Responsive Access to Space: Space Test Program Mission S26

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Abstract— Space Test Program Mission S26 (STP-S26) is the twenty sixth dedicated small launch vehicle mission of the Department of Defense Space Test Program.[*†] STP-S26 extends previous standard interface development efforts, implementing a number of capabilities aimed at enabling responsive access to space for small experimental satellites and payloads. The STP-S26 Minotaur-IV launch vehicle is configured in a Multi-Payload Adaptor configuration which includes the following features:

- The Multi-Payload Adaptor (MPA), which was developed by Orbital Sciences Corporation for STP to launch up to four ESPA-class satellites on the Minotaur-IV.
- Provisions for the inclusion of up to four Poly-Picosat Orbital Deployers (P/PODs) to be mounted on the Stage 4 avionics cylinder.
- A dual orbit capability provided by the Hydrazine Auxiliary Propulsion System (HAPS). The design provides volume and mass for four additional payloads attached to the HAPS avionics cylinder.

The actual payload manifest of STP-S26 includes four ESPA-class satellites manifested on the MPA and three cubesats. One of the four ESPA-class satellites is STPSat-2, the first Standard Interface Vehicle. STP implemented a flexible, responsive "dual path" process for a late satellite manifest change. The goal was to delay the final manifest decision as late as possible while minimizing risk. STP-S26 is a complex multi-payload mission and incorporates many innovative capabilities enabling responsive access to space.

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[1]
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1. Introduction

The mission of the Department of Defense (DOD) Space Test Program (STP) is to provide access to space for experiments from the DOD Space Experiment Review Board (SERB). STP-S26 is the twenty sixth dedicated small launch vehicle mission for STP. In total, STP-S26 will launch 14 experiments on seven separate spacecraft, one of the most for a single launch in the 40-year history of STP. STP-S26 will be launched on a Minotaur-IV launch vehicle being developed by Orbital Sciences Corporation (OSC) from the Kodiak Launch Complex under a contract with the Alaska Aerospace Corporation (AAC). The current launch is expected late spring to summer 2010.

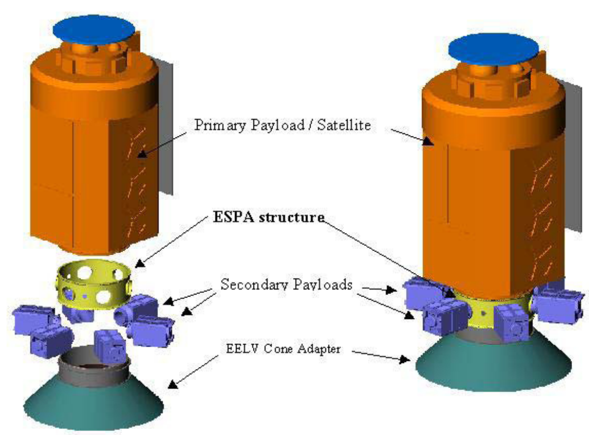

Figure 1 – Fully Loaded ESPA Stack on EELV Illustration

The STP-S26 mission extends previous standard interface development efforts intended to maximize access to space for experimental satellites and payloads. One such effort initiated by STP is the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA). Many large EELV missions launch with unused mass and volume margin. The ESPA ring was developed to accommodate up to six satellites as secondary payloads on an EELV mission. Figure 1 illustrates the ESPA ring and secondary payloads on a notional EELV mission.

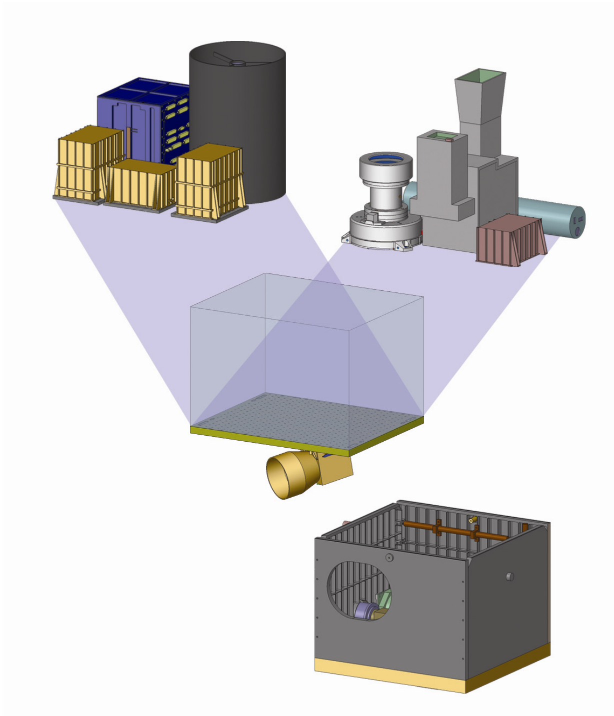

Figure 2 – STP-SIV provides a standard payload interface

The ESPA Payload Planner's Guide (reference 1) defines standards for satellites planning to be compatible with the ESPA ring. Some of the key standards:

- Mass not-to-exceed (NTE) 400 lb (181 kg) with the center of gravity CG not more than 20 in (51 cm) from the interface plane
- Volume NTE 24"x28"x38" (61 cm x 71 cm x 97 cm)

The Planner's Guide also details the mechanical and electrical interface standards, environmental testing standards, and mission integration and documentation requirements. Satellites compliant with the ESPA standards greatly increase their probability of gaining access to space.

