

A Deployment Strategy for Multiple Secondary Payloads on the MLV-05 Mission

Donald E. Keenan
The Aerospace Corporation
P.O. Box 9045, A4-413
Albuquerque, NM
(505) 846-7062
Donald.E.Keenan@aero.org

Abstract— The Department of Defense (DoD) Space Test Program (STP) provides space flight for qualified DoD sponsored experiments at no charge to the experimenter, via the DoD-Space Experiments Review Board (DoD-SERB). Through the Air Force Space Command, STP is supplied with a Medium Class Launch Vehicle approximately every 4 years for SERB payloads. The next launch will be on a Delta IV-Medium in the fiscal year 2006. Originally scheduled for 2005 the mission has been temporarily named "MLV-05". STP has initiated mission design activities and has defined a baseline mission. The current baseline is for an Eastern Range launch to low earth orbit (LEO). Five (possibly six) separate spacecraft will be deployed from an EELV Secondary Payload Adapter (ESPA) ring after which the launch vehicle's upper stage will take the primary payload to a geosynchronous transfer orbit (GTO).

This paper discusses the development of a deployment strategy for the MLV-05 secondary payloads subject to the payloads' requirements, the constraints of the separation system, and the timeline for the primary payload's orbit maneuver. The objective is to deploy the secondary payloads in a manner that limits the possibility of close approaches among these payloads and the upper stage following their separation. Because of differing ballistic coefficients the satellites will eventually fall into a natural order in the along track direction. This order dictates the sequence in which they are deployed. The uncertainty in the deployment springs determines the minimum safe difference in the deployment velocities.

Three of the satellites in the current baseline mission will form the TechSat 21 formation flying experiment. Physical constraints require the three TechSats to occupy alternating locations on the ESPA ring. Each TechSat can be paired with the satellite opposite it on the ring and the timeline for the deployment can be reduced by deploying each pair together, but in opposite directions. The strategy takes into consideration the desire of the TechSats to establish their formation several days after deployment. Should one of the TechSats fail to deploy its solar array the difference in deployment velocities allows adequate time for the others to perform collision avoidance maneuvers, if needed.

INTRODUCTION

The Department of Defense Space (DoD) Test Program (STP) is charged with obtaining space flight opportunities for DoD sponsored experiments that are approved and priority ranked by the DoD-Space Experiments Review Board (DoD-SERB). The flights vary depending on experiment requirements and available opportunities. Experiments may reach space as independent secondary spacecraft on other DoD launches, as 'piggy-back' payloads on other spacecraft, as payloads on the Space Shuttle or International Space Station, or as part of a dedicated STP launch.

Approximately every four years STP is supplied with a Medium Class Launch Vehicle to be dedicated to SERB payloads through the Air Force Space Command. This provides an opportunity to place several SERB experiments in space. The next such launch will be in the fiscal year 2006 on an Evolved Expendable Launch Vehicle (EELV), specifically a Delta IV-Medium Launch Vehicle (MLV). Originally scheduled for 2005 the mission has been

temporarily named "MLV-05". The baselined spacecraft/experiments for the mission are:

GIFTS/IOMI (with IMAGE as a 'piggy-back'), a joint NASA/DoD project. It is the primary payload and will be placed in a geosynchronous transfer orbit before propelling itself into a geosynchronous orbit

TechSat 21, an Air Force Research Lab (AFRL) experiment consisting of three separate spacecraft to demonstrate new technologies including formation flying in low earth orbit .

STPSat-1, a spacecraft developed by STP for this mission to carry four SERB experiments: Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER), Wafer Scale Signal Processing (WSSP), Computerized Ionospheric Tomography Receiver in Space (CITRIS), and MEMS – based PicoSat Inspector (MEPSI).

NPSat-1, a spacecraft developed by the Naval Postgraduate School.

Other than GIFTS/IOMI, all the spacecraft are small (< 180 kg) and all the experiments onboard those spacecraft are compatible with a LEO orbit at about 550 km and inclination of 35.4 degree.

