NOVEL PLANETARY SCIENCE ENABLED BY NETWORKED CONSTELLATIONS

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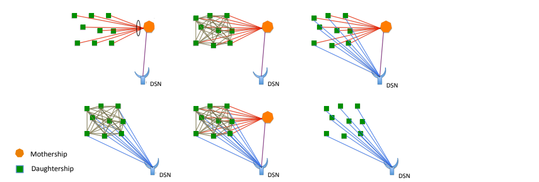
Introduction: To date, Planetary Science investigations have largely been conducted with point measurements. Notable exceptions are the rovers on Mars and GRAIL's measurements of the lunar gravity field.

The relay network established by the set of Mars orbiters is already critical to returning data from Martian landers and rovers and provides first glimpse of what a future multi-asset network at a planetary body might be.

An essential element of many of these concepts is that the "whole is greater than the sum of the parts"—the science return is enhanced only if the measurements from the individual sensors can be combined, but intra-constellation communication and coordination is often identified as a key challenge for these concepts and even more so for deep space missions that are frequently resource-constrained.

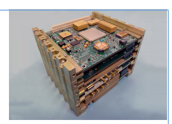
High-level alternative physical communications architectures



Various communications architectures may be considered to retrieve science data acquired by a constellation. In the simplest (lower-right), each spacecraft communicates directly with Earth; however, this architecture is not cost effective in deep space. Several alternatives show a local mothership that gathers the data, possibly performs processing that reduces the volume, and relays it to Earth. The mothership may also provide local control of the daughter spacecraft, alleviating demands on Earth operators. Inter-connections among daughterships can support relative position determination (significantly lowering Earth-based tracking needs), and facilitate real-time resource coordination within the constellation.

Smallsats/cubesats offer plausible means of implementing affordable deep space constellations – With the emergence of small platforms (CubeSat and other form factors) enabled by advances in electronics and miniaturized instruments, distributed sets of sensors will enable the realization of novel science that requires distributed measurements and push the boundaries of exploration.

Operations and optimization likely to remain (or appear to remain) significant challenge



Technological Needs – Hardware
- Demonstration of advanced deep space CubeSats 🟢
- Increased telecommunications capability 🟡
- Guidance, navigation, and control 🟡
- Robust miniaturized components 🟢
- Data storage 🟡
- Approach to building 10s of assets 🔴

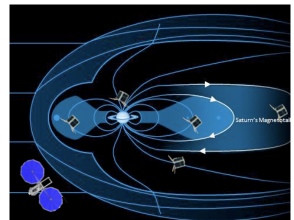
Technological Needs – Software
- On-board data analysis and science extraction 🟡
- Autonomous operations for self and situational awareness and onboard decision-making and control 🟡
- On-board resource management and optimization 🟡
- Relay automation via networking functionality for autonomous coordination between assets and improved science return 🟡

Technological Needs – Mission Design/Operations
- Optimization of design 🟡
- Mission operations 🔴
- Coordinated strategies for state estimation and motion planning for constellation of mobile assets 🔴
- New approach to fault protection and resilience against unknown space and planetary environments 🟡

🟢 Demonstration/Infusion in progress 🟡 Development in progress 🔴 No development in progress

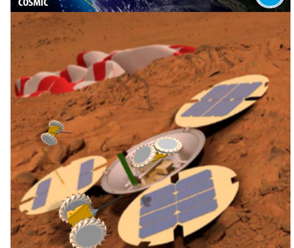
Examples of Science Applications

Distributed Measurements especially benefit science based on fields and particles (magnetic field, gravity field, energetic particles, dust) for simultaneous multi-site measurements. Seismic networking is a well known example. Networked constellations have also been suggested for the exploration of planetary magnetospheres, especially as energetic particle spectrometers and geophysical instruments are generally small enough to fit within CubeSats. Communication between assets is used to increase position knowledge accuracy, enable **real-time in situ adaptation of distributed sensing to dynamic scientific phenomena**, support **data fusion and source compression to reduce returned data volumes**, and **relay data** over interplanetary backhaul communications.

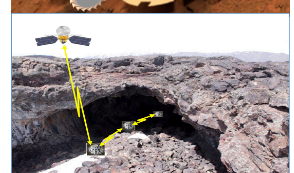


Distributed Measurements: Radio occultations among multiple spacecraft can **monitor** atmospheric conditions. This approach is analogous to radio occultation constellations using the Global Positioning System (GPS) signals on Earth, and could be used at any body with an atmosphere. Targets that have been considered include Mars, Venus, and the giant planets. Radio occultation measurements (involving multiple spacecraft pairs or a single transmitting spacecraft and multiple receivers) would enable **higher-dimensional characterization of the atmosphere** (such as wind vectors) as well as wide-scale atmospheric dynamics. Such investigations may also prove important **in preparation for crewed exploration** of Mars. (Graphic credit: UCAR/NASA/NSF/USAF/NOAA/NSPO/ONR)

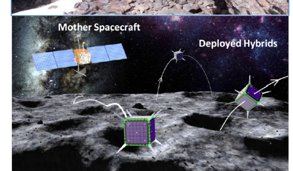
Multi-Satellite Architecture for in-depth study of a planetary body may involve surface and above-surface assets as well as one or several orbiters. An example of application is the data (particle density, vapor production, etc.) that can be obtained **from multiple vantage points** of **dynamical processes** to support the quest for habitable environments and biomolecules in the case of icy satellites. This example shows NASA's PUFFER rovers combined with a MarsDrop. The latter acts as carrier, telecom relay, and may carry its own payload complementary to the PUFFERs.
(Background MarsDrop image courtesy of and reprinted by permission of The Aerospace Corporation.)



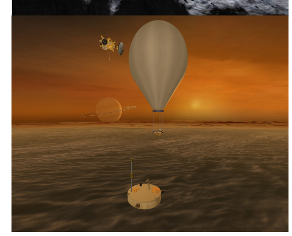
Relay Communication Network are critical to the exploration of sites with limited or no line-of-sight to a mothership. The discovery of caves both on Mars and the Moon and suspected at Titan opens new directions in the search of habitats for human exploration and past or extant life forms. The reconnaissance of these areas should become of primary importance in the future and requires special strategies for **exploration in highly resource-constrained conditions and challenging communication configurations**.



Task Distribution between assets for increased science return and decreased operational complexity. This includes scouting by small assets traveling with a larger platform, e.g., for **terrain reconnaissance** (risk, science). The scouts may relay their information based on the autonomous, on-board prioritization of their findings. The real-time sharing of information among assets would facilitate **autonomous *in situ* decision-making**. This is particular critical for systems that **operate in dynamic environments**. (Example: Hedgehog rover, NASA/Stanford/JPL/MIT)



Networking between assets should prove enabling to future missions with long roundtrip light-times, especially when vehicle cannot be easily predicted. The heterogeneous architecture shown on the right, proposed for the exploration of Titan, combines an orbiter, balloon, and boat. Weather information inferred from the balloon trajectory can be used to predict the boat motion. Telecom links between the various assets can inform on the varying properties of Titan's atmosphere. The balloon might act as a telecom relay for the boat, decreasing its power needs. Telecommunication across this dynamic system can be enabled by disruption tolerant networking. **This type of architecture might not be possible without the introduction of networking technologies.**



References: NRC Report (2016) "Achieving Science with CubeSats: Thinking Inside the Box"; NASA Technology Roadmaps: TA-04 Robotics and Autonomous Systems, TA 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems.

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