Like ESPA, the STP Standard Interface Vehicle (SIV) was developed to improve access to space for SERB payloads. Itself an ESPA-class satellite, the SIV additionally defines a standard interface for payloads. Described in the STP-SIV Payload Users Guide (reference 2), adherence to these standard interfaces makes a payload compatible with SIV and increase the probability of manifest. The SIV is designed to operate over a range of low earth orbit altitudes and inclinations and meet the power, data, attitude and thermal requirements of a broad spectrum of potential payloads. It additionally is designed to integrate onto multiple launch vehicles, including the Minotaur I, Minotaur IV, Minotaur V, and an ESPA ring. The SIV can accommodate up to four payloads weighing 132 lbs (60 kg) and requiring 100 Watts of power on orbit in total. STPSat-2 (described later in this paper) is the first SIV satellite and is manifested on STP-S26. The second SIV, STPSat-3, is currently under development.

The Minotaur-IV family of launch vehicles is developed by Orbital Sciences Corporation under the Orbital/Suborbital Program 2 (OSP-2) managed by the Space Development and Test Wing. It builds upon previous low cost launch initiatives such as Taurus and Minotaur-1. The first three stages of the Minotaur IV consist of refurbished government furnished equipment (GFE) Peacekeeper Stages 1, 2 and 3. The Stage 4 solid motor is the same Orion 38

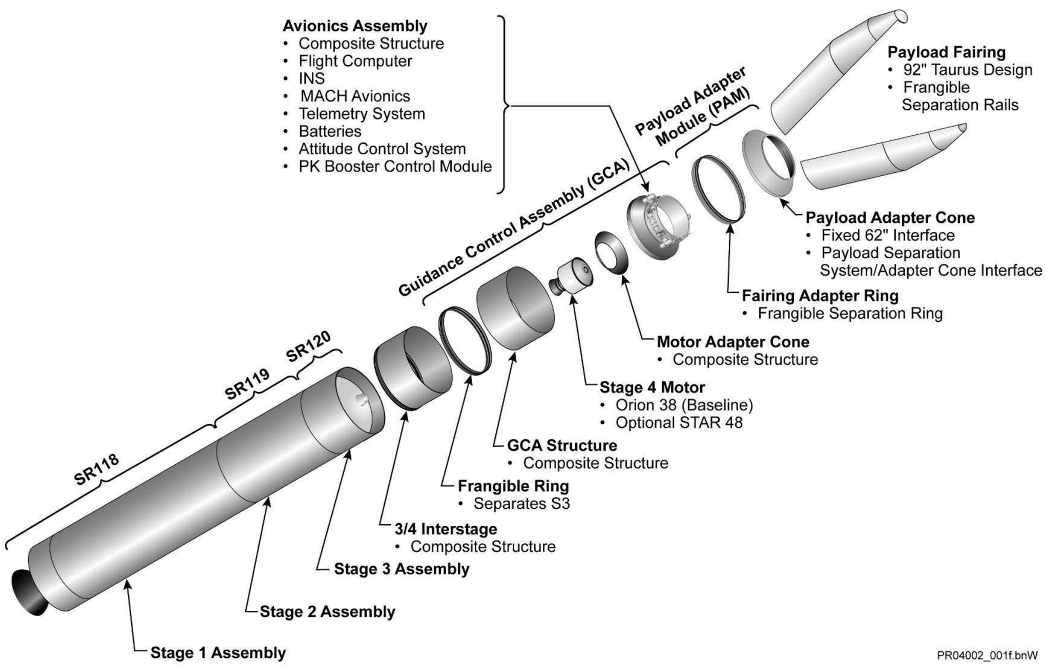

Figure 3 – Minotaur IV Space Launch Vehicle

design used on Minotaur I, Pegasus, Taurus, and other Orbital launch vehicles. An optional Star 48V motor is available for additional performance. Figure 3 depicts the Minotaur-IV launch vehicle. Figure 4 shows the Minotaur-IV mass capacity to circular low earth orbit for a number of inclinations from Kodiak, AK.