In order to accommodate multiple secondary spacecraft on a mission such as this, STP has tasked the Air Force Research Laboratory (AFRL) to develop the EELV Secondary Payload Adapter (ESPA) ring that can hold up to six small spacecraft during launch and deploy them once in orbit. Figure 1 depicts the ESPA ring and the secondary payloads below the primary payload. For this mission the five secondary spacecraft (three TechSats, STPSat-1, and NPSat-1) will be deployed after they have reached the LEO orbit and before the upper stage takes GIFTS/IOMI to the GTO orbit. A sixth secondary payload is still an option, but the slot will likely be left open for ESPA instrumentation.

There is a limited amount of time available to deploy the secondaries before the upper stage ignites. For the purposes of this study that period was limited to 45 minutes, though subsequently it was determined that the period may be somewhat longer. Most of the remainder of the paper will describe a baseline deployment sequence designed to avoid close approaches between the spacecraft either in the short term (a few hours) due to the timing, direction, and size of the deployment or in the longer term (a few days) due to the differential drag on the different spacecraft. Re-encounters after several weeks or months when one satellite has done an additional orbit relative to another were also investigated, and are discussed briefly at the end of the paper. The baseline deployment sequence described here was briefed to a working group of the 14 government and commercial

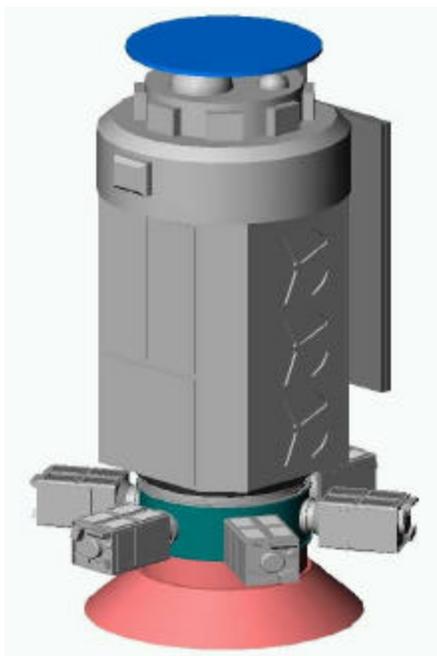


Figure 1: ESPA Ring and Secondaries Below Primary Payload

organizations involved in the project. No major concerns were raised at that time. However, the launch vehicle contractor will incorporate this baseline into a more detailed launch and ascent timeline analysis. This should confirm the reasonableness of the assumptions used here regarding the impact of the deployments on the system as a whole.

PROBLEM CONSTRAINTS

In addition to the 45 minute window for the deployment of the secondaries there are additional constraints that needed to be considered in selecting a deployment strategy.

- 1) Due to size constraints the three TechSats need to occupy alternate locations 120° apart around the ESPA ring.
- 2) STPSat-1 and NPSat-1 have no on-board propulsion and therefore cannot maneuver to avoid a close approach. The TechSats do have on-board propulsion, but it would take several orbits of checkout after deployment, at least, before they are ready to execute a collision avoidance maneuver.
- 3) Each secondary will be deployed using a Lightband system. By selecting the appropriate size and number of springs a range of separation velocities (ΔV s) are achievable. For a 181 kg satellite (near the expected mass of the TechSats and the ESPA limit for an individual satellite) the Lightband is capable of imparting ΔV s between 0.06 and 0.5 m/sec of ΔV . However, a ΔV above 0.412 m/sec would make the testing more difficult. STPSat-1 (similar in mass to the TechSats) will use a smaller diameter Lightband capable of slightly over 0.4 m/sec. The mass of NPSat-1 is about half that of the others, so using the smaller Lightband gives it a range of ΔV s between 0.15 and 0.9 m/sec. While larger ΔV s could be achieved by modifying the design, it is highly desirable to avoid such modifications. Therefore, it is prudent to come up with a deployment scenario in which the ΔV s for the TechSats and STPSat-1 are no more than 0.4 m/sec or less. NPSat's ΔV could be as large as 0.9 m/sec. The standard deviation of a ΔV from the designed value is less than 0.007 m/sec.[1]

