Virtual prototyping of human Mars missions with the Orbiter space flight simulator

by Bruce Irving, Andrew McSorley, Mark Paton, and Grant Bonin

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Bruce Irving[1], Andrew McSorley[2], Mark Paton[3], and Grant Bonin[4]

[Abstract] Although there are various tools and approaches for evaluating proposed human missions to Mars, virtual prototyping with a suitable space flight simulator offers a number of benefits and advantages. These include the ability to experiment with interrelated system-level configurations and to explore alternate propulsion options. An ability to record the simulated missions for later presentation allows analysis and feedback from other interested parties. The Orbiter space flight simulator is a free Windows-based software tool that offers these capabilities and other advantages. It is a closed-source but easily extensible program with accurate modeling of orbital mechanics and spacecraft dynamics, and reasonably accurate modeling of atmospheric flight phases. It allows relatively easy construction of proposed spacecraft and launch vehicles based on 3D models, with vehicle performance defined through configuration files or custom-programmed code modules. The general availability of Orbiter and the ease of defining such models makes such virtual prototyping feasible even at the preliminary analysis stage of mission planning. As an example of the possibilities of this approach, the authors have used Orbiter to create and investigate a virtual prototype of the design reference mission known as *Mars for Less*. This DRM is a variation of the well-known *Mars Direct* approach, but with modular components designed for easy LEO assembly, and sized for launch on existing medium lift launch vehicles. The interactive virtual prototype illustrates the scope and details of this proposed mission in visually compelling and technically accurate form. It also allows investigation of possible problems and alternative configurations through virtual flight testing and recording of flight data.

I. Introduction

THE term “virtual prototyping” usually refers to computer based simulation of a device or system in a way that goes beyond simple graphical depictions or even basic CAD (computer aided design) modeling. Virtual prototyping typically implies an ability to simulate the dynamics and even the human operation of the modeled system. For space systems, professional CAD and dynamic modeling tools may provide such capability, but usually only when the system has been CAD modeled in considerable detail. Such detailed models may not be available at the preliminary design stage.

The Orbiter (Schweiger 2004) spaceflight simulator is a closed-source but easily extensible program with accurate modeling of orbital mechanics and spacecraft dynamics at the major system level, reasonably accurate modeling of atmospheric flight phases, and excellent 3D graphics. It allows software-based construction of proposed spacecraft and launch vehicles based on relatively simple 3D models, with vehicle performance defined through configuration files or custom-programmed code modules. Orbiter is free.

Human Mars mission planning is complex, and at the preliminary analysis stage, “design reference missions” (DRMs) may be planned with analytic equations, tabular and graphical data from handbooks, and specialized orbital mechanics modeling tools (custom/in-house or commercial). Later stages may introduce CAD modeling, custom simulations, 3D graphics and animation, and other tools and methods. Orbiter can provide some of the benefits of these more advanced tools and methods quickly and at low cost, even in the preliminary analysis phase of mission planning.

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As an example of this possibility, the authors used Orbiter 2006 to implement a virtual prototype of the *Mars for Less (MFL)* mission (Bonin 2006), a module-based variation of the well known *Mars Direct* mission architecture (Zubrin 1991). We will show that Orbiter is a powerful tool for exploring mission concepts, vehicle design/performance, and parameter studies of critical mission phases, as well as an excellent environment for demonstrating and sharing ideas and creating 3D animations of all phases of a mission.

Figure 1. This Orbiter screen shot shows the Mars-ready "stack" of crew and propulsion modules that have been assembled in low Earth orbit, along with an approaching crew transfer vehicle (NASA CEV 2005 concept). In addition to its spaceflight modeling abilities, the quality of Orbiter's 3D graphics makes it an excellent visualization tool.

II. Orbiter space flight simulator

Orbiter is a free space flight simulator program that has been in development since 2000 (www.orbitersim.com, Orbiter 2006 is the current version). Developed as an educational tool for Windows PCs by Dr. Martin Schweiger of University College London (UK), it is extremely useful in teaching, demonstrating, and experimenting with orbital mechanics, atmospheric flight, space flight principles, and aspects of planetary science and astronomy. Although it is a free closed-source program, Orbiter is sophisticated and comprehensive, combining accurate physics of space and atmospheric flight, high quality 3D graphics, and a first-person pilot's perspective similar to programs such as Microsoft Flight Simulator, with both internal (cockpit) views and a variety of external views.

Orbiter provides several predefined spacecraft (e.g., Space Shuttle, ISS, futuristic "Delta Glider" space plane), along with over a hundred sample scenarios. Scenarios cover launch from Earth; atmospheric flight in aircraft-like spacecraft; attaining and modifying orbits; rendezvous/docking; transfer to the Moon; flights to Mars and other planets; entry, descent, and landing (Earth, Moon, Mars); and many others. A built-in scenario editor makes it easy to create or modify scenarios with desired orbital elements or spacecraft state vectors. A flight recorder feature allows missions to be recorded and played back, with the option to add synchronized text annotation shown on replay for training or technical explanations.

For general space mission modeling, Orbiter users can make use of its powerful and flexible open architecture to model historical, proposed future, or even fictional spacecraft. Extensive and accurate models of all major components of the Apollo/Saturn missions have been developed, as well as many historic and current launch vehicles, crewed spacecraft, and various satellites and probes. Orbiter also allows creation of simple or complex surface bases and terrain, and users can even modify planetary surface textures and atmospheric models. Open architecture extends to propulsion systems (generally modeled at the system level) and additional flight instruments, autopilots, flight data recorders, etc. Add-on builders have even modeled space tether systems, ion engines, mass drivers, space elevators, and other non-rocket-like systems. Add-ons that are made public are always freely distributed as a condition of the Orbiter software license.

