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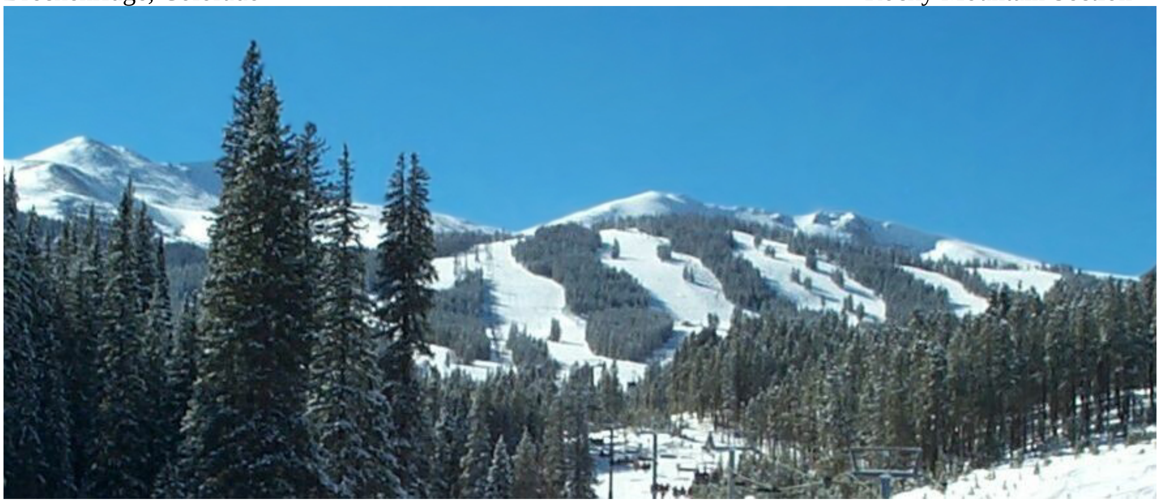

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THE MANY FACES OF THE MARS SAMPLE RETURN MISSION ARCHITECTURE[*]

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As far back as the 1960's, the National Aeronautics and Space Administration (NASA) has studied the idea of sending a robotic mission to Mars for the purpose of retrieving and bringing back to Earth samples of the Martian environment. The purpose of such a mission would be to take advantage of the capability to study Mars to the level of detail only possible in Earth laboratories. With the most recent discoveries by a small fleet of robotic spacecraft currently exploring the red planet in-situ, this idea of a Mars Sample Return (MSR) mission is once again at the forefront of NASA's Mars Exploration Program. With an earliest launch date set for late 2013, current MSR studies still face a long list of mission architecture options and technology challenges. This paper will attempt to summarize some of the Guidance and Control challenges, even if it succeeds in only scratching the surface.

INTRODUCTION

In the last few years, the current architecture for Mars Sample Return (MSR) has been developed based on successive studies performed by industry (Ball, Boeing, Lockheed Martin and NGST) and JPL, with participation from NASA Langley Research Center and NASA Marshall Space Flight Center. The basis has roots in design work that was done for a previous brief start-up of the MSR project, cancelled in 2001. An international, multi-agency advisory group – the Mars Exploration Systems Engineering Team (MPSET) – examined and advised direction on major MSR trades. In addition, two separate Science Steering Groups were convened at key crossroads points to advise on science priorities. At this point, MSR is tentatively planned for a 2013 launch, with return of the sample by 2016.

The missions of this decade are shown in Figure 1, most of which have influence on the MSR implementation. Mars Odyssey, the European Mars Express orbiter and Mars Global Surveyor (MGS) (launched in 1996) have been sending back data that are continuously illuminating new information about Mars, and based on better understandings, effect the direction of further exploration on Mars. While both the Japanese Nozomi Orbiter and European Beagle 2 Lander had mission failures, they both were significant steps in establishing an international program. The Mars Exploration Rovers (MER) currently in operation are teaching us a great deal about landing and operating on the surface of Mars, as well as rover design. More over, MER discoveries have already impacted the nature and architecture of MSR, and was

[*] Prepared for technical papers that may later be published in the proceedings of the American Astronautical Society

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the motivation adding surface mobility to MSR after a year of being de-scoped to a static lander only. The Mars Reconnaissance Orbiter (MRO) will be much more capable than its predecessors and aside from its high science value, promises to provide high resolution imaging of the surface that will aid future missions in navigating the surface and providing a basis of surface-feature-based pinpoint (<100m) landing. The NASA Phoenix Scout mission will look for subsurface water ice thought to contain organic compounds that are necessary for life, and will provide experience in subsurface sampling that will be of value to MSR. The Mars Telesat Orbiter (MTO) will not only provide a telecommunications relay function for MSR, but will be a back up for tracking an orbiting MSR sample container. It will also host an important rendezvous technology demonstration for MSR to be discussed later. New MSL landing techniques will most likely provide the basis of landing on Mars needed by the large MSR payload. MSL will also contribute substantially to advanced rover design, sample collection and surface operations for MSR.