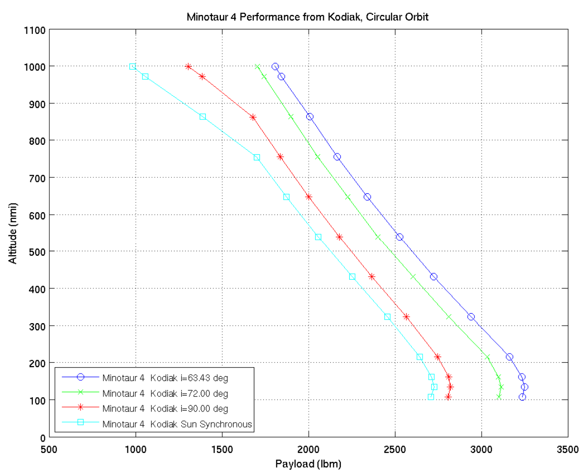

Figure 4 – Minotaur IV Performance from Kodiak

2. MINOTAUR-IV MULTIPAYLOAD ADAPTOR DESIGN REFERENCE MISSION

The Minotaur-IV Multiple Payload Adaptor (MPA) study was sponsored by the Space Test Program and conducted by Orbital Sciences Corporation between June – October 2007. The prioritized government goals for the study were:

1. Provide access to space for STPSat-2
2. Demonstrate dual-orbit capability of the Minotaur IV with Hydrazine Auxiliary Propulsion System (HAPS); same inclination, different altitude
3. Demonstrate multi-payload capability on Minotaur IV to fly additional ESPA-class SVs
4. Provide access to space for additional SERB rideshare experiments

The primary orbit was specified to be 650 km at 72 degrees inclination driven by the primary payload, STPSat-2. The secondary orbit had the same inclination and was to be circular as high as possible to demonstrate HAPS performance.

In conducting the MPA study Orbital also had some corporate objectives. These included meeting or exceeding all the study objectives, incorporating design flexibility so it could meet future mission needs and not be a single point solution, and maximizing commonality by building on existing Minotaur IV design and incorporating Minotaur-V conceptual design concepts.

Some of the deliverables of the study included:

- Configuration layout for the standard fairing for the Minotaur IV launch vehicle including payload envelopes and the proposed adapters
- Trajectory data with margins specified
- Draft interface control document (ICD) for Minotaur IV MPA Design Reference Mission, including mechanical and electrical Interfaces
- Results of preliminary coupled loads analysis

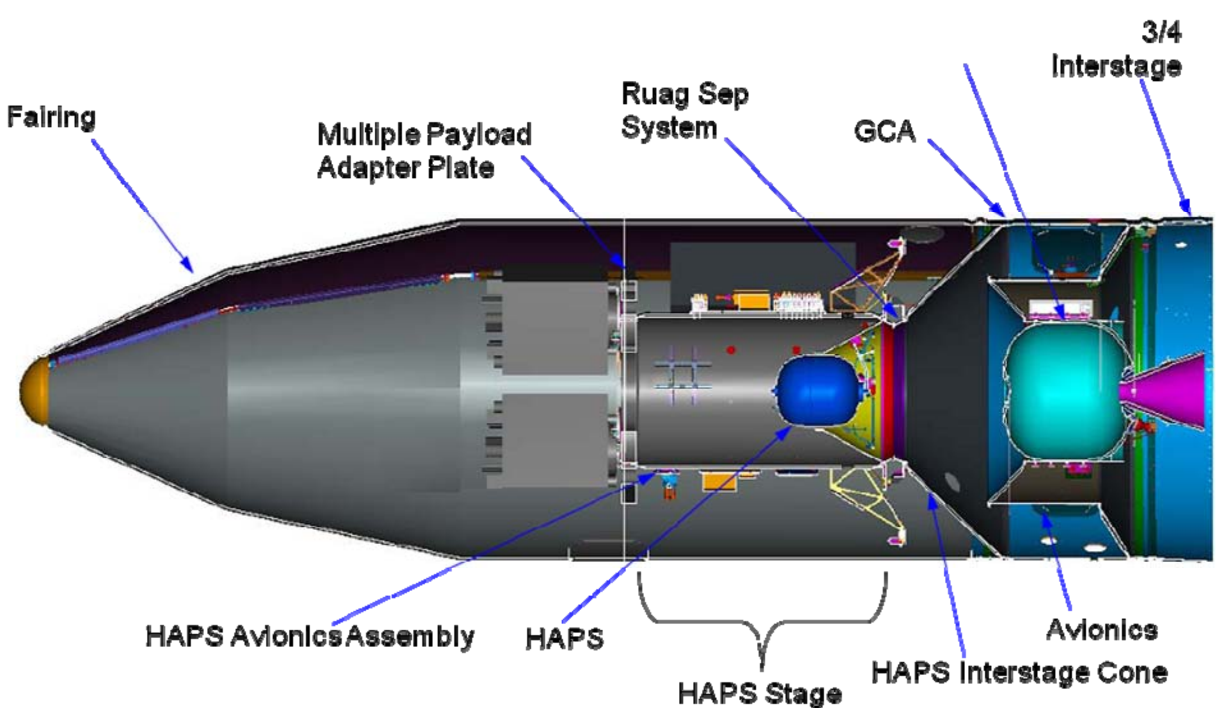

Figure 5 – Minotaur-IV MPA Design Reference Mission

- Execution plan for Minotaur IV multi-payload missions including schedules and funding profile