For Mars mission simulations, some of the existing built-in and add-on features can be used, including flight instruments, Earth launch sites, interplanetary flight planning modules, launch vehicles (e.g., Ariane-5), and 3D terrain for simulated Mars landing sites.

III. Modeling Space Systems in Orbiter

Although the core orbital mechanics, atmospheric flight, Solar System bodies, atmospheric models, flight instruments, etc. can be used without changes, virtual prototyping of a proposed mission generally requires add-on modeling. There are two main aspects to creating add-on space vehicles for Orbiter, 3D modeling and spacecraft property modeling.

A. 3D Modeling

External 3D modeling tools typically used for animation and game development (as opposed to engineering CAD tools) are used to construct 3D "meshes" which can be textured ("painted") and even animated for added realism. Multiple meshes can be combined in Orbiter to simulate multi-stage or other modular or segmented vehicles (e.g. docked spacecraft). Internal structures can be modeled but often are not, other than for optional control panels and "virtual cockpits" (a mouse-active generic "glass cockpit" view is defined by default).

B. Spacecraft Property Modeling

System-level spacecraft properties include dry mass, fuel mass, principal moments of inertia, cross-sectional areas, aerodynamic drag properties, control surfaces, reaction control systems, etc. Of course propulsion systems are also defined, but generally not as detailed physical models. Properties such as thrust; Isp; engine size, position, and thrust direction; and gimbal information may be defined, but only the most basic properties are required.

There are three methods to define spacecraft properties. "Configuration files" are a generic method that allow basic properties to be defined in a text file (satellites and even simple lunar landers can be defined this way). For more detailed control, add-on developers can program (e.g., C++) and link to Orbiter "custom DLL's" which define spacecraft and propulsion properties to any desired level of detail. The third method is a hybrid approach. A set of DLL's (spacecraft.dll, multistage.dll, etc.) defined and released by an Orbiter add-on developer (Vinka) can be used with more detailed configuration files to allow access to more of Orbiter's internal parameters without custom programming. This methods supports staging, launch guidance, more advanced aerodynamics, and even animation.

IV. Mars for Less – Mission Profile and Components

Mars for Less is the first design reference mission of the MarsDrive Consortium and was designed by Grant Bonin. The background and details of this proposed mission have been described elsewhere (Bonin 2006), but it is essentially a variation of the well-known *Mars Direct* architecture, broken into approximately 25 t modules sized for existing medium lift launch vehicles (MLLV) and designed for simple, semi-autonomous assembly in low Earth orbit. Approximately six MLLV launches would be required for the Earth return vehicle (ERV) and six more for the later Mars transfer and surface vehicle (MTSV). The basic steps of *Mars for Less* are as follows:

- The two ~25 t modules of the ERV are launched to LEO and assembled with astronaut/EVA help (astronauts reach orbit in CEV or similar).
- Four ~25 t TMI propulsion modules are launched to rendezvous with the ERV in LEO for assembly (possibly by remote controlled docking).
- The non-crewed ERV "stack" is sent to Mars on a low-energy trajectory, the ERV making an automated landing and establishing robotic/automated ISRU propellant production (CH_4/LOX).
- The MTSV "stack" is assembled in LEO about two years later, with six MLLV launches and any necessary astronaut assistance for assembly and check-out (these would be separate launches of CEV or similar). The ERV will be fully fueled with Mars-produced propellant before MTSV departure.
- The four-person Mars crew launches in CEV or similar to rendezvous with the MTSV and depart on a high-energy trajectory for ~6 month flight to Mars.
- The empty final TMI booster stage is used with a tether to rotate the MTSV to produce 0.4g of artificial gravity for most of the cruise to Mars.
- Aerocapture is used to place the MTSV in an elliptical parking orbit of Mars, and the aeroshield is again used (along with parachutes and landing stage rocket engines) to support entry, descent, and landing at the established ERV site.
- After about 2 years of exploration, the fully-fueled two-stage ERV launches to return the crew to Earth on a high-energy trajectory.
- Aerocapture is used to enter Earth orbit, and a crew transfer vehicle is used to return the crew to Earth.

V. Propulsion systems and staged TMI modeling

There are two main aspects to propulsion modeling for this Orbiter simulation of *Mars for Less*, the medium lift launch vehicle (MLLV) and the modular stages which would be assembled in orbit into a "stack" of four stages to send each spacecraft (ERV and MTSV) to Mars. Additional issues include crew transfer, and trajectory planning and guidance for the four-boost TMI.

A. Medium Lift Launch Vehicle (MLLV)

Since the mission concept is based on 25 t modules sized to fit typical MLLV fairings, any MLLV meeting these requirements could be used in principle, provided it could launch its 25 t payload into a 28.5° inclination assembly orbit of 200 km or higher. Multiple nations and organizations might thus contribute launch services to the mission. Possible launchers include Ariane-5, Delta IV Heavy, upgraded Atlas V, SpaceX Falcon-9, some possible Russian and Chinese launchers, and perhaps others. We didn't feel we needed to show multiple launchers in the simulation, so we chose to use only high quality existing 3D model of the Ariane-5 and to upgrade its assigned performance specs in some respects to represent announced or plausible near future improvements, mainly in the performance of the core engine (upgraded to Vulcain-3). We also made use of an available add-on that models the ESA Kourou launch site in some detail, although this is not an essential detail.

