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MISSION DESIGN FOR THE DEEP SPACE 4 / CHAMPOLLION COMET SAMPLE RETURN MISSION

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The Deep Space 4/Champollion mission will be the first to land a spacecraft on the surface of a comet, perform in-situ science, and collect a subsurface sample which it will return to Earth for analysis. This paper describes the trade studies resulting in the current reference mission, which uses solar electric propulsion to rendezvous with the comet Tempel 1 in December 2005 after launching in April 2003. An option which uses a chemical propulsion system to return to Earth is discussed.

INTRODUCTION

The Deep Space 4 (DS4)/Champollion mission, being developed in collaboration with the New Millennium Program at JPL, is on target for a Phase C/D start in October 1998. The goals of the New Millennium Program are to qualify advanced technologies for use on future NASA missions and to perform meaningful science with the new technology. The DS4/Champollion spacecraft (Figure 1) would perform the first landing of scientific instruments on the surface of a comet, and demonstrate technologies for collecting and returning extraterrestrial samples. These technologies include the following:

- advanced lightweight solar arrays
- high performance, multi-engine ion electric propulsion
- autonomous precision guidance and control for landing
- comet/small body anchoring systems
- subsurface sample acquisition and transfer to instruments
- integrated high performance electronics and software architecture
- UHF transceiver for communications between lander and carrier
- small transponding modem
- automated orbital rendezvous and docking

Figure 2 illustrates the current reference trajectory. DS4/Champollion would launch in April 2003 on a Delta II 7925 from Cape Canaveral Air Station. The 12 kW solar-electric propulsion spacecraft would rendezvous with the periodic Comet Tempel I in December 2005 and would spend four months at the comet in order to completely map

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the surface at high resolution. Once a landing site is selected, the lander would descend to the surface and anchor itself while the solar-electric carrier spacecraft remains in orbit to serve as a radio relay to Earth.

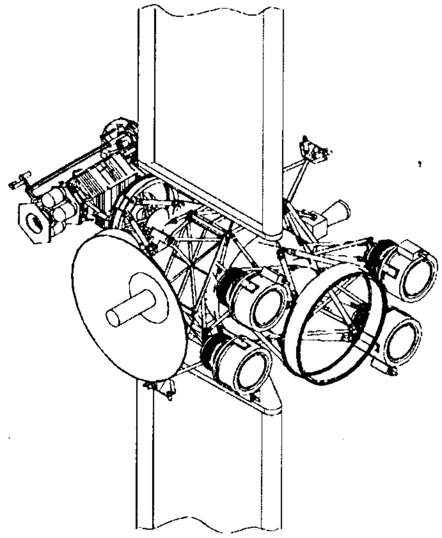

Figure 1 DS4/Champollion Spacecraft, in Cruise-to-Comet Configuration

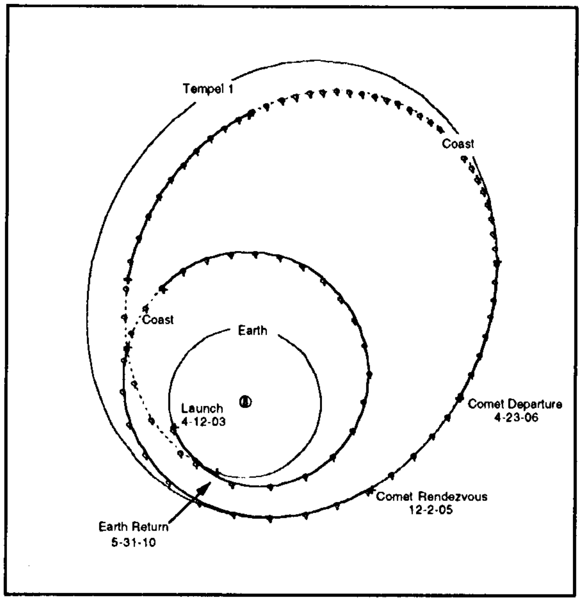

Figure 2 DS4 / Champollion Trajectory

Operations on the nucleus surface are expected to last approximately 100 hours. The DS4/Champollion lander would perform *in-situ* science (selected scientific instruments include a panoramic imager, a drill to collect samples at varying depths below the surface, a gas chromatograph/mass spectrometer, visible and IR microscopes, a gamma ray and neutron detector and physical property probes) and collect a sub-surface sample for Earth return. Then the spacecraft would detach itself from its anchor and take off, leaving the lower portion of the spacecraft and most of the scientific instruments on the comet. The lander would then rendezvous with the carrier spacecraft and transfer the sample to the sample return vehicle. Flight time back to Earth is 4.1

years using ion propulsion, delivering the sample in May, 2010. The passively cooled sample would be enclosed in a direct re-entry vehicle that would decelerate in the Earth's atmosphere and then parachute safely to the surface. The returned sample would be transported for analysis in terrestrial laboratories.

