Science and Technology Progress Report on Planetary Probes

14th International Planetary Probe Workshop

The Hague, The Netherlands, 2017

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Second Science and Technology Progress Report on Planetary Probes

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14th International Planetary Probe Workshop

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Foreword

By Bernie Bienstock, IPPW-14 International Organizing Committee Chair, Jet Propulsion Laboratory, California Institute of Technology

We are very pleased to publish our second International Planetary Probe Workshop (IPPW) Science and Technology Report on Planetary Probes. This report documents the content and findings of IPPW-14, conducted in The Hague, The Netherlands, from 12–16 June 2017. Our 14th workshop was the first sponsored by the European Space Agency (ESA) and included funding from additional European organizations, including Europlanet, Airbus Defence and Space (DS), and Delft University of Technology. Sponsors from the United States included NASA, Analytical Mechanics Associates, Inc. (AMA), and the Jet Propulsion Laboratory (JPL).

IPPW-14 was notable for several reasons: It was the most heavily attended workshop and Short Course in our fourteen-year history; it featured the highest number of presentations and posters; and it was our first workshop held in The Netherlands.

Our workshops are conducted annually following a schedule we developed in the early years of IPPW. We emphasize the workshop nature of our yearly gatherings by encouraging interactions between presenters and attendees. In fact, our yearly events have led to collaborations developed as a result of discussions among attendees.

At IPPW-14, we offered a weekend Short Course on Ocean Worlds, followed by almost five days of oral and poster presentations. We encouraged student participation and offered travel scholarships to qualifying students. All attendees were asked to vote on the first-, second-, and third-place student presentations and posters, with student awards presented during the closing session.

Our IPPW philosophy differs considerably from that of other conferences and workshops. With the exception of executive presentations during the opening session, papers were scheduled on 14-minute centers, with each speaker instructed to deliver no more than 12 minutes of material. Each speaker answered questions following his or her presentation, with an additional Q&A period scheduled at the end of each session. Session conveners briefly summarized their session findings during the closing session. These brief summaries of findings have served as the basis for this report.

Poster presenters were given the opportunity to speak to a single-slide Poster Short Talk early in the workshop to encourage attendees to review their work and provide feedback. We also held a Poster Reception, with authors providing workshop attendees additional insight into their poster topics.

This report is divided into sections that document the content and findings of the 11 technical sessions during IPPW-14. Session conveners authored their individual sections. The Program Organizing Committee, under the leadership of Ashley Korzun, Robert Buchwald, and Rodrigo Haya Ramos, managed the production of this report.

IPPW is an independent organization, without a permanent governing body. All those who participate in the organizing and award committees do so out of a desire to learn from the yearly workshops and to share a week in an exciting location with long-standing associates. Many of our attendees have been to several past workshops. They continue attending to learn about the latest science and technology in the field of planetary probes.

As with most ongoing workshops and conferences, a core group of enthusiastic volunteers revolunteer to serve on committees and devote their own time to planning and conducting our yearly events. We are proud of the work contributed over the years by our poster and oral presenters, as well as our Short Course instructors. We encourage you to read this Technology Progress Report to gain insight into the wealth of ideas offered at IPPW-14; if you have an interest in reviewing the material from previous workshops, you can find the presentations archived at https://goto.jpl.nasa.gov/ippw-archive.

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1 Introduction

By Ashley Korzun[1], Robert Buchwald[2], and Rodrigo Haya Ramos[3]

Following the first Science and Technology Progress Report on Planetary Probes, this second report is intended to again capture the many findings and technological advances presented at the annual International Planetary Probe Workshop (IPPW).

IPPW brings together engineers and scientists from government agencies and supporting organizations, industry, and academia around the world to discuss the science, engineering, and technology relevant to planetary exploration. The emphasis of IPPW is on probe exploration of planetary atmosphere environments, with significant supporting contributions on descent and landing technology and in situ exploration of bodies within the Solar System. The breadth and depth of the technical content is conducive to identification of areas for potential collaboration, not only between science, engineering, and technology, but also between international organizations pursuing exploration.

For IPPW-14, the technical program was organized to balance science, engineering, and technology in both application and destination. A special session was held on Exobiology on Mars (ExoMars) to discuss findings from the Schiaparelli lander and plans for ExoMars 2020, and a session on Ocean Worlds expanded on content from the IPPW-14 short course. A new session was held this year to discuss the emerging role of Small and CubeSat probes within this community. Other sessions focused on exploration of destinations from Mercury to the outer planets, execution of entry or deorbit, descent, and landing (EDL or DDL), sample return, and the science, instrumentation, and processes necessary to achieve the success of such missions.

This report contains summaries of the technical content and significant findings from open discussion on the following topics, in order of presentation at IPPW-14:

- ExoMars
- Mars exploration
- Ocean worlds

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- Modeling, simulation, testing, and demonstration
- Mercury and Venus
- Outer planets
- Lunar and small body exploration
- Descent and landing technology
- Instrumentation and experiments
- Aerobraking, aeroscience, and entry technologies
- Small and CubeSat probes

The chapters have been written by the session chairs responsible for the organization of both content and execution of the individual sessions. The summarized findings have been elaborated with the IPPW community through a plenary feedback session during the closing session of the workshop.

The archive for IPPW-14 and all prior IPPWs is available at https://goto.jpl.nasa.gov/ippw-archive.

2 ExoMars

By Andrew J. Ball[4] , Stefano Portigliotti[5], Thierry Blancquaert[6], Olivier Bayle[7], and Leila Lorenzoni[8]

The ExoMars Schiaparelli EDL Demonstrator Module (EDM) entered the Martian atmosphere on October 19, 2016. While the landing attempt was ultimately unsuccessful, the mission was largely nominal up to the anomaly that can be traced back to unexpected angular rate saturation behavior at the time of parachute deployment. A special session at IPPW-14 covered Schiaparelli's encounter with Mars and research results from the onboard measurements during entry and descent. The current status of plans for the ExoMars 2020 Rover and Surface Platform mission was also addressed.

2.1 Summary of Technical Content

The ExoMars session discussed Schiaparelli flight experience and preliminary research results through presentations from the ExoMars project (ESA and industry), Atmospheric Mars Entry and Landing Investigations and Analysis (AMELIA), and Combined Aerothermal and Radiometer Sensors Instrument Package (COMARS+) teams. With the recent release of the Schiaparelli anomaly inquiry report, analysts explained the causes of the "hard impact" by analyzing the available real-time telemetry during EDL. Participants presented lessons learned and resulting recommendations to ExoMars 2020, as well as remaining open points for full exploitation of post-flight analyses. The complete report on the Schiaparelli anomaly is available at: http://exploration.esa.int/mars/59176-exomars-2016-schiaparelli-anomaly-inquiry/.

Technical highlights from the ExoMars session focused on demonstration of EDL capabilities for the ExoMars program, including

- Full demonstration of accurate targeting, separation, and coasting, with a highly nominal mission up to front-shield jettison

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- First European Mars lander mission with telemetry data return
  - Real-time, low-frequency data packets (minus entry blackout, with peak deceleration recorded and retransmitted), sufficient to identify root causes of the anomaly
- Successful demonstration of the atmospheric entry systems, including survival of the aerothermal environment, aerodynamic stability, and Norcoat-Liège thermal protection system (TPS)
- Successful deployment of the parachute at high Mach number (2.05), measurement of the attitude oscillations during and after the inflation, and nominal descent dynamics under parachute
- Flight qualification of a new radar Doppler altimeter, also to be flown on ExoMars 2020
- Tracking of UHF carrier signal from Earth (GMRT)
- Successful data link to orbiters for carrier, Doppler (Mars Express, ExoMars Trace Gas Orbiter [TGO]), and telemetry (at 8 kbps to TGO)

Schiaparelli was a 2.4-m-diameter, 70° half-angle sphere-cone aeroshell flying a spinning, ballistic, unguided entry trajectory, with an entry mass of 577 kg. The vehicle successfully completed its trajectory up to entry interface, hypersonic entry, parachute deployment, and radar Doppler altimeter operation between 7 km and 4 km altitude. Transient oscillations with larger than expected angular rate during inflation of the parachute led to saturation of the inertial measurement unit (IMU) yaw channel 0.4 s after inflation. Reconstructed axial and lateral forces showed drag area oscillations at approximately wrist-mode frequency. The IMU anomaly caused premature release of the parachute and backshell from the lander and premature shutdown of the lander propulsion, resulting in a hard surface impact after free-fall from 3.6 km above the surface.

Schiaparelli was a well-instrumented entry vehicle, with a conventional IMU (6-degree-of-freedom [DOF] accelerometer and gyroscope), Flush Air Data system (FADS) comprising four front-shield pressure transducers, and a suite of thermal plugs: seven in the front shield and three in the backshell. Furthermore, the COMARS+ experiment on the backshell included 3 sensor heads (combining pressure and heat flux measurements) and a broadband radiometer. **Figure 2-1** shows the onboard sensor suite. Analysis of dynamics data from IMU and RDA has allowed for derivation of the Schiaparelli trajectory, atmospheric density and temperature profiles.

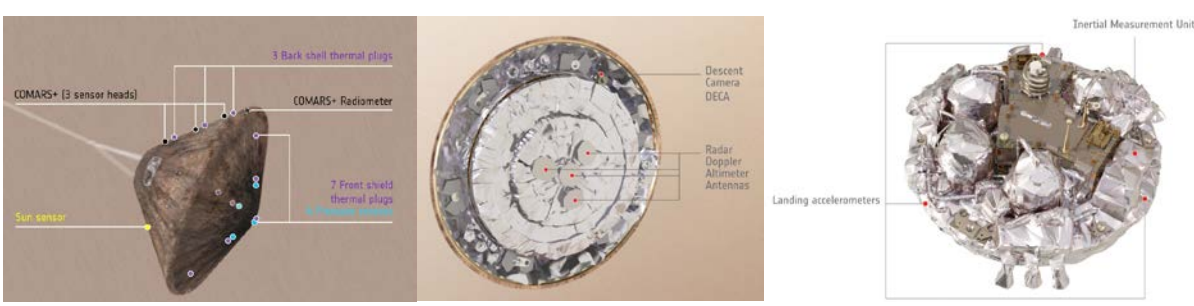

Figure 2-1. *Schiaparelli onboard EDL instrumentation.*

Front-shield pressure data was recorded and transmitted during the entry phase, but peak dynamic pressure and peak heating conditions were lost during plasma blackout and subsequently failed on landing. All FADS sensors returned meaningful data, with the exception of the stagnation point pressure transducer. This was a unique FADS dataset, only the second at Mars, which can be used to constrain atmospheric density and wind-relative attitude. The FADS reconstructed density showed reasonable agreement with IMU reconstruction. The FADS reconstructed attitude was in better agreement with flow angles from IMU acceleration ratios than from guidance, navigation, and control (GNC) IMU integration. However, the GNC initial state can be tuned to improve consistency between IMU attitude profiles. Recommendations for FADS include use of more than 4 sensors for redundancy and accuracy, calibration of sensors for temperature effects and hysteresis. Post-flight analysis continues with the limited set of EDL data (2.8 Mb returned, out of a 100-Mb EDL dataset stored in the onboard memory), with commitment to maximum investigation of existing data.

Heatshield pressure data from commercial off-the-shelf (COTS) Kulite sensors provided good quality measurement data. The temperature data is now available for further analysis, with a limited number of sensors identifying turbulent transition. TPS recession was less than 2 mm, with the exact recession unknown, leaving future work to understand pyrolysis and material response. More comprehensive post-flight analysis with thermal model correlations and inverse methods is foreseen to assess the extent to which TPS thickness may in future be reduced while maintaining adequate margins.

Flight data from ExoMars will improve modelling of aerothermal environments on the backshell of Martian entry vehicles. Specifically, backshell measurements were obtained in-flight for temperature, pressure, heat flux, and radiation. COMARS+ is a set of three combined sensors, a radiometer, and an analog electronics box. Each COMARS+ sensor measures pressure, surface temperature, heat flux, and radiative heat flux at 2.9 and 4.6 cm. The broadband radiometer measures shock layer radiation in the vehicle shoulder region. In-flight conditions near peak heating and peak pressure were captured, though data return was limited by occurrence of these events during plasma blackout. All 24 sensor channels worked perfectly, providing useful data on aerothermal environments for the vehicle backshell, fully qualifying COMARS+ on the first flight of such a sensor package. COMARS+ measured lower aerothermal loads than predicted, indicating the possibility of reduction in backshell TPS margins on future missions. The COMARS+ package also provided useful data for validation of physical models and numerical simulations for aerothermal environments. Pressure data is being used to support reconstruction of the trajectory and entry system performance.

The deployment and inflation phase of Schiaparelli's parachute (12-m-diameter disk-gap-band [DGB]) caused the module to experience an unexpectedly large transient angular rate, after which the motion under parachute was highly stable. The ExoMars EDL team continues analysis of this behavior and will work with JPL and NASA's Langley Research Center (LaRC) to better understand parachute inflation dynamics and design.

2.2 Findings

1. While not an end-to-end mission success, Schiaparelli, the ExoMars EDM, achieved significant successes during targeting, entry, and descent, demonstrating performance of critical systems at Mars while providing real-time flight data to identify and reproduce root causes of the landing failure.
2. The IPPW community continues to support full post-flight reconstruction activities for all flight projects, independent of outcome. Such practice consistently yields knowledge to refine uncertainties, margins, and system performance verification and validation efforts.
3. The EDL instrumentation flown on Schiaparelli merits reflight on future missions, and work is ongoing to extend calibration to lower temperatures to support such implementation

3 Mars Exploration

By Ashley Korzun[9], Thomas Voirin[10], and Aaron Stehura[11]

Mars, the most habitable planet beyond the Earth-Moon system, has long been a body of interest and great challenge to exploration, with seven successful landers and numerous successful orbiter missions since the 1970s. An understanding of Mars and its evolution leads to a better understanding of Earth; as a result, Mars is a near-term target destination for human exploration, driving investments in technology to support the endeavor. The Mars Exploration session addressed topics relevant to past, present, and future exploration of Mars, with topics spanning science, technology, systems, and missions for atmospheric science and environment characterization, robotic and human exploration, and sample return.

3.1 Summary of Technical Content

3.1.1 Upcoming Missions

While the 2018 Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) and Mars 2020 (M2020) lander missions are predominantly build-to-print, both missions have undertaken improvements to hardware and modelling.

3.1.1.1 InSight

Since the launch slip from 2016 to 2018, InSight has addressed risks associated with the onboard landing radar and final trajectory correction maneuver (TCM) targeting process. The InSight lander is vulnerable to heatshield-induced radar ambiguities, where under certain conditions, the heatshield can elicit false positives from the radar. The original radar activation was based on a simple, fixed timer relative to the parachute deployment event. The InSight mission design has changed to use a navigated velocity at parachute deployment to calculate and actively set the radar activation time during EDL, effectively reducing altitude uncertainty and eliminating the prior vulnerability to heatshield-induced radar ambiguities. Additional changes have been made to the

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design process of the final maneuver as a result of identified sensitivity to changes in EDL-day atmosphere knowledge to now include definition of tolerances in the entry flight-path-angle target and ground target to be used by the navigation team during the final TCM targeting process. The InSight mission is on track for a 2018 launch (period: May 5–June 8, 2018), with Mars EDL on November 26, 2018.

3.1.1.2 Mars 2020

The M2020 mission has a four-part objective to understand the possibilities for life on Mars: (1) habitability, (2) biosignatures, (3) sample caching, and (4) preparation for humans. M2020 will fly the Mars Science Laboratory (MSL) EDL architecture augmented by a range trigger and Terrain-Relative Navigation (TRN), as well as new instrumentation. The range trigger reduces the landing ellipse area by 40%, as compared to MSL; TRN allows the vehicle to avoid identified landing hazards. M2020 will be flying M2020 EDL Instrumentation 2 (MEDLI2), extending MEDLI heritage with new backshell observations and supersonic pressure measurements. Lastly, high-resolution, high-frame-rate cameras for the parachute, descent stage downlook, and rover up- and downlook have been added to the vehicle.

M2020 has started on parachute risk-reduction efforts through the Advanced Supersonic Parachute Inflation Research and Experiments (ASPIRE) project. While the parachute design was successful on MSL, the Low-Density Supersonic Decelerator (LDSD) program revealed shortcomings in the perceived conservatism of the parachute analysis and test methods, as well as in the understanding of supersonic parachute inflations. In response, M2020 is developing a strengthened parachute design in parallel to the build-to-print design from MSL, as well as investigating the impact of planetary protection bake-out heating on parachute material strength. Additional updates to MSL parachute models based on MSL parachute performance reconstruction (deployment and peak opening loads) and ground-based testing (static aero coefficients) have also been completed. Work continues to complete tuning the initial parachute attitude, update static aerodynamic tables, examine the sources of observed damping and initial excitation, and define the expected variability from flight to flight.

The onboard TRN has two components: (1) the Lander Vision System—a sensor that provides map relative localization (~40 m), and (2) the Safe Target Selection—the function that selects a safe landing target within reach of the powered flight divert capability (up to 650 m) from an onboard Safe Target Map (ground-developed). The EDL Landing Hazard Map captures landing risk due to terrain. The Safe Targets Map is a map of safe landing targets that pads the hazards to account for knowledge and control errors based on the hazard level and identifies landing spots with benign slopes (<10°). Combined with TRN, the safe targets selection approach developed for M2020 enables landing sites of significant scientific interest that were unachievable with MSL.

