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CONCEPT FOR A LUNAR TRANSFER VEHICLE FOR SMALL SATELLITE DELIVERY TO THE MOON FROM THE INTERNATIONAL SPACE STATION

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The International Space Station (ISS) has developed as a very capable center for scientific research in Lower Earth Orbit. An additional potential of the ISS that has not thus far been exploited, is the use of this orbiting platform for the assembly and launching of vehicles that could be sent to more distant destinations. This paper reports the results of a recent study that looked at an architecture and conceptual flight system design for a lunar transfer vehicle (LTV) that could be delivered to the ISS in segments, assembled, loaded with payload and launched from the ISS with the objective of delivering multiple small and micro satellites to lunar orbit. The design of the LTV was optimized for low cost and high payload capability, as well as ease of assembly. The resulting design would use solar electric propulsion (SEP) to carry a total payload mass of ~250 kg from the ISS to a 100 km lunar orbit. A preliminary concept of operations was developed considering currently available delivery options and ISS capabilities that should prove flexible enough to accommodate a variety of payloads and missions. This paper will present an overview of the study, including key trades, mission and flight system design, and notional operational concept.

I. INTRODUCTION

The International Space Station (ISS) will soon reach completion. Already it has become a fully staffed operations center in low earth orbit facilitating a wide range of scientific activities. As it transitions into a fully operational mode new uses are being explored that can fully exploit the unique attributes of this multinational facility.

One concept that traces back to the earliest ideas of space station applications has been the use of the ISS as an assembly and departure point for in-space transportation systems. While the ISS has not been designed to support large spacecraft assembly activities such as might be required for crewed missions, there are opportunities to make use of the facility in a more modest manner as a launching point for smaller robotic vehicles. Specifically, the idea of using the ISS as an assembly point for small and microsatellites that could be transported from the ISS orbit to lunar orbit in an inexpensive manner was investigated by a team at JPL in Autumn of 2009. The task began with the broad aim of developing a lunar transfer vehicle (LTV) that could be delivered to the ISS on a standard delivery vehicle, where it could be fitted with a number of small satellites. The LTV would then be launched from the ISS to a low lunar orbit, where it would deploy the satellites, perhaps carrying its own scientific payload to become a lunar orbiter itself once all payloads have been delivered.

The team explored the design space available for the task, performed high level trades and developed a point design for a vehicle and mission concept as discussed in the following sections.

LTV Requirements

As a basis for the study a number of initial assumptions were made.

- The LTV should be able to carry up to six small satellite payloads
- Average payload mass would be ~50 kg
- Payloads would be delivered to low lunar orbit at 100 km altitude
- Transit time should be less than one year (goal)
- The LTV would be delivered to ISS as a fully fuelled unit

II. TRADE SPACE

Given the initial assumptions listed above the team considered a number of high level trades to further define the mission and flight system design space. A top-level trade tree is shown in Figure 1.

The initial trade involved the means by which the LTV would be delivered to the ISS. The trade considered using the Shuttle, as well as both launch on a dedicated launch vehicle or as a secondary payload on an EELV, as well as the range of ISS cargo delivery vehicles expected to be available in the near future. Shuttle was eliminated as a result of its imminent retirement and the two independent launch vehicle choices were excluded because of the lack of rendezvous and docking capabilities. The subset of ISS cargo vehicles available was reasonably quickly narrowed to the JAXA-developed H-II Transfer Vehicle (HTV). The HTV provides the nearest term delivery vehicle with significant unpressurized payload capability. In the case of the HTV, 1500 kg up-mass is available on an unpressurized pallet, divided into three 500 kg units.

