for the NASA Human Planetary Landing Systems Capability Roadmap, though at different scales.

Robotic precursor missions to the Moon are small order, one-metric-ton landers. All of the capabilities required for such landers already exist, except for pinpoint landing which is called out in this report. The key development for pinpoint landing on the Moon is real-time visual terrain recognition during descent using orbital imagery. There are no other known capability developments required for robotic access to the surface of the Moon in order to prepare for human missions. The landers for humans will likely require new engine development, to provide a deep throttle capability, but that is out of scope for our report.

A surface Mars Sample Return is a required human precursor mission in order to assess the biohazard potential of the globally distributed dust. Most of the Mars surface capability developments called out in this report tie directly to that objective. Other Mars capability developments may be enhancing for human missions, such as autonomous deep drilling and small aircraft for scouting landing sites.

1.2 Benefits and Traceability

NASA has outlined 18 strategic objectives, the first three of which directly call for exploration of the Moon, Mars, and the solar system, respectively. In each case, the stated purpose of the exploration will require access to planetary surfaces.

The key capabilities outlined here enable missions that have high science value and that are called out as possible new starts in the next twenty years by the Mars and Solar System Strategic Roadmap Teams. In particular, missions that land greater mass, provide greater mobility, access and transport surface material from depth, and implement required planetary protection on Mars for the purpose of life detection or sample return, are enabled. Enabled missions include:

- Missions that enter the Venusian atmosphere and deliver long-lived landers to the surface
- Missions that enter the Titan atmosphere and deliver airships with surface material access
- Missions that enter the atmospheres of gas giants at high velocity.

In addition, new mission concepts for the delivery of long-duration aircraft to Venus, Mars, or Titan, and for the delivery of a large number of small landers or penetrators for network applications are enabled.

1.3 Architectural Assumptions and Legacy Activities

The design reference missions used to drive key capabilities were derived from existing Mars and solar system strategic plans, and updated as the Mars and solar system strategic roadmap (SRM) teams progressed in their work. The value of this TCP is not in any absolute dates that might be laid out, but rather in what capabilities are needed for a given mission type. Value is also measured in the amount of time required to develop those capabilities before a new start could adopt that capability at an acceptable level of remaining development risk.

Out of the set of all envisioned missions that fall in the scope of this roadmap, we selected a subset that drives the capabilities investigated. Those missions are:

- Mars Sample Return
- Titan Explorer (airship)
- Europa Astrobiological Lander
- Mars Deep Drill
- Mars Astrobiological Field Laboratory
- Venus Surface Explorer
- Jupiter Atmospheric Probes
- Neptune Orbiter (aerocapture)

Table 1 summarizes the key capability developments and the science strategy and mission launch date decisions that would drive those developments. The number of years listed in Table 1 assumes that the capability development must be complete four years before launch. It is possible to accelerate the schedule by overlapping the capability development with the project development by one to three years, given appropriate management of the development risk.

There were three previous activities that this roadmap drew on. These two provided useful material for advances in nuclear and non-nuclear power systems:

- *Advanced Radioisotope Power Systems Report*, Rao Surampudi et al., JPL D-20757 6/01, March 2001
- *Solar Cell and Array Technology for Future Space Science Missions*, Rao Surampudi, et al., JPL D-24454A, December 2003

The third provided some background for surface mobility systems and surface material access:

- *Capability Requirements Analysis and Integration 2.4 FY 2004 Robotics Summary Whitepaper*, Paul Schenker, et al.

1.4 Key Architecture / Strategic Decisions

In the table below, "heavy Mars entry, descent, and landing (EDL)" includes a set of capabilities—higher performance, thermal protection materials, guided lifting hypersonic flight, large supersonic parachutes, pin-point landing, and low velocity touchdown systems. Similarly, "planetary protection" includes spacecraft sterilization, assured containment for Earth return, and sample operations in isolation in the Earth receiving facility.

Table 1. Summary of Key Capability Developments and Mission Launch Dates

Key Architecture/Strategic Decisions	*Date Decision is Needed*	*Impact of Decision on Capability*
Decision to launch Mars Sample Return.	9 years before the intended launch.	Latest date to start planetary protection, Earth entry, heavy Mars EDL, advanced mobility, and sample handling capabilities.
Decision to launch an in situ life-detection laboratory to Mars, either rover-borne or on a fixed platform deep drill.	7 years before the intended launch (though see next row).	Latest date to start contamination reduction and sterilization, complex sample handling, heavy Mars EDL and advanced mobility.
Decision to launch a deep drill life-detection laboratory to Mars.	8 years before the intended launch.	Latest date to start an autonomous deep drill, heavy Mars EDL and down-hole instrumentation.
Decision to continue the exploration of Titan with a long-lived airship capable of surface sampling.	8 years before the intended launch.	Latest date to start airship materials, guidance and control, propulsion, and surface interaction.
Decision to explore the Venusian surface with a long-lived laboratory.	7 years before the intended launch.	Latest date to start extreme environment survival system studies and component development.
Decision to deliver deep atmospheric probes to Jupiter, or decision to conduct an aerocapture at Neptune.	12 years before the intended launch.	Latest date to start thermal protection materials, refurbish test facilities, and analysis capabilities.

1.5 Major Technical *Challenges*

See the detailed portfolio discussion in section 2.

1.6 Key Capabilities *and Status*

Based on the reference mission sets within the Mars and Solar System Strategic Roadmaps, we assumed the following mission timeline (launch dates) to prioritize the development of RAPS technology capability.

- Lunar Precursor Lander in 2011
- Mars Sample Return in 2016
- Titan Explorer (airship) in 2018
- Europa Astrobiological Lander in 2018
- Mars Deep Drill in 2020
- Mars Astrobiological Field Laboratory in 2020
- Venus Surface Explorer in 2020
- Jupiter Atmospheric Probes in 2020
- Neptune Orbiter (aerocapture) in 2023

To maintain the opportunity to perform the above missions in the stated timeline, the following technology capabilities require *immediate* development (see detailed roadmapping charts in Appendix 1).

1. Thermal protection system materials, test, analysis, and modeling
2. Supersonic parachute for Mars
3. High performance terrain sensing (both RADAR and visual terrain recognition)
4. Aseptic surface sample collection, handling, and caching
5. Spacecraft sterilization and cleaning
6. Assured containment of returned samples
7. Mid-air transition from stowed to flying airships
8. Improved wheeled mobility system

2 Detailed Portfolio Discussion

2.1 Capability Breakdown Structure

The RAPS technology breakdown structure shown in Figure 1 shows the five capability areas described here, and a second level breakdown of the critical elements of each area.

2.2 Key Capabilities

RAPS capabilities are broken into five major areas, each covered in their own section below. They are:

- Atmospheric Transit (land)
- Surface Mobility (rove)
- Accommodation of Instruments and Samples (dig/drill)
- Aerial Vehicles (fly)
- Cross-Cutting.

2.3 Atmospheric Transit

For missions to atmospheric bearing bodies, planetary access requires transit through the atmosphere, either as a means of orbital insertion (aerocapture), as a primary scientific objective (probes), or as a means of reaching a sub/surface destination (landers and penetrators). Atmospheric transit entails large energy and momentum exchange between the atmosphere and the vehicle. There are three key challenge areas for mission success: hypervelocity transit, supersonic deceleration, and terminal descent/landing.

2.3.1 Hypervelocity Transit

Over the next three decades, mission objectives will require expansion of the entry system capability in three key ways: higher entry speeds corresponding to reduced trip times, larger more massive entry systems, and precision landing. Mars robotic science and preparation for human exploration will lead this technology drive. To achieve this increase in entry performance requires advancement in traditional rigid aeroshells, and development of new deployable entry systems. For rigid aeroshells, reinvigoration of the ablative thermal protection system capability is required, both in hardware and personnel. Critical technology gaps exist from mid-density to high-density ablators for heavy Mars landers and aerocapture missions. In addition, we would require facility upgrades to return NASA's outer planet thermal protection test capability. RAPS technology development is also required in aerothermodynamic and aerodynamic prediction, and guidance-navigation-control. Deployable/inflatable aeroshells provide an alternative to traditional rigid aeroshell systems. The primary advantage of deployable/inflatable decelerators is that a large drag area can be packaged within a small volume for launch, and then be deployed without complex in-space assembly operations. The key challenges facing inflatable/deployable hypersonic decelerators include: characterization of flexible and lightweight material properties, understanding aeroelastic effects, ability to predict aerodynamic flow stability, and packaging and deployment methods.