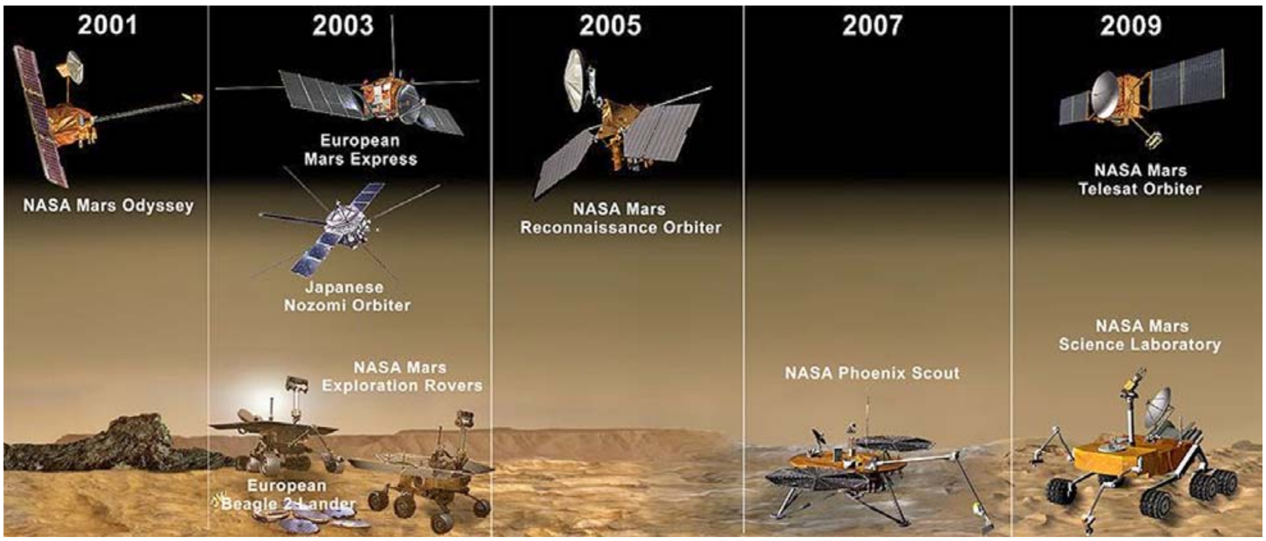

Figure 1 This decade of Mars Missions will contribute to MSR

MSR ARCHITECTURE

The reference mission scenario currently being considered is shown in Figure 2. It is annotated such that it should be self-explanatory; thus the reader is encouraged to read through the notations in the figure. The high-level requirements on the mission consist of bringing back 1/2 kg of sample consisting of rock, regolith and atmosphere. Access to the Martian surface is moderate in altitude and latitude. Modest mobility is required to get access to stratified layering like that identified by the MER mission. This mobility capability was recently added to baseline as a result of experience from MER. The primary sampling will be performed by a rock corer on a rover, while an arm/scoop/sieve is used on the lander as a backup (acquiring a contingency sample). No in-situ science is currently in the baseline.

Figure 2 Current MSR notional mission architecture

There is one area that is particularly challenging for MSR that cuts across mission segments – planetary protection, for both Mars and Earth.

Planetary protection of both Mars and Earth is central to the MSR architecture and has contributed to making the MSR mission as complex as it is currently envisioned. The planetary protection requirements — forward, back and round-trip as follows:

- The need to control the amount of sample contamination by round-trip Earth organisms to avoid false positives in life detection tests (for the purposes of this study we assumed a goal of sterilization of the entire Lander to Viking levels, or proof of <10e-2 chance of a single Earth organism in the sample).

- Sample containment assurance: The requirement that the integrated probability of back contamination be kept below a specified level (with a lack of a specific requirement, for the purposes of this study we assumed a goal of probability of release of Mars material to the Earth's biosphere to being less than 1 in a million).