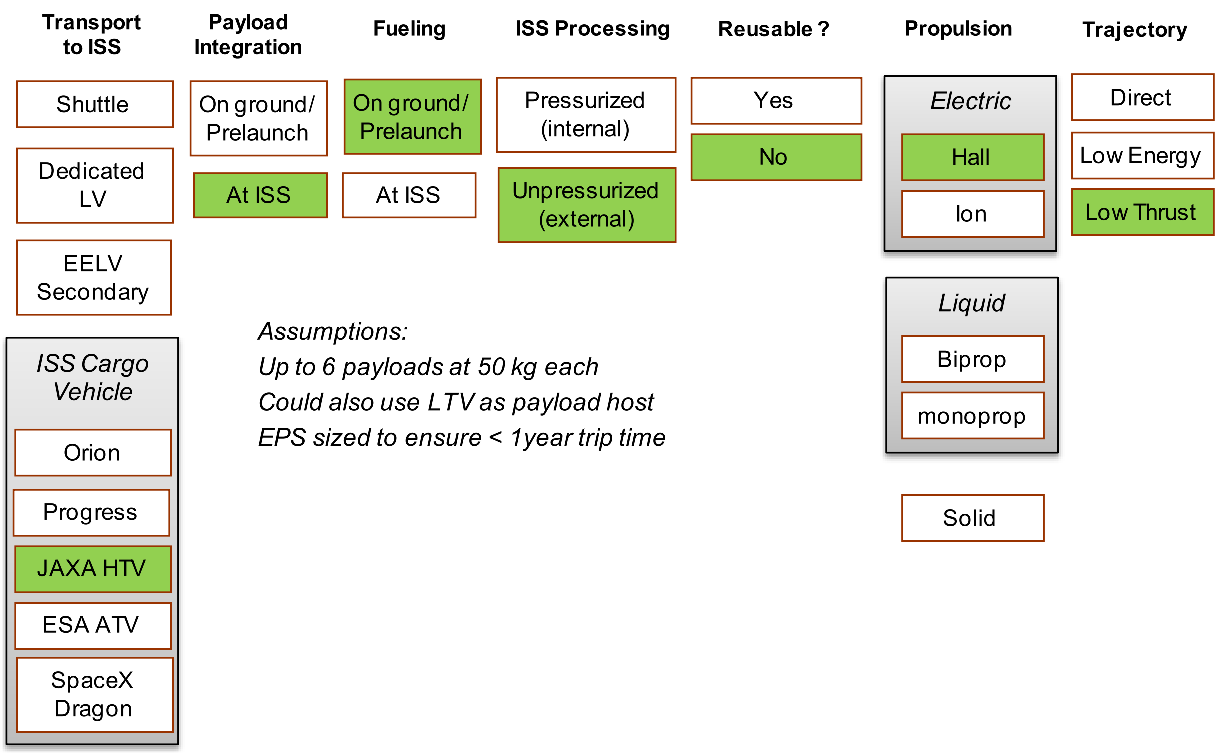

Fig. 1: Top Level Trades.

Integration of the microsat payloads was considered in a trade of whether the payloads should be integrated on the ground and launched with the LTV or launched separately and integrated at the ISS before departing for the moon. ISS integration proved to be the preferred alternative, allowing microsats to be collected at the ISS from multiple deliveries, then integrated for transfer by the LTV when a sufficient number of payloads are available.

For operational simplicity it was decided that fueling of the LTV on the ground before launch would be preferred.

Processing at the ISS (primarily mating of payloads to the LTV) might be possible to perform in a pressurized module. However, the constraints this would put on the design of the vehicle were considered too limiting and external processing was the chosen option.

Serious consideration was given to making the LTV reusable. This would involve providing propellant sufficient to allow the LTV to return to the ISS after deploying its payloads. While this was considered attractive from an operability standpoint, the additional fuel and radiation hardening requirements would unnecessarily complicate the design. This trade might be revisited for a future study, but reusability was not adopted as a requirement for the current design.

The propulsion trade quickly focused on electric propulsion after consideration of the high ΔV requirements of the mission. Liquid propulsion systems would have the benefit of a much faster transit time, but the amount of propellant required was found to nearly eliminate the vehicle's payload capability. On the electric propulsion side, designs were considered using ion engines as well as Hall thrusters, with the choice falling to Hall thrusters as a result of the higher thrust available for a given electrical power. While this comes at the expense of a lower specific impulse relative to the ion engines, the goal of <1 year transit time did not appear feasible with available ion thrusters.