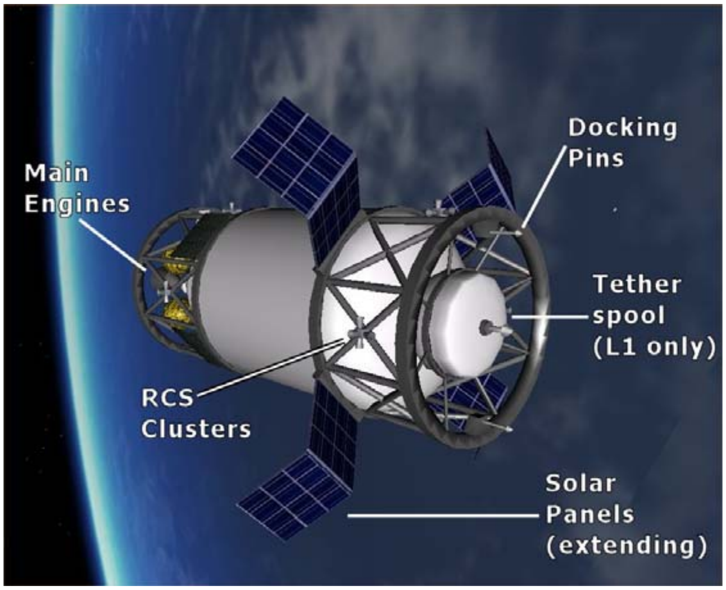


Figure 2. The "Proteus" is a conceptual design for a 25 tonne LH2/LOX modular stage designed for launch as a MLLV payload and for simplified assembly in LEO. Each Proteus stage has its own solar panels, RCS system, guidance, communications, docking aids, etc. to allow semi-autonomous operation prior to and during assembly. With simple systems and interconnects, this propulsion module could be designed to make an automated rendezvous and approach, attaching itself to the previous stack element by docking.

B. Modular TMI Stage ("Proteus")

The TMI propulsion module defined in MFL was designed from scratch for this simulation, based on the requirements of a 25 t payload consisting of 3 t of structure and 22 t of LH_2/LOX propellants (with sufficient insulation and possibly refrigeration to prevent excessive cryogenic boil-off during the several month orbital assembly period). Dubbed the "Proteus"(Figure 2), this modular stage was designed with two main Vinci engines totaling 360 kN of thrust, as well as a reaction control system (RCS), deployable solar panels, radiators, guidance/communication systems, remote control docking features, and in the case of the final stage, a spool of high-strength tether cable used to establish artificial gravity by spinning this stage with the MTSV.

With simple and standardized launch, docking, and interconnection facilities, the idea is that the Proteus could be launched to the assembly orbit from any of several sites and guided by an advanced Ariane-5 "Aestus" upper stage remotely controlling the Proteus RCS to perform automated rendezvous and docking with the in-work "stack" of previous modules, without necessarily requiring an assembly crew to be on hand. This is what we simulated in Orbiter.

In the process of developing the launch/rendezvous part of the simulation, we discovered that at the point of docking, the Ariane-5 upper stage had about 60% of its full 10 t load of storable propellants remaining. If this figure proves to be in realistic (which depends in part on the altitude of the assembly orbit), then it would greatly help in maintaining station and re-boosting the orbit of the in-work "stack" while awaiting delivery of the next "Proteus" module.

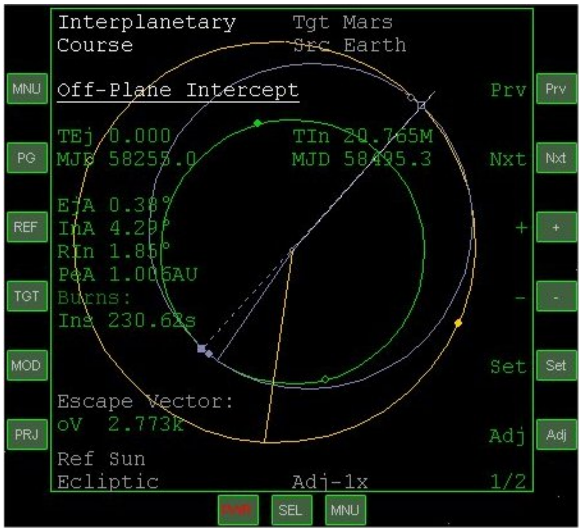
C. Crew transfer

A secondary but still important propulsion issue is crew transfer, both for on-orbit assembly and checkout (for parts of assembly that need this) and for delivery of the Mars-bound crew to the assembled spacecraft. There may be multiple options for this when the time comes (other nations and/or commercial crew transfer vehicles), but for convenience, we assumed and made use of the proposed NASA CEV and CLV, using an existing add-on for the CEV (late 2005 NASA concept) and an in-work CLV add-on modified and provided for our purposes by its author.

D. Mars trajectory planning and guidance

The final piece of the propulsion puzzle is trajectory planning and guidance. The MFL plan specifies the general class of Mars transfer orbit to be used for the ERV and MTSV, and also describes the general approach to TMI (trans-Mars injection) when there are four stages to be used in sequence to apply the required delta-V (i.e., basically to perform each of the four successive TMI burns at the periapsis of each intermediate orbit, with the final Proteus stage providing escape velocity). But because the Orbiter simulation is intended to actually get the simulated spacecraft to Mars with sufficient precision to land both spacecraft at the desired base, we needed a special tool for this purpose.