GUIDANCE AND CONTROL CHALLENGES

MSR has many challenges in Guidance and Control (G&C). The author will walk you through the mission architecture and discuss the challenges and, our current conceptual approach.

Entry/Descent/Landing

One of the premises of keeping the cost and risk down for MSR is to use the landing system developed by the Mars Science Laboratory (MSL). MSL plans to demonstrate precision landing (to 10 km), robust/safe landing and delivery of higher usable landed mass than previous missions. The MSL landing system evolved from a traditional legged platform to support the rover laboratory to one where the landing system suspends the rover from above and lowers the rover to the surface via a 10-meter tether system. This landing system is coined the "skycrane". Figure 3 depicts this current MSL landing concept. The tether is currently envisioned to be augmented with a triple-bridle for stability.

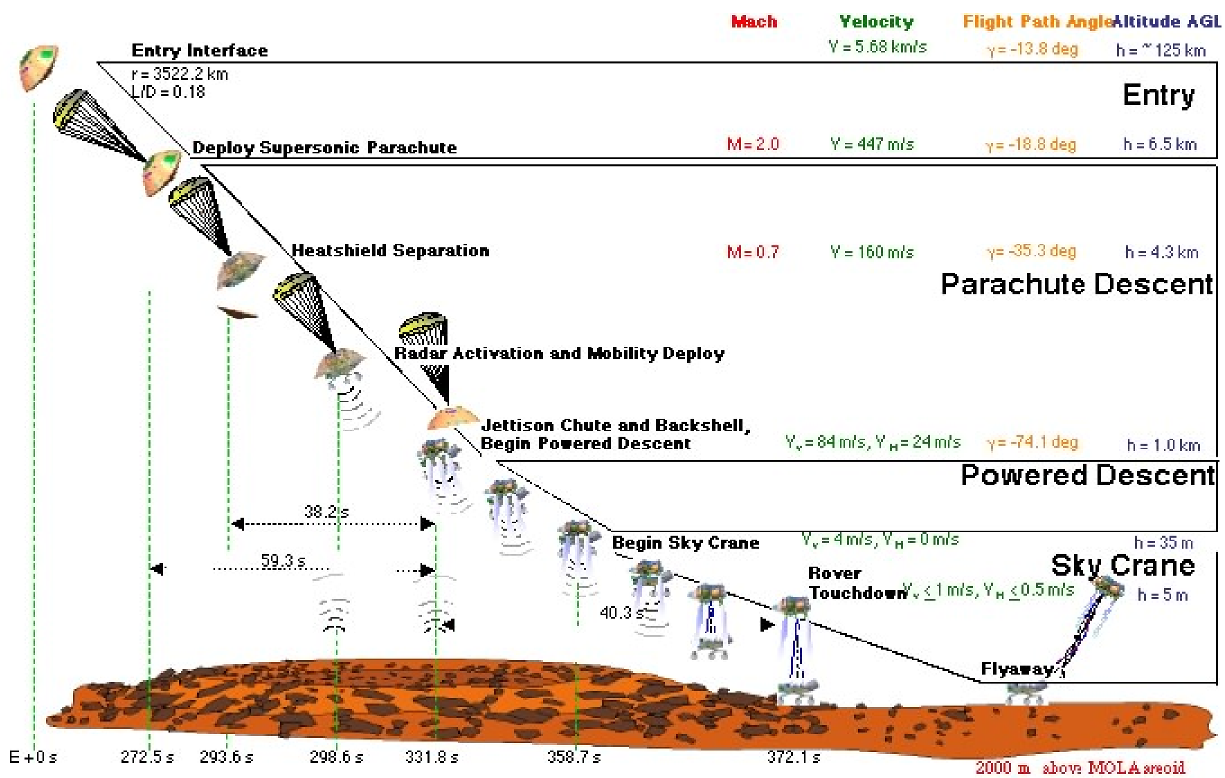

Figure 3 MSL EDL concept

Figure 4 depicts an MSR platform being lowered by the skycrane. The main benefit to landed pallets, like MSR's, is the very low landing velocity, which reduces the loads a lander would traditionally endure ($\leq$ 1 m/s).

The MSR Skycrane stage concept is shown in Figure 5. The system is monopropellant, and utilizes engines inherited from Viking flown in 1970's that are being upgraded and re-qualified. Analysis is underway. Dynamic control of this two-body landing system is a challenge. A test-stand facility is being built to dynamically test prototype units for descent and touchdown, including the potential of hot firing of the engines.