With the decision to use electric propulsion the trajectory trade fell solidly in the "low thrust" category. Direct and low-energy trajectories were evaluated as part of the liquid propulsion analysis.

Initial Vehicle Concept

As a result of these top level trades, an initial concept for the LTV took form. The guiding principle was to develop a simple spacecraft bus built around existing, flight-proven subsystems. This led the system and subsystem design to choose catalog parts where possible, and avoid the development of new technologies. The propulsion system was to be based on use of Aerojet BPT-4000 Hall thrusters, a commercially available design with flight heritage. The optimum power for this engine dictated the power system requirements in the ~5 kW range. To keep mass and packaged volume low the team decided to employ Ultraflex solar arrays (demonstrated on the Phoenix Mars Lander mission) as these currently represent the lowest mass and most compact packaging of competing solar array designs.

Packaging

The choice of the HTV as the vehicle for delivery to the ISS proved to be a major influence on the design. The HTV provides unpressurized cargo space on a pallet, as illustrated in Figure 2. The Type I pallet shown provides three envelopes for payloads. Envelope dimensions are 0.8m x 1.0m x 1.85m and maximum mass is 500 kg for each.

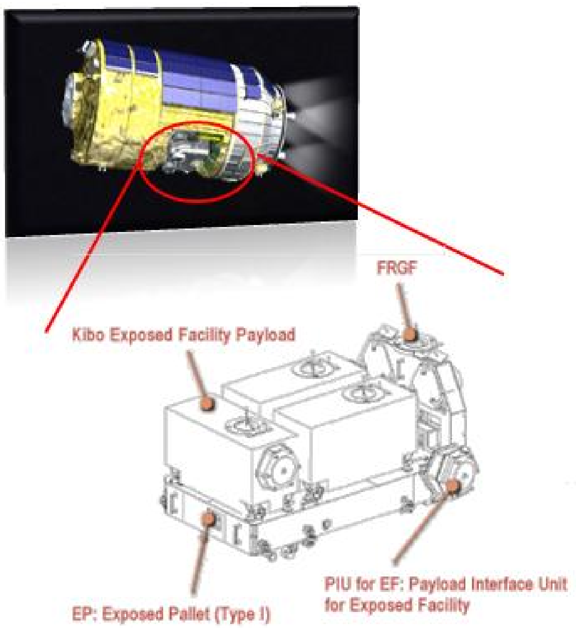

Fig. 2: HTV Type I Pallet [1].

III. FLIGHT SYSTEM CONCEPT

Once the basic features of the initial concept were decided, the team enlisted the aid of JPL's Team X concurrent design facility to develop a detailed point design, as well as a refined concept of operations. Simultaneously, trajectory design work was performed to evaluate the mission characteristics of the developing designs, as discussed in Section V.

The major driving requirement in developing the point design stemmed from the HTV accommodation requirements. The volume and mass constraints drove the team to develop an innovative two part architecture. As shown in figure 3 the resulting concept is divided into two modules for transport to the ISS; the Spacecraft Module and the Propulsion Module. The Spacecraft Module contains the majority of the subsystems commonly associated with a spacecraft bus, such as C&DH, Telecom, Electrical Power, reaction wheels, and the payload interface. The power processing unit (PPU) for the Hall thruster is also contained in the Spacecraft Module. Total dry mass of this module, including 30% margin, is 365 kg.