This paper will address the trade studies used to improve the mass performance of the interplanetary trajectory described above. Given constraints of launch vehicle capability, and targets accessibility over the desired timeframe, the current reference mission is given to best meet the project's needs and provide for a credible spacecraft design. The nature of low thrust missions is the intrinsic dependence on spacecraft design and other mission parameters.

REQUIREMENTS AND ASSUMPTIONS

Key objectives of this mission are to launch around 2003 to a scientifically interesting comet on a Delta II class launch vehicle. Scientists provide input on which comets are more interesting to explore; desirable characteristics include good gas production rates at perihelion, a normal volatile production ratio, a good record of ground-based observations and larger than a critical size. Delta II launch vehicle options include the Medlite class 7425, and the 7925. For the smaller and less expensive 7425, missions were to rendezvous with a comet and validated technologies for future sample return missions but not to return to Earth. In addition, the 7925H launch vehicle with the enhanced strap-on boosters was evaluated in the event additional performance was necessary. A separable spacecraft-to-launch vehicle adapter is considered. There may be a simpler spacecraft design with a non-separable adapter, but a separable adapter proved to provide a significant increase in net spacecraft mass. The adapter would separate from the spacecraft and remain with the launch vehicle after the final interplanetary injection is completed.

Low thrust solar electric propulsion (SEP) for the interplanetary trajectory is assumed to enable greater spacecraft mass performance as well as significantly shorter flight times than traditional chemical propulsion missions to comets.[2] The DS4/Champollion propulsion system will be derived from the Deep Space 1 July 1998 validation of the NSTAR 30 cm thruster system.[2] One deviation from the DS1/NSTAR system is the higher ΔV, and thus the larger xenon propellant load, needed by DS4/Champollion. DS1 will be flying one ion thruster with ~80 kg xenon throughput. DS4/Champollion will require significantly more throughput and thus will have multiple engines. Spacecraft design allows for one or two ion engines to be fired at a time. This mode then implies that the solar arrays could also provide more power; available solar array output for trajectory analysis was assumed to be ~11 kW (EOL) at 1 AU; with 1 kW for margin, the solar array is sized to 12 kW. For spacecraft power independently required of an operating SEP system, 350 watt is assumed.

The SEP system can operate a maximum of 90% of the time during thrusting segments to allow for activities which may likely require the spacecraft to point in a different orientation such as providing for a telecommunications link to Earth or navigation update using on-board inertial sensor systems. There will also be a 10%

contingency carried on the calculated xenon load to account for discrete thrust levels, launch windows and launch periods which have not been fully characterized yet.

For the comet mission, it is assumed that the stay time at the comet will be on the order of 140 days to allow for the comet orbital mapping tour and surface landing. When the lander lifts off the comet to rendezvous with the carrier, it will leave behind the bulk of the hardware - on the order of 60 kg - since it is not required to complete the mission.

TRADE STUDIES

Several trajectories with launch opportunities in the first half of the next decade which rendezvous with short-period comets have been identified previously.[1,3] The DS4/Champollion project chose one of these opportunities, a rendezvous with Tempel 1 launching in 2003, as the baseline, and extended the trajectory to return to Earth. A Tempel 1 comet rendezvous would occur around 2.0 AU. An Earth-return mission would take the spacecraft out to 4.5 AU from the Sun and 5.3 AU from Earth.