Figure 4 MSR lander lowered by skycrane

The Skycrane and Lander are packaged in a heatshield (bottom) and backshell as shown in Figure 6. The shapes of aeroshell and backshell are similar those used on Viking, preserving that heritage. The MSR aeroshell is currently planned to be 4.5 m in diameter to take advantage of the full dynamic envelope of heavy-lift launch vehicles (5-meter fairings). New to this entry system will be the use of lift implemented through offset c.g. and RCS control to use the lift for both precision guidance and additional flight time (slowing) in the upper atmosphere. The algorithms are adopted from Apollo (called Apollo Guidance Algorithm) and developed by Johnson Space Center (JSC). MSL, and perhaps Phoenix, will use this guidance method prior to MSR.

Also packaged in the aeroshell are supersonic and subsonic parachutes used for descent. The supersonic chute has been qualified by previous missions, most recently MER. The subsonic chute is a new design that will require qualification. The MSL technology program has taken that chute development though initial flight-testing, but since MSL has recently de-scoped to one chute, the MSR technology program will finish-up qualification.

The lander shown in Figure 7 is a new design, but assumes some MSL heritage. While the design will be challenged by landing on an irregular Mars surface, the Skycrane implementation is able to lower the lander to the surface with very low impact forces. The lander carries a rover, used to collect and cache samples remotely; sample acquisition equipment for collecting contingency samples at the lander; a mars ascent vehicle (MAV) to launch the collected sample into orbit around Mars; and the equipment to perform the transfer of sample and sample containers.

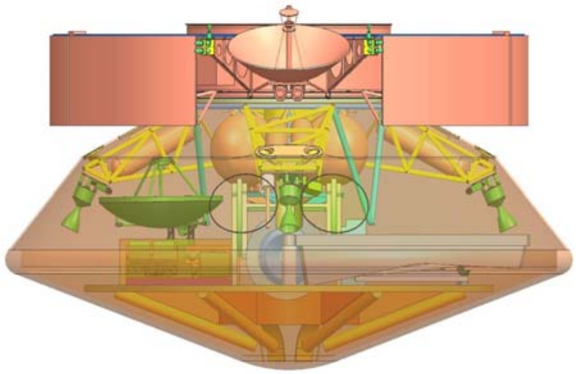

Figure 6 EDL system with Cruise Stage

Figure 7 MSR Lander – deployed, MAV ready to launch

Pinpoint Landing

While the MSL landing system is being developed to land with an error of 10km, new technology is being considered that would allow MSR to land within 100 meters of a geological feature. This would allow the project to reduce the requirements on a rover and to access specific features that have been previously identified by MRO, MSL, Phoenix or MER. This would entail an optical sensor, matching maps from images taken by MRO, and additional control authority and fuel to compensate for entry and descent errors and the effects of wind. A technology program is being funded to develop this capability.

Sample Acquisition for the Lander

Redundant arms (about a meter long), each with a scoop and sieve, are used to acquire samples from the immediate area. Trenching to a few tens of centimeters will be required to obtain sample free from lander contamination and natural surface oxidation. While previous contemporary landers use a stereo camera on a mast to view the trenching and collection area, we believe that simple arm-mounted cameras can be used effectively; this will be demonstrated in the MSR Technology Program. Acquiring the sample would utilize experience and inheritance of hardware from both Phoenix and MSL. Phoenix will utilize a 1-meter arm with a scoop that should be directly applicable to MSR (see figures 8 and 9). Autonomous testing using this arm has demonstrated its trenching capability in Mars-like terrain. This process of acquiring a sample from the lander may be adequate to get below the surface contaminated by landing. Software for visualization needed for planning and monitoring the trenching operation interactively with mission planners will have been well established and proven by Phoenix and MSL and to some extent is currently being used on MER.