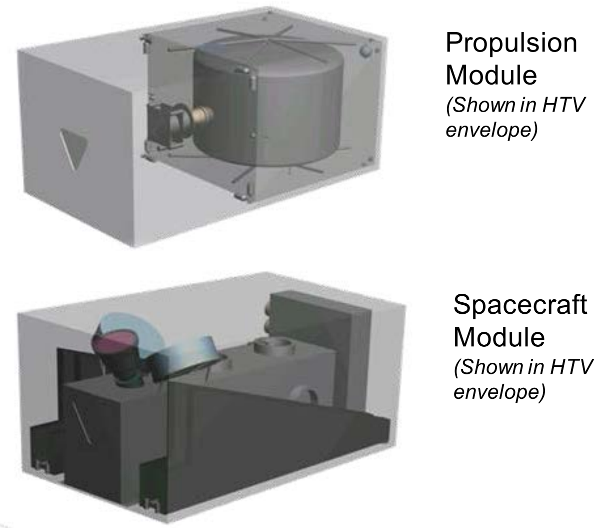

Fig. 3: Flight System Packaging.

The Propulsion Module contains the Xenon propellant tank and the Hall thruster, as well as eight resistojet thrusters for momentum unloading, thus keeping all propellant interfaces in a single module. Margined dry mass of the Propulsion Module is 128 kg, allowing a maximum fuel load of 372 kg to be carried while remain within the HTV pallet 500 kg allocation.

The two modules are designed for ease of integration at the ISS. A single mechanical interface links the modules with power and signal connections. Six payload interfaces are provided on the LTV, accommodating a total delivered payload of 250 kg. The deployed configuration of the LTV is shown in Figure 4.

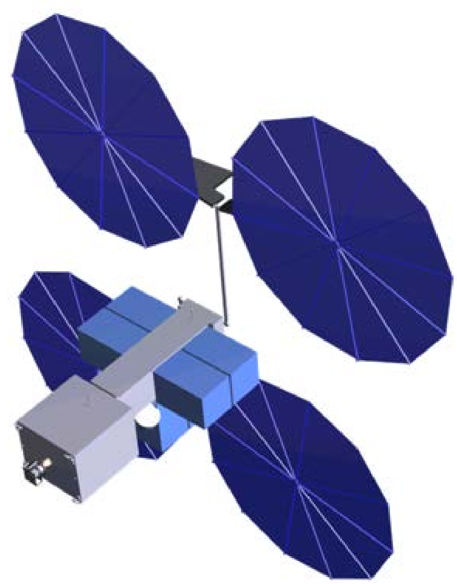

Fig. 4: LTV concept in cruise configuration showing six representative payloads (blue boxes).

IV. OPERATIONS CONCEPT

A preliminary concept of operation was developed for the LTV mission and discussed with ISS personnel. While further refinement will be needed, the basic steps in the operations concept would consist of:

1. Microsats are delivered to ISS over multiple visits as opportunities on other ISS supply missions arise. These would be stored on the ISS until a sufficient number were ready for transfer to lunar orbit.
2. The LTV would be delivered to the ISS by the HTV. The HTV pallet is designed to interface with the Japanese Experiment Module (JEM) on the ISS, which contains its own robotic manipulator system (RMS). This RMS would be used to unload the modules from the HTV pallet, mate them, and dock the integrated LTV to the JEM Exposed Facility (EM, Fig. 5).
3. Microsat payloads would be attached to the LTV using the JEM RMS
4. The laden LTV would be given a "push-off" from the ISS, and final deployments would be completed once separated.
5. Following initial system checkouts, the LTV would activate its SEP system and begin the low energy transfer to lunar orbit.
6. Once in lunar orbit, payloads would be individually deployed by the LTV.

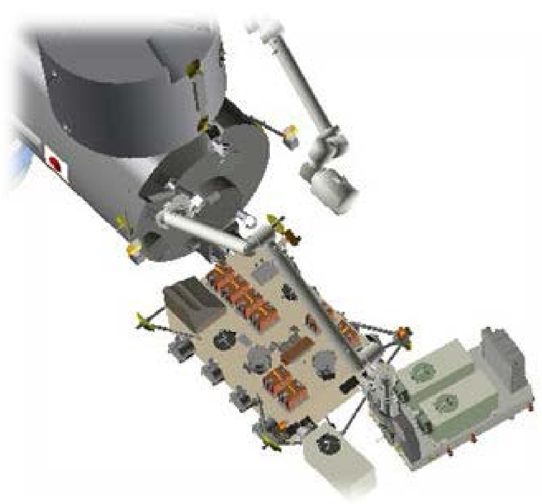

Fig. 5. JEM Exposed Facility, showing manipulation of external payloads using RMS.

