Rideshare and the Orbital Maneuvering Vehicle: the Key to Low-cost Lagrange-point Missions

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ABSTRACT

Rideshare is a well proven approach, in both LEO and GEO, enabling low-cost space access through splitting of launch charges between multiple passengers. Demand exists from users to operate payloads at Lagrange points, but a lack of regular rides results in a deficiency in rideshare opportunities. As a result, such mission architectures currently rely on a costly dedicated launch.

NASA and Moog have jointly studied the technical feasibility, risk and cost of using an Orbital Maneuvering Vehicle (OMV) to offer Lagrange point rideshare opportunities. This OMV would be launched as a secondary passenger on a commercial rocket into Geostationary Transfer Orbit (GTO) and utilize the Moog ESPA secondary launch adapter. The OMV is effectively a free flying spacecraft comprising a full suite of avionics and a propulsion system capable of performing GTO to Lagrange point transfer via a weak stability boundary orbit.

In addition to traditional OMV 'tug' functionality, scenarios using the OMV to host payloads for operation at the Lagrange points have also been analyzed. This analysis has led to definition of a mission concept to allow space weather monitoring at the Earth-Sun L1 point as well as perform the technology demonstration of an advanced solar sail payload.

INTRODUCTION

NASA Ames Research Center (ARC), NASA Langley Research Center (LARC) and Moog Incorporated (Moog) have performed initial mission and spacecraft system design enabling a low-cost combined operational and technology demonstration mission at the Sun-Earth L1 Lagrange point (L1). L1 is ideally suited for making observations of the Sun-Earth system given that objects at this location are never shadowed by the Earth or Moon. The motivation for this activity was to offer reduced cost for missions looking to operate at L1 and provide a platform for future development for other missions on the edges and outside of Earth orbit. This mission concept is called The Example Low-cost Lagrange Investigation Exploration (ELLIE).

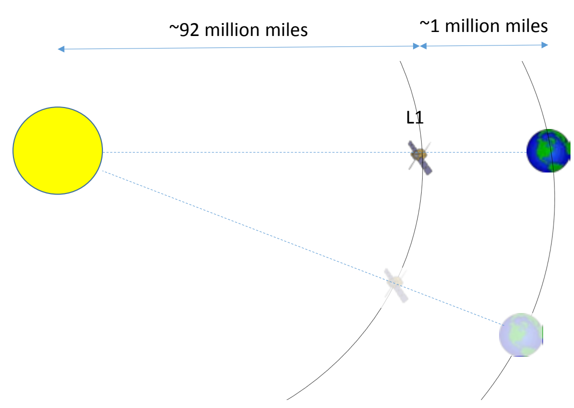

Figure 1: Earth Sun L1 Lagrange Point

Mission Partners

ARC is a world-class research facility located in the heart of Silicon Valley. For more than 75 years, ARC has led NASA in conducting world-class research and development in aeronautics, space exploration technologies, small spacecraft innovation, astrophysics, aerospace, Earth and space science. ARC has a history of developing low-cost small spacecraft for science mission. Starting in the early 1960's, ARC developed spacecraft for the Pioneer Program, followed by the Pioneer Venus Probe, the Galileo Probe, and finally Lunar Prospector. In the past 15 years, ARC developed, launched, and/or executed operations for Kepler, LCROSS, IRIS, and LADEE. NASA Ames Research Center is committed to find ways to design a low-cost spacecraft to operate critical missions for NASA and across other US government agencies. ARC has enjoyed successful partnerships with industry in developing low-cost small spacecraft. Heritage from LCROSS and LADEE fed into the concept discussed in this paper to transport secondary payloads from GTO/GEO to L1.

LaRC has a successful history of developing lightweight and deployable structures and materials technologies for space applications dating back to Project Echo in the 1960s. Ongoing spacecraft structures research includes large solar arrays, inflatable aerodynamic decelerators, advanced polymers, composite materials, and solar sail structures and systems. LaRC is the developer of Clear Polyimide-1 (CP1), the state-of-the-art material for high performance solar sail membranes, used on NASA's NanoSail D solar sail mission.[1] LaRC also leads the agency in solar sail structures modeling, simulation, structural analysis, and ground validation testing, serving as the structures validation lead for NASA's ST7 and ST9 solar sail studies, and the In-Space Propulsion Technology (ISPT) development project, NASA's most significant solar sail technology development project to date.[2] Under the ISPT program, LaRC coordinated ground validation testing and analysis activities for the project's two 20-m solar sail ground demonstrator systems. Both ISPT solar sail systems have since been studied for potential L1 technology demonstration missions. One such mission concept is described below as an example OMV rideshare opportunity.

Moog is a worldwide designer, manufacturer, and integrator of precision motion control products and systems for a variety of markets including satellites and space vehicle. Moog Integrated Systems provides a focal point to harness the breadth and depth of Moog's capability for customers at the advanced mission stage. Moog's Mountain View operation is very near ARC and along with other Moog Space has collaborated with NASA since the mid-80's.

EXISTING AND FUTURE USE OF LAGRANGE POINT ORBITS

Missions at Lagrange Points

Launched in 1978, the International Sun-Earth Explorer 3 (ISEE-3) was the first spacecraft to be put into orbit around a libration point (L1) where it operated for four years investigating the interaction between the Earth's magnetic field and the solar wind.

Currently in operation at the L1 libration point is the NASA Advanced Composition Explorer (ACE) spacecraft that monitors the solar wind in real-time. Data from ACE is supplied to the Space Weather Prediction Center (SWPC) that is part of the National Oceanographic and Atmospheric Administration (NOAA) to enable advance warnings of geomagnetic storms. The Solar and Heliospheric Observatory (SOHO) is a European led mission that has been operating at L1 since 1996 following multiple mission extensions and also provides near real-time solar data for space weather prediction. The NASA Wind spacecraft has also been in operation at L1 since 2004 and provides complete plasma, energetic particle, and magnetic field input for magnetospheric and ionospheric studies.

Geomagnetic storms can impact the electric power grid, aircraft operations, the accuracy of the Global Positioning System (GPS) as well as affecting both unmanned and manned spacecraft. For example, in July 2012, a massive solar storm missed Earth by one week purely due to the instantaneous position of the Earth with respect to the sun at that time[3]. It is thought that if Earth had been hit by the storm, the event would have been as powerful as the 1859 Carrington event[4] likely with devastating consequences for may technological systems.

Most recently, in February 2015, (NOAA) Deep Space Climate Observatory (DSCOVR) was launched and in June 2015 arrived at the L1 Lagrange point. DSCOVR will eventually replace ACE as America's primary warning system for solar magnetic storms headed towards Earth but, for now, the two spacecraft operate in tandem. In addition to space weather-monitoring instruments, DSCOVR is carrying two NASA Earth-observing instruments that will gather a range of measurements from ozone and aerosol amounts, to changes in Earth's radiation budget—the balance between incoming radiation (largely from the sun) and that which is reflected from Earth.

Future Missions at Lagrange Points

Many missions are in the proposal phase for operations at L1 but the next spacecraft destined for launch is the European Space Agency (ESA) and NASA-led Laser Interferometer Space Antenna (LISA) Pathfinder. LISA Pathfinder will place two test masses in a nearly perfect gravitational free-fall, and will control and measure their relative motion with unprecedented accuracy. LISA Pathfinder will prove key systems such as drag-free attitude control of a spacecraft with two proof masses, the feasibility of laser interferometry in a specific frequency band as well as the general reliability of key components. A successful LISA Pathfinder mission would allow the full LISA system to be built and deployed that would be able to detect and accurately measure gravitational waves.

