Planetary Exploration Science Technology (PESTO)

Small Body Technologies

Carolyn Mercer
NASA Glenn Research Center

Briefing to the Small Body Analysis Group (SBAG)
January 18, 2018
Mountain View, CA
“The committee unequivocally recommends that a substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources. **This program should be consistently funded at approximately 6 to 8 percent of the total NASA Planetary Science Division budget.**”

“The committee recommends that the Planetary Science Division’s technology program should accept the responsibility, and assign the required funds, to continue the development of **the most important technology items** through TRL 6.”
How to determine “the most important technology items”?

• Planetary Technology Working Group Members surveyed the VEXAG, OPAG, SBAG, Mars Program, and the Decadal Survey

• Then assessed each technology identified by the AGs using the following Figures of Merit:
  • Critical Technology for Future Mission(s) of Interest
  • Degree of Applicability across PSD Missions/needs
  • Work Required to Complete
  • Opportunity for Cost Sharing
  • Likelihood of Successful Development and Infusion
  • Commercial Sustainability

• Corporate knowledge includes previous studies, e.g.:
  – “PSD Relevant Technologies,” G. Johnston 1/7/2011
  – https://solarsystem.nasa.gov/missions/techreports

New Office established by PSD: Planetary Exploration Science Technology Office (PESTO)
**Community Technology Inputs**

(VEXAG, OPAG, SBAG, Mars Program, Decadal, Surveys)
from: Planetary Science Technology Plan, April 9, 2015

<table>
<thead>
<tr>
<th>System Technologies</th>
<th>Applicable Technology</th>
<th>NEAR TERM MISSIONS</th>
<th>MID TERM MISSIONS</th>
<th>FAR TERM MISSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Small Bodies</td>
<td>Outer Planets</td>
<td>Venus</td>
</tr>
<tr>
<td>In Space Propulsion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerocapture/Aeroassist</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entry (including at Earth)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Descent and Deployment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landing at target object</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerial Platforms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landers - Short Duration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landers - Long Duration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile platform - surface, near surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ascent Vehicle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample Return</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planetary Protection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Storage - Batteries</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Generation - Solar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Generation - RPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Control - Passive</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Control - Active</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rad Hard Electronics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extreme Temp Mechanisms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extreme Temp Electronics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communications</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autonomous Operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN&amp;C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote Sensing - Active</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote Sensing - Passive</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probe - Aerial Platform</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In Situ - Space Physics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In Situ Surface - Geophysical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In Situ Surface - Long Duration - Mobile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TRL Levels**
- **High TRL** - limited development and testing needed
- **Moderate TRL** - major R&D needed
- **Low TRL** - notable technical challenges

**Outer Planets input based on the OPAG white paper “Outer Planet “Roadmap of 2009**
Planetary Science Division Prioritized Technologies
April 2016

PLANETARY TECHNOLOGIES
• Electronics (high temperature)
• Communications (high bandwidth, high datarate)
• Solar Power (low intensity, low temp)
• Power Systems (high temperature)
• RPS surface power
• RPS orbital power
• System autonomy (GNC, Prox Ops, C&DH, sampling ops, FDIR)
• Small Spacecraft Power, GNC, Propulsion, Comm
• Planetary Ascent Vehicle for Sample Return
• Heat Shield technologies for planetary entry and sample return
• Computing and FPGAs (high performance/low power/rad hard)

INSTRUMENTS
• Life Detection for Ocean Worlds
• Low mass, low power instruments for cold, high rad ocean world environments
• Low mass, low power instruments for small spacecraft

OCEAN WORLDS
• Electronics (low temp, low power, rad-hard)
• Actuators/mechanisms (low temp)
• Planetary Protection Techniques/component and material compatibility
• Ice Acquisition and Handling (>0.2 m depth)
• Ice Sample Return
• Pinpoint Landing on Titan

EUROPA
• Ice Acquisition and Handling (surface, cryo)
• Batteries (low temp)
• Pinpoint Landing on Europa
• Landing Hazard Avoidance
Planetary Missions
Prioritized Technologies