Fortunately a member of the Orbiter add-on community again came through, with a planning and guidance module called Interplanetary MFD (IMFD) (Nikkanen 2006). IMFD is a sophisticated interplanetary flight planning tool which runs as an installed instrument (MFD) within Orbiter. It has features for automatically generating feasible transfer orbits based on the specified departure and arrival dates, as well as additional modules or sub-programs for launch, "orbit eject" from the source planet to the planned trajectory, burn-vector guidance (manual and automatic), base approach planning, orbital entry, and more. It even has a feature for performing gravitational assists (swing-by maneuvers), though we did not use this feature. IMFD makes it easy to experiment with trade-offs on delta-V vs. transfer times, approach velocity, and other factors.



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Interplanetary      Tgt Mars
Course              Src Earth

Off-Plane Intercept

TEj 0.000           TIn 20.765M
MJD 58255.0         MJD 58495.3

EjA 0.38°
InA 4.29°
RIn 1.85°
PeA 1.006AU
Burns:
Ins 230.62s

Escape Vector:
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Figure 3. The Interplanetary MFD (IMFD) add-on by Jarmo Nikkanen is an advanced flight planning and guidance tool that runs within Orbiter's standard MFD (multi-function display) instrument windows. It displays trajectory data in both graphical and numerical form, and uses the mouse-operated buttons around the perimeter to control its operation. This screen is set up for a 240 day near-Hohmann Mars transfer orbit.

VI. Spacecraft modeling

The basic architecture of *Mars for Less* is derived from *Mars Direct*, in particular the advance placement of the non-crewed ERV on Mars, where it produces its own propellant for the return to Earth prior to the astronauts' departure from Earth. The key differentiators of the MFL approach are related to the assumption that a suitable HLLV (120 t payload class) may not be available. The use of smaller MLLV's requires breaking the mass of each Mars-bound vehicle into six modules (~25 t each), and this in turn leads to the need for Earth orbital assembly. Further assumptions of using existing and proven technologies and identical parts whenever possible also enhance the relative affordability of MFL.

A. Basic design/modeling issues

Spacecraft design and specified performance for the Orbiter models followed these mission guidelines and Bonin's specific recommendations whenever possible, but in some cases, modeling and experiments with Orbiter identified areas where the design might be improved. We also took advantage of the flexible nature of Orbiter to introduce some changes from the original MFL that looked promising if not essential, such as the use of an inflatable aeroshield for Mars aerobraking and EDL.

The use of available MLLV's such as the Ariane-5 set some dimensional as well as mass constraints. Existing launch fairings imposed a diameter of ~4.5 m for payload modules. Bonin considered the internal volume and layout of the spacecraft and concluded that it is sufficient, but a 4.5 m envelope makes for a relatively narrow living space even with two vertical levels. We created an expanded fairing for the Ariane-5 and did some work on a wider (~ 6 m diameter) MTSV, but decided to stay with the original dimensions for this Orbiter project. Originally the MTSV and ERV had nearly identical forms as suggested in Bonin's basic design, but in the end we decided that while internal systems and even most structures could be common, that the external form of the ERV would be a biconic shape for Earth entry. Some studies consider this to be a relatively inefficient shape for the ERV, but it allowed us to try out another entry method, and it made it easy to distinguish the two vehicles in screen shots and videos.

B. Modularization and assembly

We designed the complete spacecraft first and later broke them into modules for simulation of Earth orbital assembly. Assembly was not modeled in great detail (e.g. structural, electrical, and plumbing connections are not modeled), but we did consider how to break up the parts geometrically and functionally, as well as how assembly might be accomplished. Since each half of the MTSV or ERV is not an independently functional spacecraft, a "tug" spacecraft, tethers, astronaut EVA's, and possibly other approaches would be needed to support on-orbit assembly. We experimented with tethers connected with the help of small remote control spacecraft. We speculated that in the absence of a robot arm as available on the shuttle or ISS, the combination of tug spacecraft (MLLV upper stage or CEV type spacecraft) and tethers would still require astronaut EVA assembly because of the complex nature of the connections between the two spacecraft modules (structural, electrical, life support, etc.). This is different from the interface between the propulsion modules we dubbed "Proteus" and which we assumed could be more or less "plug and play" connections established by docking, as discussed in section V. Orbiter tests at this level were visually supportive of our ideas but not definitive.

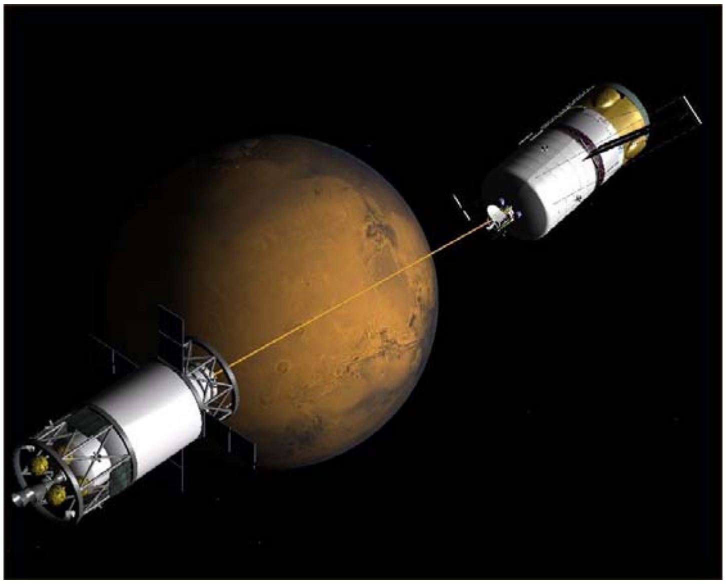

Figure 4. The MTSV and the spent final "Proteus" stage approach Mars, still tethered and spinning to produce artificial gravity for the crew. The Tether MFD is a very flexible add-on that allows experiments such as this and many other tether applications to be simulated in Orbiter. In this picture, the tether is very short for visual purposes. Its actual length would be about 1.5 km.