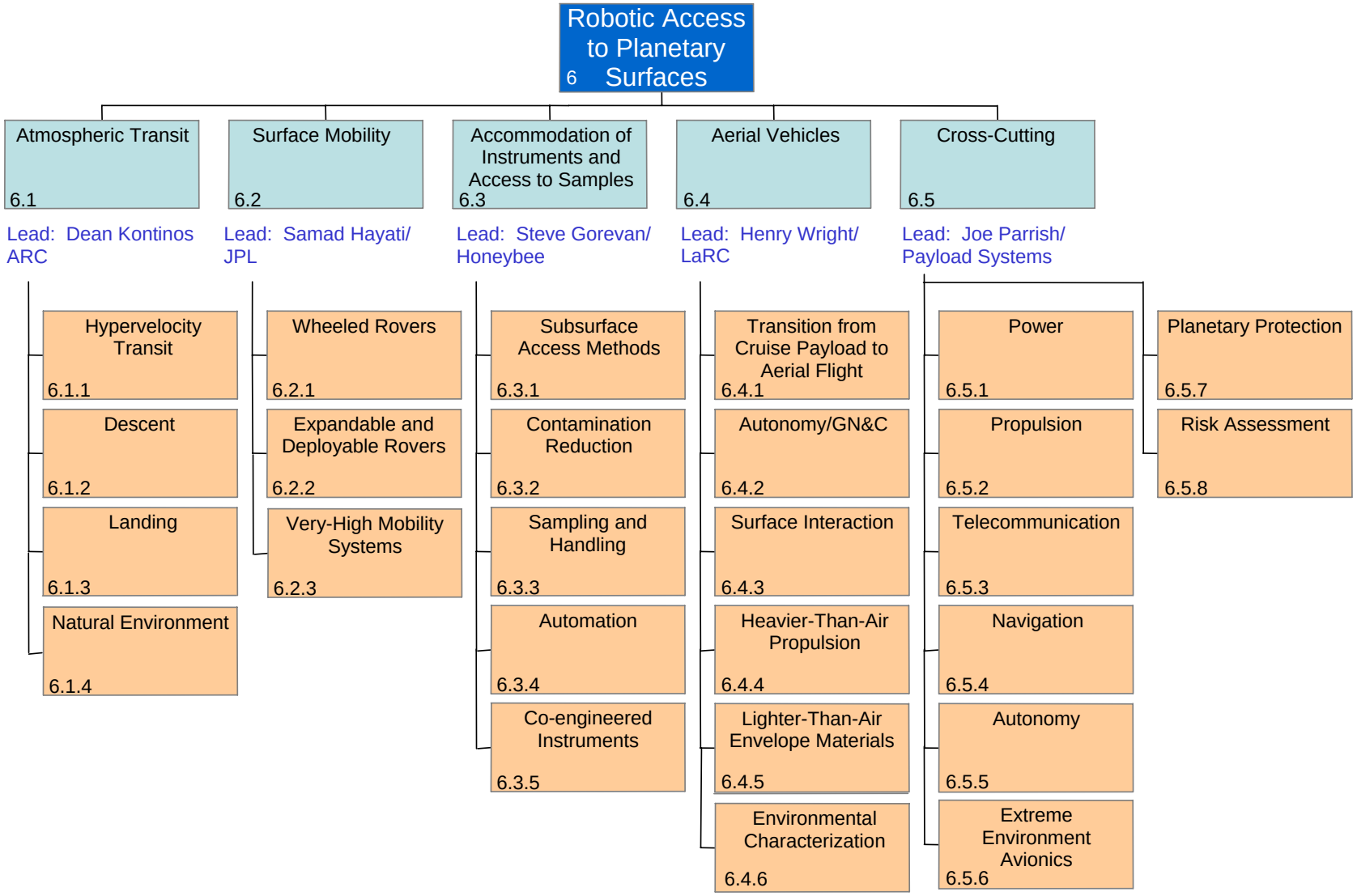

Figure 1. Capability Breakdown Structure (CBS)

2.3.2 Supersonic Deceleration

The descent phase begins after the hypervelocity transit at supersonic speeds. The primary challenge of this mission segment is to decelerate the vehicle while maintaining aerodynamic stability. For pinpoint landing, control authority is also a requirement. We have identified key capabilities in deployable aeroshell decelerators—supersonic and subsonic parachutes. For a planetary body with an atmosphere, the use of textile supersonic decelerators has proven to be beneficial in terms of performance/weight trades. An increase in allowable Mach number over 2.3 and parachute drag area over 140 m^2 is necessary for Mars landers greater than ~1000 kg entry mass. We recommend immediate development of a high Mach, large drag area parachute to accommodate a 4000 kg entry mass. Additionally, continued advancements in subsonic parachutes would enable increased mass capabilities (i.e., clustering) and precision landing capabilities (wind drift compensation and guidance/steering systems).

2.3.3 Terminal Descent and Landing

All surface missions require a spacecraft to land on unprepared natural terrain. The landing system's primary role is to accommodate the mission-specific payloads, integrate with the entry/delivery systems, and safely place the payload in a usable configuration on a wide range of natural terrains. The state of the art lies in legged and airbag landers with both fixed impulse and throttleable propulsion systems. The skycrane landing system is currently being developed for the Mars Science Laboratory mission. This approach has broad application to other landed missions and additional investments should be made to ensure that its full capability is explored and made available to future missions. High deceleration penetrators and impactors have received some attention over the years, but their unique capabilities and requirements have not been fully explored. Airbag landing systems can benefit greatly from advances in materials. The use of advanced soft-good materials could yield up to 25–50% savings in airbag mass. High performance sensing is vital to increasing the reliability and performance of landing systems. The most basic sensors are altimeters and velocimeters. Except for Apollo and Viking, whose terrain sensing technologies are no longer available, all of the recent lander missions have used modified military radars. There is a strong need for high performance terrain sensing customized for the unique requirements of spacecraft landing, high accuracy, low velocity, low and high altitude. Beyond altimetry and velocimetry, there is a need for terrain sensing systems for use with hazard detection, avoidance, and pinpoint landing systems.

Table 2 below summarizes enabling capabilities, current status, and development time of atmospheric transit.

Table 2. Atmospheric Transit Capabilities Summary

#	*Enabling Capability*	*What it Enables [Strategic Roadmap Reference]*	*Current Status*	*Development Time*
1	Deployable aeroshells and decelerators	A deployable aeroshell could be used to increase the frontal area (and drag) post-launch to enable low, ballistic, coefficient entry profiles, characterized by low heating rates, for high entry masses. Deployable systems could be used for the hypersonic and/or supersonic deceleration segments for direct entry and/or aerocapture at any of the atmospheric bearing bodies. [Mars, Solar System]	Rigid aeroshells with relatively high ballistic coefficients that rely on ablative thermal protection systems. A recent Russian inflatable flight test was unsuccessful. In the US, there have been system studies for deployables and inflatables. The key issues are deployment, aerostability, and control.	5–12 yrs. Hypersonic and Supersonic systems, although sharing some common technology, are likely separate development paths.
2	Supersonic and subsonic parachutes	An increase in allowable Mach number over 2.3 and parachute drag area over 140 m^2 is necessary for a Mars lander greater than ~1000 kg entry mass. High-landed mass systems at Mars may require a subsonic decelerator in addition to the supersonic decelerator system. Steerable systems will enable pinpoint landing. [Mars]	Current capability is limited to the Disk-Gap-Band (DGB) for Mars, Titan, and high altitude portions of Earth sample return. The DGB canopy was flight qualified with a total of 3 supersonic flights over 33 years ago (Viking 1972).	5–7 yrs
3	Thermal protection system technology	Entry vehicles experience extreme heating. Models for predicting the heating environment and thermal protection materials for managing the heat load are needed to enable heavy Mars landers, Neptune Aerocapture, and giant planet probes; and to maximize payload for Venus aerocapture, Venus direct entry, and mid-mass Mars missions. [Mars, Solar System]	Few existing mid-density ablators; heritage high-density materials no longer available and inadequate for missions to gas giants. Potential for multi-use TPS for aerocapure then entry. High uncertainties exist for radiative heating, transition, aft-body heating, and shock layers with high amount of ablation products. Insufficient flight data to validate heating models.	5–8 yrs
4	Atmospheric measurement and terrain sensing	Flight through a planetary atmosphere is complicated by 1) lack of atmospheric knowledge (density, winds, dust content, etc.) and 2) lack of apriori knowledge of specific landing terrain. To reduce risk during entry, an on-going commitment to orbital and in-situ (instrumented entry vehicles) measurements is required. Strong need for high performance terrain sensing customized for the unique requirements of spacecraft landing. [Mars, Solar System, Lunar]	Minimal atmospheric knowledge of Mars, Venus, Titan and Neptune. Good for Earth return. Except for Apollo and Viking, whose terrain sensing technologies are no longer available, all of the recent lander missions have used modified military radars. Their performance is mediocre for the types of missions being considered.	Atmospheric observation from orbit and in-situ. Density and wind prediction by 2015. Opacity prediction by 2020. 5 yrs for instrumentation development
5	Flight sciences	Advancement of aerodynamics, guidance, navigation and control technology will enable modulated drag and lift entries, likely using control surfaces, for pinpoint landing. Ability to construct credible aerodynamic databases for flight vehicles, with reduced design margin and higher reliability. [Mars, Solar System]	Current robotic systems are ballistic, resulting in high decelerations and large landed footprint. State-of-the-art demonstrated guidance, navigation, and control (GN&C) system is Apollo/Shuttle.	5 yrs

2.4 Surface Mobility

Surface mobility deals with mobility on planetary surfaces for robotic missions. The scope of this subsection is limited to the mechanical system and associated hardware and does not include the controls or autonomy. The latter is discussed in the Autonomous Systems and Robotics Capability Roadmap. Swim capability was considered, but was dropped from this document because its application is several decades in the future.

In general, mobility has the following advantages: 1) targeting specific features, such as rocks, outcrops, and craters, 2) effectively eliminating landing error, and 3) allowing exploration of several geologically interesting regions.

2.4.1 Major Technical Challenges

A. Traverse on natural rough terrain:
A useful concept is the "mean free path" (MFP) of a vehicle. For a given vehicle on a given terrain, MFP represents the average distance that a randomly-placed vehicle can move forward before it is immobilized by a terrain hazard. For terrain with random, compact hazards like rocks, if the MFP is more than about five vehicle lengths, then the terrain is generally rich with paths from any starting point to any goal point. It is crucial to design planetary exploration vehicles so that they have a reasonable MFP on the expected terrain. Major technical challenges are in the design of wheeled vehicles that show significant improvement relative to existing rovers. Improvements are required in rover architectures (navigation sensors and increased computer power to allow more autonomous operations), long life actuators, and increased MFP.