- High-Temperature Compatible Electronics
- High Bandwidth, High Data Rate Communications
  - Large Deployable Reflectors and High Power TWTs
- Low Intensity/Low Temperature Solar Power
- High-Temperature Compatible Power Systems
  - Batteries
  - Power Generation
  - Low-Intensity High-Temperature Solar Cells
- RPS Power
  - Orbital and Surface: Radioisotope Thermoelectric Generator – eMMRTG
  - Orbital: Radioisotope Thermoelectric Generator - Next Gen RTG
  - Orbital and Surface: Dynamic RPS
- System Autonomy
  - Autonomous Navigation for EDL
  - Reactive Science Autonomy
  - Efficient Planetary Surface Science Ops
- Small Spacecraft
  - Propulsion – Electric & Non-Toxic Chem
  - Power, GNC,& Communications
- Planetary Ascent Vehicle for Sample Return - Mars Ascent Vehicle
- Heat Shield Technologies for Planetary Entry and Sample Return
  - Thermal Protection Systems
  - Aerocapture
  - Deployable Aeroshells
- High performance/low power/rad hard computing and FPGAs
  - Chiplet Augmentation, Advanced Space Memory, Co-Processors/Accelerators, System Software, Development Environment, Power, Computer
Prioritized Technologies – SMALL BODIES

DRAFT TIER 1

- Anchoring and Sampling Mechanisms for Small Bodies (new)
- Small Spacecraft
  - Propulsion–EP & Chem
  - Communications
- Low Intensity/Low Temperature Solar Power
- System Autonomy
  - Efficient Planetary Science Ops
    - Navigation for Proximity Ops (new)
    - Fault Protection (new)

DRAFT TIER 2

- High performance/low power/rad hard computing and FPGAs
- High Bandwidth, High Data Rate Communications
  - Large Deployable Reflectors and High Power TWTs
- System Autonomy
  - Autonomous Nav for Descent/Landing
  - Reactive Science Autonomy
- Heat Shield Technologies for Cryogenic Sample Return
- Ice Sample Return
  - Integrated Cryogenic Chamber

DRAFT TIER 3

- RPS Power
- System Autonomy
  - Planetary Surface Science Ops – Rovers
- Planetary Protection
- High-Temperature Compatible Power Systems – if needed for PP
Technical Goal

(1) Long-duration thruster firings are required to generate high delta-V, therefore high Isp is needed to reduce the propellant mass and volume to fit within a SmallSat. Rad-tolerant to survive long-duration flight in deep space. Requires high power solar arrays.
   a. Packages to 3U-4U. 150-300 W (I\textsubscript{2} or Xe) (1300 – 1500 sec, 2,000 to 10,000 hours).
   b. ESPA-class. 300-600 W (Xe or I\textsubscript{2}) (1300 – 1500 sec, 6,000 to 10,000 hours).

(2) System packages to <1U. Rad-tolerant to survive long-duration flight in deep space. <100 W, 0.1 to 1.2 mN, 2000-5000 sec Isp, 5,000 to 15,000 hours. Typically BIT (Xe or I\textsubscript{2}), or electrospray (ionic liquids).

Mission Applications

(1) Direct transportation to the moon, Mars, Venus, and main asteroid belt from GTO; higher power missions e.g. to Europa.
   a. CubeSat missions
   b. ESPA-class missions, enables larger science payload.

(2) Enables low power, rideshare missions <12U. Missions like LunaH-Map, Lunar IceCube, and DAVID. No new power system requirements.

Technical Status

The gap is lifetime.

1) 100 to 600 W electric thrusters performance has been demonstrated with the required Isp and thrust. Flight-like power processing units have not been developed (compact, high power density, rad hard). Iodine cathodes have not yet been developed.
   a. 200 W Xe thrusters have demonstrated 1800 hours of operation (then soft failure), and 80 hours using iodine propellant (test ended before failure). 200 W, 30 krad iSat flight PPU being built.
   b. 600 W I\textsubscript{2} thrusters have demonstrated 80 hours of operation (test ended before failure). 600 W brassboard PPU being built

2) 100 microNewton thruster performance demonstrated to 200 hours until failure (MIT). In-space demo with limited operability (MIT 2015 and 2016, Busek 2018). BIT thruster 500 hour life test. MicroNewton thrusters flew on LISA Pathfinder.
Technical Goal

Reliable radiation-hardened Communication Systems for CubeSats and small satellite platforms capable of operating in extreme environments of Venus, Moon, Asteroids/NEOs (Small bodies), Ice Bodies/Ocean Worlds/Outer Planets, and Mars. Communication systems include deployable direct-to-earth systems with rates of tens to hundreds kbps and provide accurate relative position knowledge for formation flying for spatial and/or temporal measurements that span large distances or in specific regions of interest.