Earlier in 2017, M2020 downselected to three landing sites, none of which were feasible with MSL: Jezero, NE Syrtis, and Columbia Hills. The assessment has included better landing ellipse performance due to augmented EDL capabilities, a range trigger, and TRN, as well as new methods of assessing landing site safety and surface operability with similar or better fidelity compared to the MSL assessment at the time of site selection. Final selection of the landing site for M2020 is scheduled for summer 2018.

3.1.2 Potential Sample Return

A robotic-scale sample-return mission from Mars was identified as one of the highest priority goals in the 2011 Planetary Sciences Decadal Survey. The Mars Exploration session included topics on sample return from the Martian system (Mars, Phobos). Key aspects of the technological chain were addressed: sample characterization, launch from the Martian surface (Mars Ascent Vehicle, or MAV), capture and sample bio-containment, transfer back to Earth, and curation of samples once returned to Earth.

The MAV is a key element of the conceptual Mars sample-return (MSR) architecture, constrained by limits on the performance of the EDL system that delivers the MAV to the surface, and the requirement to perform autonomous, atmospheric flight on another planet with environments differing from those of a typical Mars entry. A current MAV mission concept was presented by NASA/JPL that relies on delivery by an MSL/M2020 heritage EDL system, samples cached by M2020, and launch from candidate M2020 landing sites to an orbit with a lifetime of at least 10 years. The point of departure configuration for this MAV is a single-stage vehicle with hybrid rocket motor, shown in Figure 3-1. Plans are ongoing for an Earth flight demonstration of the liquid-injection thrust vector control (LITVC) and hybrid motor in 2019 at Mars-relevant conditions by launch from a high-altitude balloon.

Airbus Defence and Space (DS) presented a concept for a Phobos sample-return mission in the mid-to-late 2020s. The mission proposes vision-based navigation for descent for overall GNC landing accuracy of <35 m. Samples are acquired using a rotary brush mechanism and are returned to Earth using a passive, spin-stabilized Earth return capsule (ERC) design (see Figure 3-2) at velocities up to 12.5 m/s before executing a hard landing.

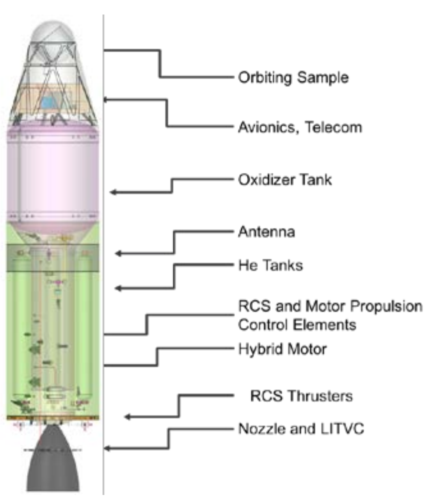

***Figure 3-1.** Mars Ascent Vehicle with hybrid propulsion for robotic-scale Mars sample return.*

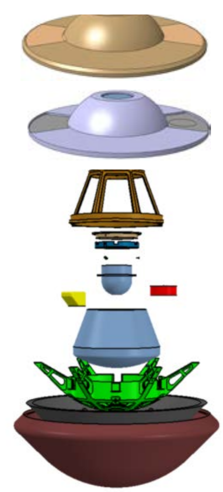

***Figure 3-2.** Earth return capsule for a Phobos sample-return mission.*

The most credible MSR concept of operations would require the 'fetching' orbiter at Mars to have the robotic capability of sealing the orbiting sample into a biocontainment system. This biocontainment system would be required to preserve the Earth's biosphere from contamination due to microbes from Mars. Technology, including hardware, is under development to (1) break the chain with Mars, (2) contain the samples, and (3) monitor and confirm containment. A proof-of-concept has been demonstrated.

Unlike the US and Japan, the EU does not presently have a curation facility designed to store and analyze samples returned from in situ, extra-terrestrial space exploration. The EURO-CARES project is developing a roadmap to create such a facility with consideration of planetary protection, instruments and methods, facilities and infrastructure, analog samples, portable receiving technologies, and outreach.

3.1.3 Advances in Modeling and Science for Mars Exploration

Development of key, Mars-specific, environment and physics models were also discussed, covering updates to the European Mars Climate Database (MCD), a new method for identification of drilled rock powders, and sunlight power availability on the surface.

V5.3 of the MCD, a freely available model, provides mean values and statistics for pressure, atmospheric density, temperature, and winds, as well as quantities derived from models for the Martian water cycle, chemistry, thermosphere, and ionosphere. The MCD includes the ability to include 4 synthetic dust scenarios with considerations for the solar cycle to produce "cold" and "warm" atmospheres with varying degrees of dust loading.

The CaliPhoto method supports the ExoMars 2020 science mission by applying colorimetric analysis to identification of rock powders formed at the surface during drilling.

ESA presented improvements to modelling fidelity for sunlight power availability on the surface of Mars to support landing site selection and operations, with inclusion of recently updated models for atmospheric dust and ice particle content.

3.1.4 Entry System Performance

Lastly, the session highlighted key technological developments and mission concepts that enhance or enable general EDL mission/science performance at Mars for present and potential future missions.

NASA presented results from human-scale Mars EDL analyses demonstrating the ability of low-lift-to-drag-ratio (L/D) vehicles to land relevant (20-t) payloads at 0 km MOLA within a 50-m target coupling improved aerodynamic performance, and guidance and control strategies. These results were achieved by replacing traditional bank angle control (MSL, Apollo heritage) with direct force control and by replacing a ballast system (MSL heritage) with deployable tabs to independently control angle of attack (downrange) and angle of sideslip (crossrange). Building on results from recent studies, this analysis demonstrated direct force control to be feasible and offer several advantages over bank angle control, including lower L/D (resulting in lower angle of attack), reduced propellant usage, and reduced engine control requirements for powered descent. Work in this area is expected to continue as EDL simulations for human Mars exploration increase in fidelity.

Also presented was a novel mission architecture for large-mass payloads using the Martian atmosphere and surface for in situ resource utilization (ISRU), where the vehicle is fueled by harvesting oxidizer from the Martian atmosphere during aerobraking passes. The concept of operations is sustainable, with return-to-orbit achieved using ISRU-derived propellant for ascent as well as an apoapsis-raise maneuver to resume aerobraking passes. The design closes with 81 aerobraking 'scooping' passes for a human-class mission.

3.2 Findings

1. Concerns exist for the future of Mars exploration after the M2020 and ExoMars 2020 missions. Human exploration of Mars in the 2030s is NASA's goal, but at the present, there is no explicit path for bridging the gap between the current 1 t payload capability and the 20+ t payload capability required for human exploration. The IPPW community posed two primary questions: (1) "What human-class EDL technologies require flight demonstration at Mars?", and (2) "Could there be a precursor mission in the 2020s to bridge the payload capability gap, demonstrate new technologies such as supersonic retropropulsion (SRP) and guidance and control strategies, and possibly deliver a MAV or other architecture elements to further exploration objectives?".
2. Backshell radiation during entry at Mars continues to challenge the present modeling and margin philosophy. The severity of backshell radiative heating increases with vehicle scale and will significantly challenge the design of future vehicles for Mars exploration.
3. With commercial plans to explore the surface of Mars and continuing interest in MSR from multiple space agencies, it is recommended that planetary protection be given higher priority in planning and design. If human exploration is to occur in the 2030s, the window for MSR and the search for life may be closing.
4. Recommended topics for future IPPWs include the following: (1) science updates from Curiosity, (2) follow-up discussion of the ExoMars 2020 and M2020 missions, (3) ASPIRE results and any impacts on M2020, (4) MSR updates and targeted areas for collaboration, (5) status of human Mars EDL architectures and their connection to present capabilities and ongoing technology development, (6) commercial Mars exploration plans, (7) backshell radiative heating environments, and (8) SRP.

4 Ocean Worlds

By Aline Zimmer[12], Andreas Frick[13], and Javier Gómez-Elvira[14]

The prospect of subsurface oceans on several Solar System bodies as potentially habitable environments has exciting implications for astrobiology. The in situ exploration of ocean worlds such as Europa, Titan, and Enceladus could offer important clues to answer the fundamental question of whether life exists elsewhere in the universe. The Ocean Worlds session addressed the exploration of these worlds, including science goals, enabling instrumentation and technologies, as well as current and future mission concepts.[15]

4.1 Summary of Technical Content

4.1.1 Summary of Presented Mission Concepts

Talks and posters addressed various mission concepts, technologies, and analyses relevant for the exploration of ocean worlds. Missions concepts discussed were elements of the current NASA Europa Lander concept, the proposed Joint Europa Mission (JEM), the "Akon" Europa penetrator, and the "Dragonfly" proposal for a rotorcraft lander to explore Titan.

4.1.1.1 NASA Europa Lander Concept

The NASA Europa Lander (**Figure 4-1**) is currently in pre–Phase A with a Mission Concept Review completed in June 2017 as a step towards Phase A development. The Lander would notionally launch on a Space Launch System (SLS) Block 1B in the mid-2020s. The current concept is the result of several architecture trade studies, including "piggyback" delivery or a shared launch vehicle with the Europa Clipper Mission, before converging on a separate launch. The Europa Clipper Mission would provide landing site reconnaissance and potentially telecommunication relay support, as well as shared technology development, but it is an independent mission.

[12] Jet Propulsion Laboratory, California Institute of Technology
[13] Jet Propulsion Laboratory, California Institute of Technology
[14] INTA/CAB
[15] Predecisional information, for planning and discussion only.

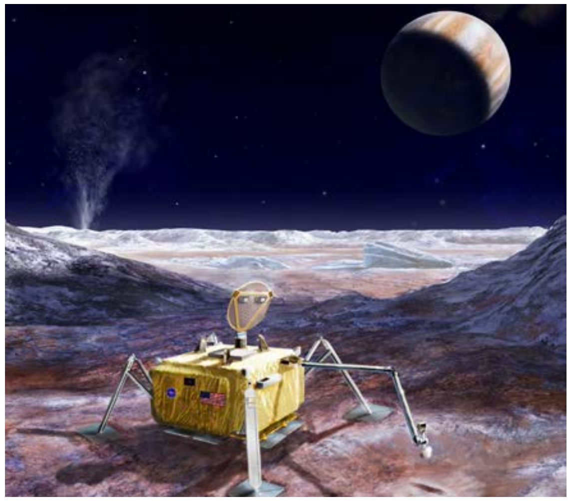

Figure 4-1. *Conceptualization of NASA's Europa lander.*

Following interplanetary cruise on board a Europa Clipper-derived spacecraft, the Lander would be delivered to the Europa surface by means of a solid rocket motor (SRM)–based deorbit stage and a liquid-fueled descent stage. Final delivery would occur via a “Sky Crane” maneuver similar to that employed by the MSL and planned for M2020. The Lander itself would be powered by primary batteries and perform an approximately 20-Earth-day surface mission to gather five samples. The notional suite of onboard instrumentation is designed to address the goals documented by the recommendations of the Europa Lander Science Definition Team:

- Life (search for evidence of life)
- Habitability (assess habitability)
- Context (support future exploration)

A path towards a safe landing was presented that includes site simulation (to inform the design), site reconnaissance (provided by Europa Clipper), site selection (downselect to best science potential), and site certification (quantifies safe landing risk). A surface phase concept was developed that provides robust sampling and science opportunities with respect to mission constraints including stored energy, thermal management, relay asset availability, and incurred radiation dose.

4.1.1.2 Joint Europa Mission (JEM)

Another concept to deliver a lander to the surface of Europa was presented as the Joint Europa Mission. JEM is a proposal in response to the call for a medium-size mission opportunity in ESA’s Science program (M5). The JEM mission concept could deliver a NASA-provided lander platform equipped with an ESA-provided Astrobiology Wet Laboratory (AWL), among other instruments. The concept employs an ESA-procured Carrier/Relay/Science orbiter platform with its own proposed science payload and is designed to launch on a NASA SLS.

4.1.1.3 Akon Europa Penetrator

Akon involves delivery on an instrumented penetrator to Europa's subsurface at 300 m/s and penetration of up to a few meters. Based on ESA-funded development, the Akon impactor features a two-bay design with a short-lifetime bay housing a drill and instrumentation for sample analysis and a heated bay for longer-lifetime data storage and relay. Full-scale testing occurred in 2013, with the test article surviving 340-m/s impacts at 25° pitch angles. Akon is envisioned to be a science enhancing element as part of larger missions such as Europa Clipper, Europa Lander, or JUpiter ICy moons Explorer (JUICE). A proposal was submitted in response to the ESA M5 call in October 2016.

4.1.1.4 Dragonfly

Dragonfly is a relocatable lander proposed to the NASA New Frontiers program to explore Titan using a multi-rotor aerial mobility system enabled by Titan's relatively low gravity and dense atmosphere.[16] Dragonfly would be delivered via a traditional atmospheric entry and descent (using an aeroshell and parachute) followed by powered flight to an initial landing site. Science measurements would be completed and batteries recharged by means of a radioisotope generator over a single Titan sol (~16 Earth days), before the vehicle transitions to a new landing site selected with the help of ground-in-the-loop (GITL) planning. A gimbaled high-gain antenna (HGA) provides a means for direct-to-Earth (DTE) communications. Dragonfly's eight rotors provide mechanical redundancy and operate in a flow regime similar to that of ultralight aircraft, sailplanes, and wind turbines on Earth. Figure 4-2 illustrates the rotorcraft concept.

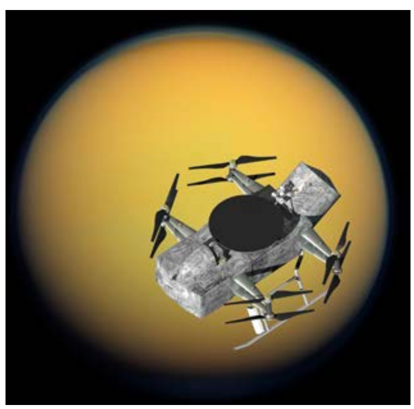

Figure 4-2. Dragonfly eight-rotor aerial mobility system at Titan.

4.1.2 Summary of Supporting Technologies and Analyses

Given the diversity of ocean worlds in the Solar System and their relatively limited in situ exploration thus far, several novel analytical methods and supporting technology developments were discussed as part of this session. While the discussion in this report section focuses on the proceedings of the Ocean Worlds session, developments relevant to ocean worlds were also

[16] In December 2017, Dragonfly was selected as one of two New Frontiers Step 2 studies.

presented in other IPPW sessions given the cross-cutting nature of many of these topics. The following technology and analytical topics were addressed as part of the Ocean Worlds session:

- **Titan Aerocapture Simulations:** A simulation of the flow along an aerocapture trajectory at Titan (**Figure 4-3**) was presented with the goal of assessing whether a backshell is required for such a maneuver. For the representative test case, the simulation indicated that while convective heat flux would not induce a particularly severe environment on the backshell, radiative heat flux on the backshell may not be negligible. The simulation could be coupled with a radiation transport solver to address this question.

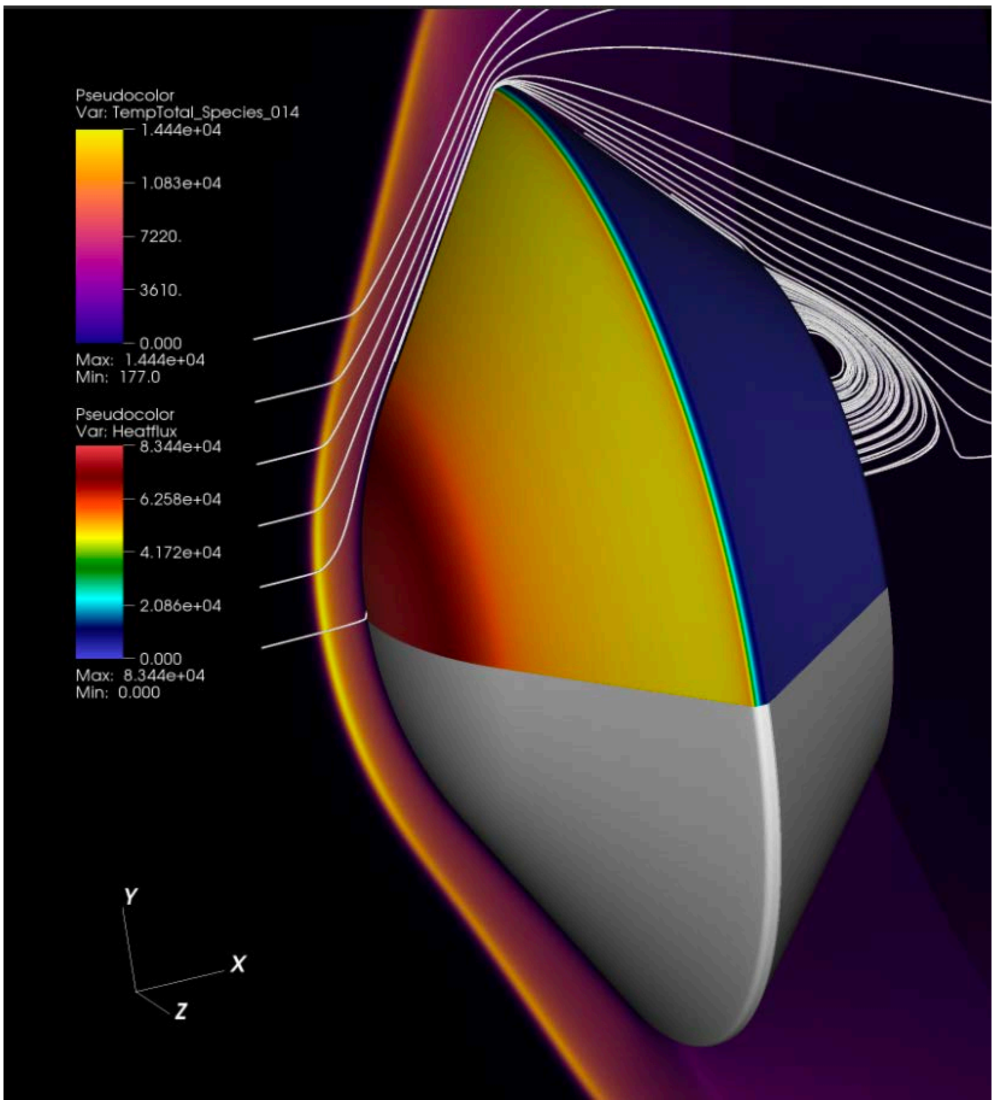

Figure 4-3. *Example flow solution to assess backshell environments for Titan aerocapture.*

- **Europa Lander Touchdown System:** To address risks posed by Europa's yet unknown topology on the scale of a lander spacecraft, a novel touchdown system was devised to achieve high stability in the presence of large terrain relief. The system includes four landing "stabilizers" that passively adapt to the surface during the touchdown event as delivered via the "Sky Crane" maneuver. These stabilizers would mechanically rigidize to their lock position once a “belly pan” contacts the surface, in order to maintain the main lander body relatively level. The concept is illustrated in **Figure 4-4**.