In this paper, a set of requirements relevant to such future missions has been both identified and analyzed. The resulting point design solution is The ELLIE mission that can be used as a convenient baseline for future mission planning.

Utility of Solar Sails for Space Weather Monitoring Missions

Severe solar space weather events, and in particular, solar flares and ejections of magnetized plasma called coronal mass ejections (CME), can produce major disruptions to terrestrial electrical power grid operations, communications, including Global Positioning System (GPS) signals, and in some cases satellite electronics. CME with magnetic orientations antiparallel to the Earth's magnetic field are particularly disruptive. Instruments on NASA's ACE spacecraft, and soon to be operational DSCOVR spacecraft, both stationed at the Sun-Earth L1 point, currently provide the only direct warning of an imminent dangerous CME impact with the Earth. Warning times are currently on the order of 30-60 minutes, depending on the velocity of the CME event.

Stationing spacecraft with space weather monitoring instruments at an artificial Lagrange point (ALP) closer to the Sun than the natural Sun-Earth L1 point could directly increase warning of major solar weather disruptions, permitting electrical power grid and satellite operators more time to take preventative action to mitigate damage and disruption to their systems. Positioning space weather monitoring instruments at or about an ALP closer to the Sun requires continuous thrust from a spacecraft, which is impractical using conventional chemical propulsion systems. Solar electric propulsion can provide the required thrust for short durations, but would be impractical for mission durations beyond five years. For the long mission durations desired for an operational space weather early warning system (10 years or more) solar sail propulsion systems have been proposed[5]. A solar sail uses a large, lightweight reflective membrane to develop thrust from direct momentum transfer of reflected solar photons[6]. Since this requires no propellant, a solar sail can, in principle, provide thrust indefinitely, subject only to the durability of its membrane sail in the space environment.

Since the technological maturity of solar sails is still relatively low, a technology demonstration mission (TDM) for a solar sail system capable of meeting the requirements for an improved warning time space weather monitoring system is needed. Ideally, this solar sail TDM would demonstrate deployment and operability of the solar sail system in its eventual operational environment, in this case, the sub-L1 environment. The OMV approach outlined herein would enable such a solar sail TDM to be accomplished at relatively low cost. In this paper, the ELLIE mission provides a description of one such possible solar sail TDM.

ACHIEVING LAGRANGE POINT ORBIT USING RIDESHARE OPPORTUNITIES

All of the past and future L1 missions described in the early part of this paper relied on a dedicated launch. This means that the sponsor of each mission provided all of the funding to pay for space access. This approach is the traditional method of lifting payloads to space and, in recent years, squeezed national space budgets have pressured mission designers to find a more cost effective approach. An example of such efforts is the United States Air Force (USAF) investigation into the feasibility of launching two GPS spacecraft on a single Evolved Expendable Launch Vehicle (EELV) that could potentially save around $50M in launch cost per spacecraft[7]. This is one example of multiple spacecraft being launched on a single vehicle and there is now a growing sector within the space industry identifying and exploiting such "Rideshare" opportunities for multiple mission sponsors looking to share launch costs.

There are several types of rideshare opportunities appearing. At the most basic, a hosted payload is a sensor or other instrument that leases accommodation space (including resources such as power and communications bandwidth) from another spacecraft splitting both spacecraft launch and development cost. Dedicated rideshare missions are entire flights that are procured (typically by brokers) with launch capacity split between different paying customers. Such customers pay different rates based on parameters such as their position on the stack and size. A Secondary

Rideshare launch is when additional spacecraft are deployed into orbit using the excess capacity of large launch vehicles originally hired for use by a single spacecraft.

It is this latter scenario that forms the basis of the launch strategy for ELLIE. Moog and NASA have identified that there are roughly twenty five commercial launches a year to Geostationary Transfer Orbit (GTO) and that typically five to ten of these are classed as US launchers. In addition, the US government also typically launches between two to eight GTO missions per year. ELLIE seeks to take advantage of both this cadence of launch opportunities to GTO and the contribution towards launch costs from another passenger. Not covered in this paper but analyzed as part of this exercise, the ELLIE team performed a survey of specific GTO rideshare opportunities and included candidates in both the project schedule and cost.

MOOG ORBITAL MANEUVERING VEHICLE

The Orbital Maneuvering Vehicle (OMV) is a Moog capability that draws from the depth and breadth of experience gained supporting missions over the last 40 plus years. Moog supplies a variety of systems and components to the launch vehicle and spacecraft community that can be brought together in for alternative OMV mission applications. The OMV concept has grown from the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA). The ESPA was originally developed by Moog for the USAF to access unused launch capacity for high value US Government missions. The ESPA is traditionally housed between the primary passenger and the launch vehicle upper stage and carries small satellites that can be deployed after safe jettison of the primary. This concept is now well proven and has been flown on Atlas V, Delta IV, and Falcon 9, allowing use of full launch vehicle capability.

Originally the ESPA was developed in a six port configuration with each port capable of deploying spacecraft up to 180kg using a low-shock separation system. Today, numerous ESPA configurations are available with different heights, numbers of ports and port capacity of up to 300kg. In addition, Moog has worked with US Government and commercial partners to develop the capability to deploy swarms of cubesats of various sizes. Configuration options are numerous with traditional Poly Picosat Orbital Deployer (P-POD) type deployers recessed within the ESPA ring or cubesats launched from systems mounted directly on ESPA ports.

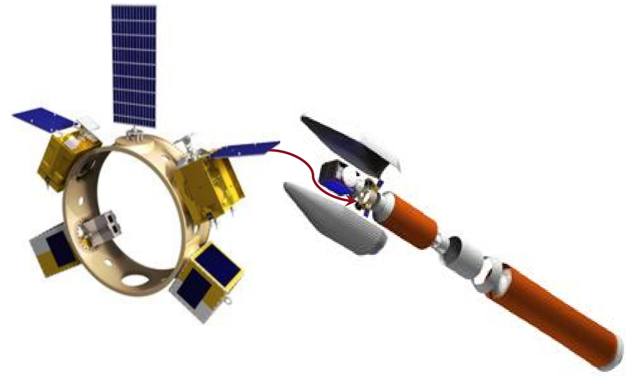

Figure 2: ESPA is a proven rideshare technology

The exponential increase in the capability of small satellites means their missions are deliver higher and higher value for commercial, scientific and government customers. However, as the capability of small satellites increases, the ability of mission sponsors to gain the optimal value from their payloads can only be achieved if spacecraft can be placed in optimal orbits. The traditional rideshare model enables small satellites access to opportunity launches to destinations that are either driven by the motivations of the primary passenger or a compromise of desired destinations for truly shared launches. Launch vehicles have both limited final stage restart capability as well as a difficulty executing complex ejection strategies to meet the needs of (what could be) dozens of spacecraft. From the small satellite perspective, on-board propulsion capabilities are typically modest so that large orbital maneuvers from injection to desired orbit are not possible. The OMV offers the capability to bridge the performance gap between limited upper stage and small satellite propulsive capability to place small satellites in their optimal orbits.