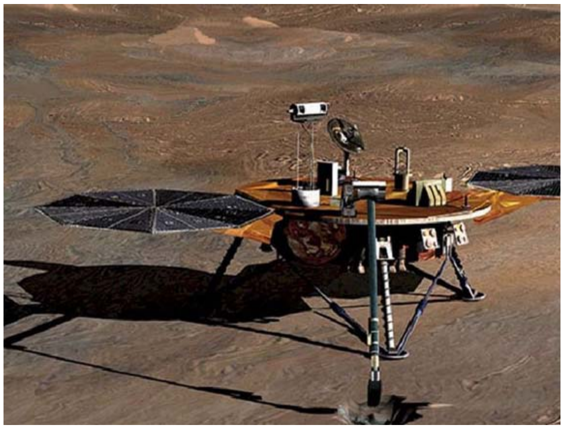

Figure 8 Phoenix Lander

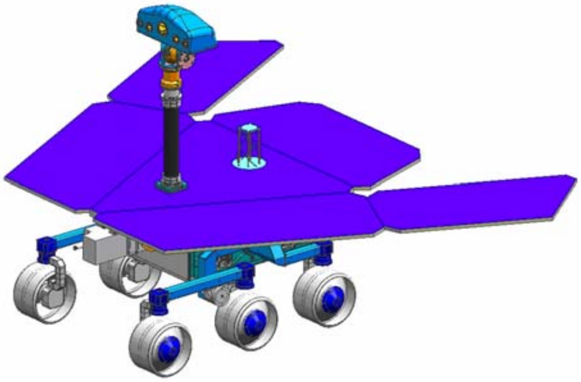

Figure 9 MSR Fetch Rover

Rover Sample Acquisition

The experiences learned from MER have led to the current MSR concept adding a rover to obtain samples, particularly cores, from stratified material some minimal distance from the lander. The rover currently planned has the capability to traverse about a km and communicate both through the lander and directly to an orbiting asset. The rover is similar but smaller than MER, and is based on the same developmental rover, FIDO, that MER based their design on. The Rover carries a rock corer, that is also capable of picking-up regolith, and the mechanisms needed to fill a canister with cores. The operational capabilities needed will have been demonstrated on MER and MSL.

Mars Ascent Vehicle

Once the sample is packaged in a 16 cm Orbiting Sample (OS) container, it is loaded into the MAV. The MAV is baselined as a solid-propellant, two-stage, three-axis stabilized vehicle, weighing about 285 kg (including the 5 kg OS). Figure 10 shows the MAV configuration, with the smaller second stage with thrusters for 3-axis control and the OS mounted on a spin-eject mechanism inside the nosecone. It launches the OS into a circular orbit of 500 km+/- 100 km and within 0.2 degrees of inclination. The MAV would transmit enough telemetry during ascent to allow reconstruction of events in case of failure. In addition, it carries a UHF beacon for location by orbiting assets to aid in location of the OS. The beacon, both in the OS and the MAV, will be new developments, requiring technology funding.

The MAV, however, is a new development for the Mars environment. We have chosen to include two Earth-based developmental test flights as part of the project costs. MAV design would be performed early in the project and qualified before CDR. Trying to match dynamic pressure and flight timeline to that of Mars is difficult and requires that the test launches be performed starting from high altitude balloon flights (62,000 ft). See figures 11 and 12.

Figure 10 Mars Ascent Vehicle typical solution (from LMA study)

Figure 11 Dynamic pressure comparison

Figure 12 MAV flight profiles

Orbiter/Earth Return Vehicle

After transit to Mars, the Orbiter performs propulsive Mars Orbit Insertion (MOI) maneuver, into an elliptical 1-3 day orbit with a 240 km periapsis (apoapsis 35,000 km to 75000 km), setup for aerobraking. For this maneuver and the departure from Mars, the orbiter would require over 3000 kg of mono-propellant. Aerobraking would be used (to save fuel) over the next 6 months to circularize the orbit to 500 km for rendezvous with the OS. Future studies will examine the possibility of eliminating the need for aerobraking, which is viewed as an additional risk for an already complex mission. Depending on the mission scenario, an all-chemical propulsive MOI with staging might be available, with no new technology. The other alternative is aero-capture, which would most likely require a technology demonstration prior to relying on it for MSR. NASA's In-space Propulsion program is helping MSR explore aero-capture options.

The Orbiter/ERV (see Figure 13) carries the Earth Entry Vehicle (EEV), the equipment for detection/rendezvous/capture of the OS and transfer of the OS to the EEV, the spin/release mechanism for the EEV, and the propulsion for earth return. Once in circular orbit, the Orbiter/ERV would maneuver to, rendezvous with, and capture, the OS.