- **Europa/Enceladus Plume Comparison:** Cassini measurements of Enceladus’s plume activity were compared and contrasted with evidence of plumes on Europa provided by the Hubble Space Telescope. While the Enceladus eruption is ongoing (the intensity may vary over an orbit, but it never stops), Europa’s eruptions appear to be sporadic. Differences in column densities were noted.
- **Discussions and Poster Presentations:** Poster presentations included space design for robotic entry at Titan; trajectory design for missions to Enceladus, flow simulations of a submarine operating on Titan; cryogenic characterization of aluminum-gallium-nitride/gallium nitride (AlGaN/GaN) devices; and the Cosmorbitrap high-resolution mass analyzer.

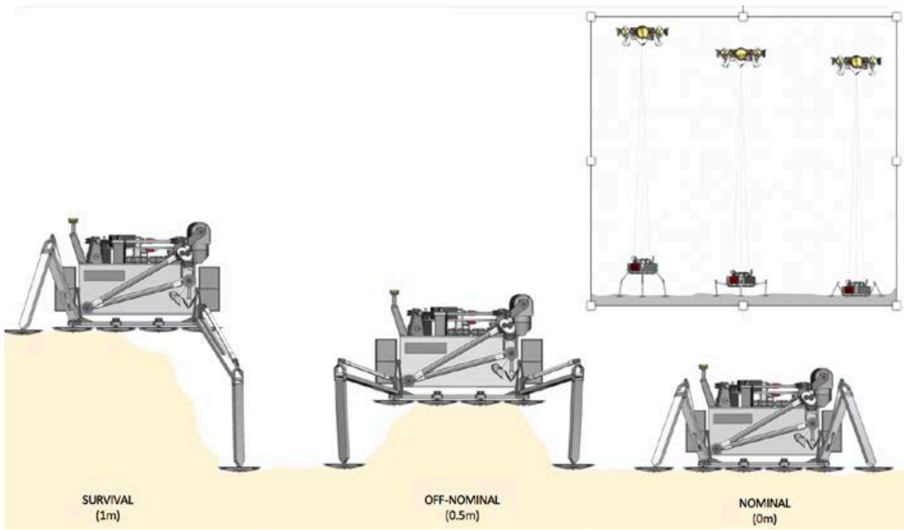

Figure 4-4. *Concept for Europa lander touchdown system with passively adaptive landing stabilizers.*

4.2 Findings

1. The establishment of a dedicated Ocean Worlds session for the first time at IPPW, preceded by a short course on the same topic, reflects growing scientific interest and technological readiness for in situ exploration of these worlds. This would be a natural “next step” within the context of discoveries at Titan and Enceladus by the concluding Cassini-Huygens mission, the ongoing development of the Europa Clipper and JUICE flyby missions to the Jovian system, as well as recently discovered evidence of plume activity at Europa by the Hubble Space Telescope.
2. Ocean worlds are prime targets for future probe missions because they have complex geophysical processes and a high potential for habitability, but have been explored only remotely. Some ocean-world missions currently proposed or under development have life-detection as an explicit goal. For context, the Viking missions at Mars in the 1970s remain the only direct historical corollary in this pursuit, with life-detection methods having advanced significantly since.

3. Future ocean-worlds exploration benefits from a diverse set of technology developments ranging from deorbit, descent, and landing techniques for safely landing on potentially difficult or unknown terrain, spacecraft systems capable of operating in adverse environments (e.g., cryogenic temperatures or high radiation), robust sampling systems, astrobiology-focused instrumentation, and planetary protection implementation methods.
4. Given that ocean-world missions generally require relatively long cruise durations and larger ΔV, sustained and frequent exploration of these worlds could be programmatically challenging. Potential avenues for mitigating these challenges include planning for discovery-driven exploration and concepts of operations that function in absence of readily available “infrastructure”, such as prepositioned telecommunications relay assets or broad high-resolution imaging coverage.

Ocean worlds in the Solar System represent a broad category of exploration destinations with distinct scientific goals and technology requirements. Scientific exploration of multiple ocean worlds in close coordination (for example, as part of dedicated agency programs or internationally) could provide additional context and result in individual scientific investigations mutually informing each other, particularly as part of the broader search for life in the Solar System.

5 Modeling, Simulation, Testing, and Demonstration

By Michelle Munk[17], Alan Cassell[18], Douglas Adams[19], and Albert Haldemann[20]

The Modeling, Simulation, Testing, and Demonstration session focused on modelling and simulation advancements in EDL areas, including computational fluid dynamics (CFD), GNC, materials and TPS modelling, decelerator systems, integrated/optimized capabilities, and related disciplines. Current work in EDL testing and demonstration techniques, diagnostics, and results was also a major component of this session. Work advancing the state-of-the-art of current capabilities and technologies, as well as comparing and leveraging both testing and computational models was especially relevant to this session.

5.1 Summary of Technical Content

Modeling, simulation, testing, and demonstration are at the core of EDL systems development. Since planetary EDL systems cannot be fully tested on Earth, these four functions are critical to maturing and qualifying flight systems to meet atmospheric and surface science objectives at destinations in the Solar System.

The session included a total of 20 oral presentations, with an even split of 10 presentations on modeling and simulation and 10 presentations on demonstration and testing. In addition, there were 15 session posters that touched on a variety of topics.

A major component of the session focused on current work in EDL testing and demonstration techniques, diagnostics, and results. Work to advance the state-of-the-art of the current capabilities or technologies, or comparing or leveraging both testing and computational models, was also represented. Mars was the topic of several presentations, from entry trajectories, to blackout analysis, to parachutes. Several papers dealt with modeling and testing approaches/considerations. Materials modeling was also well-represented.

[17] NASA Langley Research Center
[18] NASA Ames Research Center
[19] Applied Research Laboratory, Johns Hopkins University
[20] European Space Agency

Session highlights included (1) discussion on improved arcjet capabilities and diagnostics using lasers, x-ray tomography (**Figure 5-1**), and emissivity measurements, (2) progress in assessing asteroid threats, and (3) Technological and Educational Nanosatellite (TechEdSat) 6 (**Figure 5-2**), which is on its way into Earth's atmosphere. Workshop participants were reminded that TPS materials modeling is extremely complex; although parchute testing is difficult, predicting parachute behavior is even more challenging.

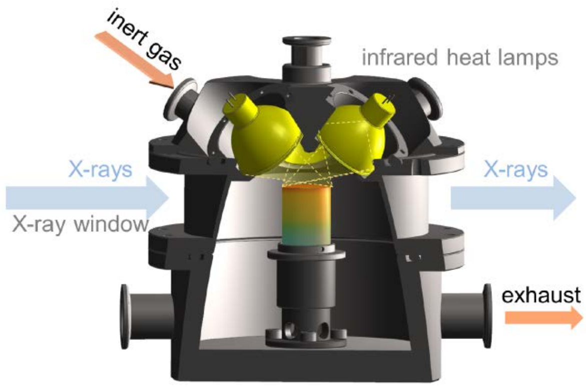

Figure 5-1. *Radiation furnace for in situ X-ray tomography of ablation.*

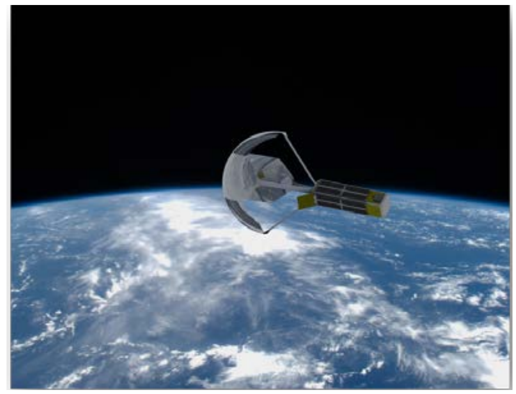

Figure 5-2. *TechEdSat 6, demonstrating entry interface targeting with 50-km accuracy.*

A number of trends were evident during the session that were common to several presentations. There is a need for new data and new ways to obtain data, in order to seed and validate model development. Efforts in this area are being pursued. There is much testing activity, both ground and flight, but generally at relatively small physical scales. Careful planning of both testing and simulation received significant attention in the session presentations. It was also evident that the EDL community is on the brink of several breakthroughs. Use of supercomputing resources is becoming more feasible and common but also drives the need for more validation data. In particular, these powerful assets support improved CFD—effectively a computational wind tunnel—and both parachute and splashdown dynamics. Finally, physics-based materials modeling is becoming more mainstream with improved accuracies.

5.2 Findings

There were a number of points and ideas for potential future work and collaboration noted during the discussion at the end of the oral session. There is a pervasive need for ground facility diagnostics. X-ray sensing offers an opportunity to observe the real-time TPS ablation behavior. It was also noted that modelers of gas dynamics (aerothermodynamicists) typically do not have experience with materials (chemistry), and there was general support from IPPW participants for more interaction between the two fields. In gas dynamics and material response investigations, care must be taken in considering measurement effects, as small sensors can affect large areas. It would be most beneficial to establish common data and/or common materials standards as a mechanism to both enable and foster international cooperation in the EDL discipline. And finally, some good advice from modelers and testers was provided: Be aware of uncertainties of flight dynamics - maintain adequate margins as no model is perfect, and there are always deficiencies.

This was a very diverse session, in terms of both content and presenters. The 35 oral and poster participants hailed from 17 countries and 26 organizations, including 11 student submissions (four oral presentations and seven posters). Of these, 51% were from the U.S., and 49% were non-U.S., with participants comprising 20% females and 80% males, and spanning an age range of 61 years.

6 Mercury and Venus

By Richard Otero[21]and James Cutts[22]

The Mercury and Venus session focused on past and planned science and engineering architectural design, and instrumentation for missions to Mercury or Venus. The session also addressed the role of advancing technology in exploring both planets.

6.1 Summary of Technical Content

6.1.1 Summary of Presented Missions and Missions Concepts

6.1.1.1 ESA/JAXA BepiColombo (Mercury)

The first two papers of this session focused on BepiColombo, which is a joint mission of ESA and the Japan Aerospace Exploration Agency (JAXA) to Mercury. The mission comprises two satellites to be launched together: the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO). The mission will perform a comprehensive study of Mercury, including its magnetic field, magnetosphere, interior structure, and surface. BepiColombo is scheduled to launch in October 2018, with arrival at Mercury planned for December 2025, after a flyby of Earth, two flybys of Venus, and six flybys of Mercury. This Flagship-class or Cornerstone mission was planned as part of ESA's Horizon 2000+ program; it will be the last mission of the Horizon 2000+ program to be launched.

The BepiColombo spacecraft consists of four modules, as illustrated in **Figure 6-1**: the MPO, the MMO, a sunshield to protect the spacecraft from the intense solar heating, and the low-thrust solar-electric Mercury Transfer Module that propels the two spacecraft after launch on an Ariane 5 Evolution Cryotechnique Type A (ECA) launch vehicle to the point of Mercury orbit insertion. At this point, a chemical propulsion system, which provides much larger thrust levels but for short periods, is used to accomplish orbit insertion.

[21] Jet Propulsion Laboratory, California Institute of Technology
[22] Jet Propulsion Laboratory, California Institute of Technology

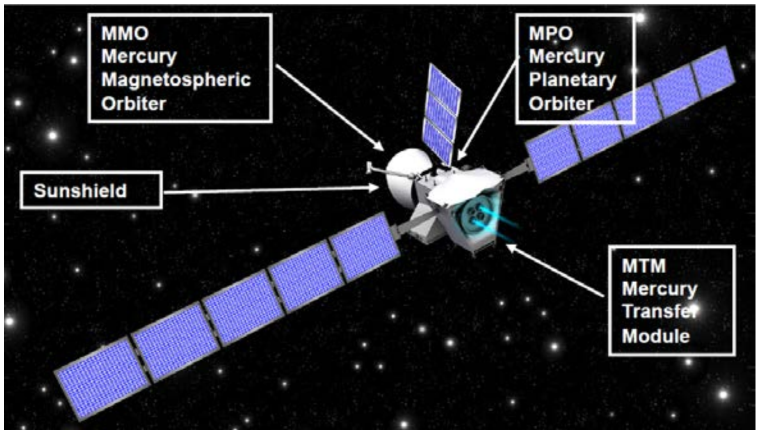

Figure 6-1. *In-flight configuration of the BepiColombo Spacecraft for cruise to Mercury, showing the four spacecraft modules.*

BepiColombo is not the first spacecraft to orbit Mercury—this feat was first accomplished by NASA's Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission—but this is the first occasion where two spacecraft are deployed in Mercury orbit at the same time. The ESA MPO will also orbit very close to Mercury in a low-eccentricity polar orbit (480 km × 1500 km, with a period of 2.3 hours) compared to MESSENGER (200 km × 10,300 km, with a period of 12 hours). The spacecraft will be nadir-pointed for much of that time, with many of the eleven instruments pointed directly at the planet.

The close, near-circular orbit, which optimizes surface science and high data return (1550 GB/year) also places many technical demands on the spacecraft systems, including the need for high ΔV and intense thermal environments. Although most ESA science missions have required a single major new technology focus area, for BepiColombo there were many new technologies required, including the solar electric propulsion (SEP) system, thermal control, and mechanisms capable of operation in the severe thermal environment. The BepiColombo spacecraft was undergoing integration and test at the time of IPPW-14 in June 2017; some attendees were able to visit the European Space Research and Technology Center (ESTEC) and see the 4200-kg vehicle stacked in launch configuration.

6.1.1.2 Venus in Situ Atmospheric and Geochemical Explorer (VISAGE) Concept

This VISAGE concept has been proposed to NASA's New Frontiers (NF-4) program as a lander mission to perform atmospheric and surface investigations over a duration of a few hours in the searing and caustic environment on the surface of Venus. Data is relayed back to Earth through the cruise stage, which deploys the lander. During the descent phase, the spacecraft would obtain images from below 15 km, and once on the surface, measure the elemental and mineral composition at two depths at two drill sites. Leveraging advances in instrumentation that have occurred in the thirty years since the Soviet-era Venera landers, VISAGE has scientific capabilities that far exceed those of Venera. Figure 6-2 is a detailed illustration of the VISAGE lander concept.

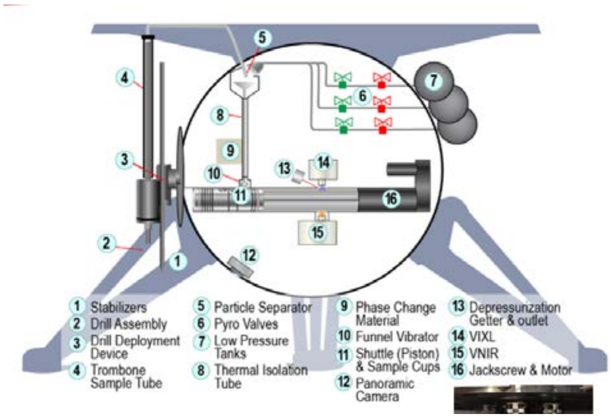

Figure 6-2. *Schematic of the VISAGE lander with its spherical pressure vessel illustrating the soil sampling system. The drag plate on the top of the lander would be used to stabilize the vehicle during terminal descent.*

6.1.1.3 Atmospheric Sample Return from the Habitable Zone of Venus

This student-led concept examined the feasibility of returning a sample from the cloud layer on Venus, where temperatures and pressures are comparable to those on Earth. This mission could be viewed as a stepping stone to Venus-surface sample return, but in light of the growing interest in the chemistry and possibly even biology of the clouds, exploration and sample return from the cloud layer has become a scientific target of interest in its own right.