Although the LTV was not designed to be reusable through a return to the ISS, it was recognized that the vehicle itself would provide a capable spacecraft bus in lunar orbit once it has deployed its independent payloads. It would be possible to use this bus as a host for one or more instrument payloads that stay attached to the LTV. Data and power interfaces are provided at each payload attach point and with attention to interface requirements definition this could become an attractive feature, enabling more capable observations at a minimal cost. It would also be possible to have the unloaded LTV operate as a telecom relay satellite after the payloads are deployed. The flexibility provided by the LTV flight system and mission concept leave a wide range of options open for use of the vehicle beyond its payload delivery function.

V. MISSION DESIGN

Detailed low thrust trajectories were developed for the LTV mission, optimized for maximum payload delivery. The resulting trajectory is illustrated in Figure 6. The total mission time from ISS to a 100 km lunar orbit is ~18 months with the maximum payload mass of 250 kg. This represents a balance of propellant mass and payload mass, limited by the maximum capability of the HTV unit mass. Trip time is a major consideration given the radiation dose implications of a slow transit of the Van Allen belts, and an optimization for a faster transit could reduce this trip time somewhat, with an attendant cost in payload capability.

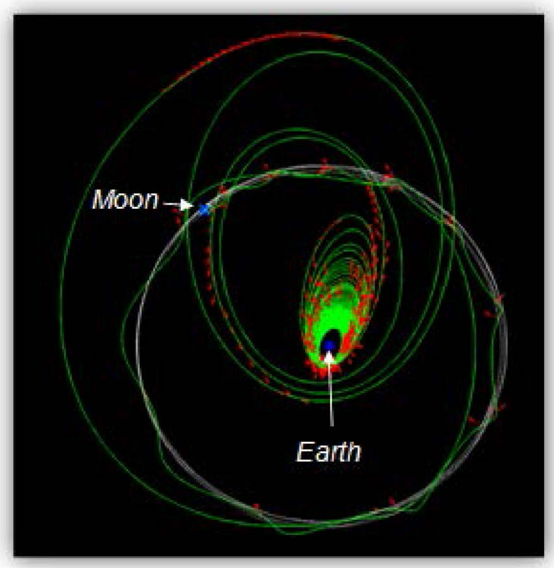

Fig. 6: LTV Mission Trajectory.

Radiation Dose Modelling

As mentioned above, the slow transit of the Van Allen radiation belts required by this mission concept would result in significant radiation dose to the LTV and payloads. This is mitigated somewhat by the relatively high inclination of the ISS orbit, but radiation dose would be a factor that must be considered in the design.

Radiation analysis was performed for the baseline trajectory described above for the combination of trapped protons and electrons, as well as solar proton and Bremsstrahlung dose during the mission. Results of the modelling indicate that a total ionizing dose of about 64 krad (behind 100 mils Al) would be seen by the LTV. For comparison this is a slightly higher dose than that seen by geosynchronous satellites over the course of their lifetimes, but well within the range of current parts and manageable through judicious design.

SUMMARY

The ISS provides an orbital base for a variety of activities, expanding as the facility nears completion. The concept of using the ISS as an assembly and launching point for lunar-bound microsat payloads is an activity for which the ISS is uniquely suited, with infrastructure already in place to accommodate operations necessary to deliver, assemble, and launch an LTV in a mission like the one described in this study. The flight system as conceived is buildable using currently available subsystems and components and requires no new technologies. The mission concept is relatively straightforward and would open a path to a rich variety of low cost lunar missions, and the spacecraft bus could itself be used as a host for more capable investigations.

This study was a first look at this exciting concept. While significant work remains to refine and optimize flight system and trajectory designs, indications are that the concept would be a feasible and attractive augmentation of the capabilities of the ISS.

ACKNOWLEDGEMENTS

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