Small Mars Missions based on Common Spacecraft Systems: 1. Mars Stationary Orbiter (MSO).

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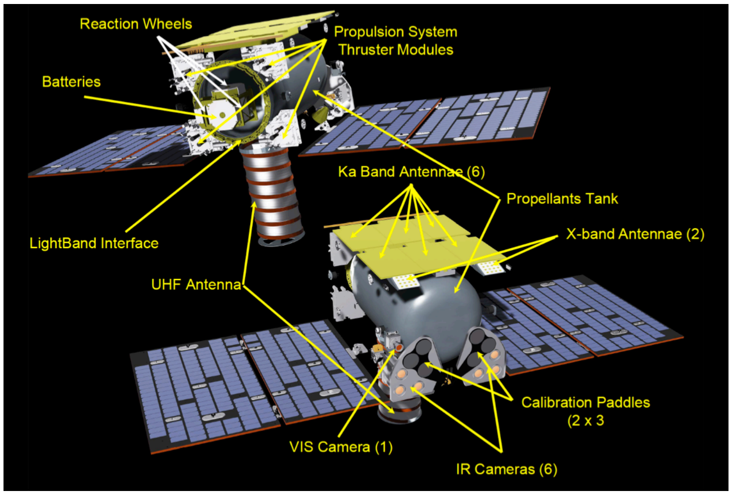
Introduction: We followed a component approach to spacecraft design, similar to 20th century audio entertainment systems, as opposed to pre-packaged systems. The focus is on finding the highest quality subsystems for deep space environments to mix and match for planetary application; as opposed to choosing from fully integrated systems designed for Earth orbit. Deep space missions are primarily distinguished from terrestrial missions by the need for high delta velocities (ΔV), deep space telecommunications compatibility, large data volumes, variable power requirements and availability, and broad operating temperature ranges.

Our objectives are to send vehicles to Mars with high value science instrumentation, diversify the launch opportunities beyond dedicated direct Mars trajectories (rideshares from GTO, or Cis-lunar launches), and address both scientific and technical goals. This abstract first describes the subsystems we have developed for a self-funded Mars spacecraft, with the intention of addressing the primary major weakness of our previous NASA proposals, *i.e.,* that we had not previously built a spacecraft. The abstract then describes a simple orbiter mission, science objectives, science payload, for a atmospheric science and lander relay infrastructure demonstration, all for an ESPA-standard class S/C with total wet mass of 230 kg.



MSO in fully deployed configuration, showing large external
components but not the bus box structure (so interior features are visible)
Vehicle is Standard ESPA dimensions ~ 100 cm x 67 cm x 60 cm

Spacecraft Subsystems:

Flight Computer and Telecommunications (Radio): We selected the Rincon AstroSDR, a combined flight computer and software defined radio with soaceflight heritage. The main ASDR device is executing Linux on a dual core ARM Cortex A9 processor, supported by a large FPGA 1GB ECC RAM, and 8GB radiation tolerant NAND flash memory. A 2TB flash memory allows storing all science data from our example mission onboard for long portions of the mission for downlink flexibility as data rates vary significantly. Onboard *Python* support enables flexible scripting and fast development.

GNU Radio running on the ASDR supports features of a functional DSN compatible transceiver, including, BPSK/QPSK modulation with residual and suppressed carrier downlink, turbo codes, DDOR, and PN and sequential ranging. A Prox-1 compatible UHF radio has been developed. The radio is capable of generating arbitrary waveforms and is easily software upgradeable in Mars orbit. The system can also generate a GPS-like navigation signal (using the onboard atomic clock) and upgraded encoding/modulation schemes for inter-asset links. Maximum radio bandwidth is ~50MHz operating nominally at a UHF intermediate frequency. UHF is upconverted to X- and Ka-Band and converted down from X-Band to UHF for DSN uplink. The downlink system performance is 85.6 dBm EIRP at Ka-Band. An additive manufacturing process produced Ka-Band slotted waveguide antennas to form a 2x3 array for the primary downlink. Two X-Band patch medium gain antennae support the primary uplink and contingency downlink. Expected peak rates are: downlink from Mars = 815kb/s (Ka-Band for a 2024 launched mission), X-band uplink to S/C 64kb/s. UHF Prox-1 Forward link to surface 373kb/s, UHF Prox-1 Return link from surface 2.4Mb/s to areostationary orbit.

Flight Software: We chose Advanced Solutions, Inc. (now part of RocketLab) for the flight and attitude control subsystem software. ASI's modular, reconfigurable MAX flight software allows mission specific solutions to be created using standard interfaces, configuration files and tools to minimize development time. MAX includes the On-board Dynamic Software Simulator (ODySSy) which allows "test like you fly" operations at all stages of integration. ASI also provides their Ground Data System (GDS) for a complete software solution that allows commanding, telemetry display and logging and ground operations to be included from the start of I&T.

