SOLAR SAILS: FROM INTERPLANETARY CUBESATS FOR REMOTE SENSING TO PHOBOS SAMPLE RETURN TO CLIPPER SHIPS FOR PRE-PLACING HUMAN EXPLORATION EQUIPMENT IN MARS ORBIT. R. L. Staehle[1], B. Betts[2], L. D. Friedman[2], H. Hemmati[1], A. T. Klesh[1], M. W. Lo[1], P. Mouroulis[1], P. J. Pingree[1], J. Puig-Suari[3], T. Svitek[4], A. Williams[3]. [1] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena CA 91109, robert.l.staehle@jpl.nasa.gov; [2]The Planetary Society, 85 S. Grand Ave., Pasadena, CA 91105, bruce.betts@planetary.org; [3]CalPoly Aerospace Eng'g, San Luis Obispo, CA 93407, atwillia@calpoly.edu; [4]Stellar Exploration, 174 Suburban Road, Suite 120 San Luis Obispo, CA 93401, tomas@stellar-exploration.com

Challenge Area 2: … Innovative Exploration Approaches. Time Frames: Near-, Mid-, and Longer-Term

Introduction: Application of solar sail propulsion to some kinds of Mars missions could reduce their cost, in some cases significantly. As mass delivered to Mars grows with ever-larger Mars missions, costs are increasingly driven by the cost to launch and handle increasing masses of propellant used to execute the missions. Solar sails require no propellant, and during the time periods of interest, would have the capability to deliver mission delta-Vs of 1 – 5 km/sec/year.

Evolving CubeSat technology (s/c <~10kg) with modest size practical solar sails would enable inexpensive spacecraft to carry out special purpose missions in interplanetary space and at the planets. CubeSat/solar sail technology initiated with NASA's NanoSail-D [1] and The Planetary Society's LightSail™ development [2] has led to Interplanetary CubeSat concepts that can serve a Mars program architecture. Application by ~2018 would be possible using the NIAC-sponsored Interplanetary CubeSat architecture[3] to carry piggyback spacecraft that could navigate to Mars, and make high-spatial resolution composition maps of Phobos and Deimos, as well as heliocentric asteroids. Beginning perhaps ~2025, a pair of Interplanetary CubeSats could fly together to one of the martian moons, with one landing, and the other intercepting a sample from the lander and returning it to Earth orbit for pickup.

Much larger solar sails, like those envisaged in the 1970s for the Halley's Comet Rendezvous mission [4], and even larger ones compatible with heavy launch systems now in development, could serve as a trucking fleet to carry supplies to Mars orbit ahead of the first human explorers, while eliminating the need for multiple launches worth of propellant.

2018+ Remote Sensing and Satellite Surface Applications: An Interplanetary CubeSat fitting the 6U form factor (10x20x30 cm) has been defined carrying an imaging spectrometer of compact optical configuration, measuring surface reflectance in each spatial pixel from 450 – 1650 nm at 10 nm intervals, based on ongoing PIDDP work [5].

An example spacecraft would have 2U devoted to this instrument, 2U for the 10x10 m solar sail with its deployment mechanism, 1U for an optical telecom flight terminal capable of 2 kbits/s from 2 AU, and 1U for all other spacecraft subsystems, plus deployable photovoltaic panels. This 10 kg s/c could be launched as a secondary payload with any larger Mars-bound mission. With longer flight time, any launch as a secondary payload to C3~0 is suitable. In the worst case, any launch to geostationary orbit would be suitable, with the addition of ~2.5 years flight time to spiral out of GEO to Earth escape. In this case, lunar flybys and use of the Interplanetary Superhighway reduce flight time somewhat. At 1 AU, sustained power levels >50 W are possible with modest deployed solar panels of the type now being prepared to LEO demonstration. The noted optical downlink could operate at ~5 W input power, downlinking to the 5 m Palomar telescope at 1550 nm wavelength with a 3 db link margin, and receving lower-rate uplink at 1030 nm.

Instead of an imaging spectrometer, different instruments could be supported on such a spacecraft.

Landing on Phobos or Deimos. A modest step from the above capability is to move to *in-situ* sensing. "Landing" on a small body is more like docking. Typical orbital velocities and translation rates are cm/sec. Therefore, a spacecraft that is maneuvered into a close orbit using a solar sail's low thrust could be maneuvered to a "stop and drop" landing using low-energy pathways, with the sail surface ensuring a stable and predictable orientation of the 6U central spacecraft body to the surface of the target body. Solar panels could continue to provide power when illuminated by sunlight, and an rf antenna could relay signals to a relay receiver in Mars orbit as has become common practice, or to a second Interplanetary CubeSat built for that purpose, which then points its optical telecom terminal to Earth during downlink opportunities.