Shown in Figure 6-3, the concept uses the Adaptable, Deployable Entry and Placement Technology (ADEPT) aeroshell to carry an ascent vehicle and sampling system into the Venus cloud layer. The parachute is deployed at 65 km above the surface, and gas and cloud aerosol particles are sampled as the vehicle descends to 50 km near the base of the clouds. A three-stage solid-rocket ascent vehicle is required to return the sample to orbit. From this point, the mission architecture is similar

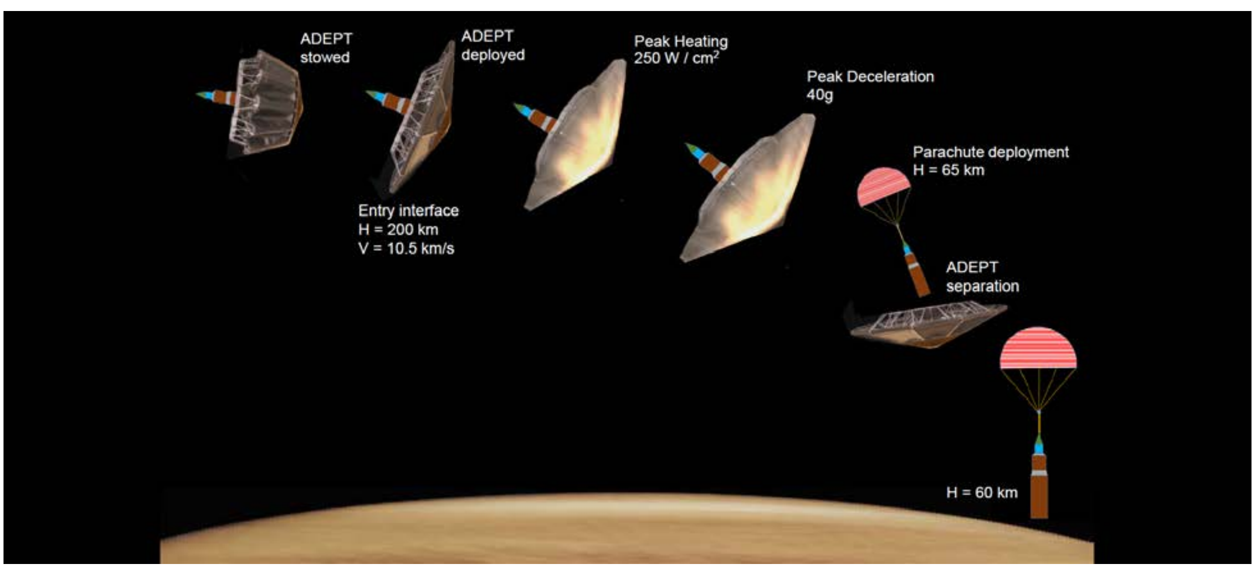

Figure 6-3. *Concept for a Venus atmospheric-sample-return mission from the Venus cloud layer.*

to that for MSR but with no requirement for planetary protection, since it has been determined that even if there is life in the highly acidic Venusian clouds, it could not adapt to Earth's environment.

6.1.2 Summary of Supporting Technologies and Analysis

Topics in this session focused on Venus and looked beyond short-duration landers to vehicles capable of much longer periods in the Venusian environment. Methods proposed included flying or floating above the surface and near-surface regions of high temperatures or employing technologies that could extend survival on the surface.

NASA's Planetary Science Division (PSD) is performing a study of Venus Aerial Platforms with the objective of formulating a roadmap for use of the most promising concepts in missions and initiating a technology development effort for bringing these concepts to maturity. Many of these concepts have been featured in past IPPW meetings and include constant-altitude superpressure balloons similar in concept but much larger than the heritage VEGA balloons, variable-altitude balloons capable of traversing the Venusian cloud layers, hybrid airships such as the Venus Atmospheric Maneuverable Platform (VAMP), and solar-powered aircraft. The Venus Aerial Platform Study, which involves a team of scientists, technologists, and mission architects is examining the science value of each type of vehicle as well as technical feasibility and maturity. A student-led poster described one approach to altitude and stability control of a Venus balloon by using a mixture of helium and water for buoyancy.

A different discussion centered on an approach for extending the surface lifetime of a lander from the few hours possible with VISAGE to a window of 50 to 120 hours. The key new technology enabling this advance is a lithium-combustion power system in which lithium reacts with the carbon dioxide environment to generate heat and produce 13.3 kW_{th} of heat, which would be used to keep the payload cool (2.0 kW/h) and generate electric power (0.33 kWe). The concept draws on experience with lithium-combustion-based power systems developed to power torpedoes for the U.S. Navy. A computational model of the lithium-carbon dioxide reactor has already been developed. Work is now under way on a laboratory lithium-combustion facility in order to validate the model predictions. The experimental setup is shown in Figure 6-4. Present testing uses pure carbon dioxide, but future plans include evaluation of system performance when there are gas contaminants to the input gas flow. Beyond this, NASA's Hot Operating Temperature Technology (HOTTech) program is now supporting research on an iodine vapor-driven technology for both electrical power generation and cooling.

6.1.3 Entry, Descent, and Landing (EDL) Issues at Venus

Discussion in this session centered on environmental challenges for EDL in Venus missions. These challenges include: several sulfuric acid cloud layers, a high-density atmosphere that requires a trade between high-G entry loads and large heat load trajectories, high surface temperatures (460°C) challenging the duration of any landed mission, and high (100-bar) pressure at the surface requiring pressure vessels to tolerate such loads. Mission concepts and technology development

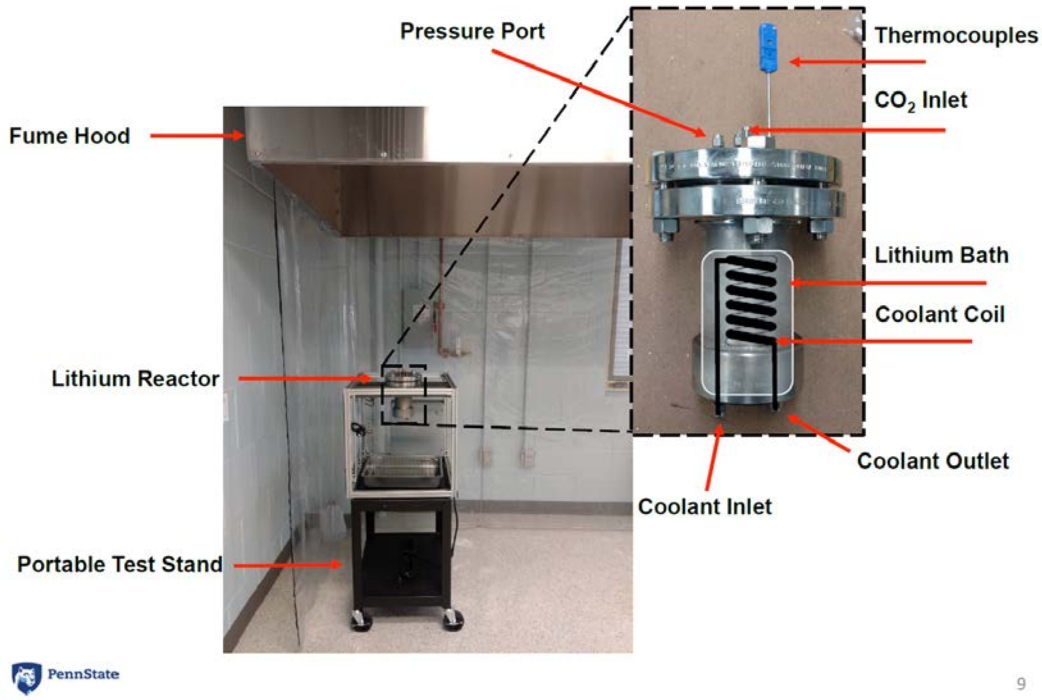

Figure 6-4. *Experimental lithium facility to investigate combustion of lithium in carbon dioxide as an energy source for extended Venus surface operations.*

for Venus missions have attempted to address these entry concerns or incorporate them as features of their mission design.

Several materials suitable for the sulfuric acid environment were discussed. Vectran is an example of an extremely strong material that has been used in manufacturing ballutes at Earth and could be used as a parachute or balloon material. Also discussed was the applicability of Teflon coatings on more traditional parachute or balloon fabrics to increase robustness to the acid mist. In contrast, two Russian Venera missions used fiberglass parachutes down to the surface. These parachutes were reefed by a Kevlar band, which disintegrated and melted away during descent. This design is an excellent example of using the environment within a mission design (whereas more common reef cutters may have issues functioning in a hot environment), but this specific design likely produces a highly variable flight transition considered too risky for traditional NASA missions. After using these two parachute designs, subsequent Venera missions switched to a metallic drag plate for the remainder of the descent.

The high-density atmosphere at Venus has been challenging for several missions, with allowable sensed deceleration as a common active constraint on entry missions. A steeper trajectory increases the efficiency of historical ablative materials like carbon phenolic, leading to a lighter TPS as the poor insulation capabilities of these materials are not well suited for long heat pulses. This design resulted in an impulse to go steeper until the allowable sensed deceleration was reached, which is a strong function of the construction of the onboard instrumentation. Heatshield for Extreme Entry Environment Technology (HEEET), developed at NASA's Ames Research Center, is a dual-layer TPS that allows future entry mission concepts at Venus to realistically explore shallow entry trajectories. The outside layer of a dual-layer system is focused on ablation, while the innermost layer is composed of an insulator. The insulator can be half the density of the ablative layer, allowing shallower trajectories resulting in a lighter heatshield due to the thinner layers with this design. HEEET is an enabling technology for the exploration of Venus, permitting 100 Earth-G EDL designs with a TPS that does not require the bulk and complexity needed for traditional peak 250 Earth-G designs.

Another approach to Venus EDL is to use deployable or inflatable systems that sharply reduce the ballistic coefficient, and when combined with shallow entry angles, can offer an alternative to HEEET. The viability of these approaches will be receiving increased scrutiny both for very small mission studies as part of NASA's Venus Bridge concept and for larger missions such as VAMP, which would feature an airship inflated prior to orbit entry. The design includes a thermal protection layer in addition to layers designed to protect the vehicle from sulfuric acid during float conditions.

6.1.4 Extending Surface Operations at Venus

The Venus surface temperature of nearly 500°C severely limits the surface operations of traditional landed mission designs. Three different approaches were presented to address this constraint on surface operations:

- Descend to the surface and address all the science questions within the limited time allowed by robust phase-change materials (PCMs) of several hours
- Descend to surface and perform active cooling of the lander to extend lifetime to 120 hours
- Float or fly in the atmosphere where temperatures are close to Earth ambient

A benefit to the use of PCM is in its simplicity and comparatively high technology readiness level (TRL), with the drawback being the limited time of a few hours enabled for exploration at the landing site. These materials were used on several prior missions to the Venus surface. The VISAGE proposal completes the necessary science within the time enabled by PCM in a passive cooling approach, exploiting the extraordinary advances in instrumentation that have occurred since the last Venus surface mission.

The active cooling approach for Venus is much more complex and currently at a very low TRL. Development would involve not only the lithium-based combustion system but also iodine-based power generation and cooling systems. The potential of this system is to enable a 5-day mission on the surface of Venus, or 50 times the duration possible with VISAGE.

Aerial platform concepts approach the heat transfer problem at Venus by avoiding the hot surface regions altogether. Venus balloons have already flown, and concepts now being considered range in TRL depending on the degree of altitude and lateral control they offer. There is a band of Earth-like temperatures and pressures in the 60-50 km altitude zone, conditions desirable for aerial exploration and the ability to conduct Earth-based testing. If a system can demonstrate robustness to the sulfuric acid environment, there is potential for missions of many weeks to months in the cloud layers of Venus. In situ measurements would contribute greatly to Venus atmospheric science, and geophysical measurements such as seismic and magnetic fields are also possible from aerial platforms.

6.2 Findings

1. Mercury's mysteries will be unveiled by BepiColombo, a highly-capable and technology-rich joint ESA-JAXA mission to be launched in October 2018 and arriving at Mercury in December 2025.
2. Technologies currently under development for Venus by NASA include HEEET, an enabling technology for "low-G" Venus entry mission design, and various HOTTech high-temperature electronics and electrical systems technology that will enable long-duration surface missions.
3. Venus mission development concepts include efforts to improve heritage designs through integration of emerging entry technologies and efforts to extend the lifetime of in situ missions through either the use of aerial platforms or long-duration surface platforms requiring HOTTech.
4. The technology challenges for Venus exploration in the descent phase are very different than those for Mars. For example, parachute inflation in the dense Venusian atmosphere is much less stressing on the parachute design, but strength reductions from the corrosive environment over the deployed lifetime must be accommodated.

7 Outer Planets

By David Atkinson[23], Kunio Sayanagi[24], Olivier Mousis[25], and Bert Vermeersen[26]

The Giant Planets are time capsules from the epoch of Solar System formation. Within the atmospheres and interiors of the Giant Planets, fingerprints of the chemical and physical conditions existing at the time and location at which each planet formed and the processes by which the Giant Planets and our Solar System formed, can be found. In situ measurements of Giant Planet atmospheric composition and processes help constrain models of Solar System formation and evolution, the origin and evolution of atmospheres, and the large-scale structure of our Solar System, including Earth. The Outer Planets session addressed concepts for proposed and potential future Outer Planet probe missions, as well as technologies and instrumentation designed to enable exploration of the extreme environments found in the atmospheres of the Giant Planets.

7.1 Summary of Technical Content

The Outer Planets session focused on outer planets missions and concepts with atmospheric probes. Technical content at IPPW-14 discussed several future atmospheric probe mission concepts at various stages of development and one innovative reanalysis of data from a past mission. The session demonstrated that giant planet atmospheric entry probes form a distinct class of missions, one of significant interest to the IPPW community.

7.1.1 Session Overview

A summary of the topics from this session is as follows:

- Ice Giants flagship mission
    - Addressed a priority of 2013-2022 Planetary Decadal Survey
    - A NASA-funded Science Definition Team study
    - Presented an overview of mission architecture options

[23] Jet Propulsion Laboratory, California Institute of Technology
[24] Hampton University
[25] Aix Marseille Université
[26] Delft University of Technology

- Hera Saturn probe
  - Proposed to the ESA M-Class program
  - Presented a science case to probe Saturn
- Saturn PRobe Interior and aTmosphere Explorer (SPRITE) probe
  - Proposed to the NASA New Frontiers program
  - Presented an engineering implementation of Saturn probe
- Small Next-Generation Atmospheric Probe (SNAP)
  - Mission concept study funded by NASA Planetary Science Deep Space SmallSat Studies (PSDS3) Program
  - Presented a design overview
- Decoding Huygens's descent dynamics
  - Presented an analysis of the Huygens accelerometer to characterize atmospheric turbulence
- Two-staged Saturn probe for 60-bar atmosphere
  - Mission concept study funded by NASA LaRC
  - Separating a deep-stage from a shallow-stage allows a probe to reach the water condensation level of Saturn at 20-bar

7.1.2 Session Highlights

The presentation on the outcomes of the Science Definition Team study of the Ice Giants flagship mission demonstrated NASA's commitment to progress on implementing a future flagship mission to Uranus or Neptune. A flagship mission to an Ice Giant is the third flagship mission priority recommended by the 2013 Planetary Science Decadal Survey after (1) the sample-caching portion of MSR and (2) exploration of Europa.

The presentations on two "Medium Class" Saturn probe proposals, submitted to NASA and ESA, are currently under evaluation at each agency. In addition, the session included a two-stage Saturn probe concept study at NASA LaRC. The three presentations demonstrate strong interest by the planetary exploration community for a Saturn probe mission as well as high technology readiness for such a mission. The proposal submitted to ESA's M-class program is Hera, with Olivier Mousis of Aix Marseille Université as Principal Investigator (PI). The proposal submitted by PI Amy Simon to NASA's New Frontiers program is SPRITE.

The SNAP concept is one of 19 studies on small planetary spacecraft missions supported by NASA's PSDS3 program. Two proposals focused on in situ atmospheric probes. The 19 selected proposals were among 102 proposals submitted; they demonstrated strong community interest for not only in situ atmospheric probes but also exploration with small-scale platforms. The original solicitation stated that the program would select approximately 6–15 proposals; the selection of 19 proposals demonstrates the agency's commitment to respond to substantial community interest.

7.1.3 Discussion

Ice Giant Flagship Science Definition Study: After the Ice Giant Flagship presentation, the benefits of aerocapture into orbit was the subject of discussion. Aerocapture technology was considered in the Science Definition Team study, since the technique has the potential to increase payload mass and to enable reduced mission transit times. Shortened mission transit time would be a significant benefit to earlier science return and increase the cadence of missions to the outer Solar System. However, the increased mission cost of aerocapture was found to be greater than the cost of additional payload. Thus, aerocapture does not enable additional science payload without increasing overall mission cost. Aerocapture is also not necessary to answer the priority science questions identified by the decadal survey.

Hera Saturn Probe: The discussion on Hera focused on two points. First, the presentation concluded that a probe designed for Saturn is also viable for missions to Uranus, Neptune, and Venus. Thus, a common probe design to serve those mission needs would be beneficial. Second, it was noted that the mass spectrometer for Hera, at 16 kg, is heavier than the 13.2-kg instrument flown on Galileo. Questions were raised as to whether the Hera design improves results. Hera's mass spectrometer has heritage from Rosetta, which has a higher mass resolution than the Galileo instrument. The presentation concluded that, even though the Galileo mass spectrometer has a lower mass resolution, it could still satisfy the threshold-level science goals for a Saturn probe mission.

Proposed SPRITE Saturn Probe: Figure 7-1 shows the concept of operations for the SPRITE Saturn probe. The presentation emphasized that a single in situ measurement would greatly aid interpretation of remote-sensing results for the rest of the planet. A question was asked whether the "Grand Finale" dive of the Cassini orbiter into Saturn would return similar data to that proposed by SPRITE. The presenter noted that Cassini orbiter's final dive was not expected to reach the depths nor return the volume of data from an entry probe. However, the descending Cassini orbiter measurements of upper atmospheric composition and chemistry would benefit entry-probe measurements.