Trade studies were made to determine the effects and sensitivities of several spacecraft and trajectory parameters on the overall mission design. The evolution to the current reference mission (described above) was guided by these trade studies and limited by the constraints placed on the project such as launch vehicle capability. The fact that the sensitivities are a function of the concurrent assumptions is important to keep in mind; each trade study did not evaluate the effect on every other past trade study, but only on those that were realistic for the mission. One of the main differences between the design of missions which use low-thrust propulsion and those that use chemical propulsion systems which are relatively high-thrust is that low-thrust trajectories are directly dependent on several spacecraft parameters, particularly mass and power as they change over long thrusting periods, and the optimum trajectory changes as the spacecraft design changes and matures.

At an early stage in the mission design, the solar arrays were sized to output 8 kW at 1 AU since this was a typical value used in past mission option studies[1]. Due to engine lifetime limits and the total throughput required for the trajectory, the spacecraft was designed with 4 engines; however, a maximum of 2 engines could be operated simultaneously to provide sufficient mass for a realistic spacecraft design. Configuring the engines to allow them to operate in pairs or individually required additional mass for positioning and gimbaling mechanisms. The engines have a minimum power level at which they can operate – about 500 watts. But if the engines could only operate in pairs, the power would be insufficient to operate them beyond about 2.8 AU. This situation places severe restrictions on the trajectory, forcing the rendezvous to occur closer to perihelion and a much shorter stay time. Allowing single engine operation enables the engines to operate out to about 3.5 AU, increasing the performance in terms of final spacecraft mass by over 70 kg while also enabling much longer stay times at the comet. Thus the spacecraft is designed such that the engines can operate in pairs or individually.

At this point the effect of several spacecraft and trajectory parameters on the final spacecraft mass (after the final SEP engine burn and prior to Earth entry) was examined. The performance of the trajectory is measured by the final spacecraft mass, which is maximized by the trajectory design software. A longer stay time at the comet than past studies has allocated for was much desired by the scientists to allow for more complete comet characterization and also for greater probability to successfully land on the comet; however, the final spacecraft mass decreases by 29 kg as the stay time is doubled from 60 to 120 days (Figure 3).

Parts of the spacecraft dedicated to the comet surface science can be left at the comet does not have to be accelerated to the final trajectory headed for Earth. As shown in Figure 3, leaving 25 kg more at the comet (50 - 25 kg) only decreases the final spacecraft mass by 15 kg, resulting in a 10 kg gain in net spacecraft mass.

Certain operational modes of the spacecraft, such as autonomous optical navigation or a data link to Earth, require the engines to be shut down periodically or thrusting in the wrong direction. The duty cycle is the percentage of time (on a weekly basis) that the engines may operate. The effect of a change in duty cycle (assumed constant throughout the mission) is shown in Figure 4.

Also shown in Figure 4 is the change in final spacecraft mass as the minimum power at which the engines can operate is reduced. This minimum power level has the largest effect on the return portion of the trajectory. As the spacecraft advances further from the Sun and the output power from the solar arrays decreases, the engines are on until the minimum power level is reached, and they turn back on as soon as possible as the spacecraft proceeds back toward Earth.

A few options were studied that proved not be significant in impacting spacecraft mass. The final spacecraft mass for a 30-day launch period is less than 3 kg below the optimum for the period. The trajectory can be altered to fly by Mars on the initial outbound portion of the trajectory, but such a flyby reduces the final spacecraft mass by 10 kg.

The solar array reference power is the power output from the solar arrays at 1 AU. This reference power has a significant effect on the final spacecraft mass and the sensitivity of the mass to a change in value of other spacecraft and trajectory parameters. Figure 5 shows the variation of spacecraft mass with solar array reference power. Higher power levels provide many advantages, and the decision was made to increase the reference power from 8 to 11 kW. At the higher power level, the mass performance is affected less by a degradation in solar array output. Additionally, the spacecraft mass is 10 times less sensitive to an increase in power required by the spacecraft other than for the engines (-0.057 kg/kW at a reference power of 11 kW as compared to -0.56 kg/kW at 8 kw). The stay time at the comet can increase to about 120 days without affecting the final spacecraft mass. Staying for 140 days reduces the mass by 1 kg.

Restricting the rendezvous portion of the trajectory such that the engines only operate in pairs instead of allowing an individual thruster to operate would decrease the final spacecraft mass by 5 kg including an increase in propellant mass of about 20 kg. For the return portion of the trajectory, we examined using a smaller thruster that is more efficient at low power levels. The thruster being considered for development can operate down to a minimum power of 250 watts, enabling it to operate at the largest heliocentric radius that the trajectory reaches. Using this type of thruster for the return leg instead of one of the larger engines would gain about 25 kg in final spacecraft mass.