**Venus:** Comm systems for SmallSat-class spacecrafts (range 3U to 24U, ESPA class). Probe: Direct to earth on operational in high temperature and high pressure (450C, 92 bar) mission life XX???. Orbit: X-band IRIS direct to Earth with Mission life up to 5 years.

**Moon/Mars:** Comm systems for SmallSat-class spacecrafts. Up to 100kRad Radiation tolerance. 4 Year mission life. UHF micro-strip antennas; 50 MB/week; 50 kps required orbiter within 3,000 km, IRIS, UHF link to orbiting assets; potential UHF direct to Earth, 256 kbyte/sec down; 300 Mbyte/day; 3 hour window. Laser communications capability to upto ? Mbps over ? km.

**Small Bodies:** 5W laser comm, deployable, 6” high gain Ka-Band, X-band antenna configured to be swappable with flat-panel solar array, X-band IRIS w/reflectarray antenna, X-band to DSN, 5 year life time. 0.02° pointing accuracy.

**Icy Bodies/Outer Planets/Ocean Worlds:** Comm systems for CubeSat Probes and SmallSat-class spacecraft (~180 kg 3U to 24U) for up to 8 year mission life. Low temperature (230K) and high radiation operational environment (3 Mrads) for batteries (??? WHr/kg, ??mAh) and electronics. X-band through carrier s/c to DSN. 50 cm antenna, X-band nav, Ka-band downlink, direct to earth, Iris + Ka PDA, UHF uplink to orbiter.

Mission Applications

If power systems technology above are realized for:

**Venus:** it will enable the extended exploration of Venus (atmospheric and surface) for up to 1 year vs 2 hours with current technology.

**Moon:** it will enable multi-point mapping of lunar surface using smallsats to understand lunar evolution ...

**Mars:** it will enable a constellation of SmallSats will enable simultaneous measurements of Mars environment; observing the Martian environment over a Martian year, furthering knowledge of Mars’ composition, temperature, ion escape/sputtering

**Small Bodies:** it will enable constellations of cubesats probes to multiple small bodies or probes utilized to “point and stare” at a specific small body target.

**Icy Bodies/Outer Planets/Ocean Worlds:** it will enable exploration of ourer worlds such as Uranus via Probes or provide multipoint measurements to investigate modes of solar wind coupling in Jupiter as well as neutral atoms escape.
Prioritized Technology: Low Intensity/Low Temperature Solar Power

### Technical Goals
- Improve solar cell conversion efficiency, & eliminate need for screening
- Improve radiation resistance
- Develop solar array concentrator elements to mitigate LILT conditions
- Specific objectives to be demonstrated are:
  - > 40% efficient solar cells at LILT
  - > 8 W/kg array specific power at 5 AU
  - Extended lifetime in high radiation environment near Jupiter

### Technical Status
- Low mass, flexible, fold/roll out array concepts demonstrated by STMD
- SOA cell technology requires pre-screening due to select against performance degradation under LILT conditions
- Inverted Metamorphic Multijunction (IMM) solar cell technology may show improved performance in LILT environments compared to SOA technology

### Mission Applications:
- Increases range of missions that can be solar powered versus radioisotope power systems
  - Enable solar powered spacecraft to 10 AU distances include Saturn and its moons
  - Increase power for and enable long duration Jupiter (4% irradiance, -140 C) and Saturn (1% irradiance, -165 C) orbital missions
- Reduce the power system mass and and volume of the electric propulsion missions to small bodies, asteroids and outer planets
  - Change of cell from SOA triple junction to next generation inverted metamorphic multi-junction (IMM) on Europa Clipper would result in >20% cell mass reduction and 2% efficiency improvement
- Gains in efficiency and reductions in mass are destination specific, but may also be applicable to 1 AU missions.
  - Concentrator concepts to reduce mass may have benefits for solar array protection from radiation in Earth polar orbits and near Jupiter.
## Technical Goal