Attitude Control: ASI also supports MSSS with attitude control design and analysis, applying the experience they gained on numerous missions including Osiris-Rex, Juno, MRO, and Mars Insight. Our team surveyed available ACS components and selected a set of robust, flight proven hardware from vendors who are leaders in their fields. The Sinclair Interplanetary (also now part of RocketLab) Star Tracker ST-16-RT2 delivers 5" (arcsec) cross-boresight accuracy and 55" about the boresight, featuring a 15 x 20° FOV in a radiation tolerant design. Sinclair will also supply the GEO rated 1.0 Nms reaction wheels. These units are rated for over 60 krad total dose and LET immunity to 50 MeV-cm2/mg and deliver up to 100 mNm of torque. The Sensonor STIM377H IMU provides precise stable gyro and accelerometer data with better than 0.3 °/hr bias instability and 0.15 $°/\mathrm{hr}^{1/2}$angular random walk. New Space Systems Sun Sensors provide sun reference for rapid safe mode recovery. The system provides 0.10° control with 0.05° knowledge for staring during data collection and transmission to earth and 0.5 deg control during slews at up to 1.4 °/sec.

Mission-specific Sub-systems:

Propulsion: MSSS has teamed with Stellar Exploration Inc, to provide propulsion and power subsystems as well as mission support. The propulsion system utilizes hydrazine and nitrogen tetroxide as the propellants for the eight 5 N axial thrusters which are used for the major maneuvers and sixteen 0.5N hydrazine monopropellant attitude control thrusters to provide roll control precise orbit adjustments and desaturation of the reaction wheels. 152 kg of propellant is stored in a single common-bulkhead titanium tank that is the largest component of the spacecraft and fits within a composite bus primary structure to which the rest of the components are attached. This large propellant mass fraction gives MSO a 3000 m/s ΔV capability, enabling it to reach Mars Synchronous Orbit from a GTO starting point. The pump-fed thrusters can be throttled. The low pressure tanks simplify launch integration especially for rideshare payloads, and is preferable from launch safety risk perspective.

Power: Six Stellar Exploration flight proven battery modules have extensive heritage from the Iceye radar satellites and others missions. This 400 Wh battery supports continuous science and communication activities even for the longest 79 minute Mars eclipse period. The power distribution and regulation electronics is similarly based on heritage designs. DHV is providing the MSO solar array producing at least 172 Watts at the maximum distance from the sun while the spacecraft is Earth-pointed.

Payload: MSO features seven cameras from MSSS to image the entire disk of Mars including ≥ 100 km above the limb. The visible light C50 camera will provide RGB color images of Mars with a Bayer pattern filter on its 1944x2592 pixel CMOS detector at 3.2 km Nadir scale and 7.7 km scale at the edge of the FOV. Six mid- to long-wave infrared IR3C cameras employ uncooled SCD 640x480 microbolometer arrays with custom optics and filters fron TORC to provide between 14 and 14 km Airy Disk scale at the edge of the FOV. The mid-wave IR channels are centered around 7.9 μm, 9.3 μm, and 11.8 μm to observe surface temperature, atmospheric dust opacity, and water ice opacity respectively. The long wave IR channels are designed to observe between 14.1 and 15.0 μm to recover atmospheric temperature over three altitude bands. Observations will be made of the entire visible Mars disk every 15 minutes for an entire Mars year in the baseline mission.

Mission Objectives*:* The primary objective is to get into Mars orbit. We selected a Mars stationary orbit at 0±2°N, 75±5° E, that views Curiosity and InSight at <60° emission angle and Perseverance and the MSR vehicles at emission angles ~20°. MSO can communicate at maximum data rates with two landers simultaneously, and at any time of day (on Earth or Mars), enabling 24/7 operations. MSO is a tech demo for legacy surface comm systems.

The primary science objectives are to continue 27 years of orbital monitoring of the surface and atmosphere of Mars at visible and thermal IR, at scales amenable to analysis by GCMs and other models. A constellation would be needed to provide global coverage.

To meet the objective of increasing the number of Mars launch opportunities, we recognized that GTOs provide a perigee velocity of 90% of escape velocity. GTO rideshare launches are much less expensive and greatly outnumber launches to direct to Mars. We designed our ESPA-class S/C and propulsion system (230 kg wet mass) to launch **before** the nominal Mars launch date during a given opportunity, providing flexibility for finding a ride. Early launches then raise their apogees to cis-lunar phasing orbits, and use these to reach the appropriate locationr on the date of the requisite TMI.

Costs: Prior to starting development of MSO, we spent ~$6M performing concept and design studies. Thereafter, our total Phase A-D cost, of which ~74% has already been spent, is ~$18M. Phase E costs, including pre-launch DSN testing, launch, DSN tracking and data collection during Cruise and in-orbit, and mission operations in orbit, are estimated to be ~$18M, for a total mission cost of ~$36M, including rideshare launch.