The result of the study was the Minotaur-IV MPA design reference mission. The results met all the Air Force objectives and incorporated commonality and reuse wherever possible. Figure 5 depicts the configuration layout for the MPA design reference mission. In this configuration the HAPS with its avionics cylinder sits atop a RUAG separation system on the HAPS interstage cone. On top of the HAPS cylinder is the non-separating multi-payload adaptor (MPA). Figure 6 shows an upper view of the MPA.

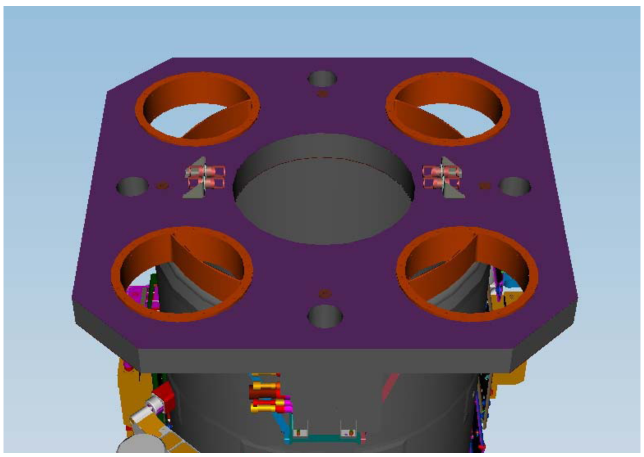

Figure 6 – Minotaur-IV Multi-Payload Adaptor

The MPA has the capacity to accommodate four ESPA class satellites, each weighing up to 400 lbs (181 kg) and measuring 24”x28”x38” (61 cm x 71 cm x 97 cm). Figure 7 depicts an arrangement of four ESPA class payloads on the MPA showing inter-satellite clearances and clearances to the fairing dynamic envelope.

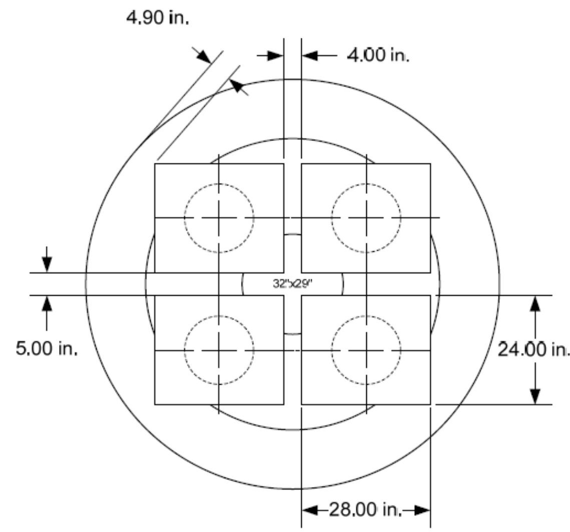

Figure 7 – Arrangement of four ESPA-class satellites on the MPA

The Minotaur-IV MPA design reference mission also provides volume and mass for deploying space vehicles from the sides of the HAPS avionics cylinder. Figure 8 shows the configuration of the HAPS auxiliary payload space. There are locations for four payloads each having a volume not to exceed 20” x 20” x 48” (51 cm x 51 cm x 122 cm). The HAPS cylinder can either accommodate a configuration of two payloads each up to 130 lb (59 kg), or four payloads each up to 65 lb (30 kg). Future MPA missions could utilize this capability to deploy spacecraft into either the primary or secondary orbit.