RELATIVE MOTION AND NATURAL ORDER

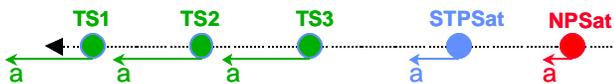
The timing, size, and direction of the deployment ΔV s determine the relative locations of the secondaries in the first few orbits (or days) following deployment. However, after time the differences in atmospheric drag among the satellites eventually overcome any initial velocity differences and determine their relative locations and velocities.

The acceleration due to atmospheric drag on each satellite is proportional to $C_d \cdot A/m$, where m is its mass, A is its average cross-sectional area perpendicular to its velocity vector, and C_d is the drag coefficient. Note that in some texts the ballistic coefficient is defined as $m/(C_d \cdot A)$ while others define it as $C_d \cdot A/m$. We will use $m/(C_d \cdot A)$ and thus the

atmospheric drag is proportional to the inverse of the ballistic coefficient. C_d can vary between 2 and 4 and a typical value of 2.2 was used for these satellites. The estimated orbit average ballistic coefficient for the TechSats with the solar arrays deployment is between 8 and 16 kg/m² depending on the orientation of the solar panels which changes over the course of a year. STPSat-1's orbit average ballistic coefficient with solar arrays deployed is estimated to be 32 kg/m². The arrays on STPSat-1 do not change orientation with the seasons so the orbit average ballistic coefficient is nearly constant. NPSat-1 does not have deployable solar arrays and its ballistic coefficient is estimated at 121 kg/m².

The relative motion caused by the drag is non-intuitive. Rather than slowing down relative to a drag free spacecraft, as the satellites decay into lower orbits due to the drag they actually speed up. Similarly, a ΔV in the anti-velocity direction lowers a satellite's orbit and decreases its period. So, even though the satellite initially falls behind its previous orbit (or in this case the upper stage it is deployed from), within about a quarter of an orbit it drops below and moves ahead of its previous orbit. Likewise, a ΔV in the positive velocity direction raises the orbit and, on average, slows the satellite relative to its previous orbit.

The differences in ballistic coefficients force a natural ordering of the satellites in the along track direction. No matter what order or direction the secondary satellites are initially deployed, eventually the TechSats will decay into a lower orbit than the others (assuming they do not conduct any maneuvers to raise their orbits) and move ahead, NPSat-1's orbit will decay the least so it will fall behind, and STPSat-1 will be in between as shown in Figure 2.



a= along track acceleration relative to drag free spacecraft

Figure 2: Natural Order

DEPLOYMENT SEQUENCE

Given that the inertial velocity of an object in a 550 km orbit is over 7.5 km/sec and the size of an achievable ΔV with the Lightband system is less than one meter/sec, any component of a ΔV perpendicular to the velocity vector (i.e. radial or crosstrack) has essentially no effect on the magnitude of a satellite's velocity vector. Therefore it has no impact on the satellite's period. Thus, radial and crosstrack components of the ΔV don't affect the relative along track locations of the satellites from one orbit to the next. Since the primary object of this analysis is to keep the satellites separated in the along track direction, we will focus on ΔV s in the positive or negative velocity directions.