So far, OMV capability has been described as a secondary launch adapter or tug for small satellites. As utilized on ELLIE, the OMV concept also has a third dimension where the ESPA ring itself can act as the core spacecraft structure. Here, port mounted payloads and other hardware are not deployed from the ESPA but stay attached to perform their mission following separation of the entire ESPA from the launch stack. As shown in Figure 3, the secondary adapter, tug and spacecraft structure functions are not mutually exclusive. Moog has worked on many missions where the OMV performs a variety of functions enabling novel mission capability.

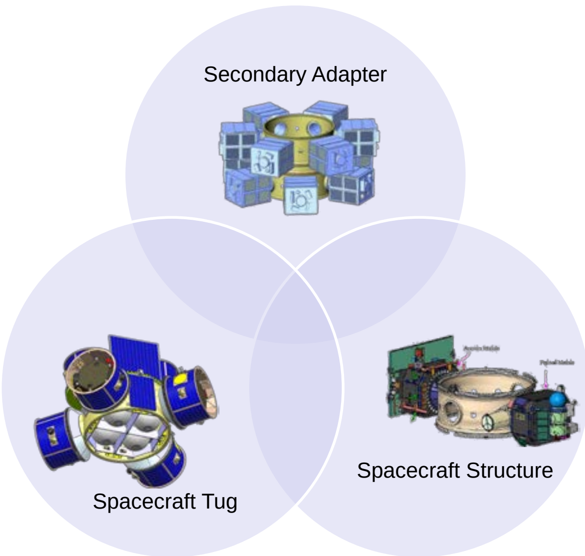

Figure 3: OMV Overlapping Applications

For OMV, the range of capabilities and performance offered are extremely wide so that typically customers do not approach Moog to purchase an Off The Shelf (OTS) catalog product. Instead, high level capabilities that the OMV could offer at mission level are examined to decide where factors such as payload utility and mission budget are best served. Moog performs early sizing analyses of OMV subsystems against both mission performance and cost to allow identification of an early baseline. This baseline is incrementally modified as the mission moves from formulation to formal design phase.

The use of the ESPA to enable OMV-type applications has been well proven and Moog is proud to have been an integral part of missions such as the NASA LCROSS lunar impactor and the USAF Deployable Structures Experiment (DSX) and EAGLE programs. On these programs, Moog was a hardware supplier at the subsystem and component level and is able to provide almost all of the hardware for future OMV. Such vertical integration is extremely valuable as it reduces the additional profit margins of teams of external suppliers and allows for a streamlined program execution where the effect of mission and design modifications on top level cost, risk and schedule can be quickly evaluated. The following bullet points demonstrate that solar panels and batteries are the only major item that Moog would outsource for a typical OMV application:

• The core ESPA structure is a heritage Moog product line produced by the CSA division. Moog CSA is also the world-leader in vibration isolation providing hardware to reduce spacecraft loads imparted by the launcher as well as smoothing the jitter environment seen on orbit by payloads due to disturbance sources such as wheels, gimbals or thermal shock.

• Moog Broad Reach Engineering (BRE) is the world leader in high reliability flight avionics for small satellites. Typically, OMV employ the BRE Integrated Avionics Unit (IAU) that provides the main flight computer, handles all On Board Data Handling (OBDH), performs power conditioning (array and battery control) and load switching as well as precision orbit determination.

• As well as hardware, BRE provides complete flight software suites. Software is also provided for use with EGSE for ground system checkout, full mission simulation and ground operations. Together with Moog hardware capability in attitude control sensors and actuators, BRE is able to specify Attitude Control /Guidance, Navigation and Control (GNC) subsystems and design/code the control algorithms.

• Moog In Space Propulsion (ISP) has decades of experience providing monopropellant and bipropellant components and systems. Moog also has relationships with Electric Propulsion providers enabling very high efficiency (Isp) OMV applications.

• Moog has a strong gimbal capability allowing provision (when needed by specific missions) of 1 and 2 degree of freedom solar array drives, antenna pointing mechanisms and even Electric Propulsion gimbals for thrust vector control.

The following sections describe the specific vehicle configuration selected for ELLIE.

ELLIE MISSION

ELLIE Top-Level Mission Requirements

Based on discussions with potential mission sponsors and payload providers, the ELLIE team used the following key parameters as top-level mission requirements:

- 3 year operational design life at L1, mission life of 5 years, consumables for 10 years
- Selective redundancy philosophy to meet the needs of a NASA class B mission
- Sun pointing accuracy, 0.08deg control and 0.007deg knowledge
- Total payload mass 212.7kg, 180kg for the technology demonstration payload and 32.7kg

- for the permanently hosted sun observing instruments.

- Power to the payloads during cruise to L1 is negligible (just heaters) at 10W and 38W average during L1 operations.

- Payload and spacecraft command and telemetry links are through the Real Time Solar Wind (RTSW) S-Band ground station network.

- Sufficient propulsive capability for the L1 transfer and station keeping at L1.

Top-Level ELLIE OMV Description

Figure 4 shows the OMV configuration selected for OMV. The ESPA has four auxiliary ports, two of which are used for the permanently hosted sun observing instruments and one that is used to house the solar sail technology payload. It should be noted that the fourth port is currently left vacant on ELLIE. This allows room for either an additional GTO payload to be carried and released at GTO, an Earth staring instrument set or further payload(s) to be jettisoned (like the sail) for operations upon arrival at L1. Utilization of this fourth port will allow additional customer funds to be added to the mission, decreasing core ELLIE mission cost further.

It should be noted that the options carrying additional payload to L1 would likely require modifications to a number of subsystems (for example bigger arrays or more delta-V) but such growth is readily permissible with the Moog modular OMV design philosophy.

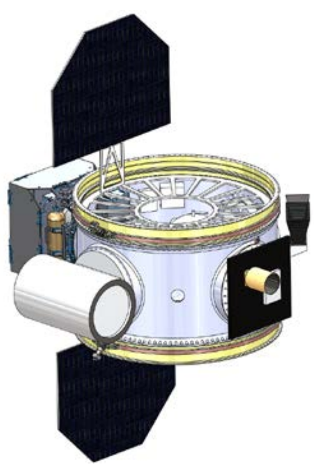

Figure 4: ELLIE OMV

Figure 5 a notional ELLIE OMV configuration with an additional port carrying a FANTM-RiDE dispenser. FANTM-RiDE has been developed with Moog and Tri-Sept™ Corporation and can carry various combinations of both cubesats and microsatellites. Note that the solar sail payload is not shown in Figure 5 for simplification purposes.

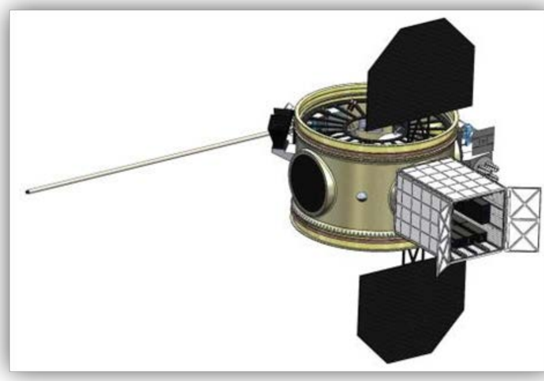

Figure 5: OMV with Space Weather Payloads and FANTM-RiDE Smallsat Dispenser

As with typical Moog designs, the ELLIE OMV is configured to keep platform subsystems inside the ESPA to the maximum degree. This allows for payloads to utilize external space as much as possible. Star trackers, communications antenna and solar arrays are the only platform items that are housed externally. Within the ELLIE OMV is the propulsion system and all other avionics elements required to complete the mission.