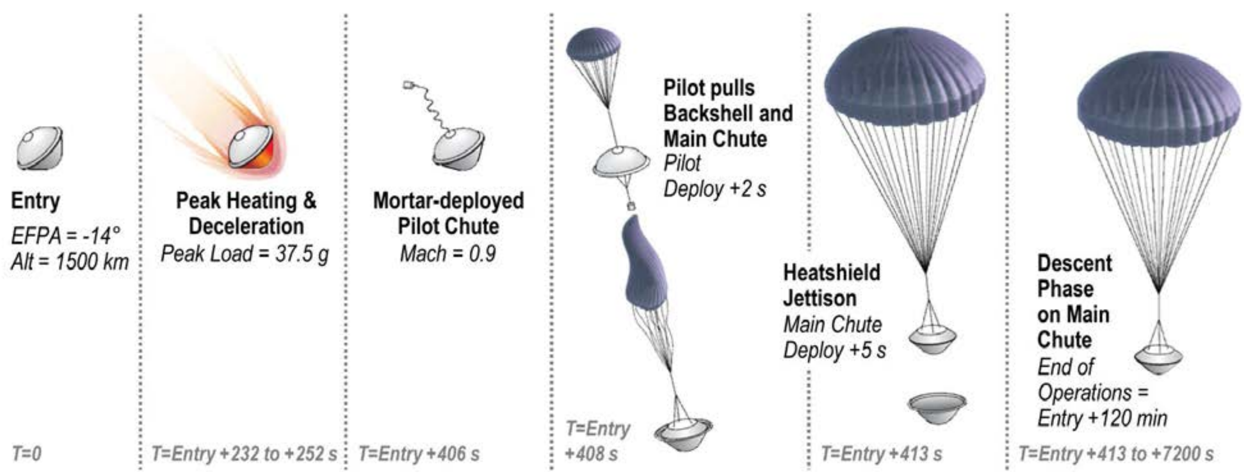

Figure 7-1. Proposed SPRITE concept of operations.

SNAP Uranus Probe: The SNAP Uranus probe design is shown in **Figure 7-2.** Much of the SNAP discussion focused on the carbon nanotube-based atmospheric composition sensor considered for the probe. The NanoChem (a carbon nanotube-based atmospheric composition sensor) instrument, under development at NASA's Ames Research Center, does not require a vacuum pump, allowing for significant mass savings in design. Within the sensor, a carbon nanotube mesh is doped with different materials, causing changes in the resistivity of the mesh when exposed to different gas molecules. The sensitivity to different gas molecules can be tuned using various doping materials. During the closing session, it was noted that during IPPW-1 small probes instrumented with solid-state sensors were discussed as future approaches for exploring the deep atmospheres of the Giant Planets; it is rewarding to see more recent studies trending back in that direction.

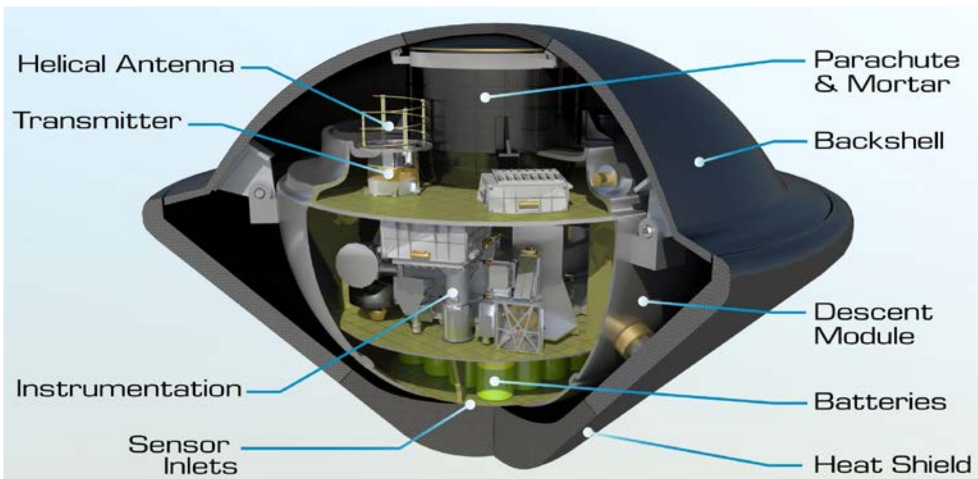

Figure 7-2. *SNAP Uranus probe.*

Huygens Descent Reanalysis: An innovative new reanalysis of the Huygens descent dynamics was performed using onboard engineering acceleration sensors during the probe descent through Titan's atmosphere. The research concluded that future probes should carry 3-axis accelerometers and 3-axis angular accelerometers to measure probe dynamics and to provide higher-fidelity turbulence and aerodynamic buffeting data.

Two-staged Saturn Probe: The results of an engineering design study to test whether releasing a small sensor package would enable in situ measurements of Saturn's water condensation level, predicted to be at the 20-bar pressure altitude level, concluded that such an approach could enable in situ measurements and return data down to 60+ bar level.

7.2 Findings

For the Ice Giant flagship mission concept considered during the NASA Science Definition Team study, enabling technologies currently under development include the following: Enhanced Multimission Radioisotope Thermoelectric Generator (eMMRTG), HEEET, and a Doppler imager.

For the Hera Saturn probe, the presenter concluded that a probe designed for Saturn is also viable for missions at Uranus, Neptune, and Venus. The Hera mission has a high-TRL design and is ready for a flight mission. In addition, the Hera mission team and ESA are open to cooperation and coordination with the NASA New Frontiers program.

For the SPRITE Saturn probe, a technological highlight is that such a mission would be viable with currently available technology as a battery-powered mission, potentially without a radioisotope heater unit (RHU). The mission concept has a high-TRL design, with HEEET as the only component still under development.

For the small atmospheric entry probe, SNAP, the carbon nanotube-based composition sensor requires environmental testing under relevant conditions. The concept study demonstrates that solid-state sensors enable significant miniaturization of entry probes enabling an entirely new scale of planetary exploration.

The reanalysis of the Huygens probe descent profile illustrated valuable lessons learned from various studies of probe descent dynamics over the past decades. Engineering sensor data yielded improved characterization of atmospheric structure, although not originally intended for scientific analysis.

The two-stage Saturn probe design study demonstrated that the increased mission complexity of adding a second stage to an atmospheric probe has a significant potential science return by enabling access to in situ measurements from Saturn's water condensation levels.

As a general remark, the gains of aerocapture and radioisotope thermoelectric generator (RTG) power in terms of increased mission duration were also discussed at IPPW-14. Cassini is a good example of a mission that returned tremendous volumes of data over its ~10-year extended mission; this would not have been possible without RTGs with large power margins. A clear benefit of aerocapture is that it allows both increased payload mass and increased power/mass margins. In addition, aerocapture enables faster transfer to destinations, thus increasing mission duration at the target. Prime-mission science priorities may be achievable without aerocapture (or RTGs) but, without aerocapture, Cassini-like extended missions to the Ice Giants may not be realizable.

8 Lunar and Small Body Exploration

By Richard Fisackerly[27], Swati Mohan[28], Ingo Gerth[29], Erisa Stilley (Hines)[30], and Robert Buchwald[31]

This session covered international missions in development, including landers and sample-return missions, as well as specific ongoing projects to enable landing and surface activities. Of particular interest were aspects of descent and landing technologies in support of future missions and architectures, including polar exploration, rover development, and human surface activity preparation and exploration.

Small body exploration is a growing mission class that has unique scientific potential. Small, airless bodies are currently being targeted to enhance understanding of the origin of the Solar System, evolutionary processes that led to the formation of the planets, as well as the search of primitive classes of organics that can shed light on the origin of life. The wealth of scientific data return has been recently demonstrated by the Dawn and Rosetta missions. The number of future mission concepts, planned missions, and missions underway to their respective targets (e.g., Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer [OSIRIS-REx], Hayabusa 2, and Psyche) demonstrates the continued great interest in airless bodies, with a possibility of unveiling their many mysteries. This session covered mission overviews, descent and landing architectures, and in situ science and instrumentation related to this mission class.

Key technology development is needed to achieve future mission objectives. Many technologies are now being applied. Some overlap very well with technology in development for other types of planetary probe missions, such as TRN, hazard detection and avoidance, and autonomy during landing, while others address the specific needs of small and airless body landings.

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[27] European Space Agency
[28] Jet Propulsion Laboratory, California Institute of Technology
[29] OHB System AG
[30] Jet Propulsion Laboratory, California Institute of Technology
[31] Airbus Defence and Space

8.1 Summary of Technical Content

The session covered a wide variety of topics addressed by seven oral presentations and three posters. One talk and two posters were delivered by students.

- The topics were split between two small body talks and five lunar exploration talks.
- Presenters represented JAXA, ESA, industry (Airbus DS, OHB), and academia (Stanford University, Beijing Institute of Technology).
- Four talks and one poster discussed missions currently in work:
  - Package for Resource Observation and in Situ Prospecting for Exploration, Commercial Exploitation and Transportation (PROSPECT) drill and science package as part of a cooperation between ESA and Roscosmos for the Luna-Resurs mission
  - JAXA's Outstanding MOon exploration TEchnologies demonstrated by NAno SemiHard Impactor (OMOTENASHI) CubeSat lunar lander
  - ESA's Asteroid Impact Mission (AIM)
  - The German Aerospace Center's (DLR's) lunar mission candidate, the Moon Advanced Resource Utilization Viability Investigation (MARVIN)
- Other presentations discussed technology and landing dynamics (hopping rovers, landing impact, scale dynamic testing).
- The posters focused primarily on the Moon, current mission formulations (MARVIN), and future studies.

Figure 8-1 shows the concept for hedgehog hopping rovers, a small dynamic platform capable of long-range and short-range surface exploration.

Other missions in work currently across industry, though not presented here, include Psyche, OSIRIS-REx, and the series of Russian Luna missions.

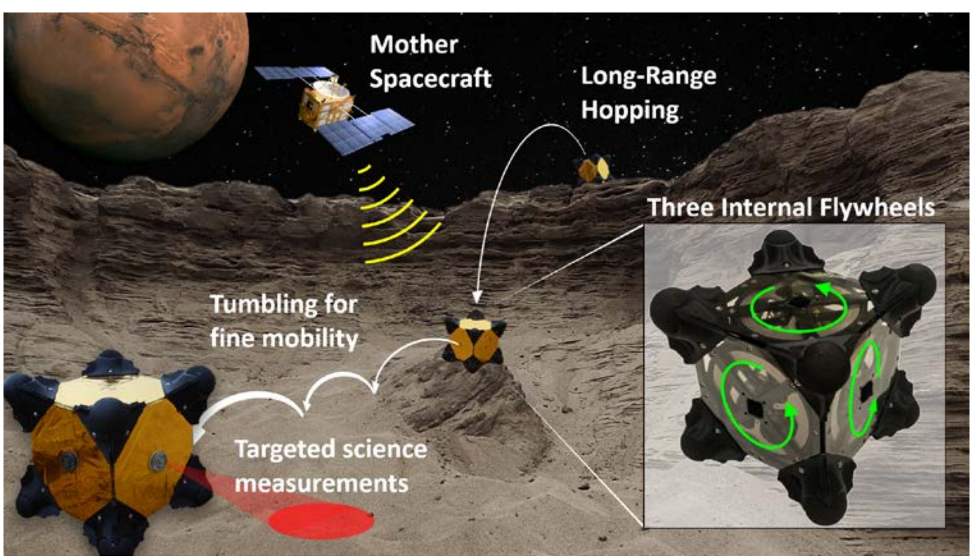

Figure 8-1. *Hedgehog hopping rovers. Artist's concept.*

8.2 Findings

1. Exploration of lunar and small bodies remains a serious thrust for several major space agencies (e.g., ESA, China National Space Administration [CNSA], JAXA, Roscosmos, and NASA) with several near-term landing missions (Chang'e5, Chandrayaan 2, Luna Glob, and Resurs). ISRU and surface sampling are the primary foci of lunar exploration. Consumables that can be produced using the available resources at the landing site can support significantly increased surface-mission durations, and enable a future, long-term human presence on the Moon. Furthermore, the Moon is considered a stepping stone towards other Solar System exploration missions for technology demonstration and production of propellant and consumables. Landing site selection and ISRU processes are closely linked and should be integrated more fully in the early stages of mission planning.
2. The low gravity of lunar and small bodies is a key driver in landing system design. Qualification is often completed using scaled landers and/or numerical simulations. In particular, a solid understanding of the contact dynamics is key for a reliable prediction of touchdown dynamics and verification of safe landing conditions. Due to the lack of knowledge about the surface of the target body prior to landing, some predictions of the landing environment must be based on advanced statistical methods or similarity analyses.
3. In addition to the technical challenges, the low gravity of lunar and small bodies calls for new technologies that make use of this characteristic. Innovative mobility concepts such as hopping rovers require a small amount of energy to travel across large distances. The random nature of the rover motion after the first contact can be compensated for by dividing the distance into several smaller hops necessary to reach a dedicated target.
4. The upcoming Orion missions provide opportunities for several lunar CubeSat missions flying piggy back on NASA’s SLS. An example is JAXA's 6U OMOTENASHI surface probe, which will perform a semihard landing using a solid-rocket braking motor and an airbag for terminal landing shock attenuation. Simulations and tests have demonstrated the potential of this new concept.

9 Descent and Landing Technology

By Soumyo Dutta[32], Christine Szalai[33], and Svenja Woicke[34]

The objective of various technologies used during the descent and landing phases of EDL are to dissipate a spacecraft's remaining kinetic energy from the entry phase of flight while also directing vehicles to their target landing conditions and making final preparations for landing. This session focused on the engineering and technology of these EDL phases and covered topic areas including aerodynamic decelerators, SRP, GNC strategies, navigation sensors, terrain-relative sensing and characterization, autonomous targeting, propulsion, and touchdown systems, architecture transitions, and instrumentation.

9.1 Summary of Technical Content

Participants from governmental agencies, commercial entities, and academia presented twelve papers and four posters detailing the ongoing efforts to support future EDL missions. The main topics are grouped into five key areas:

- Precision landing technologies, including TRN, hazard detection, and avoidance
- Parachute decelerator technologies
- Touchdown dynamics simulation
- Supersonic retropropulsion (SRP)
- Deorbit, descent, and landing (DDL) technologies for airless bodies

Presenters at the descent and landing technology session represented numerous organizations, including NASA, ESA, U.S. and European space industries, and European, Chinese, and American universities.

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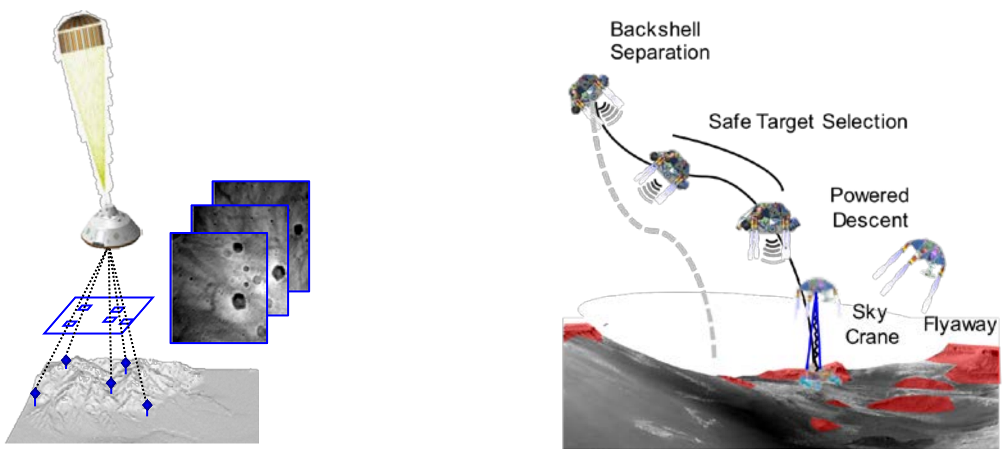
[32] NASA Langley Research Center
[33] Jet Propulsion Laboratory, California Institute of Technology
[34] Delft University of Technology

9.1.1 Precision Landing Technologies

Terminal descent guidance—especially to support precision landing, TRN, and hazard detection—was a major topic of discussion.

Representatives from NASA's M2020 project discussed the TRN system that is now part of the mission baseline. Figure 9-1 shows a notional representation of the TRN system during EDL for M2020. The discussions were presented by Mohan et al., Montgomery et al., and Otero et al. During parachute flight, the vehicle's Landing Vision System will generate images to correlate position with an onboard map. The updated position estimate is then used during the powered flight phase by the Safe Target Selection system to divert to a safer landing point within a reachable set of locations based on an onboard hazard map.

European presenters also showcased their work in precision landing technology. Diedrich et al. from Airbus DS presented the Precision and Intelligent Landing using Onboard Technologies (PILOT) project, which plans to combine the use of lidar, two imaging cameras, and an onboard landing processing unit for precision landing and autonomous hazard detection and avoidance. The technology will be used on Roscosmos's Luna-Resurs mission to the Moon in the early 2020s. A flight opportunity for the PILOT landing camera will be provided by Roscosmos for risk-reduction purposes in the frame of the Luna-Glob mission in the late 2010s. Woicke et al. discussed methods of combining hazard detection and TRN, which are currently considered disparate techniques. Solari et al. noted that precision landing requirements could be achieved along with hazard detection and avoidance.