B. Traverse on steep slopes (cliffs, gullies) or very rough terrain (not traversable by wheeled vehicles):
For extreme terrain, the vehicle needs to be able to surmount extended hazards such as escarpments, cliffs, and steep slopes. Biology gives an abundant "existence proof" that walking vehicles can, in principle, surmount most extreme terrain. In very low-gravity environments, such as moons or small bodies, hopping is an attractive approach. In higher gravity, rappelling shows promise.

2.4.2 Enabling Capabilities

1) Six-wheeled rovers have reached technology readiness level (TRL) 9 maturity, but still lack critical features, which include: modular and miniaturized avionics, better and more robust sensors for autonomous navigation, efficient and customized solar cells, long life electronics, actuators, batteries, and miniaturized communication devices. Although most of the above technologies are cross cutting, customization to rovers and integrated prototype designs will require funding for improved six-wheeled rovers. These capabilities can be achieved within 5-10 years. This capability is responsive to technical challenge A).
2) Expandable rovers (e.g., rovers that have inflatable wheels that fold out from the stowed position or other types of deployable rovers) address the need to achieve large mean free paths and the ability to traverse steep slopes. These vehicles can even move on liquids, which may be applicable to Titan. We expect that this type of roving capability can be developed to TRL 6 within 5 years. These systems can be advanced to provide precise physical interaction with their environment, such as sampling and instrument placement on science targets for in situ experiments, within 10 years. This capability is responsive to technical challenge A).
3) Other mobility capabilities such as walking (very rough terrain), rappelling (steep cliffs), and hopping (low gravity bodies) are at low TRL. The theme might provide seed funding for pre-

liminary development of these concepts and then have a "shoot-out" to select a small number of concepts for further development. These systems may require 15–20 years to provide the required capabilities. This capability is responsive to technical challenge B).

Table 3 below summarizes enabling capabilities, current status and development time of surface mobility.

Table 3. Surface Mobility Capabilities Summary

#	*Enabling Capability*	*What it Enables [Strategic Roadmap Reference]*	*Current Status*	*Development Time*
1	Improved wheeled mobility platforms	Ability to execute more sophisticated autonomous rover algorithms by the added computing power and navigation sensors. Also, enables longer lasting and electro-mechanically less complex rover hardware, which adds to the system's robustness [Mars, Lunar]	Six-wheeled rovers have reached capability readiness level (CRL) 7 for a certain class of rovers, but their design is very complex, cannot survive Martian climate without complex and expensive protection, and are not very autonomous, partially because their computation power is very limited.	5–10 yrs
2	Expandable rovers	In order to increase the mean free path (MFP) of rovers and still keep the stowed volume small, deployable rovers can be developed. One particular implementation is rovers with inflatable wheels [Mars, Lunar]	Technology of inflatable wheeled rovers has been developed to CRL 3–4. These prototype rovers have been deployed in the field and have shown to perform well in sand, rocky terrain, and on water.	5 yrs, CRL from 4–6; to use these platforms for in situ exploration require 5 more yrs
3	Walking, rappelling, hopping mobility systems	Objective is to develop mobility systems that can provide the capability to explore very difficult to access regions on planetary surfaces (such as gullies and cliffs and very rough terrain) [Mars, Lunar]	Prototype systems have been developed to demonstrate the principals of these types of mobility systems. These prototypes are at very low CRLs (1–2).	15 yrs to CRL 6 (in three phases of 5 yrs each)

2.5 Accommodation of Instruments and Samples

To understand the history of Mars (and other planetary bodies), the study of the subsurface and rock interiors is essential. Objectives include gaining insight into site geologic, climatic and astrobiologic history. Three major technical challenges need to be addressed.

2.5.1 Accessing the Subsurface

On the Earth, established drilling techniques are employed to reach inside rocks or deeply into unconsolidated materials. Many terrestrial drilling rigs operate in extreme environments and access multi-kilometer depths. However, these drilling approaches are not unduly constrained by the mass, power, volume and operational time limits that constrain planetary surface operations. Due to these limits, useful technology transfer applied to planetary drilling is very limited. New drill bit designs must be generated to leverage low power and thrust/torque sinks. With no operator support on planetary surfaces, reliable electromechanical bit changeout systems must be incorporated to accommodate multiple borehole sorties. For penetration to take place, cuttings must be removed from the borehole with new designs compatible with automated operations. Ingenious means of reacting thrust and torque loads, perhaps from mobile platforms, must be devised. For depths below 20 meters, boreholes must be stabilized in novel ways that minimize mass. Punishing duty cycles imposed on long duration missions require drilling systems to be built from new and robust materials. A deep Mars drill will (for instance) be a complex and unprecedented electromechanical system.

2.5.2 Sample Integrity

Analytical instrumentation sent to planetary surfaces must have access to samples that are pristine. This will require close control of forward contamination of drill bits and related hardware. Localized bio-barriers for drills and bits must be implemented and in situ decontamination systems may be required. For sample return, maintaining sample integrity will require new hermetic container technologies, in situ sterilization methods and breaking the sample contact chain. For in situ investigations, cross contamination mitigation is necessary to ensure the integrity of sample analysis. Sampling system chambers and staging areas must be cleaned in situ to prevent cuttings from one sample being transferred for analysis with other samples. Surface drilling, crushing and sieving systems must be designed to minimize contamination of samples from lubrication and other materials. These processing actions must also minimize the loss of volatiles. Pristine sample access may only be attainable by transporting instrumentation down the borehole requiring the development of new co-engineered systems of instruments with drills.

2.5.3 Automation

Autonomy as a capability is the technological and operational means by which a system acquires situational, environmental, and proprioceptive awareness aimed at the completion of mission objectives. Autonomy capability includes the development of reliable and flexible automation, fault and state diagnostics, embedded sensing, motion-control and teleoperation. Platforms may require both executive level control for mission planning, navigation, sensor fusion, and diagnostics, as well as low-level control of motors and sensors. Diagnosis of fault and state modes is a challenge given the heterogeneous nature of the subsurface. A drill capable of accessing 10s of meters to kilometers will encounter different materials such as regolith, rock, ice or combinations of these materials in unknown configurations, each requiring different operational approaches to penetration, chip transport, wall integrity and sample acquisition. To diagnose the state or fault mode, systems will require a range of embedded sensors to determine weight on bit, torque on bit, temperature and vibration. This telemetry needs to be synthesized, analyzed and used for autonomous real-time planning. Faults

and failures must be diagnosed rapidly and recovery modes must be planned and implemented, possibly without the intervention of human supervisors. In some cases a degree of human supervision or teleoperation may be accommodated. These low-level autonomy capabilities are highly integrated with the device, and are distinct (though used by) the higher-level autonomy capabilities addressed by the Autonomous Systems and Robotics Capability Roadmap.

Table 4 below summarizes enabling capabilities, current status and development time for accommodation of instruments and samples.

Table 4. Accommodation of Instruments and Samples Capability Summary

#	*Enabling Capability*	*What it Enables [Strategic Roadmap Reference]*	*Current Status*	*Development Time*
1	Subsurface access (defeating and removing material, reacting loads, and maintaining borehole integrity)	Acquisition of samples from mm to km depths and in situ borehole analysis [Mars, Solar System]	Surface abrasion (TRL 9); 2.5 to 10 cm drilling/coring (TRL 5); 1 meter (TRL 5); 10 meters (TRL 4–5); 100 meter (TRL 3); 1 km (TRL 2)	2.5–10 cm drilling/coring 1 yr; 1 meter +2 yrs; 10 meters +3 yrs; 100 meter +10 yrs; 1 km +10 yrs
2	In situ contamination reduction (forward, cross and back)	(1) Integrity of sample and borehole analysis, (2) protection of environments under investigation, (3) in situ bio-barriers, (4) breaking sample transfer chain, (5) hermetically-sealed sample containers [Mars]	In situ decontamination technologies have not been well defined and developed (TRL 1–2)	9 yrs
3	Sampling and handling	(1) Precision acquisition and delivery of subsurface samples to instrumentation and/or containers, (2) preservation of sample ingredients (e.g., volatiles), (3) processing samples to accommodate in situ instrumentation [Mars, Solar System]	Sample handling, transport and processing systems have been demonstrated in laboratory settings (TRL 2–4)	4 yrs
4	Automation	(1) Complex operations (e.g., long-duration deep drilling) with minimum ground loops, (2) auto-diagnosis of robotic system state, fault and recovery modes [Mars, Solar System]	Significant development is necessary to achieve autonomous access across a range of depths. Successful Mars-analog field tests employing autonomous control techniques have been completed (TRL 1–4).	Concurrent with depth development
5	Co-engineered instruments	Mass, power, volume, and operation time reduction for subsurface access, sampling and instrument hardware (e.g., instruments built in to drill strings) [Mars, Solar System]	MPT is supporting down-hole instrumentation efforts (TRL 1–4)	4 yrs

2.6 Aerial Vehicles

Aerial vehicles provide a new perspective for discovery while filling a unique planetary science measurement gap, that of regional-scale, near-surface observation. At the current time, NASA's core science missions do not include aerial vehicles. However, the National Research Council (NRC) Decadal survey recommended aerial exploration of Titan as a follow-on to the Cassini-Huygens mission and both the Venus In-Situ Explorer and the Venus Sample Return missions have been identified as reference missions requiring lighter-than-air platforms. In addition, science teams from around the world are intrigued with the potential for observations of Mars via aerial vehicles. Powered airplanes provide the potential for precise surveys of specific regions while balloons and airships provide the potential for longer-term observations of a region. With advances in autonomous operations, the demonstrated benefit of aerial vehicles for Earth science, and recent successful flight test experience in relevant planetary environments, aerial vehicles have emerged as a credible implementation approach for planetary science. Table 5 provides a high-level time-line for aerial platform missions for Mars, Venus, and Titan.