Figure 6 shows a block diagram of the ELLIE OMV showing the major elements of each subsystem. Spacecraft structure is provided by the ESPA that interfaces with both the launch vehicle upper stage as well as the attached and jettisoned payloads. The S-Band communications subsystem is shown together with Guidance, Navigation and Control (GNC) sensors and actuators. Major elements of the pressurized hydrazine propulsion subsystem are shown together with the Integrated Avionics Unit (IAU) that provides Command and Data Handling (C&DH) as well as Power Conditioning and Distribution Functionality (PCDU).

ELLIE OMV Hosted Payloads

The ELLIE OMV is an ideal carrier for solar physics instruments and science opportunities. It can readily accommodate instrumentation to measure the flow velocity, or speed of solar particles, diagnose the temperature and density of solar plasma, electron and proton flux, magnetic field analyzers, small telescopic imagers such as coronographs and heliospheric analyzers, and measure electromagnetic radiation spectra. As a high stability, high delta-V spacecraft, the OMV is also generally ideally suited for science missions in any Earth orbit and the inner solar-system.

There are many types of payloads that can be hosted on the OMV to meet a mission at L1. One type of mission that would benefit orbiting at L1 is for the monitoring and early warning of space weather. Effects from magnetic storms has shown to have a detrimental effect on space assets and ground stations.

Coronal mass ejections (or CMEs) are huge bubbles of gas threaded with magnetic field lines that are ejected from the Sun over the course of several hours. Coronal Mass Ejections disrupt the flow of the solar wind and produce disturbances that strike the Earth with sometimes catastrophic results. Coronal Mass Ejections can damage global positioning systems, communication networks, and even interfere with power grids.

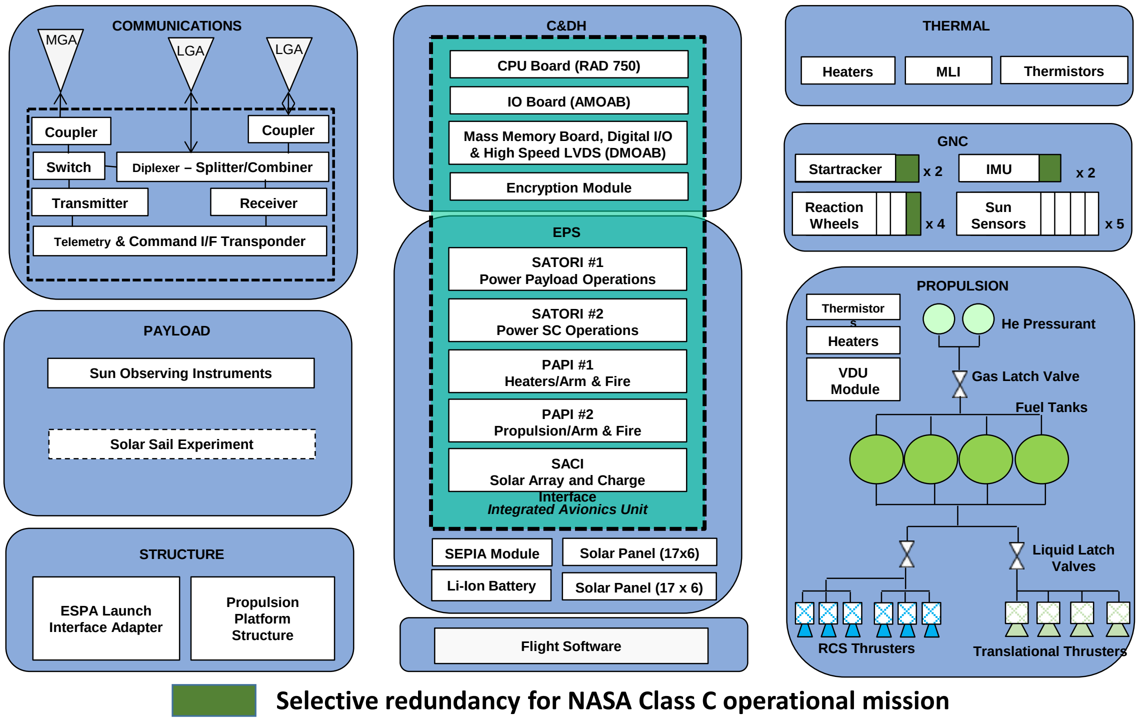

Figure 6: ELLIE OMV Block Diagram

The types of instruments that would be needed for taking the measurements that could help in the early predictions of a magnetic storm are magnetometers, faraday cup, particle ion packages, and coronagraphs.

Other types of payloads that could be on the OMV with solar weather instruments is a solar sail technology demonstration mission (TDM) which could enhance solar weather predictions beyond just instruments carried on the OMV at L1 by getting closer to the sun.

Technology Demonstration: Solar Sail Spacecraft

An example ELLIE OMV-ferried solar sail TDM rideshare spacecraft is pictured in Figure 7.

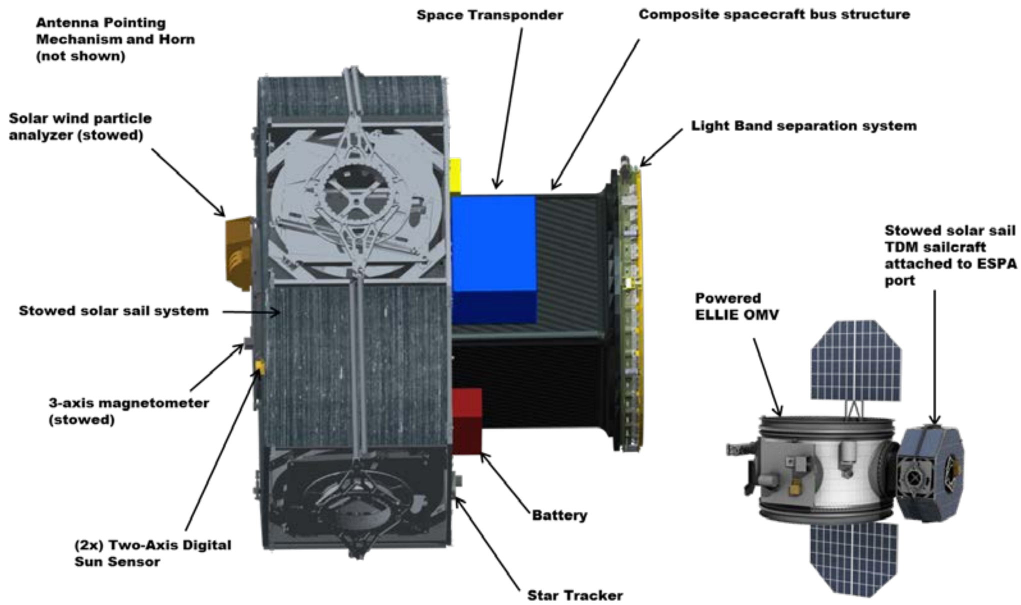

Figure 7: Solar Sail Technology Demonstration Mission rideshare spacecraft.