C. Tethers and other issues

Another feature we decided to model was the use of a tether to connect the spent final Proteus module and the MTSV to allow them to be spun to generate pseudo-gravity (presumably Mars-level 0.4g) for the astronauts' six-month voyage to Mars. This was another example where an existing add-on was available, a general tether simulation module (or Tether MFD, MFD meaning multi-function display, the virtual cockpit "computer screen" used to display Orbiter instrument data). This add-on was used to pull together modules in simulated assembly as well as for the rotational-G simulation.

Tether simulation pointed to issues with the placement, deployment, and use of solar panels for power generation. During the cruise to Mars, it was assumed that the spacecraft would be oriented such that the plane of the G-rotation would face the Sun (i.e., rotation axis parallel to the Sun-spacecraft vector). If the solar panels could also be oriented to lie in the plane of rotation, this would maximize the illuminated area and eliminate variation of generated power with the period of the rotation. We concluded that this would require solar panels which could be rotated about their long axis once deployed.

We also considered two variations of aeroshield structure and deployment, a rigid aeroshield that deploys by unfolding, and an inflatable aeroshield. After a number of test flights and redesigns, we decided to adopt the inflatable aeroshield. Additional discussion on this is included in subsection D of the following section on EDL.

VII. Entry, Descent, and Landing (EDL)

The MFL mission (Bonin, 2006) makes use of aerobraking maneuvers in the Martian atmosphere, initially to enter into a bound orbit, and then to land on the surface. Unlike a robotic mission, a human mission will have to pay special attention to the g levels experienced during aerobraking. The Orbiter space flight simulator can be used to investigate these g levels and iterate associated system design/parameters where required.

Orbiter has a fairly realistic atmosphere model, allowing g levels to be investigated on a spacecraft with known properties such as mass, area and drag coefficient. The g level can be written to a file or displayed in real time on the screen while a trajectory, with initial conditions defined in a scenario file, is being flown. With Orbiter's modular design and inherent flexibility it is possible to modify or possibly redesign a system in the mission. The results of adding parachutes or extra engines to an existing spacecraft can be observed to determine how these extra components may affect the behavior of the spacecraft. The trajectory can then be run again to observe how the system changes effect the flight of the aerobraking spacecraft.

A human will be able to tolerate g levels of 3g to 5g for a short period after spending six months in reduced gravity (Condon et al., 1999). Descending from Mars orbit, as opposed to a faster direct entry from the transfer orbit, helps to alleviate this problem. With Orbiter it is possible to set up the trajectory and to investigate the variation in g level due to navigation capabilities and L/D effects. It is even possible to use the RCS system to steer the craft in real time and obtain immediate results.

With simple aerocapture scenarios the g levels will build up to a maximum during entry into the atmosphere and then fall off. Aerocapture is relatively straightforward when compared with the EDL sequence required to land the craft. The Martian atmosphere is about a hundredth the density of Earth's atmosphere. Parachutes are consequently less effective on Mars and have to be relatively large to slow the craft in time. The time available for EDL related events is limited by the relatively low altitude of hypersonic deceleration.

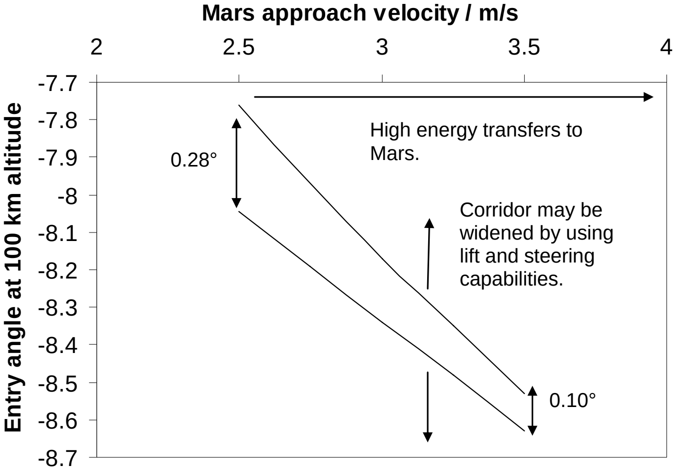

Figure 5. The aerocapture corridor at Mars for a purely ballistic MTSV. Note the corridor is extremely narrow. Mars robotic missions have shown the ability to meet entry angle delivery accuracy of ±0.25° as mentioned by Braun et al. (2006). Condon et al. (1999) show in fig 10-4 that a crewed spacecraft with a modest L/D of 0.25 will have an aerocapture corridor about 1° wide with a usable corridor 0.22° wide. The corridor can be increased by 73% by increasing the L/D to 0.4.

Although it will require research and development, it seems plausible that new high-Mach parachutes can be developed to provide high-speed deceleration in the near future. It is reasonable to expect that the human body cannot be modified to withstand high g levels in the near future. It is important to bear this in mind when designing an EDL system.

Orbiter is a sophisticated space flight simulator and has been extensively tested by the Orbiter community in this regard. To verify that the atmospheric model for Mars had been implemented correctly, results from Orbiter were checked against a standalone program. The standalone program, referred to here as "aerobrake calculator" (AC), was coded in Fortran using a numerical solution to the equations of motion in 2D. This program was also useful for determining scenario initial conditions for aerobraking and EDL investigations in Orbiter.