Using the higher performing Delta 7925H instead of the 7925 would result in a gain of about 54 kg to the spacecraft, which is on the order of half of the additional injected mass that can be provided by the 7925H at a given launch energy. A 20 kg adapter left with the launch vehicle upper stage would result in a net gain for the spacecraft of 11 kg. This mission option is listed in Table 2. For the smaller 7425 mission, a comet rendezvous mission is also in Table 2. Without the constraint to return to Earth, the rendezvous date is optimized at a later arrival date.

Table 1
LAUNCH VEHICLE OPTIONS

Launch Vehicle	Mission Type	Launch Date	Comet Arrival Date	Earth Arrival Date	M_{inj} (kg)	$M_{s/c}$ (kg)	S/C Array (kW)	M_{prop} (kg)
7425	Comet Rendezvous	4/11/03	2/4/06	N/A	702	452	7	250
7925	Comet Sample Return	4/23/03	12/2/05	6/1/10	1066	666	11	400
7925H	Comet Sample Return	5/6/03	12/2/05	6/2/10	1141	719	11	422

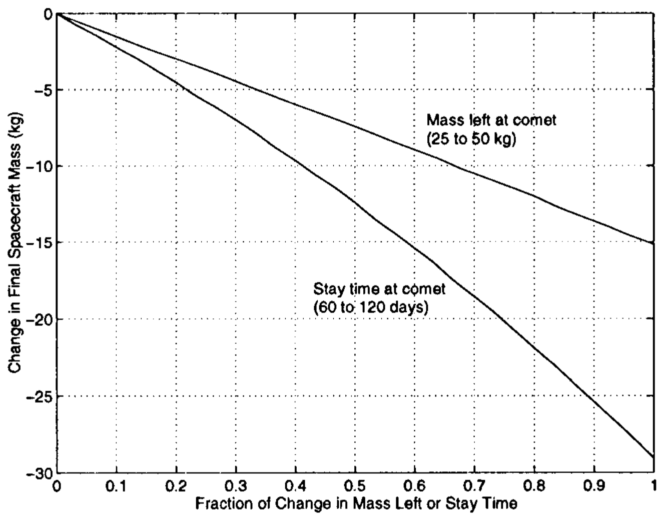

Figure 3 Effect of Stay Time and Mass Left at Comet on Final Spacecraft Mass

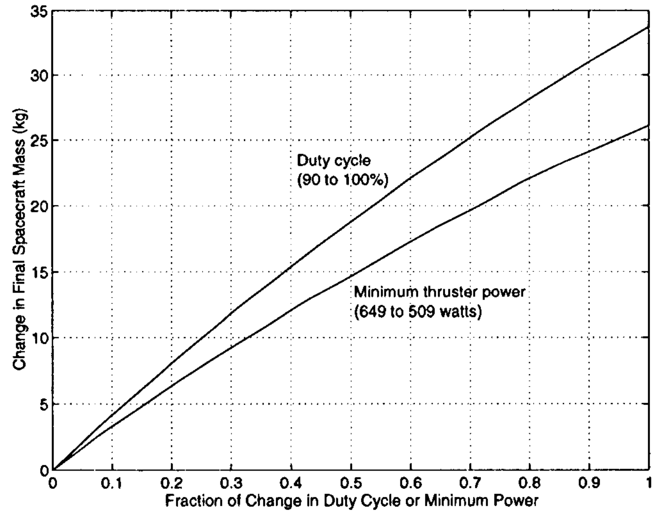

Figure 4 Effect of Duty Cycle and Minimum Thruster Power on Final Spacecraft Mass