Table 5. Mapping of System Level Capability for the Candidate Mission Destinations

Destination	*Today*	*+10 Years*	*+20 Years*	*+30 Years*
Mars	• Rocket Airplane (500–800 km) • Glider (40–100 km)	• Propeller Airplane (10,000 km) • Balloon–90 days	• Propeller Airplane (global) • Balloon (global) • VTOL	• Airplane ("infinite") • Airplane (local reconnaissance)
Venus	• Balloon (100 hours–high altitude)	• Rocket Airplane • Balloon (global) • Balloon (low altitude)	• Propeller Airplane • Airship (global)	
Titan	• Balloon	• Airship (90 days)	• Airship (global) • VTOL	• Airship ("infinite")

2.6.1 "Heavier Than Air" Platform

Today's airplane technology is sufficiently mature to enable first flight on another planet. Typical issues for airplanes revolve around the balance between mission range, payload capacity, and flight precision. Minor extension of the aeroshell extraction strategy demonstrated with the two Mars Exploration Rovers is sufficient to enable a low-risk airplane transition from a stowed payload to a functional science platform. A preplanned aerial traverse of 500–1000 km, with a corresponding flight time of 60–120 minutes is achievable with current autonomy, control, and propulsion technologies. Inertially propagated navigation uncertainty is the limiting factor for autonomous aerial flight. Propulsion using existing spaceflight-qualified rockets and propellants (liquid or solid) is consistent with the traverse range. Surface interaction through mid-air release of surface sensor pods is readily achievable.

2.6.2 "Lighter Than Air (LTA)" Platform

The Soviet Vega-2 mission at Venus successfully demonstrated balloons in planetary exploration (June 1985). While this successful flight demonstrated use of a balloon as a science platform, specific technologies essential for flight at other destinations (e.g., Mars or Titan) were not addressed. Further, Venus provides two distinctly different operating environments: high altitude (~50 km) where Earth-like conditions prevail (the Vega operating locale), and the low altitude (<15 km) where high temperature and pressure conditions exist. Key technology issues for airships and balloons revolve around the trade between mission endurance and payload capacity. Balloons for high altitude on Venus with up to a 90-day mission duration are considered state-of-the-art, while LTA

platforms for Mars, Titan, and the low altitude of Venus require additional development and testing. For first flight, the state-of-the-art regarding surface interaction is limited to deployment of sensor pods for ground impact. Soft landing coupled with surface survival is a key technology development area with near term potential for success.
Planetary aerial platforms share the following technical challenges:

1. Reliable deployment of the aerial vehicle (airplane, glider, vertical take off and landing [VTOL], balloon, or airship) during descent, followed by transition to controlled vehicle flight.
2. An extended duration operation capability with sufficient robustness and margins to accommodate the large range of uncertainties in planetary exploration. Autonomy, propulsion (heavier than air), and envelope materials (lighter than air) issues.

A reliable strategy for extending the operations capability of the aerial vehicles to include direct interactions with the surface through either deployed payloads while in flight or through controlled landing.

Table 6 below summarizes enabling capabilities, current status, and development time for aerial vehicles.

Table 6. Aerial Vehicles Capability Summary

#	*Enabling Capability*	*What it Enables [Strategic Roadmap Reference]*	*Current Status*	*Development Time*
1	Develop reliable strategies for mid-air transition from a stowed payload to a flying platform	This is the primary technical challenge for all aerial vehicles. Follow-on development enables longer duration missions and/or increased science payload mass fractions. [Mars, Solar System]	**Airplanes:** Current methods rely on rigid wings and empennages with hinges, latches, and energy absorbing devices, demonstrated with high-altitude balloon Earth-based testing; ~TRL 5–6. Use of inflatable lifting surfaces has been demonstrated, but not in a relevant environment; ~TRL 4–5. **Balloons/Airships:** Demonstrated on Venus at high altitudes (Soviet Vega). Sub-scale Mars balloons have been developed and tested in high-altitude Earth-based testing; ~TRL 4–5.	Airplanes with rigid elements to TRL 6 in ~2 years. Airplanes with inflatable elements to TRL 6 in ~5 years. Airplanes with propellers to TRL 6 in ~4–5 years after propeller selected. Balloons/Airships for Mars to TRL 6 in ~3–4 years.
2	Improve long term navigation knowledge to < 1 km while in flight.	Exploration of precise features or regions. Delivery of surface payloads to specific coordinates. [Mars, Solar System]	Use of IMU to propagate position knowledge and is at TRL 8–9. Use of IMU in a planetary aerial vehicle flight is at TRL 5–6. IMU propagation errors limit near-term flight durations to a few hours before a position or state update is required. Crude terrain recognition techniques were demonstrated as part of the MER terminal descent; however, the flight speeds were lower than what is used for an airplane or VTOL. Promising navigation solutions include use of orbital assets for 2-way range and Doppler tracking, optical flow techniques, and terrain recognition.	Validation of an integrated inertial navigation solution with on-board navigation aids and processing to TRL 6 within 2–3 years. 2-way ranging and doppler from existing orbital assets to TRL 6 within 2–3 years. Terrain recognition to TRL 6 within 3–4 years.
3	Fault-tolerant flight capable of in-flight recovery of computer reboots and other system failures. **Airplanes:** Capability of flying a mission with duration >10 days with only periodic updates on preferred flight path. **Balloons/Airships:** Capability of flying an autonomous mission with duration >30 days with only periodic updates.	Extended duration operations and access to a much larger regional (or global) area at a low altitude. [Mars, Solar System]	Terrestrial systems have demonstrated end-to-end autonomy (airplanes and balloons). Soviet Vega balloons demonstrated autonomous mission. High altitude flight testing on Earth in relevant environment have demonstrated precursor GN&C methods at TRL 5. Long duration autonomous GN&C for either airplane or LTA at TRL 3–4.	Early fault tolerant systems can be developed to TRL 6 within 2–3 years. Long duration fault tolerant systems can be developed to TRL 6 in 4–5 years.
4	Long duration powered flight requires efficient propulsion. Enabling capability is an integrated propulsion system (propeller with a fuel cell) for flight duration >10 days.	Extended duration operations and access to a much larger regional (or global) area at a low altitude. [Mars, Solar System]	Use of rocket propulsion is at TRL 5. Near-term development efforts are needed to move to TRL 6 for flights of between 1–2 hours. Propeller propulsion systems are at TRL 3–4. Rest of system is below TRL 3 (fuel cells integrated for planetary airplanes).	Propeller to TRL 6 within 5 years. Integrated propulsion system to TRL 6 within 7–8 years.
5	Long duration flight of a balloon or airship requires extensive material development.	Extended duration operations and access to a much larger regional (or global) area at a low altitude. [Mars, Solar System]	Venus balloon materials (high altitude) at TRL 9. Venus balloon materials (low altitude) at TRL 3–4. Mars balloon materials at TRL 4–5. Recent high altitude flight testing on both Mars and Venus concepts. Titan airship materials at TRL 3–4.	Mars balloon/airship materials to TRL 6 within 2–3 years. Titan airship materials to TRL 6 within 3–4 years. Venus low altitude balloon materials to TRL 6 within 5–6 years.

2.7 Cross-Cutting

A number of technologies cut across the key-enabling capabilities for planetary surface access. The following cross-cutting technology challenges are highlighted because they must be met to enable a broad variety of robotic exploration missions to planetary surfaces, and may not be as strongly advocated by the other capability roadmaps. Critical cross-cutting technical challenges include: (1) power generation and storage, (2) extreme environment avionics/mechanisms, (3) telecommunications, and (4) planetary protection.

2.7.1 High-efficiency, Scalable Power Generation and Storage

Robotic systems accessing planetary surfaces will require high-efficiency conversion and storage at scales ranging from milliwatts to kilowatts. In the case of solar power, there is a need for crystalline cells with efficiencies of 45% or better, and thin-film cells with efficiencies of 15% or better. For radioisotope power, there is strong interest in micro-RPS systems (below 100 W) to enable long-lived small vehicles and remote observation instruments. For power storage, there is a need for primary (non-rechargeable) batteries with energy densities of 500 W-hr/kg or better, and secondary (rechargeable) batteries with energy densities of 200 W-hr/kg or better. Furthermore, the extreme environment capabilities discussed below are applicable here, with particular emphasis on high-G tolerance (5000 G and above).

2.7.2 Avionics and Mechanisms for Extreme Environments

The envisioned mission set involves extremes of temperature, pressure, deceleration, and pressure. Existing avionics and mechanisms are not adequate to survive in these extreme environments. Ambient surface operational temperatures range from 460° C (for Venus surface missions) to −240° C (for comet sample return missions). This very broad temperature range will drive the need for new types of electronic devices and mechanisms. Impact loading for hard landers and penetrators drives the need for high-G tolerance. The deceleration levels for impactors may be as high as 50,000–100,000 G. Validation of high-G tolerance may require mission-specific testing. Radiation levels for Jovian system missions may exceed 180 krad/day. Some development for high radiation tolerant electronics has been performed in support of the Europa Orbiter mission. Further work is needed in materials compatibility, particularly for non-metallic items such as elastomers and propellants. Atmospheric pressure levels for Jovian probes may exceed 1000 bar. Test facilities that can replicate the relevant environmental conditions (e.g., combined temperature and pressure) are needed.