A. Spacecraft Aerodynamic Model

A simple aerodynamic model of the MTSV is described here based on Bonin (2006) and flight tests in Orbiter. The MTSV was chosen for aerobraking experiments because it has to transfer a human crew to the surface of Mars and is therefore the most sensitive element of MFL in terms of g level constraints.

The MTSV consists of four components that are assembled in Earth orbit before traveling to Mars. These are the "hab," garage, lander and aeroshield (heat shield). In Orbiter they are assembled into a whole spacecraft using the generalized docking ports facility. Each component has its own set of properties such as mass, drag, lift, etc. For a single spacecraft, forces will act on the geometric center of the mesh. For a multi-component spacecraft there will be an effective center where forces will act. By combining the dimensions and masses of the components, the center of mass is calculated to be 7.4 m behind the center of the MTSV heat shield.

B. Atmosphere Model

The Martian atmosphere, like that of the Earth, can be divided into distinct isothermal or adiabatic sections. Within these levels the temperature will either increase or decrease with altitude (adiabatic) or it will remain constant (isothermal), determining the variation of density with altitude. In Orbiter's static atmosphere model, five levels are used, derived from data from the real Martian atmosphere, and the model cuts to vacuum at 100 km. For an entry vehicle with a high enough ballistic coefficient such as the MTSV, this abrupt cutoff has little practical effect, as significant hypersonic decelerations start between 60 km and 70 km.

The atmosphere will be dragged along as the planet rotates. The rotational speed of the atmosphere was found to be an important factor in when making final orbit calculations for planning aerocapture maneuvers. The speed of the atmosphere will be at most 280 m/s. Orbiter simulates the rotation of the atmosphere. Not including atmospheric rotation in the pre-aerocapture calculations results in an approximately 10% error between predicted orbit semi-major axis and actual orbit in Orbiter. Including the rotation of the atmosphere in the calculations reduces discrepancies between calculated and measured final orbits in Orbiter to less than 0.2 %

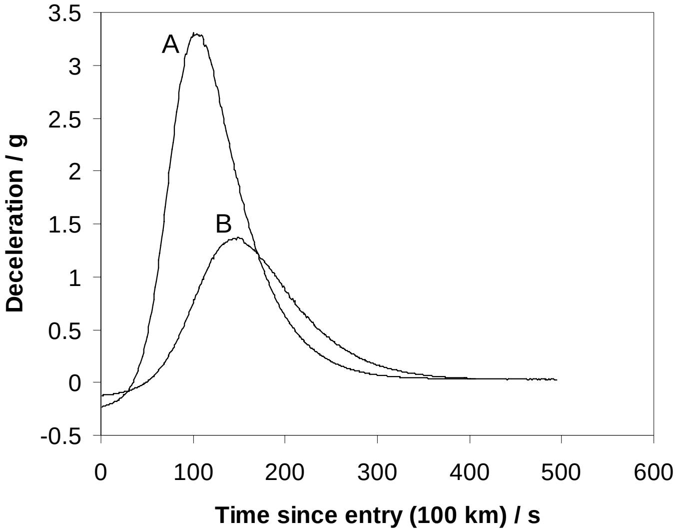

Figure 6. The g levels experienced by the MTSV crew during aerocapture into Mars orbit. Peak (A) results from an aerocapture into a 0.2 eccentricity orbit around Mars. The entry speed was 7 km/s. Peak (B) results from an entry speed of 3.8 km/s (Hohmann transfer from Earth) and a final orbit with an eccentricity of 0.2. The plots end when the spacecraft exits the atmosphere at 100 km.

C. Aerocapture G-level Trials

To enter into an orbit around Mars an aerobraking spacecraft has to first pass through the atmosphere. The flight path through the atmosphere has to be carefully planned for several reasons. First the spacecraft has to pass through a flight corridor, the boundaries of which are determined from the delta V required for capture into a bound orbit. A spacecraft that undershoots the corridor, passing through the denser part of the atmosphere, where the drag force is greater, will lose too much energy and intersect the surface. A spacecraft that overshoots the corridor, passing through the upper, less dense parts of the atmosphere will experience less drag and consequently fly back off into space.

Another constraint on the flight path for crewed missions is human g tolerance. A crew that has been in reduced gravity will suffer from muscle wastage, including the heart. For a deconditioned crew the maximum tolerance is estimated as 3g and 5g. Therefore it is important to fly the spacecraft along a path that minimizes the forces on the crew. For a purely ballistic entry this may simply involve an additional constraint on the corridor so excessive forces are not encountered.

To define the overshoot and undershoot boundaries of the MTSV ballistic flight corridor, the standalone aerobrake calculator program was used with an automated algorithm to search for aerobraking trajectories that resulted in an orbit around Mars. Once the flight corridor had been calculated it was a simple matter of using the initial conditions from a successful trajectory to create a scenario in Orbiter. Figure 6 shows results in Orbiter from trajectories close to the undershoot