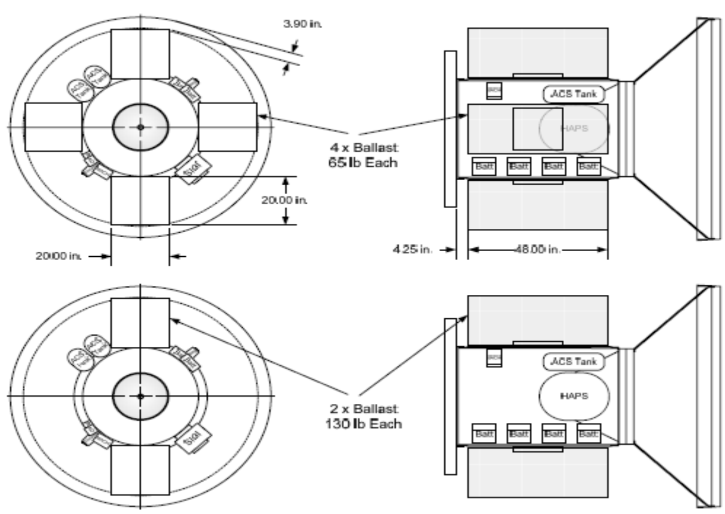

Figure 8 – HAPS cylinder showing mass/volume available on future MPA missions

Finally, the Minotaur-IV design reference mission has provisions for up to four P/PODs to be mounted on the stage 4 avionics cylinder. The locations of the P/PODs are shown in figure 9. Additionally, if the HAPS cylinder locations are not being used by larger spacecraft, up to four P/PODs could be deployed from the HAPS cylinder.

In total, if all payload capability were utilized on the MPA, HAPS cylinder and P/POD locations, the Minotaur-IV MPA design reference mission could launch 12 separate satellites into at least two different orbits.

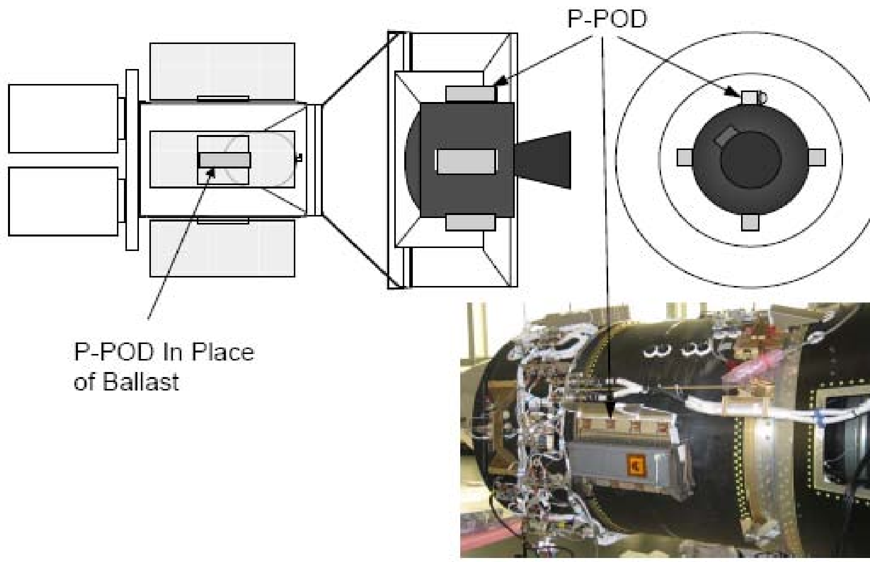

Figure 9 – P/POD Locations

3. Design Reference Mission on STP-S26

Having reviewed the conceptual design reference mission for the Minotaur-IV MPA, the actual implementation of this capability on STP-S26 will be reviewed. The STP-S26 mission will deliver four ESPA-class satellites and two cubesats to a 650 km circular orbit at 72 degrees inclination. The Hydrazine Auxiliary Propulsion System (HAPS) will then deliver two ballast masses to a secondary orbit as high as possible with a goal of 1200 km (circular), demonstrating the dual orbit capability of the Minotaur IV launch vehicle. The four ESPA-class satellites attach to the launch vehicle via the MPAP and will deploy using Planetary Systems Corporation (PSC) Mark II Motorized Lightbands (MLB). The two cubesats will deploy from Poly-Picosatellite Orbital Deployers (P/PODs) attached to the either side of the Stage 4 Orion-38 motor. STPSat-2 is the mission's primary space vehicle, and the S26 mission's three secondary payloads are FalconSat-5, Formation Autonomous Spacecraft with Thruster, RELNAV, Attitude and Crosslink (FASTRAC), and Fast Affordable Science and Technology Satellite (FASTSAT). The two cubesats are Radio Aurora Explorer (RAX) and Organic/Organisms Exposure to Orbital Stresses (O/OREO).

STPSat-2, the primary payload for the STP-S26 mission, is the first use of an STP procured Standard Interface Vehicle (SIV). STPSat-2 weighs 297 lbs (135 kg) and accommodates two Space Experiment Review Board (SERB) experiments: the Space Phenomenology Experiment (SPEX) and the Ocean Data Telemetry Microsat Link (ODTML). SPEX demonstrates suitability of sensors in the space environment. ODTML provides two way data relay from ocean and terrestrial sensors to users.