2.7.3 Planetary Protection for Missions to Potentially Biologically Active Regions – Forward and Back

Future planetary exploration missions will involve potentially biologically-active areas (Categories IV-C and V), including the surface and subsurface of Mars and the subsurface of Europa. These mission types require forward planetary protection (PP) to ensure that the destination sites are not contaminated by Earth-originating organisms, and, in the case of returned samples, back planetary protection is needed against potential biohazards. Spacecraft-level sterilization facilities (i.e., large ovens) are needed. For sample return missions, the most significant back PP requirement is for assured containment of returned samples. Once samples are returned, there are unique requirements for handling samples returned from potentially biologically active areas, e.g., multidirectional containment to simultaneously protect the Earth from a potential biohazard and preserve scientific value of the sample during access and investigation.

2.7.4 Telecommunications Under Extremely Challenging Conditions

It is not enough to merely access extremely challenging places in the solar system. We must also return data from these exotic locales, and it is not a given that there will be a stable, clear path for radio frequency or other traditional communication methods. In particular, long-range subsurface access may require high-data-rate wireless communication through liquid and/or solid materials. Planetary mission applications will most likely require unique levels of miniaturization, robustness, and reliability, at bandwidths significantly above those currently utilized in terrestrial applications (e.g., communication with submarines). Further testing in relevant environmental conditions (combined temperature and pressure) is needed. Other planetary missions (e.g., entry probes, penetrators, aerial vehicles) have relatively short mission duration while collecting large amounts of data. This mission type requires robust onboard data storage along with strategies for delivering the stored data after the end (possibly destructive) of the data-collection phase of the mission. Solid-state recording devices must be compatible with potential extreme environments.

Table 7 below summarizes enabling capabilities, current status and development time for cross-cutting technologies.

Table 7. Cross-Cutting Capability Summary

#	*Enabling Capability*	*What it Enables [Strategic Roadmap Reference]*	*Current Status*	*Development Time*
1	Develop higher-efficiency, scalable solar and radioisotope power generation	Scalable power systems offering higher efficiencies are either highly enhancing or enabling. [Mars]	**Solar Power Generation** SOTA is 27% efficiency for triple-junction crystalline cells; <10% for thin-film cells. No active dust mitigation for planetary surface missions. **Radioisotope Power Generation** Present radioisotope power systems are 100 We output or greater, with mass of 20kg or greater.	Crystalline cells e ≥ 45%; thin-film cells e ≥15% within 5 years. Miniature RPS systems (Power output ≤ 100 We) within 5–6 years.
2	Develop avionics and mechanisms capable of surviving in extreme environments	Scientifically interesting targets abound in the solar system, but involve extremes of temperature, pressure, radiation, and deceleration – well beyond the capabilities of current avionics and mechanisms. [Mars, Solar System]	**Temperature** Most ruggedized components are suitable for MIL-SPEC temperature range of −40 to +85° C, which is unsuitable for most planetary applications. **Pressure** Most advanced systems are for terrestrial applications (subsea, oil exploration) and have not been space qualified. **Radiation** Radiation-rugged COTS devices are typically for nuclear events, not total dose, etc. **Deceleration** Avionics ruggedness is generally limited to 10's or 100's of G's for COTS devices. Some DoD applications (e.g., smart artillery shells) can tolerate 1000's of G's.	**Temperature** Extreme environmental temperature ranges from −270C to +460C; unprotected elements survivable between -180C and +125C within 4–5 years. **Pressure** Pressure vessels and instruments tolerant of 1000 bars within 5–6 years. **Radiation** Avionics and mechanisms tolerant of 180 krad/day within 5–6 years. **Deceleration** Avionics and structures tolerant to 100,000 G in 4–5 years.
3	Develop high-data-rate wireless communication through liquid and solid materials	Data return from missions to deep subsurface locations. [Mars, Solar System]	Current systems involve short distances (laser through water, RF through walls) or extremely low bandwidth. High bandwidth long-distance wireless comm through liquids and solids does not currently exist.	Long-range, high-bandwidth, through-media telecom capability in 10–20 years.
4	Develop robust onboard data storage and strategies for post-mission data delivery	Data return from missions where a controlled landing or (other end to mission) is not ensured. [Mars, Solar System]	Crashworthy (Black box) technology has not been miniaturized, nor has it been coupled to extremely robust, self-powered communication capability.	Integrated data recording/ telecommunication package for small missions in 4–5 years.
5	Provide forward and back planetary protection for missions to potentially biologically active areas	Missions to, and returned samples from, regions of potential biological activity. [Mars, Solar System]	Planetary protection levels IV-C and V are not readily achievable with current technology; i.e., sterilization at the spacecraft level, sterilization of modern materials and avionics, and handling of potentially biohazardous returned samples.	Advanced sterilization methods can reach TRL 6 in 3–4 years. Returned sample handling can be developed in 5–6 years.

2.8 Facilities

Robotic access technology development and flight system qualification requires access to numerous unique facilities across the country, as well as support of the resident engineering talent that has honed a unique skill set. A small set of facilities exist which are vital for RAPS applications. Most of these same facilities also have direct application to the Human Planetary Landing Systems Capability Roadmap.

No ground-based facility exactly replicates high-energy flight conditions. Instead, individual facilities have been developed that replicate a particular aspect of hypervelocity flight. When combined with analysis and flight test capabilities (e.g., sub-orbital balloon and sounding rocket programs), these ground-based facilities anchor robotic access technology development and flight system qualification.

- Wind-tunnels achieve fluid dynamic similarity to flight. These facilities are used to obtain aerodynamics across a large range of relevant Mach number regimes, patterns of heating to the vehicle, and the behavior of transition to turbulence for the specific vehicle shape. Because these facilities do not replicate the energy of the flow, flight heat-transfer conditions are not obtained.

- Arc-jets are used to understand thermal protection system response during hypersonic entry. These facilities achieve sustained flight heating rates in an aero-convective environment, i.e., the heat rate, temperature, heat load, and shear to the test sample is flight-like. In this manner, the thermal response of flight hardware can be determined. The existing facilities are required for qualification of Mars entry and Earth return thermal protection systems. For planetary probe missions to the gas giants, entry heating is a complex combination of radiation and turbulent convection in a hydrogen/helium atmosphere. The Giant Planet Facility, a leg on the Ames Research Center (ARC) arc-jet complex, was used to test thermal protection material in a radiative/convective H/He environment. This portion of the Ames test complex is no longer operational, and would need to be refurbished as part of development of future probe missions to the gas giants. The AEDC arc-jet is a good complement to the Ames facility in that it provides high pressure, high enthalpy test conditions. Such test conditions are ideal for thermal protection system testing of a robotic mission to Venus.

- Ballistic range facilities are the appropriate choice for determining dynamic aerodynamic force coefficients which are of significance for aerostability assessment. In a ballistic range test, a small projectile is fired along the test chamber and the aerodynamic forces are reconstructed by tracking its dynamic motion. These facilities can also be used to obtain stagnation-point heating and noise-free transition data. The Eglin AFB ballistic range is typically used by current robotic Mars and Earth programs. The ARC ballistic range offers the advantage of controlling the gas composition and pressure, albeit for smaller models.

- Combinations of fluid dynamic and energy similarity can be obtained in shock tunnels such as the T5 facility at Cal Tech and Large Energy National Shock Tunnel (LENS) at University of Buffalo Research Center. These facilities produce data to validate the combined chemical kinetic and fluid dynamic convection models that are used to predict convective heating in flight. Neither tunnel is operated by NASA. Instead, NASA personnel generally obtain test time in one of the above two facilities, depending on the specifics of the given flight project.

- The ARC Electric-Arc Driven Shock Tube is used to understand the high temperature atomic, chemical kinetic, and gas dynamic behavior of the atmospheric gases at high temperature, which is essential for shock layer radiation modeling. It is the sole remaining facility of its kind in NASA. In this test facility, the tube is filled with the gas of interest and a shock wave of appropriate strength is sent down the tube. Cameras affixed to windows within the tube record the brightness and spectral resolution of the gas as the shock wave passes. This information is used to develop detailed physical models required for aerothermodynamic flight prediction.

- RAPS test requirements frequently require access to low density relevant. Such access is typically made possible through high-altitude flight testing. NASA's Balloon Program supports high altitude Earth payloads up to 8,000 pounds. The Air Force Balloon Program supports lighter payloads, with the heaviest launch in the last 5 years being approximately 4,000 pounds. On the commercial side, GSSL, Inc. frequently launches Earth payloads of up to 500 pounds to over 100,000 feet.

The table below details the facilities deemed essential to RAPS capability development. It is recommended that NASA form a test facilities team to develop a uniform cost basis for these facilities. Because of the critical nature of the test facilities and the resident expertise, this cost information is vital for planning RAPS and other technology capability development (e.g., Human Planetary Landing Systems).