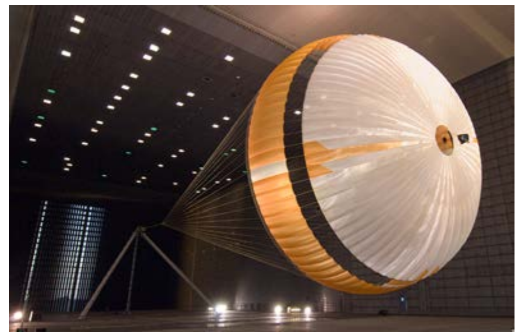
(a) Landing Vision System during parachute flight. (b) Safe Target Selection during powered flight.

***Figure 9-1.** Notional representation of components of the Terrain-Relative Navigation system on the M2020 mission.*

9.1.2 Parachute Decelerator Technologies

Testing of parachute decelerator technology related to the design of new systems was another major topic presented. Wu and Yang discussed the design, simulation, and testing of ram-air parachute systems under development in China for controlled recovery of a 1000-kg cargo after booster separation. CFD models were developed for the ram-air parachutes, and tests were completed via static rigs and dynamic drops to validate the simulations. Villar et al. and O'Farrell et al. discussed full-scale testing of the supersonic Mars parachute design for M2020 through workmanship testing in wind tunnels and dynamic testing via a series of sounding rocket flights. Despite the interest in powered landing technologies for the next generation of space vehicles, there is still interest in development of parachute technologies that continue to serve a need for certain classes of missions, as demonstrated by the testing shown in Figure 9-2.

(a) Ram-air parachute system testing in China.



(b) M2020 parachute workmanship testing.

Figure 9-2. *Parachute technology testing.*

9.1.3 Supersonic Retropropulsion, Touchdown Dynamics, and Landing on Airless Bodies

Other presenters discussed updates to descent and landing technology work from prior IPPWs and the application of these technologies in a novel EDL location.

One such update was the current status of SRP. Edquist et al. presented an update on NASA's SRP research, which has largely consisted of updated computational modelling, wind tunnel testing with cold gas nozzle flow, and analysis of SRP flight data from U.S. commercial entities. Blette et al. discussed methodology to model SRP separation to avoid recontact for concepts requiring a change in configuration following entry.

Another frequent topic discussed at IPPW is powered descent guidance and touchdown dynamics. Benito discussed ongoing work by NASA to evaluate newer powered descent guidance logic, which is fuel optimized while achieving the goals of precision landing. S. Schröder et al. discussed DLR's work to model and improve landing system design during touchdown, including testing in simulated lunar conditions. K. Schroeder et al. discussed continued progress in the design of Tension Adjustable Network for Deploying Entry Membrane (TANDEM), a tensegrity-based vehicle under development at Virginia Tech and NASA, to serve as a flexible entry vehicle that can transition to a lander within the same structure.

Finally, a new topic discussed was how to apply the descent and landing technologies on an airless body, such as Jupiter's moon Europa. Kipp et al. discussed the design of the proposed NASA Europa lander and how the novel deorbit, descent, and landing architecture leverages components of a more traditional EDL architecture, such as TRN and powered descent guidance used at Mars.

9.2 Findings

1. Interest in TRN: There is a strong interest in TRN on both sides of the Atlantic with support from two flight projects—M2020 and Europa lander—and programs such as PILOT. IPPW should continue to encourage results from these projects to be shared in more depth as the technology matures, perhaps through a dedicated TRN session.
2. Parachute testing lessons learned should be shared: During the session, there were presentations demonstrating a renewed interest in parachute research from the US (M2020 and the ASPIRE project) and China (ram-jet parachute). There were additional presentations and posters at IPPW presented by Lingard and Underwood that discussed the parachute drop tests for the ExoMars 2016 mission. There should be consideration in future IPPWs for dedicated sessions to compare testing results, and to discuss lessons learned, even if testing details cannot be publicly shared.
3. Additional information of interest on SRP research and its impact on human-scale Mars missions: Edquist et al. presented the current status of the SRP research that is ongoing in the US. There were several questions from the audience on the current thinking about human-scaled Mars exploration missions and SRP. Future IPPWs should include more presentations on this topic.

10 Instrumentation and Experiments

By Michael Pauken[35], Luis Castañer[36], and David Mimoun[37]

Science instruments and experiments are the fundamental means to unlock the secrets of our Solar System. This session covered the development and implementation of past, present, and future science and engineering instrumentation for probes exploring planets, moons, and other small bodies. Engineering and science topics were brought together in this session to discuss the fundamental goals, requirements, and challenges of instruments and experiments, to understand the practical limitations of data collection from in situ or remote sensing techniques, and to share lessons learned from instrument development and implementation activities.

10.1 Summary of Technical Content

10.1.1 Overview

The presentations in the Instrumentation and Experiments session were focused on four main topics:

Thermal protection systems:

- MEDLI2: Thermal sensors for TPS
- UV GaN photodetectors for shock-layer radiation
- Recession measurements in PICA and ZURAM: seeded PICA+ReG (metallic grid embedded in the material)

Planetary drilling:

- Ultrasonic Planetary Core Drill (UPCD) Antarctica test campaign
- Ultrasonically-assisted hammering

Chemical and physical sample analysis:

[35] Jet Propulsion Laboratory, California Institute of Technology
[36] Universitat Politèchnica de Catalunya
[37] ISAE

- LithoSpace: Preparation of thin slices of rocky materials for microscopy
- LOAC-S: Light Optical Aerosol Counter and Sizer: Light instrument for aerosols counter/sizer
- AWL: Astrobiology Wet Laboratory for Europa Lander
- VISTA: Volatile in Situ Thermogravimetry Analyzer
- Mass spectrometer: Cosmorbitrap

Sensors:

- Heat-flow sensor for Venus
- Simple, robust 3D anemometers for Mars
- BAROCAP: pressure sensors with long heritage

10.1.2 New and Most Relevant Instruments

Two of the above instruments are new and should be considered in planning future missions:

The LithoSpace automated system for petrographic thin section preparation is a unique instrument enabling potentially significant in situ geologic evaluation on rocky planets. While there was minimal discussion on this topic, perhaps because the audience did not have experience in this area, the session conveners and others in the audience concur that this technology is important and should impact future mission planning.

LOAC-S, a light aerosols counter/sizer for planetary atmospheres, is the space-adapted version of the LOAC instrument that has been tested in different terrestrial environments. The design is shown in Figure 10-1. This is an important new instrument for characterizing atmospheres. The sensor is able to measure aerosols with a minimal particle size of 0.1 mm, although there are limitations on the concentration that can be detected.

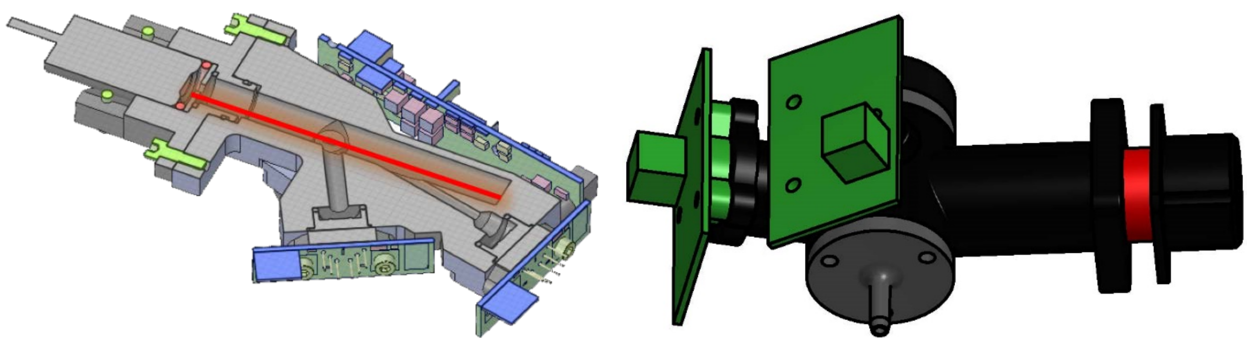


Figure 10-1. *Design of the LOAC-S instrument for counting and sizing of light aerosols in planetary atmospheres.*

10.1.3 Additional Instrumentation Highlights

- MEDLI2 significantly improves the sensor suite of MEDLI (MSL) by adding backshell sensors and broadband radiometers to the existing pressure and temperature measurements.

- For TPSs, there were discussions on the materials used for metallic grids, buried wires, etc. and how instrumentation and observation influence ablation.
- The ultrasonic planetary core drill has difficulty in ice/water combinations because the material potentially freezes around the drill head, making further movement difficult. The problem is not expected to occur at Mars or on other icy worlds. Global warming is rapidly affecting the permafrost/tundra in polar regions, making it increasingly challenging to find adequate analog test sites on Earth for Mars and icy body applications.
- Ultrasonic-aided hammering for drilling more than doubles drilling efficiency as compared to drilling with no ultrasonic excitation.
- Mass spectrometer development continues, with a mass resolving power of 50000 (m/z=56) presently achievable. Future developments are aiming for a mass resolving power of 100000, for a 1 s measurement.
- The AWL concept for detection of organic and inorganic biomarkers through immunoassay of surface ice samples for a Europa lander was presented. The proposed sensor suite includes current large field instruments, which will be miniaturized for future flight on landed icy body missions.
- Organic compounds are the next level of molecular investigation, with emphasis on the characterization of high-molecular-weight species, which are important to more fully understand planetary constituents. The VISTA instrument uses thermogravimetry with two sensor heads to characterize organic compounds at low power, low system volume, and with ability to be self-temperature-compensating.
- The design for a heat flux sensor to measure heat loss from the interior of Venus at the surface, allowing scientists to distinguish between different hypotheses for Venus planetary evolution was also presented. Fabrication of the first two sensor prototypes has been completed. While questions were raised about its effectiveness for the sampling area and sample time duration, it remains a promising design for in situ thermal measurements in the extreme surface environment on Venus.
- A spherical 3D wind sensor for Mars, a much simpler instrument than the Mars Environmental Dynamics Analyzer (MEDA) or Rover Environmental Monitoring System (REMS) (with only six signals compared to 48 on MEDA), was demonstrated to have achieved improved dynamical response and viability as a fast, robust, and simple sensor.
- New BAROCAP NG gas pressure sensor has improved capability over previous versions flown on six probe missions prior to its implementation in the Schiaparelli Dust Characterization, Risk Assessment, and Environment Analyzer on the Martian Surface (DREAMS) instrument. Qualification testing of the new sensor demonstrated improved temperature dependence stability, reducing the notable uncertainty sources for these sensors based on changes in temperature dependence between calibration and mission application. This sensor has been selected for use on both M2020 and ExoMars 2020.

10.2 Findings

The ever-present challenges to reduce measurement uncertainty, system mass, volume, power, and complexity, and survivability in extreme environments remain. Data collection during transit of probes through planetary atmospheres is a primary objective of many proposal calls and missions. IPPW continues to be a valuable opportunity to connect the science, engineering, and technology development communities pursuing such exploration.

11 Aerobraking, Aeroscience, and Entry Technologies

By Rodrigo Haya Ramos[38], Karl Edquist[39], and Marcus Lobbia[40]

Probe missions to bodies with an atmosphere use a combination of aerobraking, entry (up to the initiation of the descent and landing sequence), and/or atmospheric flight technologies. For example, heatshields must be designed to withstand severe heating environments as the vehicle is decelerated via hypersonic aerobraking or entry through the atmosphere. This session covered engineering, physics, and technologies that enhance and enable atmospheric braking or entry missions, such as entry vehicle and TPS design; methodologies for assessing aerothermal, thermal/ablation, and aerodynamic performance; specific implementation concepts such as SRP; inflatable/deployable heatshields; use of active systems to improve entry control/guidance and GNC technology.

11.1 Summary of Technical Content

Inflatable Aerodynamic Decelerators (IADs) were presented, primarily related to NASA's hypersonic inflatable aerodynamic decelerator (IAD) (HIAD) technology development efforts. Presentations included topics ranging from a description of the HIAD on United Launch Alliance (ULA) (HULA) flight test demonstration preparation, a lifting HIAD using aeroshell deformation, application to Mars high-mass EDL missions, and an overview of the European activities in this field. **Figure 11-1** depicts the design of a HIAD for an upcoming low-Earth-orbit (LEO) technology-demonstration mission by NASA (left) and a preliminary design of an IAD for a Mars lander with a 2000-kg entry mass from Vorticity Ltd. (right).

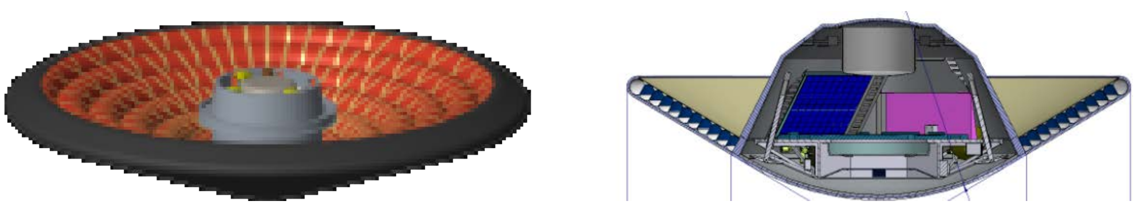


***Figure 11-1**. HIAD concept for a NASA technology demonstration mission from LEO (left) and an IAD design for a robotic-scale Mars lander from Vorticity Ltd. (right).*

[38] SENER

[39] NASA Langley Research Center

[40] Jet Propulsion Laboratory, California Institute of Technology

Thermal Protection Systems (TPSs) is another relevant topic for the session, addressing both aerothermodynamics and materials. NASA's Entry Systems Modeling (ESM) technology development project, NASA's Heatshield for Extreme Entry Environment Technology (HEEET) project, and Airbus initiatives for future heatshields were presented. Specific technology aspects such as ablation modeling, magnetohydrodynamic flow interaction for enhancing deceleration and preventing TPS impact damage, and microtomography for measuring ablative TPS properties were addressed in the poster session. TPS physics maturation through small demonstration probes developed by students was also covered during this year's session.

Sample Return would be a long-term mission that could act as a technology push. An example is the terrestrial technology demonstration of hybrid propulsion with LITVC for a MAV. The design of the ERC for a comet sample-return mission was selected as representative of the challenges of Earth high-speed entry.

Aerodynamics aspects were part of several presentations focused on ground testing, flight control, and the interaction between aeroacoustics and structure during atmospheric entry. The flight experiment design and required ground testing for a deployable aerodynamic decelerator was presented as part of the NASA's ADEPT project. Flight hardware for the upcoming ADEPT SR-1 flight (2018) is shown in **Figure 11-2**.

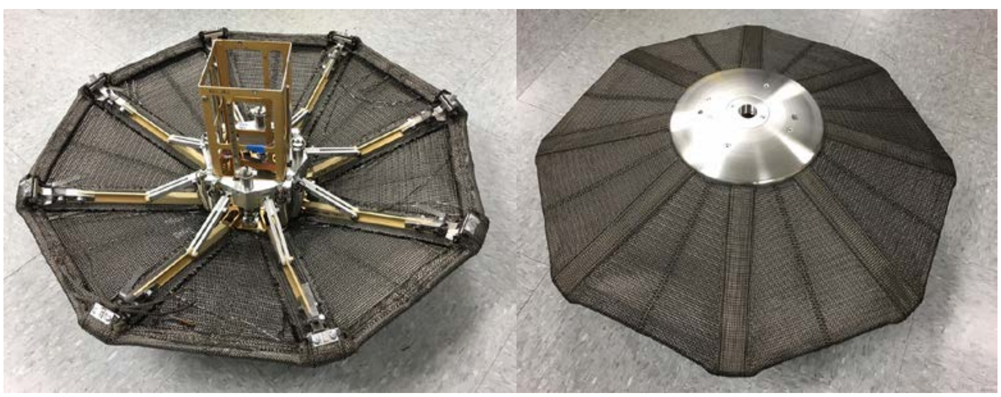


Figure 11-2. *ADEPT SR-1 flight hardware (0.7 m diameter).*

Guidance, Navigation, and Control (GNC) systems in the session covered technologies beyond specific mission developments. Presentations included, at the GNC subsystem level, the challenges in moving from an experimental mission such as the Intermediate eXperimental Vehcile (IXV) to its operational evolution (Space Rider). Another perspective was the control of the entry interface point through drag modulation in the exoatmosphere. University research work was highlighted by topics including electric/magnetic field plasma actuators for entry control, the application of a nonlinear adaptive control law during entry, and the improvement of aerodynamic performances in capsules using flaps.

Aerocapture was presented in the session through research activities related to the use of leader probes to characterize the atmosphere before Neptune aerocapture and the creation of local atmospheres for aerobraking using penetrators on icy bodies.

11.2 Findings

Aerobraking/aerocapture:

- Aerobraking and aerocapture were primarily addressed in other sessions with target body-dedicated talks.
- One student presentation proposed a leader probe to cope with the “chicken and egg´” challenge of atmosphere modeling for Neptune aerocapture.

Aerosciences:

- Advanced model development in CFD (unsteady simulations, Fluid-Structure Interaction, shock layer radiation, etc.) was shown as part of NASA’s Entry Systems Modeling project.
- Improvements were presented on microscale model development for thermal-ablation analysis.

Entry technologies:

- Maturity of the HIAD concept has reached 6m-diameter scale in the US. An orbital mission has been proposed to reach Mars-relevant heating and pressure conditions at Earth.
- Europeans have tested new flexible TPS designs for HIADs and have developed reference Mars missions.
- Europe is developing a testbed for in-orbit demonstration applicable to exploration, where the vehicle itself is a technology push.
- NASA proposes to apply its Earth entry capsule technology developed for Stardust to a comet sample-return mission. The sample-return capsule would reach speeds higher than Stardust.
- NASA is nearing TRL 6 for the HEEET woven TPS materials for extreme environments, with the technology included in several recent proposals.
- Europe is investigating conformal ablators and new materials and is investigating alternatives to phenolic resin (used in TPS manufacturing) due to environmental concerns.
- The MAV design trade space for MSR remains open, with movement towards a possible Earth technology flight demonstration in 2019 for hybrid propulsion with LITVC.
- A sounding-rocket flight test of a nano-ADEPT technology recently passed PDR and is scheduled to launch in April 2018.
- Several approaches to perform experimentation at limited cost were discussed in numerous sessions, including the use of sounding rockets or CubeSats launched as piggy back payloads. The session highlighted the need to reduce experimentation costs in maturing technology, in advance of program and mission infusion.