The US Air Force Academy's FalconSat-5 is a 354 lb (161 kg) cadet-built spacecraft hosting the Space Plasma Characterization Source (SPCS) and two SERB experiments: Wafer-Integrated Spectrometers (WISPERS), and intelligent Miniaturized ElectroStatic Analyzer (iMESA). SPCS is a Hall Effect thruster using cold xenon and ammonia gas propellant. WISPERS will measure SPCS plume ions. iMESA will measure the ambient plasma environment, temperature, and spacecraft charging. FalconSat-5 is fully ESPA compliant.

FASTRAC is a 119 lb (54 kg) spacecraft built by students at the University of Texas at Austin. UT-Austin's space vehicle won the 2005 University Nanosatellite competition, attaining Air Force Research Lab sponsorship and a ride on the STP-S26 mission. The two-satellite system will separate after deployment from the launch vehicle, and then calculate relative position and velocity between spacecraft. FASTRAC's primary goal is to measure errors and residuals of its relative navigation algorithm. It has applications in space situational awareness and formation flight. FASTRAC is fully ESPA compliant.

FASTSAT is a 330 lb (150 km) spacecraft developed by NASA Marshall Space Flight Center, the Von Braun Center for Science and Innovation (VCSI), and Dynetics Corporation. FASTSAT carries six SERB experiments: three technology demonstrations, and three NASA atmospheric research experiments. The technology demonstrations are Threat Detection System (TDS), NanoSail Demonstration (NS-D), and a Miniature Star Tracker (MST). TDS is space-qualifying advanced technology. NS-D is a free flying solar sail that will deploy from a P/POD built into the satellite after FASTSAT has separated from the launch vehicle. The NASA atmospheric research experiments are Thermospheric Temperature Imager (TTI), Plasma Impedance Spectrum Analyzer

(PISA), and Miniature Imager for Neutral Ionospheric atoms and Magnetospheric Electrons (MINI-ME). TTI's objective is to increase the orbit propagation accuracy of LEO assets during solar and geomagnetic storms by remotely measuring thermospheric temperature and atmospheric atomic oxygen. PISA measures resonance frequencies which depend on electron density, temperature, and magnetic field strength. Finally, MINI-ME remotely senses magnetospheric plasma to improve space weather forecasting.

University of Michigan students developed the Cubesat RAX, supported by NASA Goddard. RAX's objective is to understand the microphysics of plasma instabilities which lead to field aligned irregularities of electron density in the polar lower ionosphere. The CubeSat O/OREOS was developed by NASA Ames research center. Its objective is to demonstrate autonomous, in-situ biological organism and organic specimen exposure and detection technologies.

4. Responsive Late Manifest Process

At approximately 18 months before the S26 launch, the manifest MPA space vehicles were STPSat-2, FalconSat-5, FASTRAC, and AFRL's Calibrated Orbiting Object Project (COOP). Due to unforeseen problems, COOP withdrew from the S26 mission. The S26 program office then initiated a trade study to find the best replacement.

Objectives of spacecraft selection included:

1. Maximize SERB payloads flown
2. Minimize risk of flying a spacecraft mass model (if the spacecraft was not ready for launch, they must fly a mass model instead of causing mission delay)
3. Minimize risk to the S26 launch vehicle and other spacecraft
4. Minimize cost to STP

Requirements of spacecraft selection included:

1. Spacecraft must be able to meet all S26 schedule and technical requirements.
2. Technical risk to the Minotaur IV and other manifested spacecraft must remain acceptable.

The trade study identified FASTSAT and Cornell University Satellite (CUSat) as spacecraft that could meet S26 schedule and technical requirements and would not cause unacceptable risk to the S26 mission. CUSat is a SERB ranked (46 kg) two satellite system with applications in proximity operations similar to FASTRAC.

At the time of the S26 manifest trade study, FASTSAT had not completed a Preliminary Design Review (PDR), whereas CUSat had completed its Critical Design Review (CDR) and was fully integrated. With six SERB payloads, FASTSAT maximized SERB payloads flown (STP's highest priority objective), but would have to design, integrate, and test on an extremely accelerated schedule to meet S26 mission milestones. Thus, to mitigate schedule risk to the S26 mission and minimize risk of flying a spacecraft mass model if FASTSAT were manifested but could not meet the S26 launch date, STP pursued a dual path spacecraft manifest. The dual path carried FASTSAT as the primary manifest choice, with CUSat as a "hot backup."

To support the S26 dual path manifest, Orbital identified launch vehicle cost, schedule, and technical risks to a late spacecraft manifest change. Orbital's preliminary parametric studies accounted for various spacecraft mass properties, allowing the launch vehicle to mechanically accommodate spacecraft manifest changes with insignificant technical impact.

However, if Orbital performed the remaining CLAs with only the primary spacecraft, a manifest change would require them to redo these analysis, impacting both schedule and mission cost. Thus, to mitigate this risk, the S26 program office put Orbital on contract to perform cases of all remaining preliminary CLAs for both FASTSAT and CUSat. The STP Director would make the manifest decision before the final verification CLA, which would incorporate test-verified models of all spacecraft and launch vehicle components.