A propulsive maneuver then would initiate a Type-I cruise to Earth. Initially targeted to pass by Earth, the Orbiter would be retargeted in the last few days to release the EEV toward earth entry about four hours out, then would perform a divert maneuver into a non-earth-returning trajectory. Because of assured containment requirements, the trajectory will need to be reliable but not more than previously demonstrated (Genesis). One of the areas that will need to be addressed is how to assure reliable targeting, such as multiple solutions and/or teams to add additional confidence.

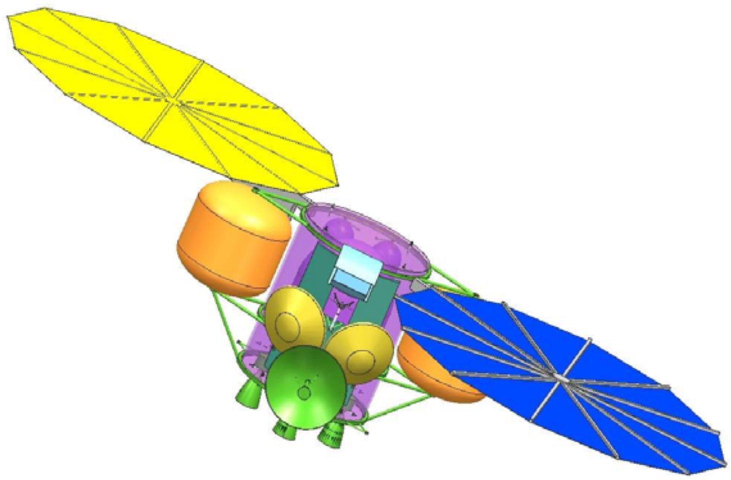

Figure 13 ERV/Orbiter concept

OS Detection, Rendezvous and Capture

Detection of the OS once in orbit is baselined to be via an OpNav camera being developed for optical navigation for MTO and demonstrated on MRO. Analysis has shown that locating a lost OS from a medium altitude orbit can be achieved within a few days. If MSR in fact uses aerobraking, the relative orbital configurations may make that process more difficult. The OS will also have a UHF beacon as an alternate source that could last a couple of years. And as previously stated, the MAV will have a UHF beacon which will provide an additional (as well as the MAV’s optical cross-section) for early convergence.

The UHF beacon signal will be recorded by a broadband mode on the Electra UHF communications payload (first flown on MRO) on MTO and the MSR orbiter. The raw one-way Doppler data and occultations will be post-processed on the ground for solutions.

A wide angle visible camera (already flown on MER for other purposes) is planned for close proximity operations

Semi-autonomous rendezvous algorithms have been extensively studied by both JPL and Draper Laboratory, and solutions are available. A typical scenario is shown in Figure 14. A rendezvous and autonomous navigation technology demonstration is planned to be flown on MTO in 2009. It would develop and use all the equipment necessary for MSR, except for the capture portion. It will use a dummy OS and perform several rendezvous.