Table 8. List of NASA Facilities Deemed Essential to RAPS Capability Development

Facility	*Location*	*Role*
Aerothermodynamics Complex	NASA LaRC	Understanding hypersonic aerodynamics and convective heating, including transition to turbulence
Aeroballistic Research Facility	Eglin AFB	Gather free-flight aerodynamic data using shadowgraph and laser interferometry
Arc-Jet Test Facility	NASA ARC	Development and qualification of TPS under flight-like thermo-structural conditions. High enthalpy, low pressure conditions (Earth and Mars entry, Outer-planet missions require facility refurbishment).
Arc-Jet Test Facility	AEDC	Development and qualification of TPS under flight-like thermo-structural conditions. High enthalpy, high pressure conditions (Venus entry).
Transonic Dynamics Tunnel (TDT)	NASA LaRC	Perform sub-scale developmental testing of supersonic decelerators and planetary aerial platforms in relevant conditions
National Full-scale Aerodynamics Complex (NFAC)	NASA ARC	Perform full-scale load testing at representative loads and Reynolds number for Mars & Titan supersonic decelerators and full-scale testing of Mars airplane propeller drive systems.
National Scientific Balloon Facility (NSBF)	NASA WFF (Palestine, TX)	Perform high altitude balloon drop testing essential for scaled flight testing at relevant conditions (Mach and Reynolds Number) for supersonic decelerators. NASA suborbital balloon and sounding rocket programs mitigate risk for planetary aerial platforms.
Plum Brook Facility (Vacuum Chamber)	NASA GRC	Allow full-scale testing of landing systems at Mars surface pressures. Allows scale testing of balloons and airships at representative (Mars and high-altitude Venus) pressures.
Vertical Spin Tunnel	NASA LaRC	Perform sub-scale testing of entry systems and planetary aerial platforms to investigate subsonic stability characteristics.
T5 facility	Cal Tech	Understand hypervelocity convective heating, including transition to turbulence.
LENS	CUBRIC	Understand hypervelocity convective heating, including transition to turbulence
Ballistic Range	NASA ARC	Gather free-flight aerodynamic data using shadowgraph and laser interferometry. Quantifying transition effectiveness of ablated materials.
Electric-Arc Driven Shock Tube	NASA ARC	Understand the high temperature atomic, chemical kinetic, and gas dynamic behavior of the atmospheric gases at high temperature for developing radiative heating models.

3 Process

3.1 Summary History of RAPS Technology Capability Portfolio

A summary of the process employed in developing this technology capability portfolio is given below:

1. Define scope of roadmap, Oct 14, 2004
2. Select team members to cover scope, Nov 1, 2004
3. Conduct public session to solicit input, Nov 30, 2004
4. Conduct three workshops with invited experts
   - Dec 15–17, 2004, JPL
   - Feb 2–4, 2005, ARC
   - Mar 3–4, 2005, Georgia Tech
5. Construct TCP themes (3rd workshop)
6. Detail roadmap actions (April 05)
7. Executive Summary (May 05)
8. External Review (June 05)
9. Final Report (July 05)

In addition, members of the RAPS team gave summary presentations to the Mars and Solar System Exploration Strategic Roadmap teams and received briefings from those two teams at the conclusion of the Strategic Roadmap process.

3.2 Summary of Meetings

RAPS met three times. The first two meetings (December 2004 and February 2005) consisted of invited presentations by experts in topics of interest and the development of a plan for writing assignments to the group. Due to significant overlap with Human Planetary Landing Systems Roadmap team, portions of these meetings were held together. The last meeting (March 2005) was a working meeting to develop draft write-ups.

The following topics were discussed in the first two meetings.

First meeting: Mars drilling; subsurface access; solar system exploration plans; planetary protection; extreme environments; Apollo Lunar Module EDL and Command Module Earth entry; past Mars landings; challenges for 2 MT Mars EDL systems; touchdown systems; challenges and methodologies for 10–50 MT Mars landing; Earth testing and validation of landing systems; Mars precursor missions; pinpoint landing control; relevant observations of Mars; autonomy and control; rover technology; and lighter-than-air flight.

Second meeting: planetary aircraft; drilling sensors and autonomy; drilling, advanced surface mobility (rolling, walking, climbing, rappelling, etc.); aerocapture; supersonic and subsonic decelerators; descent propulsion; communications; pinpoint landing; inflatables; aerothermal design, prediction, and test; TPS materials and systems; TPS test facilities; TPS flight experiments and measurements; super/subsonic test facilities; terminal descent test facilities; EDL verification and validation; and Earth test flight platforms (balloons, rockets.)

3.3 Capability Breakdown Structure

See Figure 1.

3.4 Relationships to Other Roadmaps

Following are the relationships with the other capability roadmaps (there is no roadmap #1). The key relationships are shown in italics.

2. **High Energy Power and Propulsion**: RAPS assumes the provision of nuclear power systems, both in the 100 We class and the < 1 We class.
3. **In-Space Transportation:** RAPS assumes the provision of ascent and autonomous rendezvous and capture systems for sample returns, RAPS provides aerocapture.
4. **Advanced Telescopes and Observatories:** No relation. Remote observations of planetary atmospheres and surfaces may provide engineering and operational information for entry, descent, and landing systems.
5. **Communications and Navigation:** RAPS assumes the provision of relay radios and services for low-energy data transmission, radio-navigation data types, and frequent access to surface assets.
7. **Human Planetary Landing Systems:** RAPS provides ground-based test facilities, high-altitude Earth test infrastructure, sustained environmental observation, visual terrain recognition, and hypersonic guidance experience, as well as an experienced cadre of Mars landing practitioners. In the long run, RAPS would benefit significantly from the increased landed mass capability of the one-tenth scale human landing demonstration systems.
8. **Human Health and Support Systems:** No relation.
9. **Human Exploration Systems and Mobility:** No relation. Robotic assistants to humans are covered in human health and support systems (HESM), not RAPS.
10. **Autonomous Systems and Robotics:** RAPS assumes the provision of high-level autonomy for surface and aerial exploration systems, in particular for mobility to targets, articulation and surface interaction at targets, and goal-oriented resource management.
11. **Transformational Spaceport/Range Technologies:** No relation.
12. **Scientific Instruments and Sensors:** RAPS provides surface and atmospheric access to in situ instruments and sensors, and assumes the provision of downhole instrumentation integrated with deep drilling systems.
13. **In Situ Resource Utilization:** No relation. Robotic mining and resource extraction equipment are covered in ISRU and HESM, not in RAPS.
14. **Advanced Modeling, Simulation, and Analysis:** RAPS assumes the provision of detailed environmental and system simulation capabilities, including the direct incorporation of flight software, for design and verification.
15. **Systems Engineering Cost/Risk Analysis:** RAPS assumes the provision of established practices applicable to these systems for probabilistic risk assessment where such analyses are required to validate compliance with planetary protection requirements.
16. **Nanotechnology:** RAPS does not assume, but may benefit from, the provision of nanostructured, thermal-protection materials, nanoelectronics, and nanosensors to enable small entry probes.

4 Summary

Entry, descent, and landing systems do not scale up in size gracefully, and so the continuing demand on more capable delivery systems will require capability development before such missions can be considered feasible.

EDL and aerial vehicle development depend heavily on NASA test infrastructure and expertise. Special attention is needed to determine how to maintain and enhance that infrastructure and critically-skilled personnel.

Small landers require the development of high-G systems and small nuclear power sources (RPS), that would enable a new class of low-cost network science missions to provide much broader surface coverage.

Modest investments in capability developments can enable airship and airplane vehicles for Venus, Mars, and Titan and will enable a new class of science missions to be conceived and executed.

For both landed and aerial missions, precursor environmental observations will enhance and possibly enable the design and test of future systems. How the systems perform in those environments need to be well characterized, analyzed, and fed forward to reduce risk for subsequent missions.

New surface mobility systems should be developed to access difficult and treacherous terrain. One example of such highly desirable targets is putative water gullies in Martian crater walls.

Sampling capabilities will initially be driven and developed by missions. However, deep drilling and down-hole instrumentation require considerable development and demonstration before mission applications can be considered.

Extreme environment systems are essential for the envisioned strategic missions. A comprehensive program should be put in place to perform the system engineering trades to define the requirements, and then develop the capabilities.

Unprecedented degrees of contamination control for both science and planetary protection is required for life-detection missions, either in situ or via returned samples. In addition to the contamination control, the containment of Martian samples upon return to Earth must be assured to meet planetary protection requirements. Feasible planetary protection approaches must be established before we can plan and cost a Mars Sample Return mission.

5 Acknowledgements / References

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Rita Willcoxon, Al Diaz, Jens Feeley, Giulio Varsi, Chris Weaver, Steve Prusha, and Harley Thronson led, supported, and brought this roadmapping activity to a successful conclusion.