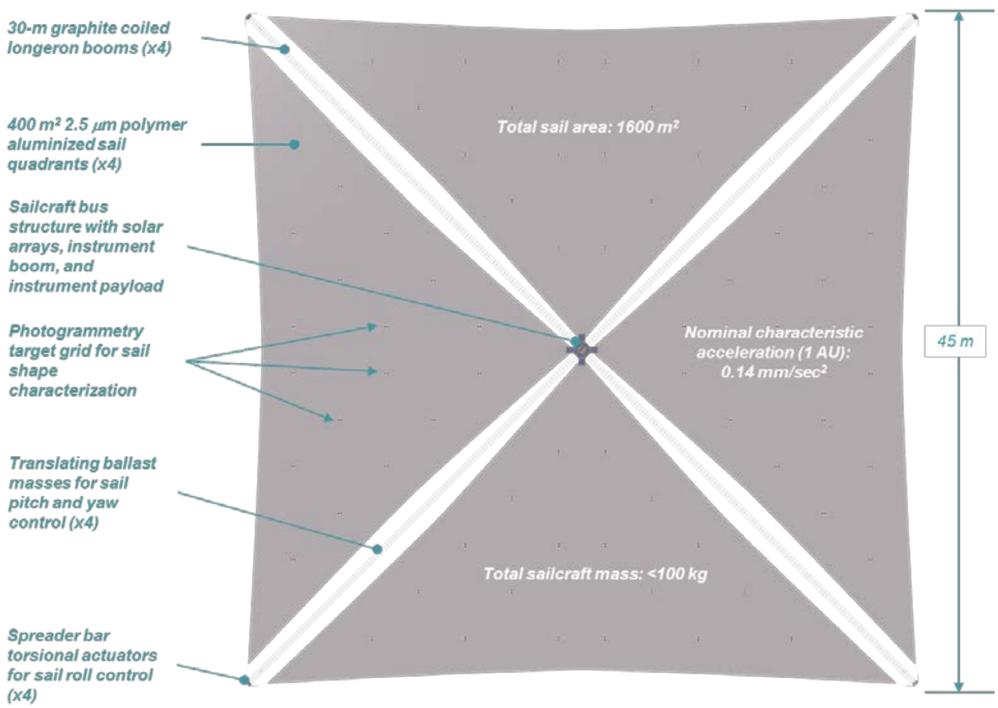

Figure 8: Deployed solar sail characteristics. Total sail area is 1600 m^2. Total sailcraft mass is < 100 kg.

The solar sail TDM spacecraft (*sailcraft*) separates from the OMV host vehicle during its ballistic transfer from the Earth to the Sun-Earth L1 point. Service power for deployment and initial checkout of the solar sail is provided by the OMV. The OMV ACS also maintains an edge-on orientation of the sail to the sun during deployment. This permits sail deployment to be performed without solar radiation pressure interference or disturbances. Sail deployment takes approximately one hour. The fully deployed sail is shown in Figure 8.

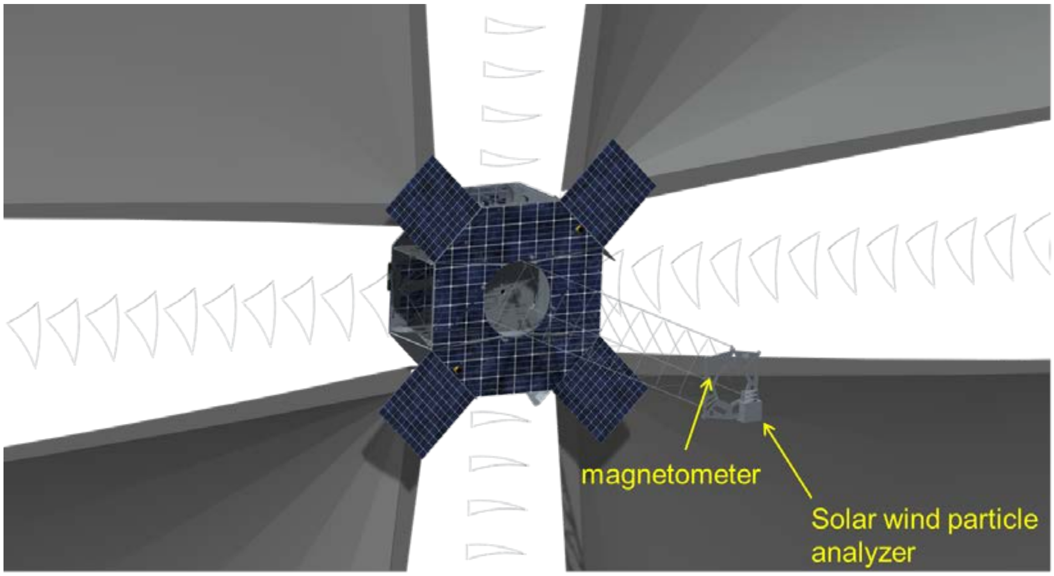

Figure 9: Solar Sail Technology Demonstration Mission particles and fields instruments

A deployable boom with magnetometer and solar wind particle analyzer instruments is also included (Figure 9). Potential interference of the solar sail with these instruments before and after deployment of the solar sail will be assessed prior to separation of the sailcraft from the OMV.

After the sail system is fully deployed, the OMV will slew the still-attached solar sail spacecraft into a safe separation orientation angle with respect to the sun. The sailcraft then separates and flies away from the OMV under the influence of solar radiation pressure alone. Verification of proper sail deployment is accomplished by HD cameras on board the OMV.

Once the sailcraft is at a safe distance from the OMV, it will perform a series of maneuvers to verify and calibrate the sailcraft Attitude Control Subsystem (ACS), after which it will depart for its destination sub-L1 demonstration orbit. Solar sail flight time from OMV separation to sub-L1 halo orbit insertion will take approximately four to six months. Potential sub-L1 destinations include station keeping at an artificial Lagrange point located at 0.987 AU, which is 30% closer to the sun than the natural L1 point (Figure 10). This station keeping point can be kept outside of a 5 degree solar exclusion zone to minimize communications interference from the sun and permit continuous solar weather monitoring by the sailcraft particles and fields instruments.

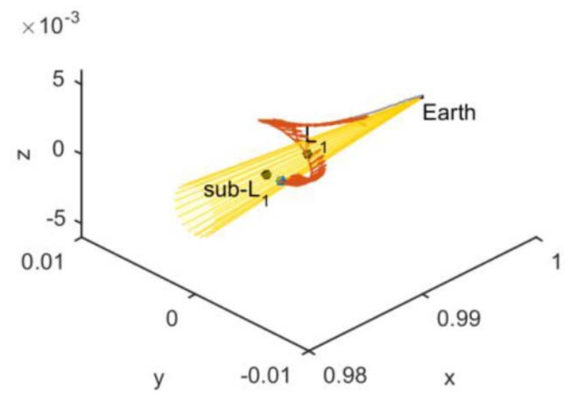

Figure 10: Solar Sail Technology Demonstration Mission sub-L1 Artificial Lagrange Point destination, with 5 degree sun exclusion cone indicated.