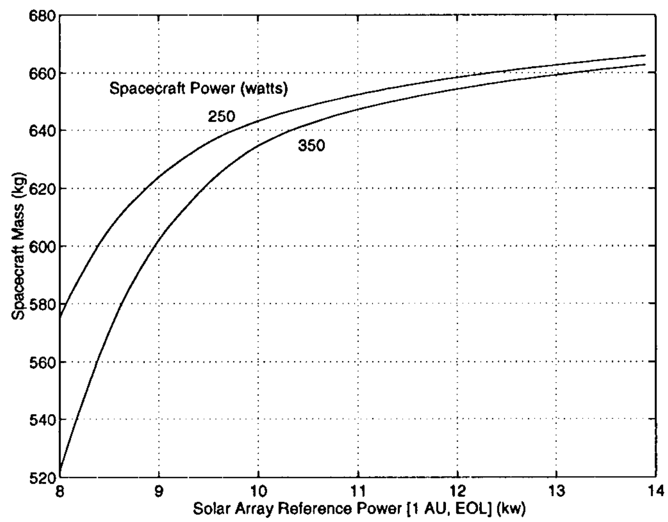

Figure 5 Spacecraft Mass as a Function of Solar Array Reference Power

HIGH-THRUST EARTH RETURN OPTION

A high-thrust bipropellant engine to provide the ΔV for the return to Earth was also examined. This option offers several advantages. Since the ion engines would not have to operate beyond about 2.5 AU, we could reduce the size of the solar arrays and remove the need to operate the engines individually. Eliminating operation of the ion engines after rendezvous removes the concern of contamination of the engines from the cometary environment and significantly reduces the effect of potential degradation of the solar arrays. The ΔV is minimized for an engine burn near aphelion of the comet's orbit, so the stay time at the comet increases to 1.3 years. Hence, the comet can be studied for a longer time, and the landing can occur during a less active phase of the comet.

On the other hand, addition of the bipropellant propulsion system hardware would reduce the net non-propulsion spacecraft mass, and the propellant mass for the return trajectory increases from 65 kg for the ion engines to 264 kg for a bipropellant system with a specific impulse of 308 s. While risk in some areas would be reduced with this option, risk in other areas may increase, scientific payload would decrease, and the cost would be higher.

EARTH ENTRY

For the optimum trajectory using the low-thrust propulsion system only, the V at Earth return is 10.21 km/s. The resulting speed at atmospheric entry (122 km altitude) is 15.06 km/s. This entry speed is much higher than previous experience (e.g., 11 km/s for the Apollo missions) and enters a regime where the aerodynamic and thermal modeling is not well understood. The technologies for developing an advanced mass-efficient sample return capsule capable of surviving such an entry will require significant resources and effort in the coming years.

Without significantly altering the current reference trajectory, the ion propulsion system can be used to reduce the entry speed slightly. For example, the entry speed can be reduced to 14.6 km/s by expending an additional 5 kg of propellant. We briefly investigated using a 2:1 reverse ΔV-EGA to reduce the V at Earth. Based on preliminary analysis, the V could be reduced to about 5 km/s (12 km/s entry speed) at the cost of an additional 2 years of flight time and approximately 25 kg of propellant. For comparison, Stardust will approach Earth with a V of 6.4 km/s.

SUMMARY

The reference mission for Deep Space 4/Champollion has evolved over the past to improve mass performance and mission return consistent with project guidelines and a credible spacecraft design. As low thrust propulsion is now beginning to be used for deep space missions, engineers are learning how to work with a mission that is very sensitive to spacecraft parameters. The various parameters studied here include: number of engines operating simultaneously, which is very dependent on how much solar power is available and what the mission's trajectory path from the sun is; sensitivity to engine duty cycling and minimum engine power, effects of longer stay times at the comet, leaving more mass behind at the comet, and alternative strategies for Earth return. Each of these parameters have significantly impacted the mass performance and requirements on the spacecraft and mission design.

However, these complex trade-offs between mission and spacecraft also offer more flexibility in designing a mission. There will be more tolerance from the mission design to recover from lower than expected performance discovered during development (for example, the solar arrays produce less output, but the mission design can absorb the effect) or an unexpected fault during mission operations (for example, the engines shut down during a burn, but the mission would not be lost). Previous missions using chemical propulsion would have had to recover from these anomalies by either degrading the performance of the spacecraft or possibly losing the mission.

While previous parametric mission studies on comet opportunities provided insight on possibilities, the DS4/Champollion low thrust mission evolution through this last year illustrates the significance trade studies on a particular mission will have in optimizing and in adding credibility to a low thrust mission design. The nature of low thrust missions is the intrinsic dependence on spacecraft design and other mission parameters, as shown in this example.

ACKNOWLEDGMENT

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