Moreover, a manifest change after Orbital began incorporating spacecraft specific inputs into launch vehicle flight software (approximately L minus 7 months), needed for launch vehicle formal system testing, would also introduce both technical and schedule risk to the mission. The S26 program office decided not to accept this risk and would make a final manifest decision before this milestone occurred.

The S26 program office managed parallel documentation and analysis for both spacecraft, to include dual Interface Control Documents (ICDs), range safety documentation, and preliminary CLAs. The S26 program office then developed the following manifest decision 'gates,' tied both to launch vehicle and spacecraft milestones:

Launch Vehicle Milestones:

1. Preliminary Coupled Loads Analyses (#2 and #3)
2. Coupled Loads Analysis #4 (using test verified spacecraft and launch vehicle models)
3. Launch Vehicle formal system testing

Spacecraft Milestones:

1. FASTSAT PDR
2. FASTSAT CDR
3. FASTSAT environmental testing
4. CUSat environmental testing

The STP Director evaluated overall spacecraft ability to meet S26 technical and schedule requirements at each of these gates. If either spacecraft failed to meet critical launch vehicle or range safety milestones, it would no longer be considered for manifest on S26. During the spacecraft manifest trade study, CUSat had already submitted most required spacecraft models and safety documentation. By contrast, the FASTSAT team was still developing and iterating the spacecraft's models and documentation to respond to pre-PDR design changes. Because FASTSAT's accelerated schedule induced significant technical risk, the S26 program office closely evaluated all aspects of spacecraft design, integration, and test as FASTSAT completed PDR, CDR, and environmental testing. FASTSAT's relative design immaturity allowed the satellite's engineering team to respond to technical constraints imposed due to the late manifest process. At 8 months before launch, and two weeks before the start of the final CLA, the STP Director selected FASTSAT as the fourth manifested satellite on the S26 mission. At that time, FASTSAT had completed vibration and electromagnetic interference testing, and had begun thermal vacuum testing.

During the dual path manifest process, the S26 program office kept a single configuration for both manifest options whenever possible. This reduced potential for mistakes in integrated analysis or mission design. Examples of the single configuration include identical launch vehicle to space vehicle umbilical pinouts, identical spacecraft arrangement on the MPA for either manifest option, and an identical separation order for each spacecraft option. Keeping an identical separation order while maintaining a very low risk of on-orbit spacecraft collision proved to be an interesting challenge, particularly because FASTSAT (148 kg) and CUSat (46 kg) differ significantly in mass. CUSat had already ordered an 18 spring MLB. Due to its relative light mass and high number of springs, CUSat would deploy from the launch vehicle over 5 cm/s more quickly than FalconSat, and over 10 cm/s more quickly than FASTRAC. When the S26 program office was determining separation order, FASTSAT had not ordered its MLB.

Ground rules in separation order selection were:

1. As the primary spacecraft on the S26 mission, STPSat-2 deploys first to minimize its risk of collision with other spacecraft.
2. After one full orbit, spacecraft must be >800m apart.
3. Spacecraft must deploy in order of highest to lowest delta V in each direction, to ensure they would continue to move away from each other throughout their orbits.

Examining the deployment sequence with CUSat, first, meeting all ground rules lead the S26 program office to select the following deployment sequence, where +V indicates the direction of launch vehicle motion:

1. STPSat-2 in the +V direction
2. RAX in the –V direction
3. O/OREOS in the –V direction
4. CUSat in the –V direction
5. FalconSat-5 in the –V direction
6. FASTRAC in the –V direction

This separation order kept approximately 0.05 m/s delta V difference between any pair of spacecraft to ensure all spacecraft would be at least 800m apart after one full orbit.

Even with the maximum number of springs, FASTSAT would not deploy fast enough to fit into this deployment sequence in CUSat's position. The delta V difference between FASTSAT and FalconSat-5 was only 0.03 m/s—not large enough to ensure sufficient distance between the two after separation. Thus, the S26 program office kept the deployment order the same, but added a 30 degree launch vehicle yaw maneuver between FASTSAT and FalconSat-5's deployment to reduce the –V component of FalconSat-5's separation velocity. This solution provided for sufficient distance between all spacecraft as they propagate along their orbits. The deployment sequence is depicted in figure 10.