A thrust and sailcraft ACS recalibration will take place after six months to assess degradation of the sail in the sub-L1 environment, which will conclude the primary mission of the solar sail TDM. Extended sailcraft mission operations can also be supported, including potential incorporation of the sailcraft particle and fields instruments into the existing NOAA real-time space weather monitoring network. Successful completion of this TDM will validate the essential components and mechanisms of a larger follow-on, operational space weather monitoring solar sail designed to station keep at a 0.98 AU artificial Lagrange point, effectively doubling current solar weather warning time. A constellation of solar sail space weather spacecraft positioned about or orbiting this point could enhance solar weather warning time even further[8].

Launch

ELLIE assumes launch on a Space Explorations Falcon 9 launch vehicle directly into GTO. Figure 11 shows an artist's conception of the upper stage stack with the primary GEO communications satellite passenger at the top of the stack and the ELLIE OMV below.

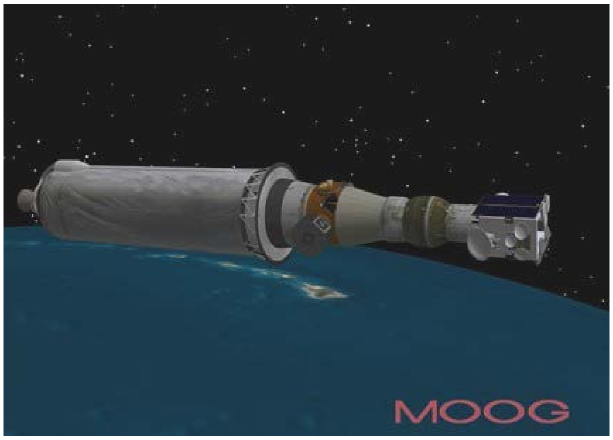

Figure 11: Artist's Conception of Upper Stage ELLIE launch stack

Following ejection of the primary passenger, and after a safe time separation, the ELLLIE OMV is released into GTO. The Falcon 9 Block 2 is rated to carry 4,536kg[9] to GTO (185km x 35,786km at 28.5deg inclination) so that the expected wet mass of the ELLIE OMV of 1097.7kg should leave 3,438.3kg of mass for the primary passenger. Figure 12 shows the OMV spacecraft easily fits inside the Falcon 9 fairing with a large amount of usable volume for the primary passenger.

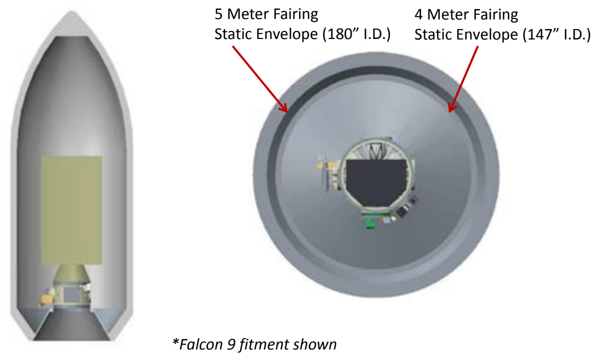

Figure 12: ELLIE and Solar Sail TDM rideshare within the Falcon 9 Fairing

Delta-V Required

After a secondary payload or OMV is deployed in GTO, a number of additional maneuvers are required to reach a Lagrange point orbit. Depending on the time frame allowed, different strategies can be used to either minimize the time or minimize the delta-v (and hence propellant mass) required.

To reach the L1 point, an example delta-v budget is shown in Table 1. This strategy requires two orbit raising maneuvers, one maneuver to enter the L1 transfer orbit, and a final burn to enter orbit at the L1 point.

Table 1: Delta-V Budget

Activity	Delta-V
Launch Vehicle drops OMV in GTO	n/a
OMV Perigee Burn	250 m/s
OMV Perigee Burn	250 m/s
Escape Burn to Transfer Orbit	250 m/s
Trajectory Correction Maneuver	10 m/s
L1 Halo Orbit Insertion	200 m/s
Station Keeping	220 m/s
Wheel Desaturation	10 m/s
Disposal Maneuver	10 m/s
Margin (5%)	56 m/s
TOTAL	1261 m/s

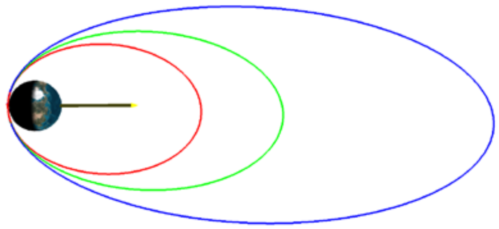

Figure 13:Orbit Raising Maneuvers

Figure 13 shows the initial GTO orbit (red), and the two orbits achieved after the perigee burns (green and blue). The third burn places the spacecraft into the L1 transfer.

The typical initial GTO orientation (argument of perigee of 180° with perigee placed near midnight) lends itself well to a direct transfer to the Earth-Sun L1 Lagrange point. A lunar fly-by trajectory to get to L1 could also be used to reduce the Delta-V insertion cost associated with small-amplitude L1 orbits, however, such transfers require longer trip times, including multiple revolutions in an Earth phasing orbits to carry out the fly-by. This strategy also places an additional restriction on the placement of perigee close to the lunar orbit plane, which may be unacceptable to most primary payloads. See reading references 10,11 and 12, given at the end of this paper, for further study.

ELLIE OMV Mass Summary

A detailed equipment list was derived based on the 5 year lifetime and redundancy appropriate for a Class C mission. Table 2 gives a summary of the ELLIE OMC mass budget with masses (including contingency) given for each subsystem. The Not To Exceed (NTE) OMV mass limit describes the maximum mass that could be ferried to L1 based on the 611kg of propellant and delta-v in Table 1.

Table 2 ELLIE OMV Mass Budget

Item	Mass + Contingency	
Avionics	19.7	kg
Communications	9.6	kg
Power	26.2	kg
ADCS	28.6	kg
Structure	240.8	kg
Propulsion	94.0	kg
Pressurization System	14.1	kg
Thermal	14.2	kg
Harness	17.3	kg
Payload	131.0	kg
Hydrazine Propellant	611.0	kg
Wet Mass	**1206.4**	**kg**
NTE Mass	**1449.0**	**kg**
Margin	**20.1**	**%**

OMV Subsystem: ESPA Ring Adapter

Moog has a large number of ESPA configurations with different numbers of auxiliary payload ports and heights. In terms of payload carrying capability, the standard family is rated to carry 180kg of (transverse mounted) payload per port while the GRANDE can carry up to 300kg per port. ESPA has significant flight heritage through missions such as LCROSS, STP-1 (that carried Orbital Express) and Orbcomm Second Generation (OG2).

For ELLIE, the ESPA Grande has been selected with four payload ports and the ability to carry a stacked primary payload above with a mass up to 6,800kg. The ESPA is a stiffness driven design that has positive margins with a no-test safety factor (2.0). Reduced weight rings are permissible for some missions and can be achieved via a thinner wall thickness while ensuring the resulting lower strength still meets acceptable margins.