In order to avoid close approaches within a few days after the deployment, it makes sense to deploy the secondaries in a way that puts them in their natural order along track with drag tending to cause them to separate further. The natural order described in the previous section then determines the ordering of the ΔV s. To put NPSat-1 at the back it should get the largest (most positive) ΔV . The ΔV s should progressively decrease from NPSat-1 through the most forward TechSat which should get the most negative (or least positive) ΔV . In order to prevent along track crossings due to the ΔV differences, the sequence of the deployments should be "outside to inside". That is, the satellite's with positive ΔV s should be deployed in decreasing order of their ΔV magnitudes (i.e. most positive to least positive) and those with negative ΔV s should also be deployed in decreasing order of their ΔV magnitudes (i.e. most negative to least negative). There are six ways to divide the five satellites into those that get positive ΔV s and those that get negative ΔV s while still maintaining the natural ordering of the ΔV s. The three most natural possibilities are:

- 1) NPSat-1 and STPSat-1 get positive ΔV s and the TechSats get negative ΔV s
- 2) All the ΔV s are positive
- 3) All the ΔV s are negative

and

Option 1 has been chosen as the baseline because:

- a) the full range of positive and negative ΔV s can be used allowing the secondaries to separate from each other and the upper stage more quickly
- b) Since NPSat-1 and STPSat-1 are each opposite a TechSat on the ESPA ring, the timeline for deploying the secondaries can be kept to a minimum by simultaneously deploying two satellites in opposite directions

and

The baseline deployment sequence is shown in Figure 3

CHOOSING MAGNITUDES OF THE ΔV S

Though ΔV s as large as 1 m/sec are achievable by modifying the Lightband system, keeping the ΔV s less than 0.4 m/sec eliminates the cost of modifications and simplifies testing. The main consideration in selecting the ΔV s is to make sure the satellites that are more to the outside in the natural ordering get the larger (in magnitude) ΔV s. Since the TechSats will eventually be flying in close formation together it may seem like a good idea to deploy them with the same ΔV s. However, some variation in the actual ΔV achieved as opposed to the designed ΔV could result in the satellite that is deployed later getting a slightly larger (in magnitude) ΔV . In this case the satellites can pass very close to each other within the first few orbits. With 1 σ uncertainty of 0.007 m/sec, two deployments with the same

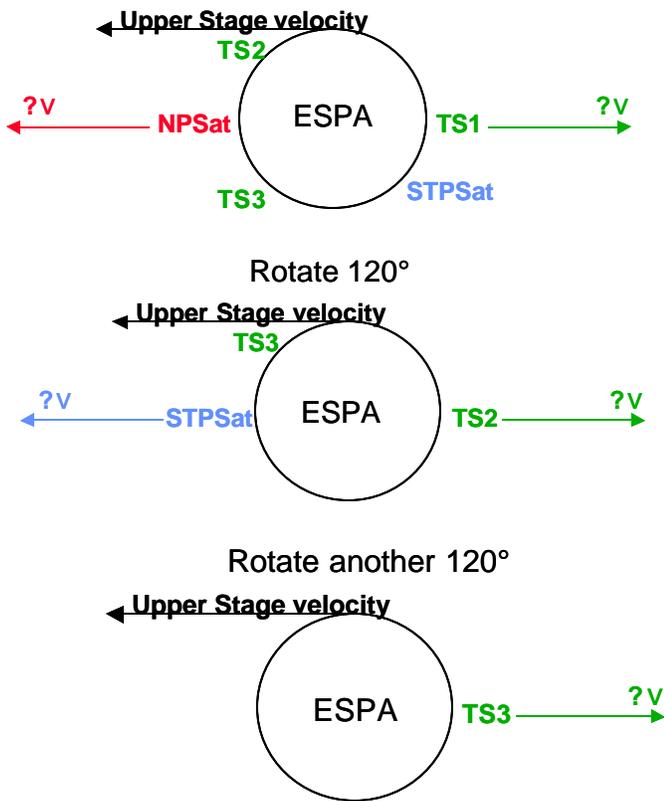


Figure 3: Baseline Deployment Sequence

desired ΔV might differ by 0.01 m/sec or more. Figure 4 shows the range between two TechSats deployed 5 minutes apart in which the first one is deployed at 0.29 m/sec in the anti-velocity direction and the second at 0.3 m/sec in the same direction. After 2.5 orbits (8 hours) the second satellite has caught up to the first resulting in a very close approach and possible collision. This graph and other pictures and analysis regarding the relative locations of the satellites during the deployment sequence were created using the Satellite Orbit Analysis Program (SOAP) developed by the Aerospace Corporation.