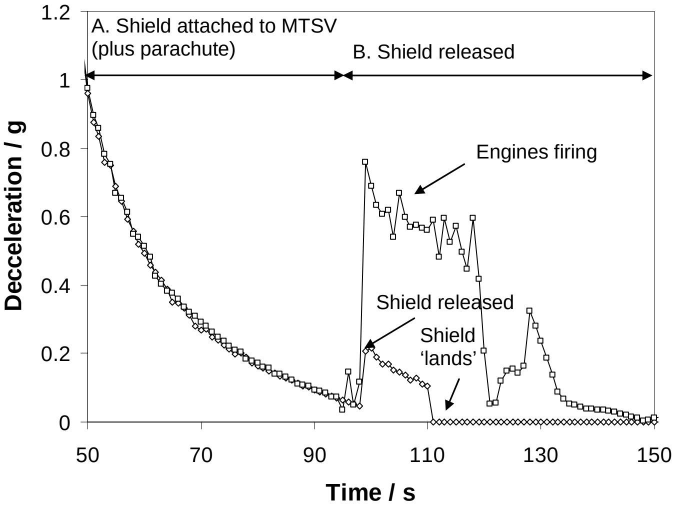

Figure 7. Deceleration of the MTSV and heat shield. Note the two sections, A and B. In section A, the g level data on the shield and the MTSV are identical because they are attached. In section B there are two g level profiles. The engines are firing in section B to pull the MTSV away from the shield. The engines are then used for the powered approach and soft landing near the ERV.

boundary of the aerocapture corridor for a low energy transfer (Hohmann) and a high energy transfer from Earth. As can be seen the g level environment on the crew is fairly benign even for a fast aerocapture (peak A). Minimum altitude reached during aerocapture was typically in the range of 30 km to 40 km.

D. EDL Experiments

After the aerocapture experiments were completed EDL scenarios were set up with expected entry speeds and entry angles. An iterative development process was required as the components of the EDL sequence are dependant on each other. The Orbiter space flight simulator proved to be quite useful for these tasks.

A 30 m parachute was fitted to the MTSV using Orbiter's docking facility. The parachute size was chosen as the recommended maximum size (Braun et al, 2006), before incurring serious time penalties. It was found, during trials that if the parachute was deployed at a velocity of 900 m/s, this allowed sufficient time to slow the craft for landing. Once the parachute had been deployed the heat shield was no longer required and had to be released to free up the rocket engines for powered descent. However because of the relatively low ballistic coefficient of the heat shield compared to the MTSV (plus parachute) the main engines had to be fired to pull the MTSV away from the heat shield. The decelerations of the shield and MTSV can be tracked in Figure 7. The shield was released at 1.5 km so the engines could then be used for the powered approach and soft landing next to the ERV. The parachute deployment and powered descent were controlled by an available Orbiter add-on called Autopilot.

After a successful landing had been achieved the g levels on the crew were checked. It was found that the maximum g loading during hypersonic deceleration was about 2g. However the deceleration caused by deployment of the 30 m chute peaked at 5g (see Figure 8), which is unacceptably high for a human crew. A staged parachute deployment was found reduce the maximum deceleration to 3g. First a smaller, 15 m diameter parachute is deployed at 900 m/s, then a large 30 m parachute is deployed about 10 seconds later at 600 m/s.

E. Thermal Investigations

The MTSV requires a relatively large diameter shield to protect it from atmospheric entry heating. It was observed by the authors, during construction of the MTSV in Orbiter, that using large rigid, solid heat shield proved to be awkward in several ways. Firstly a holding and release mechanism needs to be placed between the heat shield and the boosters which adds extra weight and complexity. Also the size of the shield could obstruct sunlight from reaching the solar panels when the MTSV was pointing in certain directions. The shield also proved difficult to release following hypersonic deceleration. This is due to its low ballistic coefficient relative to the rest of the MTSV.

A solid heat shield can provide high reliability and safe hypersonic deceleration during aerocapture and descent to the surface as it is already deployed before leaving Earth. However an inflatable heat shield has the potential to overcome many problems of a solid heat shield.

It was noted during EDL experiments that the MTSV, with the rigid heat shield, had a rather low ballistic coefficient and may consequently receive sufficiently low heating during entry suitable to allow use of an inflatable structure of similar dimensions. To determine whether an inflatable heat shield could be used the peak convective stagnation point heat rate (see equation 10-2 Condon et

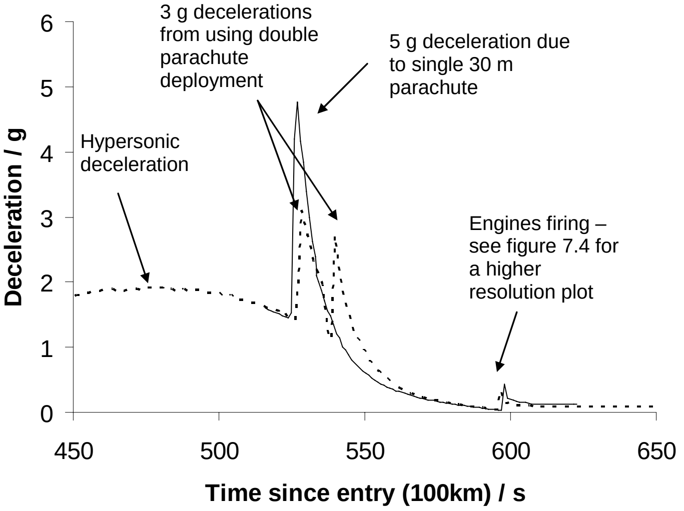

Figure 8. Decelerations of two EDL sequences compared. Both EDLs have identical initial conditions. The trajectories begin at 100 km altitude with a -3.32° entry angle and an entry velocity of 3642 m/s. The solid line shows a 5g peak which is the result of a single 30 m diameter parachute deployed at a speed of 900 m/s and an altitude of 10.8 km. The dotted line show two 3g peaks resulting from the deployment of a 15 m diameter parachute at 1000 m s-1 and a 30 m parachute at 600 m/s. The small peak towards the end of the profile is a result of the engines kicking in. Shield release occurs at the same time as engine start. This occurs at an altitude of 1.5 km and a velocity of 142 m/S. Touchdown here was at 2.5 m/s. Data captured Flight Data Recorder MFD add-on.

al., 1999), was calculated for a hypothetical shield. For a dome-sphere heat shield, with a nose radius of 10 m and a diameter of 13.5 m, the calculated values ranged from 4 to 14 W cm-2 with respective pre-entry orbit eccentricities varying from 0.1 to 0.9. As these values are comparable for those calculated for previous inflatable structure (e.g. Allouis et al, 2003) it may be possible to use an inflatable aeroshield, saving mass and solving the problems as already discussed.