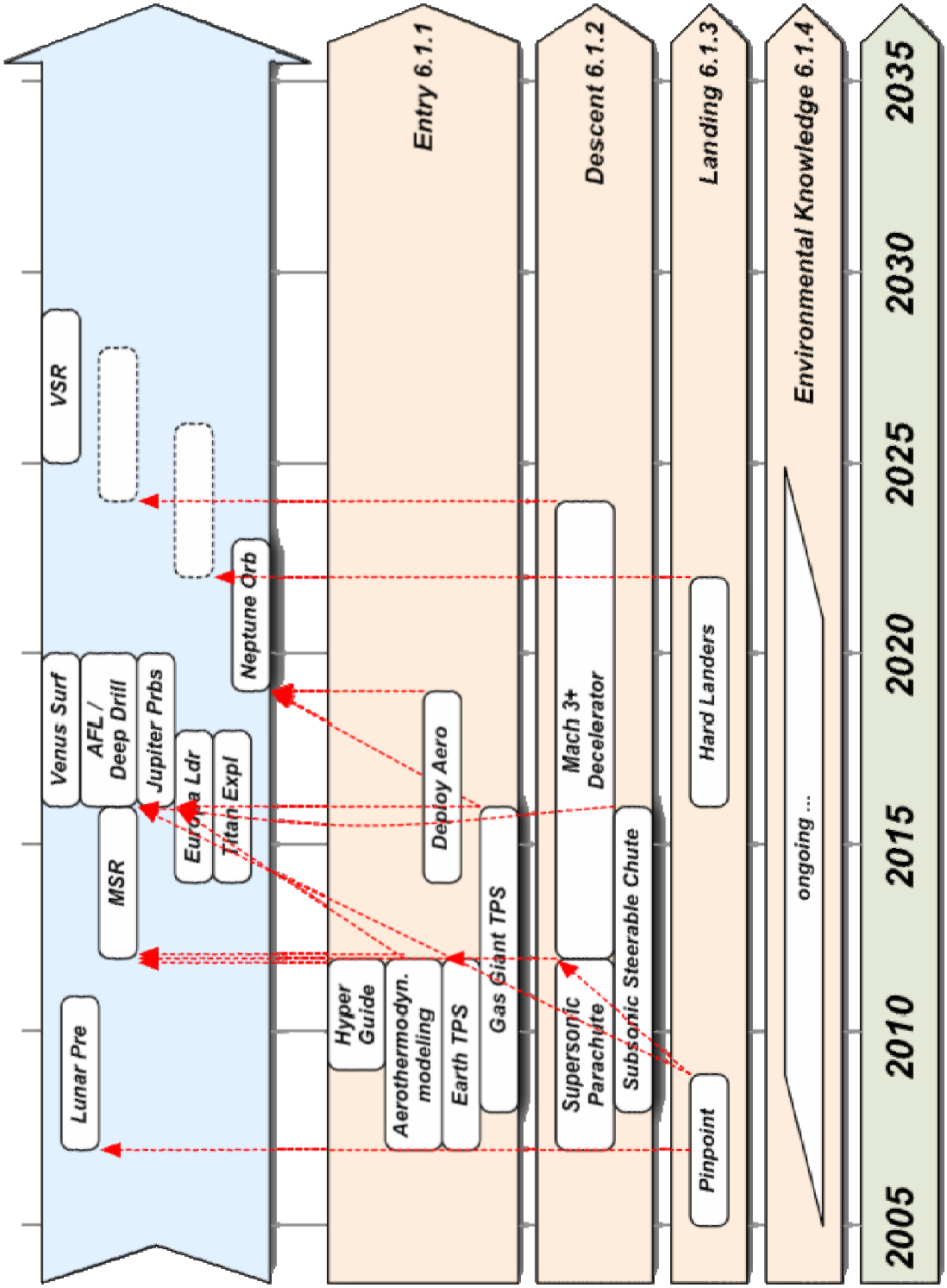
All the background materials are documented in the APIO Docushare, under Capability RoadMaps/workshops.

5.1 Acronyms and Abbreviations

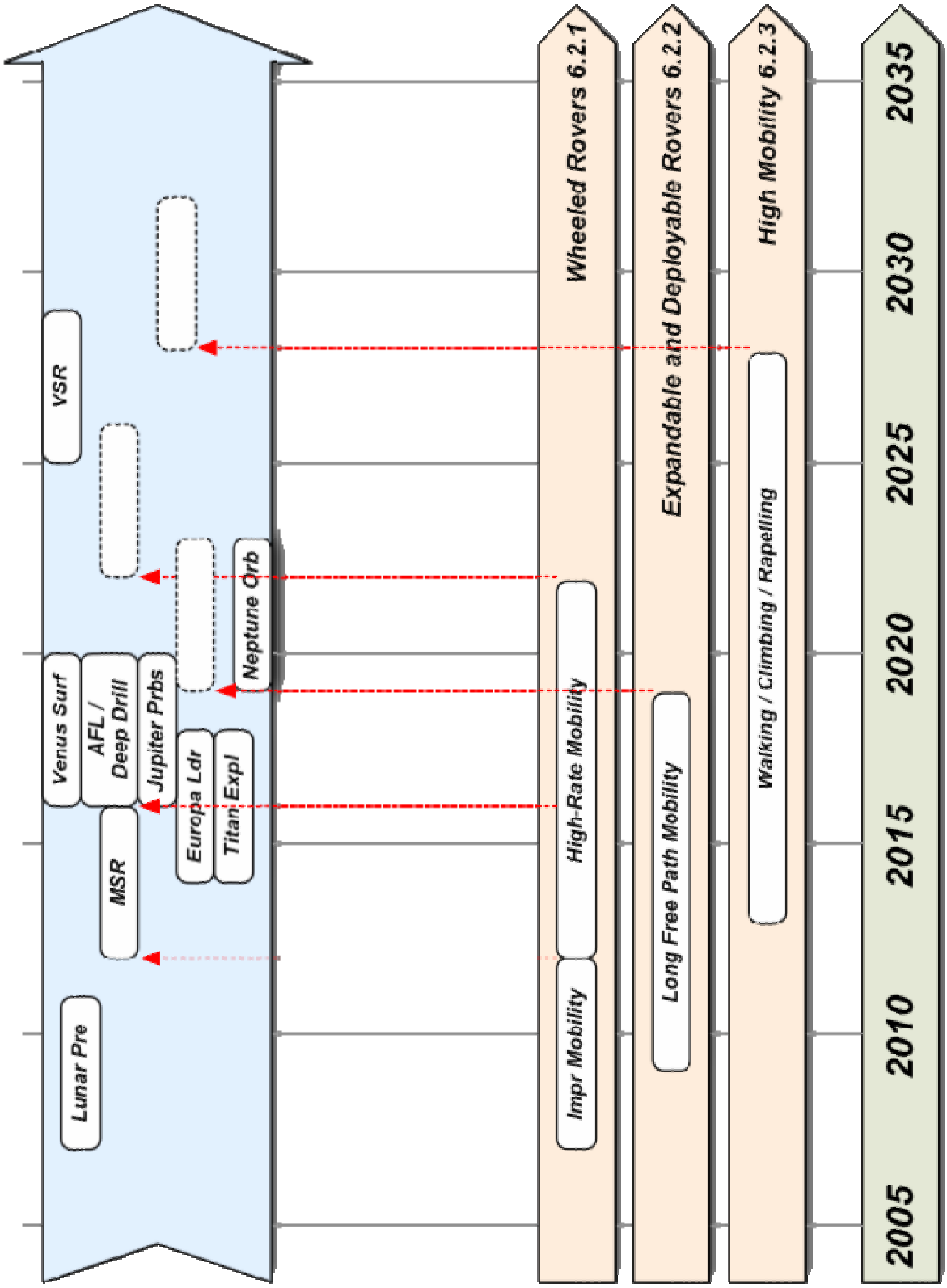
ARC	Ames Research Center
CBS	capability breakdown structure
CRL	capability readiness level
DGB	disk-gap-band
EDL	entry, descent, and landing
GN&C	guidance, navigation, and control
HESM	human health and support systems
ISRU	in situ resource unitization
LENS	Large Energy National Shock Tunnel
LTA	lighter than air
MFP	mean free path
NFAC	National Full-scale Aerodynamics Complex
NRC	National Research Council
NSBF	National Scientific Balloon Facility
PP	planetary protection
RAPS	Robotic Access to Planetary Surfaces
RPS	small nuclear power sources
SRM	strategic roadmap
TCP	technology capability portfolio
TRL	technology readiness level
TDT	Transonic Dynamics Tunnel