12 Small and CubeSat Probes

By Ozgur Karatekin[41] and Brandon Smith[42]

The Small and CubeSat Probes session covered mission concepts, scientific instruments, and new technologies for small spacecraft or CubeSat probes that perform atmospheric or surface science. Small probes can augment a primary spacecraft's science mission. They may also stand alone as independent missions in reducing life-cycle costs or by increasing spacecraft quantity.

12.1 Summary of Technical Content

This was the first time IPPW has held a session dedicated to Small and CubeSat Probes. Previous IPPWs have included presentations related to this topic, with this session serving as a trial stand-alone session. This session received a total of 13 abstracts, including one invited talk, with contributions from JAXA, ESA, and academia.

The presentations demonstrated that small spacecraft are rapidly emerging as high-value platforms for mainstream science missions. These missions are typically driven by technology capabilities rather than science requirements. As small spacecraft technology improves, so does its benefit to missions. It was clear from the session and the discussion that followed that although the application of small spacecraft to remote sensing has been growing steadily, there has not been a quick adoption of the "small" movement to in situ science with planetary probes. Nevertheless, some in the EDL community are investigating small and CubeSat probe platforms as a means to achieve mainstream science goals. Concepts presented in this session included missions that augment a primary spacecraft mission with a secondary payload probe as well as missions that simultaneously deploy multiple small probes.

The session featured an invited talk on ESA studies of interplanetary CubeSat mission concepts. The talk demonstrated that the exploration community considers small spacecraft with remote sensing instruments to be of high value toward achieving science goals. This talk was followed by two presentations from JAXA describing new technologies that enable in situ exploration with small and CubeSat probes. One presentation described a recent successful flight test of an inflatable decelerator for CubeSats. Such technology could eventually enable recovery of CubeSat-

[41] Royal Observatory of Belgium
[42] NASA Ames Research Center

class payloads at Earth or even landing on other bodies. The second presentation described the OMOTENASHI mission, which aims to land a small payload on the surface of the Moon after separating from the SLS rocket during Exploration Mission 1 (EM-1). The OMOTENASHI payload is shown in Figure 12-1. This launch platform provides the exploration community with a great option for future interplanetary missions with CubeSats as secondary or even tertiary payloads. The novel JAXA mission OMOTENASHI also demonstrates how small and CubeSat probes can leverage international collaboration to achieve global science and exploration objectives. The session concluded with a presentation on recent ground testing of an atmospheric entry system for CubeSats, describing how small spacecraft provide an excellent means of data collection for computational model validation. The same geometry may be ground-tested and subsequently flown, eliminating physical scale from the parameter space. The QubeSat for Aerothermodynamic Research and Measurements on AblatioN (QARMAN) reentry probe is shown in Figure 12-2.

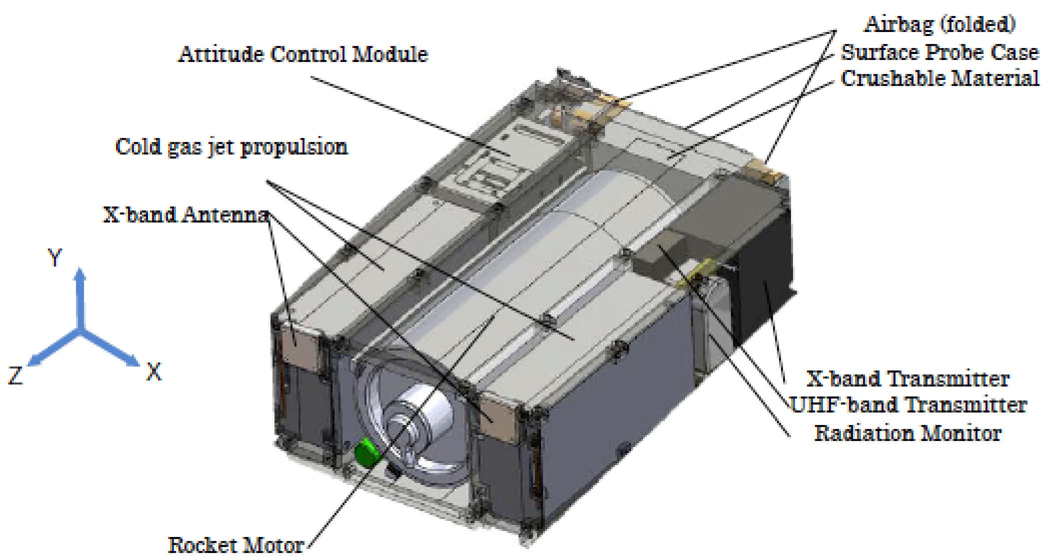


Figure 12-1. *OMOTENASHI payload for lunar exploration.*

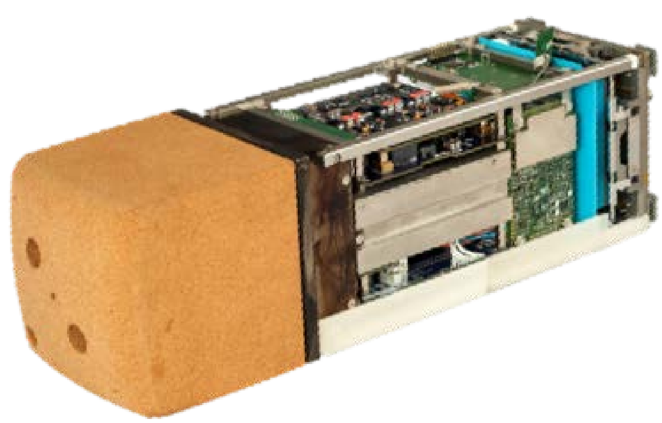


Figure 12-2. *QARMAN reentry probe (10×10×30 cm) from VKI.*

12.2 Findings

The feedback for this session was overall very positive, with the IPPW community overwhelmingly acknowledging the potential of small and CubeSat probe platforms to achieve and augment science objectives in planetary exploration. Topics on small and CubeSat probe missions should be covered in regular sessions at future IPPWs, emphasizing in situ measurements and data return for applications relevant to IPPW.

13 Acknowledgements

By Bernie Bienstock

Without the hard work of the IPPW committees, our annual workshops would not succeed. Bernie Bienstock has led the International Organizing Committee for the past eight IPPWs.

The Program Organizing Committee (POC) Co-Chairs, Ashley Korzun (US), Robert Buchwald (Europe), and Rodrigo Haya-Ramos (Europe), organized the workshop sessions and tasked all session co-chairs to document the results. Ashley Korzun edited this IPPW-14 Technology Report for consistency and accuracy, with additional editing provided by Jim Cutts and Bernie Bienstock.

The Student Organizing Committee was chaired in the US by Gregory Villar and in Europe by Svenja Woicke.

The IPPW-14 Short Course committee of Athena Coustenis, Jean-Pierre Lebreton, David Atkinson, and Ralph Lorenz planned the agenda and enlisted speakers to present the lectures.

A final word about the core planners and organizers of the IPPWs over the years, for it is through their annual voluntary efforts that our workshops, as well as this Technology Progress Report, have come to fruition. These volunteers include David Atkinson, Jean-Pierre Lebreton, Ethiraj Venkatapathy, Jim Arnold, Bernie Bienstock, Andrew Ball, Michelle Munk, Athena Coustenis, Ralph Lorenz, Richard Otero, Hannes Griebel, Michael Wright, Jim Cutts, Anita Sengupta, and Pat Beauchamp.

14 Appendix 1: Presentations and Posters by Session

All IPPW-14 presentations and posters are listed by session in Table 14-1. Sessions are listed in the order given earlier in this report.

Table 14-1. *IPPW-14 presentations and posters.*

2. ExoMars	
Lead Author	**Presentation Title**
T. Blancquaert	*ExoMars Entry, Descent and Landing Demonstrator Schiaparelli: Flight Overview and Mission Results*
S. Portigliotti	*ExoMars 2016, The Schiaparelli Mission: EDL Demonstration Results from Real Time Telemetry before Unfortunate Impact*
D. Bonetti	*ExoMars 2016 Post Flight Mission Analysis of Schiaparelli Coasting, Entry, Descent and Landing*
F. Ferri	*Atmospheric Mars Entry and Landing Investigations & Analysis (AMELIA) by the ExoMars Schiaparelli Module*
S. Asmar	*Direct-to-Earth Link from the ExoMars Schiaparelli Lander*
O. Karatekin	*Preliminary Analysis of Entry and Descent Radio Communications from ExoMars 2016 Schiaparelli*
A. Aboudan	*AMELIA Reconstruction of ExoMars 2016 Schiaparelli Module Trajectory and Atmospheric Profiles by Means of Inertial and Radar Altimeter Data*
A. Guelhan	*Achievements of the COMARS+ Instrumentation Package during the Entry Flight Phase of the ExoMars Schiaparelli Lander*
B. Van Hove	*Surface Pressure Data from ExoMars Schiaparelli Instrumented Heat Shield*
L. Lorenzoni	*Preliminary Performance Analysis of the Entry, Descent and Landing of the ExoMars 2020 Mission*
Lead Author	**Poster Title**
P. Boubert	*Investigations on CO2 Plasma Jets with the ICOTOM Radiometers of the ExoMars Descent Module*
Y. Mignot	*ExoMars 2016 - Schiaparelli's Heatshield - Development Challenges and Postflight Outcomes*
A. Moral	*Raman Laser Spectrometer (RLS) Instrument for 2020 ExoMars Mission*
3. Mars Exploration	
Lead Author	**Presentation Title**
E. Millour	*The Mars Climate Database (version 5.3)*
E. Bonfiglio	*Status of the InSight Entry, Descent, and Landing System*
A. Chen	*Mars 2020 Entry, Descent, and Landing Update*
P. Brugarolas	*Mars 2020 On-Board Terrain Relative Navigation*
D. Way	*Mars 2020 Parachute Modeling Updates*
E. Stilley	*Top Landing Site Candidates for the Mars 2020 Rover Mission*
F. Foucher	*Colorimetric Analysis to Help Identifications of Drilled Rock Powders on Mars: The CaliPhoto Method*
M. Lobbia	*Mars Ascent Vehicle—Overview and Aeroheating/Thermal Protection System Design*

A. Waymen	*Phobos Sample Return: Mission and Spacecraft Design*
A. Fumagalli	*Biocontainment of Mars Samples Returning to Earth*
A. Korzun	*Blunt Body EDL System Performance Improvements Through Direct Force Control and Deployable Tabs*
Lead Author	**Poster Title**
K. Gonyea	*Sustained Mars Exploration Through Mars Atmospheric and Surface Resource Utilization*
M. Lefland	*Mars 2020 Flight Computer Redundancy for EDL*
G. Beaufils	*Estimating the Sunlight Power Availability for a Probe or Rover on the Surface of Mars*
F. Foucher	*An European Curation of Astromaterials Returned from Exploration of Space: the EUROCARES Project*
M. Oldroyd	*On the Development and Design for an Affordable Two-Wheeled Mars Rover, MARVIN*
4. Ocean Worlds	
Lead Author	**Presentation Title**
P. Nizenkov	*Simulation of the Flow during an Aerobraking Maneuver at Titan*
D. Adams	*Dragonfly: A Rotorcraft Lander to Enable Titan Exploration*
M. Blanc	*Joint Europa Mission (JEM): A Multiscale Study of Europa to Characterize its Habitability and Search for Extant Life*
G. Jones	*The Akon Europa Penetrator*
A. Zimmer	*Early Evolution of the Mission Architecture for NASA's Europa Lander Concept*
G. Tan-Wang	*Europa Lander Concept Site Selection: Approach on Collaborative Mission Planning and Certification*
A. Frick	*Overview of the Europa Lander Flight System Concept*
S. Vernon	*Europa Lander Project: The Cruise and Relay Stage Mission and Telecom Architecture*
S. Sell	*Touchdown System for a Europa Lander Concept*
T. Kulkarni	*Surface Phase of the Europa Lander Mission Concept*
L. Esposito	*Comparing the Plumes of Europa and Enceladus*
Lead Author	**Poster Title**
K. Dowling	*Cryogenic Characterization of AlGaN/GaN Devices for Icy World Exploration*
L. Selliez	*Studies of Organics with the Cosmorbitrap, an HRMS Analyzer for Future Missions to Ocean Worlds*
D. Palma	*Preliminary Trajectory Design of a Mission to Enceladus*
E. Roelke	*Trajectory Trade-Space Design for Robotic Entry at Titan*
A. Tafuni	*Traversing Titan's Seas: Simulating an Autonomous Submarine Operating in Extraterrestrial Seas*
5. Modeling, Simulation, Testing, and Demonstration	
Lead Author	**Presentation Title**
J. Arnold	*Maturation of the Asteroid Threat Assessment Project*
M. Braun	*Enhanced Modeling of Mars Entry Trajectories for High-Mass Payload Missions*
S. Ramjatan	*Blackout Analysis of Reentry Vehicles for Martian Missions*
I. Clark	*Parachute-Induced Wrist Mode Dynamics during Martian EDL*
E. Stern	*Progress on Free-Flight CFD Simulation for Entry Capsules in the Supersonic Regime*
B. Massuti-Ballester	*Finite Rate Catalytic Models of Silicon-Carbide Based High-Temperature Ceramics*
S. Dutta	*Flight Mechanics Modeling and Predictions for the ADEPT SR-1 Mission*
V. Leroy	*Quantitative Guidelines on Radiation Model Selection for Material Response Simulation*
J. Kowalski	*Modeling Cryospheric Contact and Phase-Change Processes for Applications in Planetary Exploration*
S. Lingard	*Supersonic Parachute Testing Using a MAXUS Sounding Rocket Piggy-Back Payload*
A. Guarneros Luna	*Upcoming Exo-Brake and Nano-Sat Advanced Flight Experiments - TechEdSat 6, 7, 8*
S. Perino	*Surviving the Impact: Core Quality Testing in a New Orbiting Sample Container for Potential Mars Sample Return*

E. Leylek	*Splashdown on Titan: Peak Loads, Plunge Depth, and Resurge Time for Capsule Impact in a Methane Sea*
P. Zell	*Introducing the Laser-Enhanced Arcjet Facility*
I. Sakraker	*In Situ X-Ray Tomography of Ablation in a Portable Arcjet Facility*
A. Stehura	*Mars 2020 Terrain Relative Navigation Verification & Validation*
B. Butler	*Towards in Situ Emissivity Measurement in the HYMETS Arc-Jet Facility*
E. Trifoni	*Design of a Jet Interaction Ground Experiment in Mars Entry Conditions*
Lead Author	Poster Title
J. Cheatwood	*Optimization of Thermal Environment Control for Tensile Tests of HIAD Materials*
P. Gage	*Mission Assurance and Residual Risk: The Performance Verification Challenge for Technology Infusion*
F. Foucher	*General Reflections on the Definitions of Analogues*
E. Ching	*Lagrangian Particle Tracking in a Discontinuous Galerkin Framework*
J. Underwood	*Fluid Structure Interaction Rebuilding of Parachute Tests*
I. Sakraker	*Time Resolved X-Ray Imaging and Modelling of an Ablator*
E. Stern	*Development of High-Fidelity Material Response Modeling for Woven Thermal Protection Systems*
B. Massuti-Ballester	*Sensitivity of Oxidation Processes on Heat Fluxes Determination*
L. Peacocke	*6-DOF Entry Trajectory Simulator for Deployable Mars Aero-Decelerators*
E. Rodriguez	*Special Check Out Equipment for Entry, Descent and Landing GNC Verification and Validation*
T. Schwartzentruber	*Molecular Simulation of Materials during Hypersonic Planetary Entry*
J. Sparta	*Model Development of Parachute Dynamics during Planetary Descent*
P. Gil	*Exact Analytic Calculation of Aerodynamic Coefficients in the Hypersonic Regime for Entry Vehicles*
G. Vekinis	*Numerical Modeling of the Recession of an Ablator TPS with an Embedded ReGS Sensor*
M. Pizzo	*Advances in the Field of High Performance Parallel Computing and the Impact on Scientific Discovery*
6. Mercury and Venus	
Lead Author	Presentation Title
J. Benkhoff	*Unveiling Mercury's Mysteries with BepiColombo - An ESA/JAXA Mission to Explore The Innermost Planet of Our Solar System*
D. Stramaccioni	*BepiColombo - Engineering Challenges*
L. Esposito	*The New Frontiers Venus in Situ Atmospheric and Geochemical Explorer (VISAGE)*
J. Cutts	*Aerial Platforms for Venus Exploration*
A. Garija	*Considerations for Atmospheric Sample Return from the Habitable Zone of Venus*
C. Greer	*Lithium Combustion Power System for Spacecraft Landers*
Lead Author	Poster Title
V. Patel	*Altitude Control for High Altitude Balloons*
7. Outer Planets	
Lead Author	Presentation Title
K. Reh	*Return to the Ice Giants*
O. Mousis	*The HERA Saturn Entry Probe Mission: A Proposal in Response to the ESA M5 Call*
M. Lobbia	*Saturn PRobe Interior and aTmosphere Explorer (SPRITE): Mission Implementation Overview*
K. Sayanagi	*Small Next-Generation Atmospheric Probe (SNAP) Concept*
R. Lorenz	*Decoding Huygens' Descent Dynamics: Self-Generated and Turbulence-Forced Motions*
Lead Author	Poster Title
D. Atkinson	*The Saturn PRobe Interior and aTmosphere Explorer (SPRITE) Entry Probe Science*
K. Sayanagi	*Two-Staged Saturn Probe to Explore 60+ Bar Atmosphere*