Another problem with a solid heat shield is that during aerocapture the heat absorbed by the heat shield needs to be dissipated. One solution would be to eject the heat shield after the aerocapture deceleration is complete. However a heat shield needs to be retained for the descent to the surface. Two heat shields would ideally be needed, one behind the other, which may be difficult to engineer to avoid any damage to the second shield's surface. Inflatable structures might be easier to protect as the extended sections will initially be protected in their storage containers. A solid heat shield might be used for aerocapture with an additional lightweight, inflatable structure deployed for the descent.

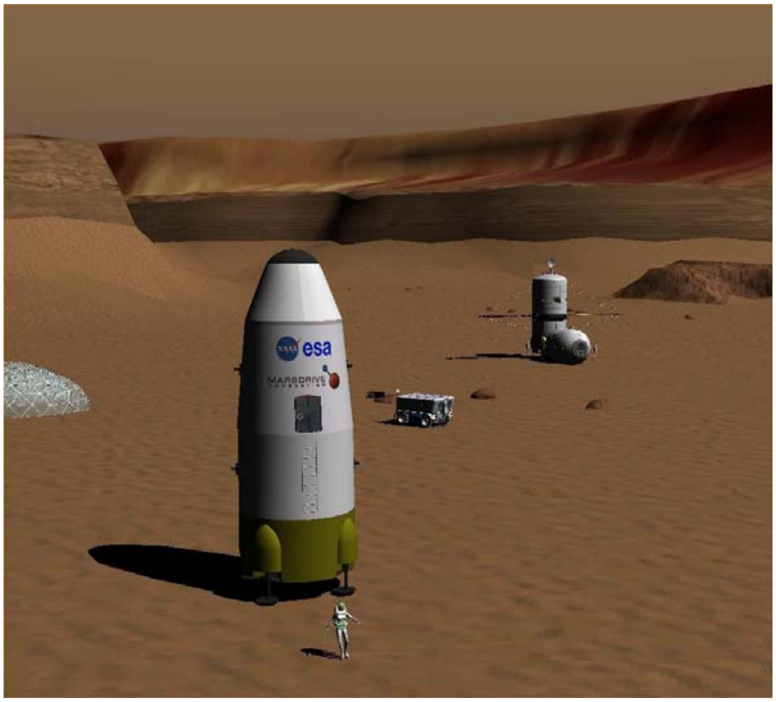

Figure 9. The ERV dominates this Orbiter view of the Mars base we dubbed "Mandya Arti" after an Australian Aboriginal legend, "how the hills came to be." It is actually modeled on an area of Mars called Vallis Dao which was an available 3D Mars terrain add-on. At the left are some inflatable greenhouses, and in the background are the Mars Rover, the MTSV, and an inflatable lab attachment for the MTSV. In front of the ERV and just visible next to the MTSV are several astronaut figures which lend scale and provide powerful symbols of the ultimate reason for doing all of this – humans on Mars.

F. Terrain and Mars base simulation

Although not strictly related to EDL, for visualization, educational, and scale comparison purposes during approach and landing, we wanted to have some sort of 3D terrain and some suitable Mars base "props." Basic planetary textures in Orbiter are "painted on" to smooth spherical surfaces, and depending on the installed resolution, this flat texture can look pretty convincing from medium to high orbital altitudes, though not so good down low. But small 3D terrain areas, surface bases, and other objects made from 3D "meshes" similar to those used to construct spacecraft can also be added. Orbiter add-on developers have again come through in this area, and we made use of a 3D model of the rugged Vallis Dao terrain as our basic landing area, constructing a simple base in the high-detail central region of this add-on. This made our landing approaches a bit more visually dramatic. In addition to the waiting ERV (landing target for the MTSV), we also furnished the base with objects such as a Mars rover, small nuclear reactor, "inflatable" greenhouses, and astronaut figures who help to establish the scale of the other objects in our pictures and video clips (Figure 9).

VIII. Conclusion

As is the case for any ambitious space venture, human Mars mission planning is indeed complex, with many interacting systems, mission phases, tradeoffs, and technical issues. Although a number of the basic issues and tradeoffs can be evaluated with simple tools such as the rocket equation, it takes an expert to look at a page of equations or an Excel spreadsheet and visualize humans landing on Mars. Professional mission planners at aerospace companies and government research centers typically have access to advanced analysis tools and even to artists (in 3D graphics and traditional media) who can help turn their equations and visions into forms that others can more easily share. Orbiter represents an intermediate solution to mission planning, education, public outreach, and preliminary analysis. It is simple and cheap enough (free) for nearly any bright and motivated person to experiment with and gain something of a hands-on appreciation for space flight, whether at home, in the classroom, a museum, or an office. Use of Orbiter for virtual prototyping in the preliminary analysis phase can extend this appreciation to the details of a particular mission plan, with the added bonus of quality static and animated 3D graphics that can help bring a proposed space mission to life – and even launch an imagination to Mars.

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