The S26 responsive late manifest process paved the way for

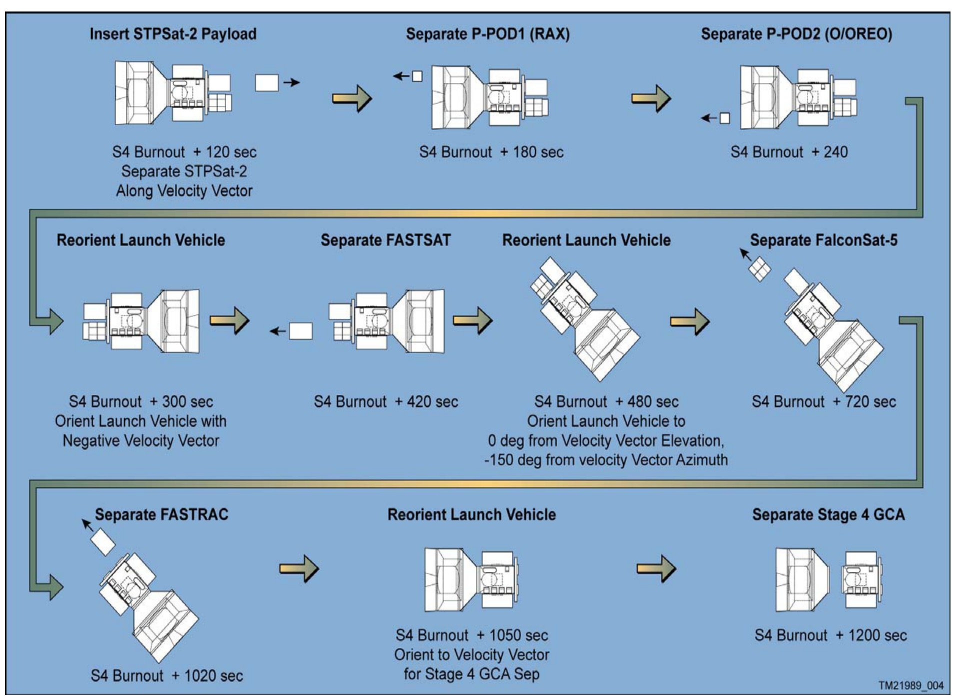

Figure 10 – STP-S26 Primary Orbit Separation Sequence

an even later manifest decision by identifying the mission constraints of CLAs and space vehicle specific inputs to launch vehicle flight software. The responsibility to stay flexible throughout the process, however, does not rest only with the launch vehicle—spacecraft involved in the manifest trade study must also respond to constraints imposed by a late manifest. For example, in S26's case, FASTSAT responded to separation order constraints by choosing the maximum number of springs on its MLB and agreeing to a not-to-exceed mass of 150 kg. There remains potential to choose a spacecraft even later in the launch preparation flow, but a later choice involves greater cost and schedule risk acceptance.

5. CONCLUSION

STP-S26 is implementing a number of features that enhance responsive access to space for DOD payloads. STP-S26 builds on previous work defining ESPA standards and provides the first launch of a Standard Interface Vehicle (SIV). It also builds on the development of lower cost launch vehicles built on surplus GFE missiles.

The Minotaur-IV MPA study defined a design reference mission that achieved a number of objectives. The MPA provides launch capability for up to four ESPA-class micro-satellites. The HAPS provides a dual orbit capability and provision for up to four additional payloads attached to the avionics cylinder sides. Additionally, up to four Cubesats can be deployed from P/PODs attached to the stage 4 avionics cylinder.

As implemented on STP-S26, four ESPA-class satellites will be deployed into a 650 km, 72 degree inclination orbit. These satellites include the prime satellite, STPSat-2, as well as three secondary satellites, FalconSat-5, FASTSAT, and FASTRAC. Two Cubesats will also be deployed into the primary orbit, RAX and O/OREOS, while a third Cubesat, NS-D, will be deployed from FASTSAT. The HAPS will demonstrate the dual-orbit capability of the Minotaur-IV with a secondary orbit of approximately 1200 km.

Due to a fairly late withdrawal of one of the secondary satellites, the program office, in coordination with Orbital, implemented a dual path manifest process to allow two satellites to be carried as candidate payloads. The final down select did not occur until approximately L minus eight months.

STP-S26 will place separate payloads into two distinct orbits. It will launch a total of 14 experiments (11 SERB payloads) and will demonstrate a number of new capabilities that enhance the responsive access to space for DOD payloads.

REFERENCES

[1] DoD Space Test Program Secondary Payload Planner's Guide For Use On The EELV Secondary Payload Adapter, Version 1.0, 8 Jun 2001.

[2] Space Test Program – Standard Interface Vehicle (STP-SIV) Payload User's Guide, 15 Jun 2008.

[3] Minotaur-IV User's Guide, Release 1.0, January 2005.

[4] Minotaur-IV Fact Sheet, Orbital Sciences Corporation.

[5] Minotaur IV Multiple Payload Adapter Study Final Out Brief, Orbital Sciences Corporation, 2 October 2007.

[6] STP-S26 Space Vehicles and OSP Minotaur-IV Launch Vehicle ICD, 1045-0605_RN_B (draft), Orbital Sciences Corporation

BIOGRAPHY

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