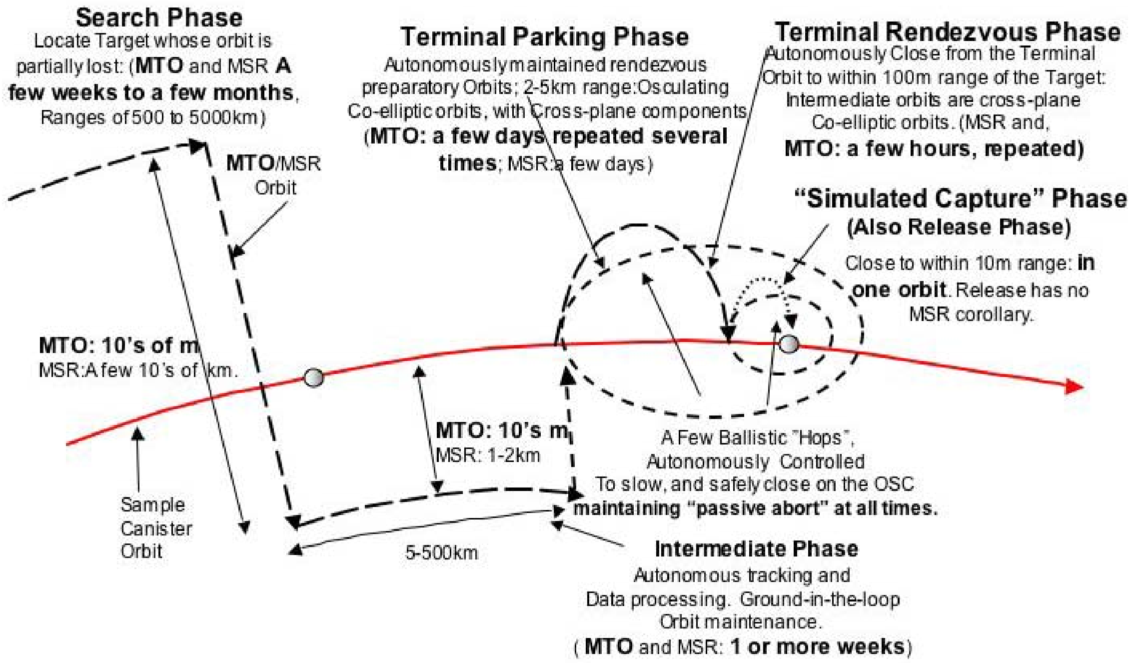

Figure 14 Typical rendezvous scenario

Designing the capture of the OS has been through many concepts. JPL has converged on a capture basket concept with which the technology program can move forward (Figure 15). Payload Systems (Cambridge, MA) has a SBIR contract to develop and build a capture mechanism test unit for the International Space Station as part of an augmentation to the SPHERES formation flying testbed. A free-flying OS, which is an adaptation of one of the SPHERES test articles, would be flown in controlled trajectories into a capture mechanism to study contact and capture dynamics. We are currently evaluating whether testing these articles in aircraft hyperbolic zero gravity flight might be adequate instead.

Figure 15 Capture basket concept

In addition, it is planned to perform approach testing at MSFC using their flat-floor and 6-DOF simulation facilities.

The Mars Technology Program is funding MTO to fly an OS detection and tracking demonstration that would release an engineering version of the OS and track the OS in orbit using their already existing OpNav camera. MTO will also demonstrate on-board auto-navigation capability by maneuvering several times to the OS within 10 m (or some safe distance). In addition, MTO would serve as a second asset to detect and track the OS during the MSR mission. MTO's Electra communications payload would have the capability to also track the UHF beacons on the OS and MAV.

Earth Entry

Reliable earth entry is key to sample containment, and LaRC has completed significant development of an Earth Entry Vehicle (EEV) to date. The EEV is a self-righting, 0.9 m diameter, 60-degree sheer-cone blunt-body atmospheric entry vehicle. The cross-section is shown in Figure 16. The central cylinder is the sample container, inside a spherical OS. Aside from another sealed container (essentially a Kevlar bag) around the OS, called Containment Vessel, the remainder of the spherical part of the EEV is crushable material and carbon-carbon composite shells. The EEV is completely passive, except for self-contained beacons used as a backup tracking aid. The design of the EEV has been guided by an initial Performance Reliability Assessment (PRA) for assuring sample containment.

Figure 16 Cross-section of EEV concept

The aerodynamic characteristics of the design have been analyzed and tested to show that aero-heating is reasonable, even to the extent that soak-back would not cause the sample container to rise above 50 C. While the study considered newer ablative materials for the heat-shield, carbon-phenolic was chosen for test and flight heritage, and knowledge of failure modes. Trajectory entry angles have been selected that limit the heat flux to within well-understood testable regime for verification. In addition high fidelity simulations have shown that if the EEV was released incorrectly (even backwards) or tumbled from a large micro-meteoroid hit, that it would right itself prior to the entry heat-pulse. Micrometeoroid impact protection of the heatshield may be necessary. Design of protective shielding is the subject of current analysis; several concepts look promising. Aerodynamic trajectory analysis has been performed to assure that landing would occur in a safe area of UTTR (the reference landing site used for these studies).

The landing of the EEV is envisioned to be a direct impact with the surface at a site like UTTR. Extensive analysis, verified by testing at the LaRC impact dynamics facility, has verified impact resistance effectiveness. In addition, a full-scale drop test (from a helicopter) of an engineering model EEV reached terminal velocity at UTTR and again validated the design. Figure 17 shows the EEV after impact being held by the LaRC team, and Figure 18 shows the impact area on the ground.

Figure 17 EEV after impact

Figure 18 Impact area

CONCLUSION

The MSR G&C challenges stem all the way from targeting earth to placing a corer on a rock. MSR has a suite of vehicles, all having a G&C focus. Some are standard fair, like the orbiter, some will be demonstrated by MSL (EDL and surface operations) and MTO (detection and rendezvous), while others are subjects of a MSR Focused Technology Program (initiated this year), including the MAV and EEV.

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