Significantly increase the efficiency of planetary surface science operations

- Increase science productivity of surface missions by increasing work efficiency index by at least 300%
- Increase efficiency of collecting, triaging, and returning informative data
- Reliable operation of in-situ probes while independent of ground control

Technology advances are required in:

- Situational/self awareness: sensing and perception, state estimation, knowledge and model building, anomaly/event detection
- Reasoning/acting: goal-based planning, task execution, diagnostics and prognostics (system health management)

## Technical Status

- Routine MER/MSL science ops requires multiple sols to approach a target, perform terminal alignment, and instrument deployment.
- 2004 "Single Cycle Instrument Project" (SCIP) demonstrated capability to perform instrument deployment in a single command cycle, which is a work efficiency gain of at least 300% (TRL 5)
- 2003-2015 "Life in the Atacama" (SMD ASTEP) demonstrated autonomous long-range traverse, science autonomy, and sampling (TRL 5)
- 2014 "Mojave Volatiles Prospector" (SMD MMAMA) demonstrated fully autonomous rover navigation in support of high-tempo science operations (TRL 5)
- 2014 "Planetary Lake Lander" (SMD ASTEP) demonstrated high-efficiency science operations using on-board situational/self awareness and reasoning/acting (TRL 5)

## Mission Applications

- Planetary science operations constantly deals with down-sampling, data prioritization, and trades. Optimizing mission performance and science productivity is a critical priority and calls for delegating some of the decision-making to the in-situ probe.
- Increasing operational efficiency will directly increase the number of sites that can be visited in a given period and science productivity
- Enable surface missions that require rapid measurement, contingency handling, or that are too slow to perform with ground control in the loop will be enabled.
- In-situ probes can establish an environmental, operational, or situational baseline, track changes as they happen, adapt their data collection rate to monitor them, and prioritize data return. This will significantly increase the return of informative science data.
- Increase utilization of in-situ probe (minimize idle time) and communications link (ensure downlink capacity is fully used).
### Technical Goal

Localization and hazard detection for EDL within 100m of point targets
- Safeguarding: Detect hazardous surface features (crevasses, fractured terrain, jagged penitente fields, etc)
- Targeting: Select final landing site during descent or low-altitude fly-over by incorporating science sensors as part of EDL process

Technology advances are required in:
- Real-time mapping and feature matching algorithms appropriate for descent and landing trajectories
- On-board landing site targeting (terrain classification, site characterization, etc) based on science potential, not just geometry
- Hazard detection in dynamic or poor lighting conditions

### Technical Status

- Traditional EDL relies on sensors that are used to measure relative range (separation distance) and to characterize terrain geometry (height, roughness, etc) without explicit estimation or representation of other characteristics (trafficability, science value, etc)
- Current EDL does not consider non-geometric information about biomarkers, materials, features, etc. that can point to areas of potentially high science return (i.e., science targets visible during EDL)
- Terrain-relative velocity estimation has been flow with radar and imaging sensors.
- Terrain-relative position estimation for precision landing (using image to map matching) on Mars and the Moon is under development, but has not yet flown and is not generalized for other bodies.

### Mission Applications

- Enable spacecraft to autonomously plan and execute landings that consider not only mission safety, but also science objectives
- Enable spacecraft to land at locations that cannot be extensively mapped prior to entry (descent through clouds, landing in poorly lit regions, etc)
- Significantly enhance the scientific return of lander missions: increases likelihood to land at a target of interest (reduce landing ellipse in order to pinpoint targets within a few meters of interest)
- Autonomous navigation serves several mission architectures that benefit from sampling high-return areas (lander only, hopping landers, lander with daughter-craft)
- Enables landing in regions currently considered to be too uncertain, risky, or difficult to access
- Enable missions to icy moons and ocean worlds
Prioritized Technology: Ice Sample Return –
*Integrated Cryogenic Chamber (ICC)*

**Technical Goal**
Preserve an ice sample at cryogenic temperatures during return and Earth re-entry for three classes of missions:

An integrated cryogenic chamber includes three types of technologies: Phase Change Materials (PCM); multistage shield and heat switch; and mechanical cryocooler.