Thus, 1-2U of a landed CubeSat could be devoted to *in-situ* instrumentation, such as a different imaging spectrometer, a microscopic imager, mass spectrometer, chemical-specific sensors, or anything else that can be built within 1-2 kg, 2000 cc, and 5-10 W.

Significant data compression could be handled as was expected to be demonstrated aboard the JPL/Univ of Michigan CubeSat On-board processing Validation

Experiment (COVE) [6] and the JPL/GSFC/CalPoly-SLO Intelligent Payload Experiment (IPEX) [7].

2025+ Satellite Sample Return: While low in TRL and concept maturity today, the idea of retrieving a sample from Phobos or Deimos with a pair of CubeSats is not as absurd as it might first appear. Developed during our NASA Innovative Advanced Concepts (NIAC) investigation, we considered if a solar sail-propelled Interplanetary CubeSat could descend to Phobos' surface. Based on *NEAR*'s encouter with *Eros*, this seemed plausible. Instead of devoting 2U to a science instrument, the landed spacecraft could use its "impact" velocity of a few cm/sec to stuff whatever might be loose on the surface into an open sleeve, the bottom of which could then close by a spring mechanism. A different spring mechanism could then launch the sample container, with a tracking beacon attached, beyond Phobos escape velocity of a few m/sec, thus placing the sample container in Mars orbit.

A second CubeSat, accompanying the lander until shortly before landing, would hover nearby, then pursues the ejected sample container, matching orbits. Final sample capture might be magnetic, as may have been inadevertantly demonstrated between Univ of Michigan's M-Cubed, and Montana State Univ's E1P CubeSats, shortly after their ejection from the same P-POD as secondary payloads aboard the NPP launch 2011 October [8]. After capturing the sample, this CubeSat would then use its sail to spiral out of Mars orbit, into heliocentric orbit and back to Earth's vicinity, using 3- and 4-body effects of the Interplanetary Superhighway to swing by the Earth-Moon LaGrange points and effect braking into Earth orbit. Depending on where human- and robotic-tended operations are then happening in cis-lunar space, the sample could be retrieved by a larger spacecraft for return to Earth.

2030+ Trucking to Mars and Back: Many of these low-thrust maneuvers to retrieve a sample from Phobos or Deimos are very similar to those required to carry equipment from high Earth orbit to Mars, and to return a reusable carrier vehicle back to high Earth orbit to pick up another load. While transit times are long (2-5 years) [9] for solar sail cargo vehicles, "propellant" mass is the sail mass, and does not increase exponentially with delta-V, unlike chemical and electric propulsion tugs. Thus a Mars-orbiting crew-capable observatory, its supplies, and propellant required for a later-arriving crew's faster return to Earth, could all be pre-emplaced in Mars orbit using "slow freighters" propelled only by sunlight. While slower than one would want to carry a crew to Mars orbit, the required mass launched off Earth could be lower by a factor of five from all-propulsive implementations. At a few thousand dollars per kilogram launched to LEO, the resulting savings could be dramatic, and alter both the date by which the first human expedition to Mars becomes feasible, and its architecture.

2018 – 2030s Progression of Capabilities: There are clearly major differences between a solar sail capable of propelling a CubeSat, and one built to haul 30 metric tonnes of cargo to Mars orbit. But in the time available, an investment equal to a very small fraction of the realizable savings could enable incremental steps along the way. Each incremental step could also enable a variety of new mission capabilities for space- and helio-physics, asteroid and planetary exploration.

In the 2018 timeframe, Interplanetary CubeSats would enable focused science investigation missions at one-tenth the cost of today's Discovery missions. Interplanetary CubeSats would not replace broader Discovery- and New Frontiers-class missions, but would make missions accessible to a broader community with greater frequency. Well-equipped universities might launch such missions as secondary payloads, responding to a few opportunities per year, instead of a few per decade. Some of these missions could address Mars-relevant science and technology development, while paving the way to higher capability at lower cost for detailed investigations of Phobos, Deimos, and from Mars orbit. The ability to maneuver without propellant to a variety of destinations will prove enabling for some exciting missions, and can pave the way to lowering costs to support the first human explorers.

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