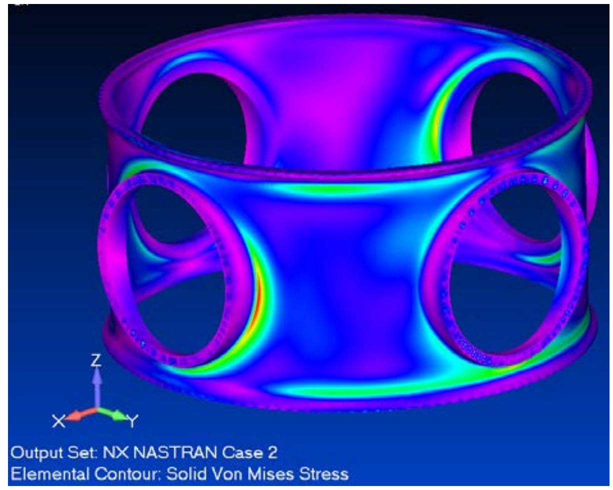

Figure 14: Four port ESPA Grande

Above and below the ESPA are RUAG adapter rings that allow hold and release with the upper stage of the launch vehicle and the primary passenger. Following release of the primary passenger and jettison from the launch vehicle only the passive portion of the adapter stays with ELLIE.

OMV Subsystem: Integrated Avionics Unit

To meet the five year mission requirement, the Moog IAU was chosen. Both command and data handling (C&DH) and electrical power system (EPS) capabilities are housed in a single chassis. The Ajeet board within the IAU provides the C&DH capabilities for the ELLIE mission. The Ajeet board combines the processing functions and the I/O necessary for a complete spacecraft C&DH system on a single 3U board. The Ajeet uses the rad-hard BRE440 system-on-a-chip (SoC) and the rad-hard Virtex-5QV FPGA. Further I/O is accommodated using a DMOAB and AMOAB board within the standard IAU 8-card chassis.

Power management for the 28V bus is provided by the EPS boards within the IAU. These boards consist of the SACI backplane and multiple PAPI switching boards. Shown in Figure 15: Moog Integrated Avionics Unit, the IAU is a single unit of approximately 6kg.

OMV Subsystem: Communications

An S-band architecture has been selected for compatibility with an existing Ground Data System infrastructure. This design leverages the flight-proven LADEE communications subsystem successfully exercised on its lunar mission, but with a higher 13dB Medium Gain Antenna (MGA) due to the increased distance at L1. The Communication subsystem employs two evolved Low Gain Antennas (LGAs) for command uplink at near 4π steradian coverage. Downlink telemetry, health and status S/C data and science data are transmitted out the MGA helix array antenna. The Space Micro S-Band transponder is the same employed by the Ames developed LADEE Spacecraft and transmits at 7W. Preliminary analysis shows that at the operational range of 1.7 M km, a 15 kbps data rate can be achieved with ~3 dB margin if a Ground Station with at least 30.5 dB/K of G/T is used.

Figure 15: Moog Integrated Avionics Unit

The communications requirements and solar exclusion zone dictated the characteristics of the L1 halo orbit. The L1 orbit has significant implications on Earth ground station visibility because of the seasonal tilt of the Earth combined with the out-of-plane halo orbit and the sizing of the halo. Large amplitude halo orbits require lower delta-V to enter and maintain, while a low-amplitude halo is much higher in delta-V to enter and maintain (200m/s+), but has better communication coverage. High latitude stations can be out of view for significant periods (months). Since the mission is for 24/7 solar weather real time monitoring, communication coverage drove selection to a small halo orbit design. The orbit is very similar to the ACE mission trajectory since it provides maximal coverage to existing RTSW earth stations. The resultant orbit is shown in Figure 16 and Figure 17.

An ACE-Like L1 Halo orbit results in the highest percentage of communications coverage, but does not always meet the 4 degree sun exclusion requirement. However, dropout has been minimal with ACE even at <1 degree angles.

This orbit also result in some periods of time (4 years out of every 10) in which there are 2 hour coverage gaps. There is no L1 halo orbit solution that can resolve this without use of additional ground station assets during this period or acceptance of the dropouts.

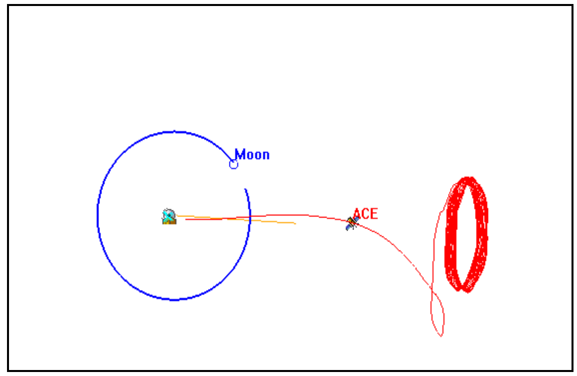

Figure 16: ACE Trajectory

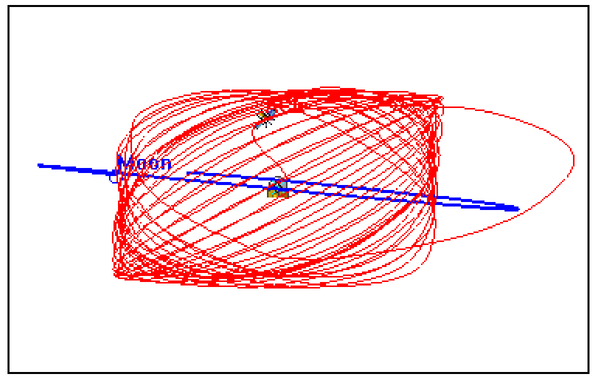

Figure 17: ACE Orbit

Further trades regarding this orbit choice, as compared to a large amplitude halo, will need to be considered. A large amplitude halo orbit has significant delta-V reduction advantages, on the order of 300-400m/s over the mission life. This has implications on propulsion sizing and overall wet mass that drive design and some cost. If a viable communications coverage solution can be found (e.g., a coverage agreement with a low-latitude ground station), then a more efficient large amplitude orbit would be a viable option.

OMV Subsystem: Attitude Determination and Control System (ADCS)

The ADCS components specified for this mission allow for redundancy and graceful degradation. Dual redundant Terma HE-5AS star trackers have been baselined for the prime attitude reference source. Given that the nominal operation orientation of the ELLIE OMV is sun facing and in plane with the ecliptic, star trackers have been mounted so that their orientation will always be orthogonal to the ecliptic plane and hence have no sun blinding periods.

During early and safe mode operations when spacecraft attitude rates could be too high for star trackers, coarse attitude control modes will rely on five Moog Bradford Coarse Sun Sensors distributed around the OMV to ensure continual field of view with the sun. During nominal operations, three axis attitude control will be affected via three Honeywell HR0610 reaction wheels with a fourth flown for redundancy.

The Moog propulsion system will be used for attitude control during early and safe mode operations as well as for momentum dumping for reaction wheels in normal mode. During delta-v operations a Northrop Grumman LN200S Inertial Measurement Unit (IMU) will supplement attitude sensor information to maintain thrust vector orientation.

OMV Subsystem: Power

The ELLIE OMV employs a Direct Energy Transfer (DET) power subsystem architecture where the solar array is directly tied to the battery and thus operates at the instantaneous battery voltage. The Solar Array Charging Interface board (SACI) is housed within the IAU and controls battery charging via a number of Field Effect Transformers (FET) that switch current from solar array sections to the battery. In this way, the 28V Lithium-ion battery is safely maintained below maximum voltage to prevent overcharge.