6 Appendix 1

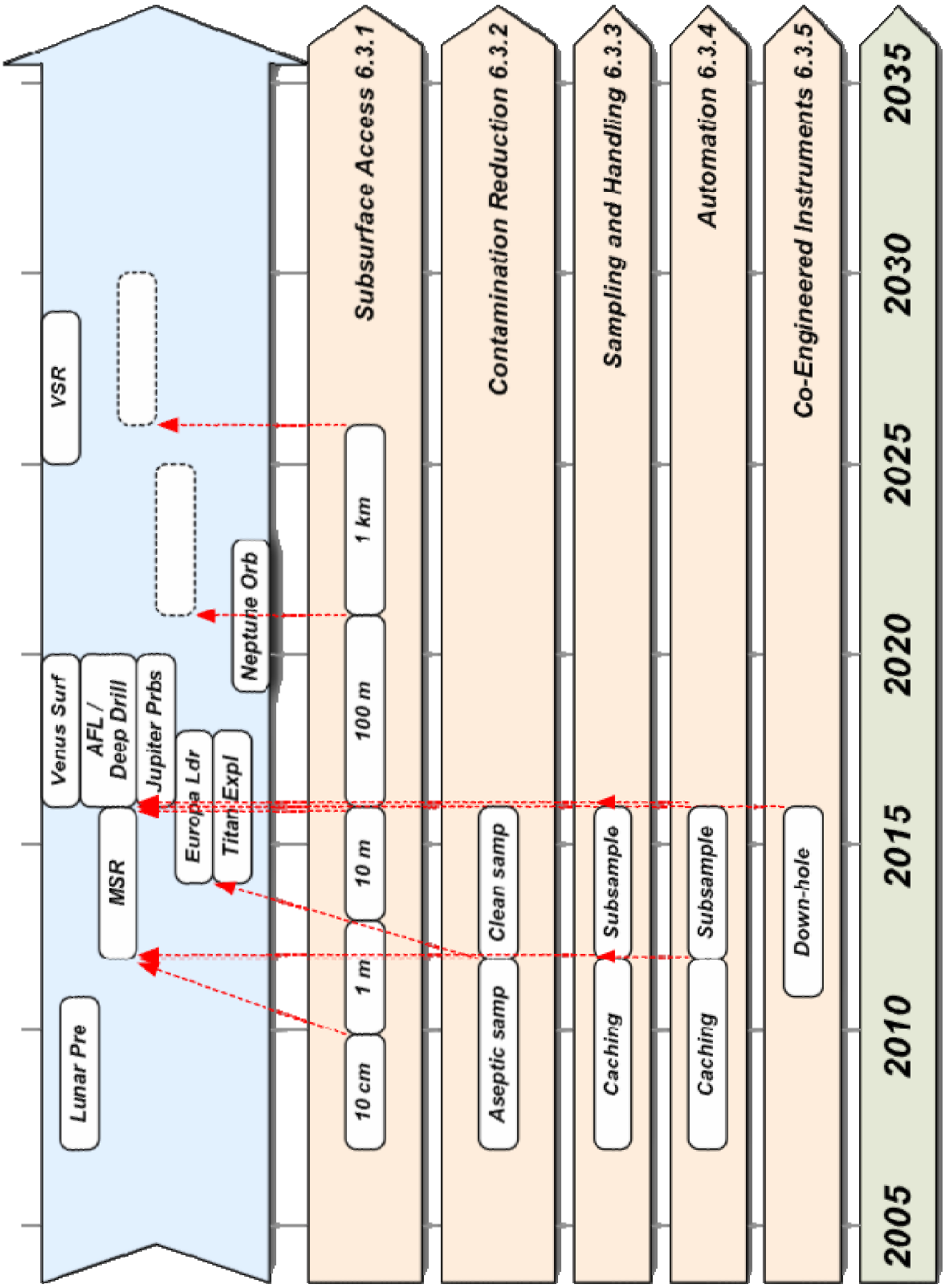
6.1 Atmospheric Transit Roadmap



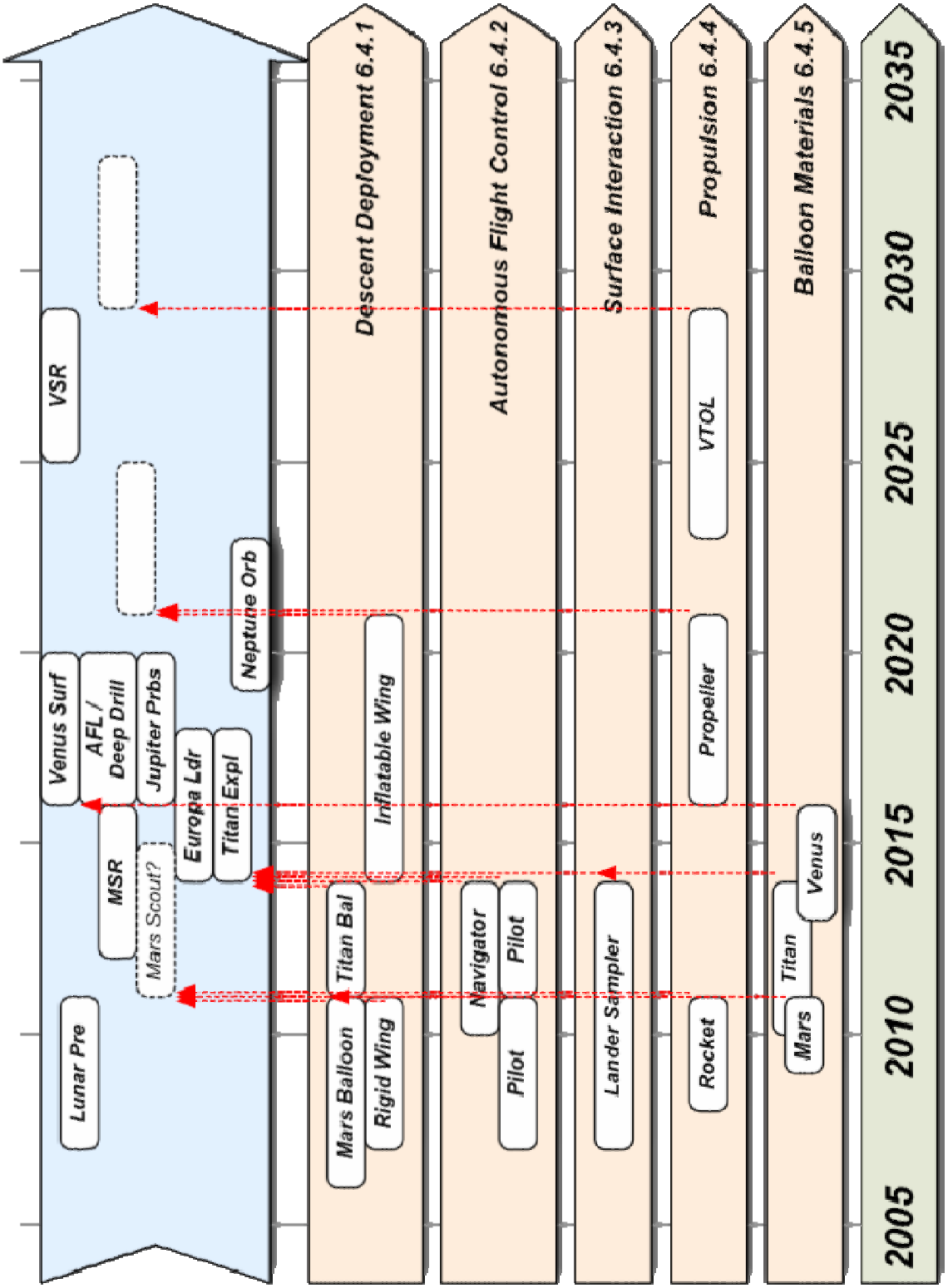
6.2 Mobility Roadmap



6.3 Sample Access Roadmap



6.4 Aerial Flight Roadmap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Venus Surf
MSR
AFL / Deep Drill
Mars Scout?
Jupiter Prbs
Europa Ldr
Titan Expl
Neptune Orb
VSR
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Mars Balloon
Titan Bal
Rigid Wing
Inflatable Wing
Autonomous Flight Control 6.4.2
Pilot
Navigator
Pilot
Surface Interaction 6.4.3
Lander Sampler
Propulsion 6.4.4
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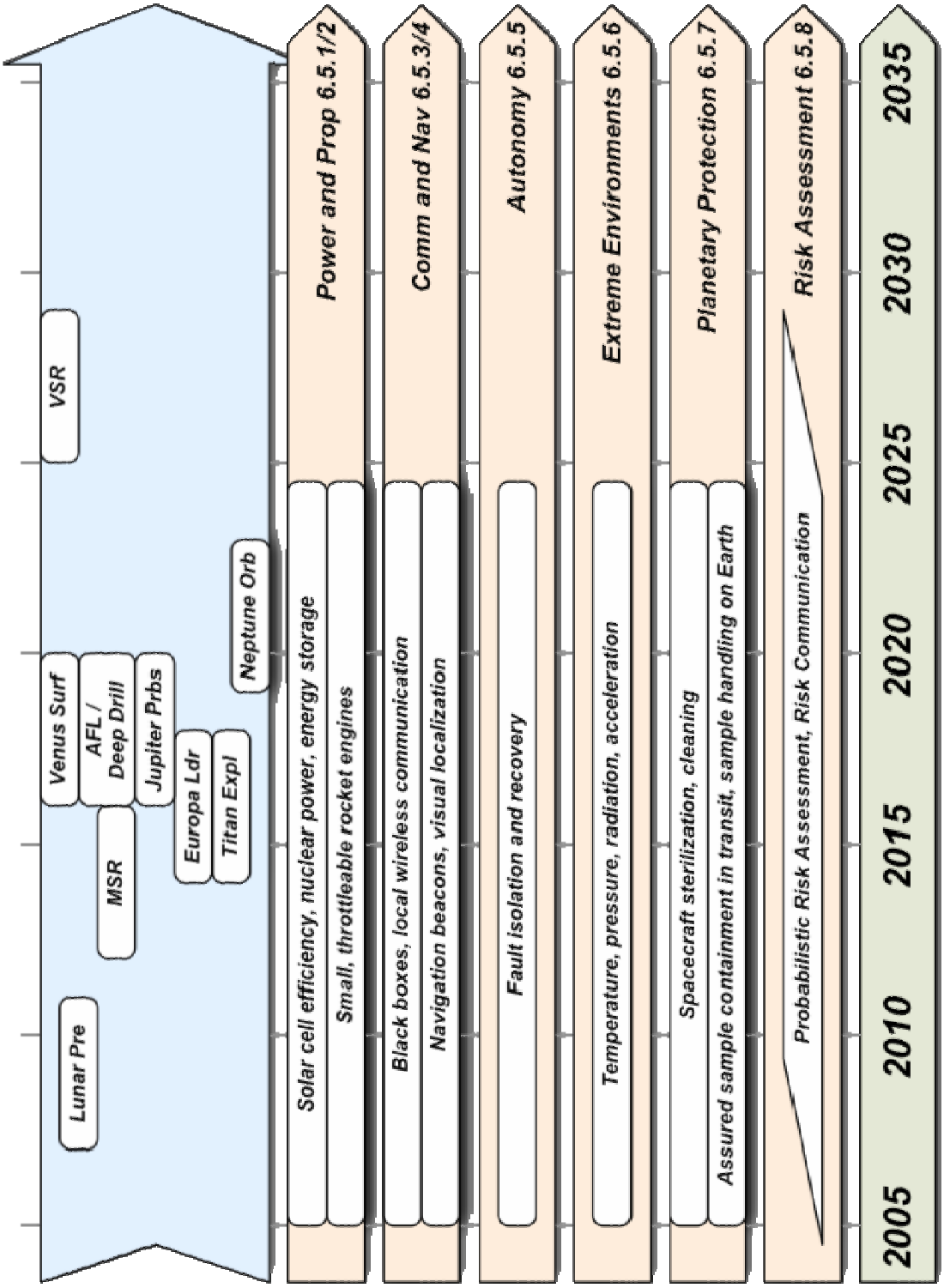
6.5 Cross-Cutting Roadmap