- **Class 1:** Sample kept between 100K – 150K
  - Adapt current PCM (e.g. Argon), cryocooler, shield, and heat switch tech. for larger heat sink caused by sample size. Develop baseline integrated Cryogenic Chamber.

- **Class 2:** Sample kept between 65K - 100K
  - Improve from class 1, heat switch reliability & multistage switch.

- **Class 3:** Sample kept 55K - 65K
  - Improve from class 2; Adapt N2 PCM
  - Improve heat switch reliability & improve efficiency of passive radiator cooling;
  - develop battery powered 2nd stage cryocooler for earth entry vehicle

- Perform trade studies between use of passive thermal radiators (PTR), size of cryocoolers, and number of cryocoolers for different mission classes and Understand location of cryocoolers: internal or external to the earth entry vehicle.

- Challenges: If batteries power a cryocooler in earth return vehicle, then battery life could be a concern. The ICC needs a hermetic seal to maintain the vacuum in the ICC needed to minimize heat transfer.

**Technical Status**
- Mars (MSR), asteroid (OSIRIS-REx), comet (CSSR in New Frontiers 4) return sample without cryocooler, potentially with phase change material to maintain < 263K through sample recovery on Earth.
- Cryocoolers exist for cooling small flight instruments, but not for the larger volume return samples. The ice samples are much larger, thus, thermal mass of samples are also much larger than the current instruments.
- No Integrated Cryogenic Chamber has been developed.
- The Verveka et al. Cryogenic Comet Nucleus Sample Return study (NASA SDO-12367) suggested two cryocoolers to keep samples below 125K, one powered by the spacecraft and one powered by batteries in the earth entry vehicle. The study assumed a 30 cm long by 15 cm diameter cooled volume.
Backup
Prioritized Technologies - VENUS

**DRAFT NEAR TERM**
- High-Temperature Compatible Electronics
  - High-Temperature Communications
  - High-temperature Computing
- High-Temperature Compatible Power Systems
  - Batteries
  - Low-Intensity High-Temperature Solar Cells
- Heat Shield Technologies for Planetary Entry and Sample Return
- Small Spacecraft
  - Propulsion – Electric & Non-Toxic Chem
  - Power & Communications
  - Thermal Protection Systems
  - Aerocapture
  - Deployable Aeroshells

**DRAFT MID TERM**
- High-temperature Power Generation Systems
- System Autonomy
  - Autonomous Navigation for EDL
- GNC
  - Attitude Determination and Control (ADC)

**DRAFT FAR TERM**
- High performance/low power/rad hard computing and FPGAs
- High Bandwidth, High Data Rate Communications
  - Large Deployable Reflectors and High Power TWTs
- Planetary Ascent Vehicle for Sample Return

**Existing RPS program**
- RPS Power
  - Orbital and Surface: Radioisotope Thermoelectric Generator – eMMRTG
  - Orbital: Radioisotope Thermoelectric Generator - Next Gen RTG
  - Orbital and Surface: Dynamic RPS

**NEW** Deployable mechanisms
- aerial platforms, long duration landers
**NEW** Sample Acquisition and Transport for high temperature/harsh atmosphere
- Electric motor, arm, actuator
**NEW** Active cooling
**NEW** Atmospheric Sample Return
Ocean Worlds
Prioritized Technologies

• Lander
  • Surface cryogenic ice sample acquisition and handling
  • Pinpoint Landing and Hazard Avoidance
  • High Specific Energy, Radiation Tolerant Primary Batteries
• Autonomy
• Ice Penetration and Sampling
  • Low-Mass, Low-Power Excavation
  • Sample Handling and Transport
  • Bioburden Reduction-Tolerant Hardware
  • Low Temperature Actuators and Mechanisms (as needed for sample acquisition/transfer)
    • Lubrication, Bearings, Testing Facility, Actuators
• Planetary Protection Techniques/Component and Material Compatibility
  • Expanded Bioburden Reduction Technique Toolbox
  • Backward Contamination Technology Demonstration

• Low-Temperature Compatible Low Power, Rad-Hard Electronics and Energy Storage

• Pinpoint Landing on Titan
  • EDL Architecture Trade Study
  • Terrain Relative Navigation
  • Guidance and Control

• Ice Sample Return
  • Integrated Cryogenic Chamber
  • Responsive Systems for Containment