Power switching and processing boards within the IAU control power supply to specific ELLIE platform and payload loads under guidance from the flight computer. The variable voltage from the Lithium-ion battery is regulated via converters within the IAU to satisfy the needs of the loads around the spacecraft. In addition to load switching to support nominal operations, the IAU is also able to load shed during anomalous event to conserve power.

The baseline solar array is split into two wings on the North and South faces of the ELLIE OMV. The baseline arrays employ Emcore ZTJ cells offering more than 500W at Beginning Of Life (BOL) and sufficient to meet EOL power requirements at the end of the mission. Each solar array has a total area of 1m^2 and conservative packing factors and degradation estimates have been used for all performance analyses. The current ELLIE OMV arrays are not required to be gimbaled given the sun staring orientation but are stowed flat for launch. Solar array sizing was driven by nominal operations when all instruments were powered and it was ensured a safe margin existed to support both payload and platform loads.

For energy storage, the ABSL (Enerys) heritage battery from the LADEE mission has been baselined that offers 24Ah modular building blocks. Two such modules have been baselined giving 48Ah for the battery system. During battery sizing analysis, seven power modes were analyzed but the driving power cases was found to be during operation of the large delta-V thrusters during L1 transit (assumed occurring while arrays not pointing at the sun). According to best Moog practice, sizing ensured that Depth Of Discharge (DOD) did not exceed 60% and that an acceptable minimum voltage was supplied during high thruster valve actuation current discharge events.

Figure 18: 24Ah modular battery building block

It should be noted that both the IAU, solar array and battery have been conceived to be modular allowing for growth or shrinkage to meet alternative missions.

OMV Subsystem: Propulsion

The OMV's propulsion system is designed to be modular to allow for an adjustment of delta-v and thrust capabilities without major changes to the system. The monopropellant options include blowdown and pressurized, Hydrazine and "green propellant" LMP-103S, and variable tank configurations. Monopropellant engines provide a wide range of thrust options from 1N to 170N. Even the thrusters are modular from an interface point of view with only three different thruster valves across that whole range. This "common but modular" design philosophy supported the initial trades for the mission concept.

As the OMV propulsion system is designed to be modular there are performance ranges based on system complexity, mass, and ultimately cost. The "entry level" configuration is designed to fit within a standard 24" (61 cm) height ESPA. The ESPA dimensions are also easily variable so there is no true "standard height" but a value of 24" (61 cm) is typical. The entry level configuration is based around six propellant tanks each 19" (48 cm) diameter to meet this self-imposed height constraint. In a pressurized configuration this has a maximum capacity of 306 kg of Hydrazine propellant.

The ELLIE OMV system utilizes four MONARC-90 thrusters for large, translational maneuvers and six MONARC-5 thrusters to meet the reaction control system (RCS) requirements. The propellant tanks and one helium pressurant tank are mounted within a composite deck internal to the ESPA ring, shown in Figure 19.

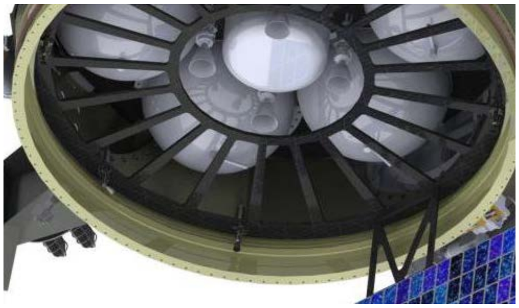

Figure 19: OMV Propulsion Tanks and Thrusters

The mission design drives the overall delta-V budget as shown in Table 1. The entry level configuration does not directly close with the desired delta-V, payload mass, and propellant mass margin (20%). It is possible to close on the delta-V budget if a portion of the budget could be provided by the launch vehicle (150 m/s) and not carrying any separable payloads to the Earth/Sun L1 orbit.

The mission baseline configuration using larger propellant tanks is used with the rest of the propulsion system the same so both trades can remain open during the project planning. To achieve the propulsion system requirements, Moog designed a system with a capacity of 611 kg of Hydrazine propellant. This was based on four taller cylindrical tanks with a correspondingly taller ESPA. This increased the system propellant mass by 100% while increasing the dry mass by only 14%. This allowed for closing the mission delta-V budget with even greater margin than the baseline 20% as shown in Table 2. Both configurations utilize the same pressurization system design and same thruster configuration. By maintaining the same thruster configuration the power system sizing remains the same.

ELLIE Conceptual Mission Operations

The following bullet points and storyboard aim to outline the basic sequence of mission events for ELLIE.

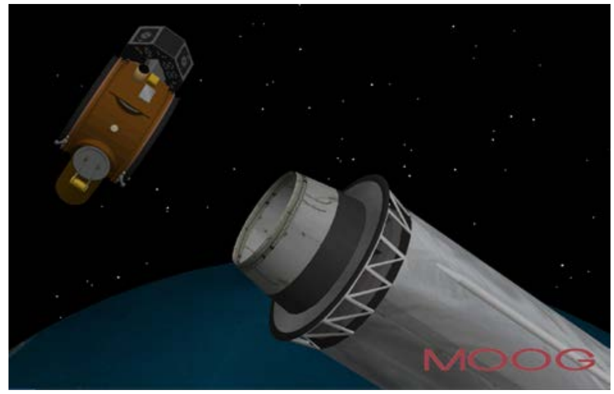

Figure 20: Primary payload and OMV separate from launch vehicle in GTO

- Following safe release of the primary passenger, the ELLIE OMV is released into GTO.
- OMV initialization is performed with switch on of the communications subsystem and IAU as well as deployment of the solar arrays.
- Using sun sensor inputs and thruster based control, a safe sun pointing mode is entered for full spacecraft checkout.

Figure 21: OMV Perigee Burn

- Propulsive maneuvers are performed and, after 3-months, the ELLIE OMV completes a single burn to enter orbit at the L1 point.
- The Solar Sail Technology Demonstration payload is deployed from the OMV and completes its mission independently using on-board systems.
- The OMV orients to a sun-staring configuration and the space weather instruments are commissioned.

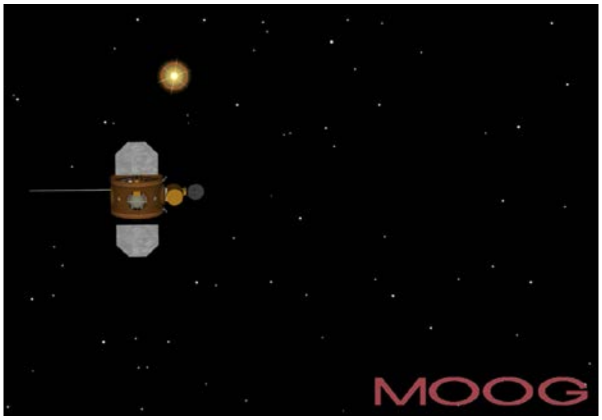

Figure 22: Sun Staring Orientation

- Five years of operations commence. Station-keeping maneuvers are performed periodically.
- When operations end, the OMV completes a small burn to move out of the L1 orbit.

CONCLUSION

ARC, LARC and Moog have worked closely together and developed a conceptual design for a low-cost L1 mission. It is possible to use existing chemical propulsion technology to transport a propulsive launch adapter from GTO to L1 as part of a shared launch with commercial or government GEO mission sponsors. This launch adapter could carry additional payloads to further reduce mission cost either dropping them at GTO en route to L1 or at L1 for ancillary mission applications.

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