8. Lunar and Small Body Exploration	
Lead Author	Presentation Title
I. Gerth	*System Design for Proximity Operations of the Asteroid Impact Mission*
B. Hockman	*Hedgehog Hopping Rovers for the Exploration of Small Solar System Bodies*
T. Yamada	*Development of Shock Absorption Structure for OMOTENASHI Surface Probe*
E. Urgoiti	*Scale Testing of Dynamic Behavior of Moon Landing*
Y. Wang	*Investigations of the Landing Impact Characteristics*
R. Buchwald	*Moon Advanced Resource Utilization Viability Investigation Study*
R. Fisackerly	*PROSPECT: ESA's Package for Resource Observation and In Situ Prospecting for Exploration, Commercial Exploitation and Transportation*
Lead Author	Poster Title
L. Sander	*MARVIN Landing Site Characterisation*
B. Pigneur	*Sustainability for Space Exploration - A Case Study for Commercial Exploration of the Moon*
F. Cipriani	*Near Surface Environment Specifications for Lunar South Pole Exploration Sites*
9. Descent and Landing Technology	
Lead Author	Presentation Title
K. Edquist	*Overview of Supersonic Retropropulsion Aerosciences*
J. Benito	*Minimum Fuel Three Dimensional Powered Descent Guidance for Planetary Landing*
M. Solari	*Reinforcement Learning Guidance for Terminal Descent and Pinpoint Landing on Mars*
S. Woicke	*A Combined Algorithm for Final Descent Hazard-Relative Navigation and Hazard Detection*
S. Mohan	*Mars 2020 Terrain Relative Navigation Performance during Landing*
J. Montgomery	*The Mars 2020 Lander Vision System: Architecture and I&T Results*
R. Otero	*Mars 2020 Robust Rock Detection and Analysis Method*
T. Diedrich	*PILOT—Precise and Intelligent Landing Using On-Board Technologies*
Y. Wang	*Design, Simulation, Analysis and Tests of a Ram-Air Parachute Recovery System*
G. Villar	*Mars 2020 Parachute Workmanship Wind Tunnel Testing*
C. O'Farrell	*Overview of the Advanced Supersonic Parachute Inflation Research and Experiments (ASPIRE) Project*
D. Kipp	*De-Orbit, Descent, and Landing on Europa: Key Challenges and an Architecture*
Lead Author	Poster Title
S. Woicke	*Comparison of Crater-Detection Algorithms for Terrain-Relative Navigation*
D. Blette	*Development of Rapid, Descent Separation Analysis Methodology*
K. Schoeder	*Taking on the Mantle of VITaL with a New Tensegrity Actuated Tessera Lander*
S. Schröder	*Analysis, Test and Simulation of Landing Touchdown Dynamics*
10. Instrumentation and Experiments	
Lead Author	Presentation Title
G. Swanson	*MEDLI2 Do No Harm Test Series*
R. Miller	*High Temperature Characterization of GaN UV Photodetectors for Shock-Layer Radiation*
B. Butler	*Remote Recession Measurements of Seeded PICA*
G. Vekinis	*Reconstructing TPS Recession Using the ReGS Sensor*
B. Massuti-Ballester	*Experimental Evaluation of an In-Flight Surface Recession Sensor for Ablative Thermal Protection Systems*
R. Timoney	*Antarctic Testing of the European Ultrasonic Planetary Core Drill (UPCD)*
D. Firstbrook	*The Performance of Ultrasonically-Assisted Hammer-Action Penetrators in Planetary Regolith*
F. Foucher	*LithoSpace: An Automated System for In Situ Petrographic Thin Section Preparation on Mars*
J. Renard	*LOAC-S, A Light Aerosols Counter/Sizer for Planetary Atmospheres*

J. Gomez Elvira	*Astrobiology Wet Laboratory (AWL) for an Europa Lander Mission*
F. Dirri	*Organic Compounds Characterization in Space: Experimental Activity of VISTA Instrument*
C. Briois	*Cosmorbitrap: R&T Development of a new HRMS Analyzer for Future Space Missions*
M. Pauken	*A Thermopile Based Heat Flux Sensor for Measuring Heat Flow on the Surface of Venus*
M. Dominguez-Pumar	*Improvement of the Dynamical Response of a Spherical 3D Wind Sensor for Mars Atmosphere*
J. Gomez Elvira	*SOLID: A TRL 5–6 Instrument for Wet Chemistry Analysis in Planetary Exploration*
H. Kahanpää	*BAROCAP NG: The Next Generation Pressure Sensor for Planetary Atmospheric Science*
Lead Author	Poster Title
B. Sonneveldt	*Instrumentation and Reconstruction for the ASPIRE Supersonic Parachute Test Campaign*
H. Hwang	*Mars 2020 Entry, Descent, and Landing Instrumentation 2 (MEDLI2) Instrumentation Suite*
A. Martin-Ortega	*Micro-Processor Qualification for Planetary Exploration*
D. Lawrence	*Entry and Descent Gamma-Ray Measurements on a Venus Probe: A New Window on the Atmosphere Profile*
G. Bailet	*INES: A Flexible and Innovative Payload for Measuring Radiation in the Presence of Ablation*
J. Gomez Elvira	*SOLID: A TRL 5–6 Instrument for Wet Chemistry Analysis in Planetary Exploration*
V. Pallichadath	*Planetary Radio Interferometry and Doppler Experiment (PRIDE) for Planetary Probes*
R. Trautner	*A New Generic Processor Chip for Instrumentation, Experiments, and Miniaturized Spacecraft*
A. Longobardo	*VISTA: A μ-Thermogravimeter to Detect Volatile Compounds in Space and in Different Planetary Environments*
11. Aerobraking, Aeroscience, and Entry Technologies	
Lead Author	Presentation Title
J. DiNonno	*HIAD on ULA (HULA) Flight Experiment Concept Developments*
J. Underwood	*European Studies to Advance Development of Inflatable and Deployable Hypersonic Decelerators*
T. White	*Detailed Design of Earth Entry Vehicle for Comet Surface Sample Return*
B. Tackett	*Taking a PEAQ at Uncertain Atmospheres (Atmospheric Prediction for Entry and Aerocapture Qualification)*
J. Benito	*Development Status of a Mars Ascent Vehicle Technology Demonstration*
R. Haya Ramos	*Mission and GNC Challenges from IXV to Space Rider*
A. Guarneros Luna	*Exo-Brake Drag Modulation Flight Experiment Results*
M. Barnhardt	*Technology Investments in the NASA Entry Systems Modeling Project*
B. Jerome	*Development of the European Conformal Ablative-Charring Material as an Extension of the ASTERM Family in the Frame of the ESA DECA TRP*
P. Wercinski	*ADEPT Sounding Rocket One (SR-1) Flight Experiment Design Summary*
Y. Mignot	*Heatshields: Techno Push-Up for Future Exploration Missions*
E. Venkatapathy	*Heat-shield for Extreme Entry Environment Technology (HEEET) Development Status*
Lead Author	Poster Title
L. Li	*Structural and Configuration Design of a Novel Hypersonic Inflatable Aerodynamic Decelerator for Mars Entry, Descent, and Landing*
B. Libben	*Prototyping New HIAD Technologies to Enhance Performance of Entry, Descent, and Landing (EDL) Systems for Human and Robotic Missions to Mars*
R. Dillman	*Planned Assembly, Integration, and Testing of a 6m HIAD Orbital Entry Vehicle*
G. Swanson	*Fabrication of the HIAD Large-Scale Demonstration Assembly and Upcoming Mission Applications*
R. Bodkin	*Gas Generators, The Challenges of Supporting Human-Scale HIADs*
S. Hughes	*HIAD Aeroshell Deformation to Generate Lift for Use in Direct Force Control Strategies*
J. Sepulveda	*Aerodynamic Capability of Flaps for Planetary Entry Vehicles*
N. Kemal Ure	*Control System Design for Mars Entry Using Nonparametric Bayesian Models*

H. Ali	*Experimental Demonstration of Magnetohydrodynamic Energy Generation in Conditions and Configurations Relevant to Planetary Entry*
J. Sparks	*Process of Providing a Small-Payload Return from International Space Station*
B. Smith	*Free Flight Ground Testing of ADEPT in Advance of the Sounding Rocket One Flight Experiment*
J. Williams	*Assessing Nonequilibrium Flow Chemistry with a CubeSat-Class Mission*
S. Pavesi	*Analytical Modelling of Internal Thermodynamics of Ablative Thermal Protection System Materials*
N. Skolnik	*Defining the Critical Depth of Impact Damage for Thermal Protection Systems*
N. Mansour	*From Tomography to Material Properties of Thermal Protection Systems*
J. Koch	*Local Terraforming of Icy Bodies as a Medium for Aero-braking Systems*
S. Coumar	*EHD and MHD Actuators: Experimental Works to Enhance Spacecraft Control and Deceleration during Atmospheric Entries*
12. Small and CubeSat Probes	
Lead Author	Presentation Title
R. Walker	*Overview of ESA Studies on Interplanetary CubeSat Mission Concepts*
K. Yamada	*Flight Experiment of Nano-Satellite "EGG" for Deployment Demonstration of Membrane Aeroshell*
J. Kikuchi	*Semi-Hard Landing and Shock Absorption Mechanism of OMOTENASHI Project*
O. Chazot	*Ground Testing of QARMAN ReenSat in SCIROCCO Plasma Wind Tunnel under Flight Relevant Conditions*
Lead Author	Poster Title
T. Moriyoshi	*Study on the Martian Exploration Probe Using a Parafoil-Type Vehicle*
A. Aguilar	*Ambient Magnetic Energy Harvesting as an Assisting Power Source*
P. Stakem	*A CubeSat-Based Alternative of the Juno Mission to Jupiter*
S. Ranvier	*SLP: A Langmuir Probe Instrument on Board a CubeSat*
N. Gerbal	*Analysis of Landing Trajectories into the Didymos Binary System of Asteroids*
J. Hanson	*University of Idaho Near-Space Engineering Program: Engaging Students in Aerospace Engineering, Technology, and Science with Near-Space Flight*
D. Handy	*Low-Cost Command and Tracking for Testing of Atmospheric Probes*
M. Feher	*Interplanetary Navigation Mission Support System*
Keynote Presentations	
Lead Author	Presentation Title
B. Clark	*Al Seiff Award Lecture*
D. Schurr	*NASA's Planetary Science Program*
P. Ehrenfreund	*Planetary Science and Exploration: DLR Highlights*
D. Parker	*E3P: Europe's New Vision for Space Exploration*
T. Yamada	*Special Topics on JAXA Space Exploration Programs*
M. Munk	*NASA's Entry, Descent and Landing (EDL) Space Technology Investments*

15 Appendix 2: Acronyms and Abbreviations

ADEPT	Adaptable, Deployable Entry and Placement Technology
AG	aerospace group
AlGaN	aluminum gallium nitride
AIM	Asteroid Impact Mission
Airbus DS	Airbus Defence and Space
AMA	Analytical Mechanics Associates, Inc.
AMELIA	Atmospheric Mars Entry and Landing Investigations and Analysis
ARC	Ames Research Center
ASPIRE	Advanced Supersonic Parachute Inflation Research and Experiments
AWL	Astrobiology Wet Laboratory
CFD	computational fluid dynamics
CNSA	China National Space Administration
COMARS+	Combined Aerothermal and Radiometer Sensors Instrument Package
COTS	commercial off-the-shelf
DDL	deorbit, descent, and landing
DECA	Development of the European Conformal Ablator
DGB	disk-gap-band
DLR	Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace Center
DOF	degree(s) of freedom
DREAMS	Dust Characterization, Risk Assessment, and Environment Analyzer on the Martian Surface
DTE	direct to Earth

ECA	Evolution Cryotechnique Type A
EDL	entry, descent, and landing
EDM	EDL Demonstrator Module
EM-1	Exploration Mission 1
eMMRTG	Enhanced Multimission Radioisotope Thermoelectric Generator
ERC	Earth return capsule
ESA	European Space Agency
ESM	Entry Systems Modeling
ESTEC	European Space Research and Technology Center
ExoMars	Exobiology on Mars
FADS	Flush Airdata Sensing
GaN	gallium nitride
GITL	ground in the loop
GNC	guidance, navigation, and control
GSFC	Goddard Space Flight Center
HEEET	Heatshield for Extreme Entry Environment Technology
HGA	high-gain antenna
HIAD	hypersonic IAD
HOTTech	Hot Operating Temperature Technology
HULA	HIAD on ULA
HYMETS	Hypersonic Materials Environmental Test System
IAD	inflatable aerodynamic decelerator
ICOTOM	Infrared CO_2 Measurement
IMU	inertial measurement unit
InSight	Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport
IPPW	International Planetary Probe Workshop
ISRU	in situ resource utilization
IXV	Intermediate eXperimental Vehicle

JAXA	Japan Aerospace Exploration Agency
JEM	Joint Europa Mission
JPL	Jet Propulsion Laboratory
JUICE	JUpiter ICy moons Explorer
L/D	lift to drag ratio
LaRC	Langley Research Center
LDSD	Low-Density Supersonic Decelerator
LEO	low Earth orbit
lidar	light detection and ranging
LITVC	liquid-injection thrust vector control
LOAC-S	Light Optical Aerosols Counter and Sizer
M2020	Mars 2020
MARVIN	Moon Advanced Resource Utilization Viability Investigation
MAV	Mars Ascent Vehicle
MCD	Mars Climate Database
MEDA	Mars Environmental Dynamics Analyzer
MEDLI2	M2020 EDL Instrumentation 2
MESSENGER	Mercury Surface, Space Environment, Geochemistry, and Ranging
MMO	Mercury Magnetospheric Orbiter
MMRTG	multimission radioisotope thermoelectric generator
MOLA	Mars Orbiter Laser Altimeter
MPO	Mercury Planetary Orbiter
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
OHB	formerly Otto Hydraulik Bremen GmBH
OMOTENASHI	Outstanding MOon exploration TEchnologies demonstrated by NAno SemiHard Impactor

OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
PILOT	Precision and Intelligent Landing using Onboard Technologies
PSD	Planetary Science Division (NASA)
PSDS3	Planetary Science Deep Space SmallSat Studies
QARMAN	QubeSat for Aerothermodynamic Research and Measurements on AblatioN
ReGS	resistive-grid sensor
REMS	Rover Environmental Monitoring System
RHU	radioisotope heater unit
RLS	Raman Laser Spectrometer
RTG	radioisotope thermoelectric generator
SEP	solar electric propulsion
SLP	sweep Langmuir probe
SLS	Space Launch System
SNAP	Small, Next-Generation Atmospheric Probe
SOLID	Signs of Life Detector
SPRITE	Saturn PRobe Interior and aTmosphere Explorer
SRM	solid rocket motor
SRP	supersonic retropropulsion
TANDEM	Tension Adjustable Network for Deploying Entry Membrane
TCM	trajectory correction maneuver
TechEdSat	Technological and Educational Nanosatellite
TGO	Trace Gas Orbiter
TPS	thermal protection system
TRL	technology readiness level
TRN	Terrain-Relative Navigation
TRP	Technology Research Programme
UHF	ultrahigh frequency
ULA	United Launch Alliance

UPCD	Ultrasonic Planetary Core Drill
UV	ultraviolet
VAMP	Venus Atmospheric Maneuverable Platform
VISAGE	Venus in Situ Atmospheric and Geochemical Explorer
VISTA	Volatile in Situ Thermogravimetry Analyzer
VITaL	Venus Intrepid Tessera Lander

16 Appendix 3: IPPW-14 International Organizing Committee

Chair: Bernie Bienstock, *Jet Propulsion Laboratory*

Co-Chair: Anita Sengupta, *Jet Propulsion Laboratory*

Michael Amato, *NASA Goddard Space Flight Center*
Jim Arnold, *NASA Ames Research Center*
Sami Asmar, *Jet Propulsion Laboratory*
David Atkinson, *Jet Propulsion Laboratory*
Tibor Balint, *Jet Propulsion Laboratory*
Andrew Ball, *ESA-ESTEC*
Pat Beauchamp, *Jet Propulsion Laboratory*
Jens Biele, *German Aerospace Center (DLR)*
Jean-Marc Bouilly, *Airbus Safran Launchers*
Bobby Braun, *University of Colorado, Boulder*
Robert Buchwald, *Airbus Defence and Space*
Neil Cheatwood, *NASA Langley Research Center*
Athena Coustenis, *Observatoire de Paris*
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Soumyo Dutta, *NASA Langley Research Center*
Karl Edquist, *NASA Langley Research Center*
Luca Ferracina, *ESA-ESTEC*
Francesca Ferri, *Università degli Studi di Padova*
Jim Garvin, *NASA Goddard Space Flight Center*
Ingo Gerth, *OHB System AG*
Hannes Griebel, *Inmarsat*
Ali Guelhan, *German Aerospace Center (DLR)*
Rodrigo Haya Ramos, *SENER*
Jeff Herath, *NASA Langley Research Center*
Scott Hubbard, *Stanford University*
Helen Hwang, *NASA Ames Research Center*
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