Besides the spring uncertainty, another factor resulting in slightly different ΔV s than might be expected is that the release of the springs not only pushes the deploying satellite in the desired direction, but also pushes the upper stage and the undeployed satellites in the opposite direction. Since the upper stage and GIFTS/IOMI combined weigh over 15,000 kg and the deploying satellites weigh less than 200 kg, by conservation of momentum this reactive ΔV is about 1% of that of the deployed satellite or a few 1/10,000ths of a m/sec. Deploying secondaries in opposite directions reduces the cumulative impact on the upper stage and the later deploying satellites. So, as long as the differences between the ΔV s for the satellites is on the order of several 1/1000ths of a m/sec this effect will not disrupt the ordering of the actual ΔV s.

A further consideration is the possibility that solar arrays fail to deploy on one of the satellites. A TechSat without its solar arrays deployed has a ballistic coefficient of about 80

kg/m² as compared to as little as 8 kg/m² for one with the solar arrays deployed. Figure 5 shows under moderate atmospheric density the range between the middle TechSat whose solar arrays do not deploy and the other two whose

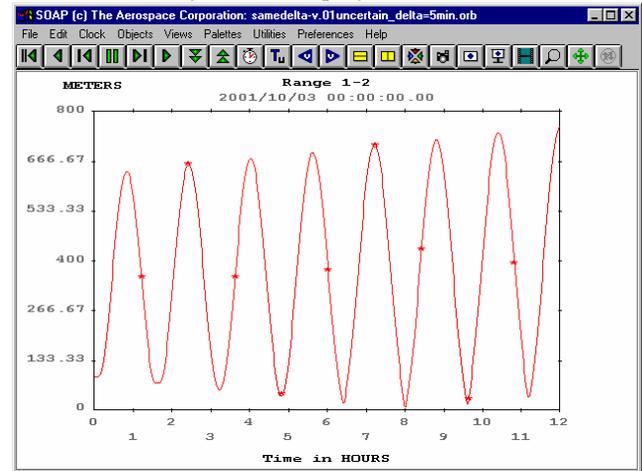


Figure 4: Nearly Equal Deployment ΔV s

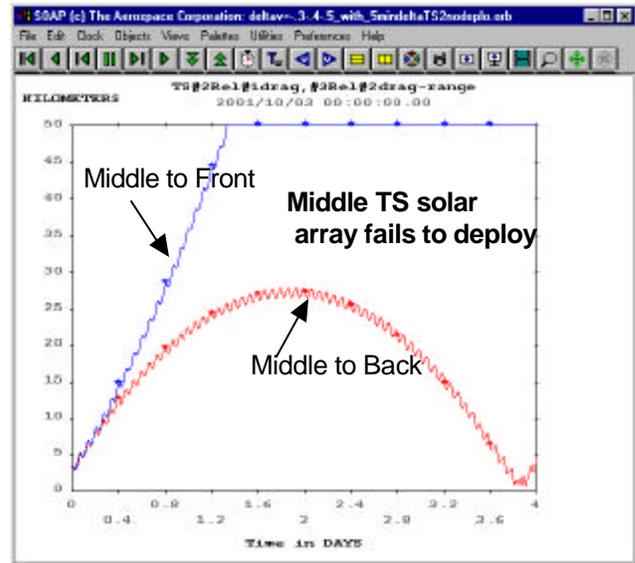


Figure 5: Ranges after Solar Array Fails to Deploy

arrays do deploy. The second (middle) TechSat is deployed with 0.1 m/sec less ΔV than the first and the third 0.1 m/sec less than the second at five minute intervals. After four days the third TechSat would catch and pass the middle TechSat. In conditions of very high atmospheric density (5×10^{-13} kg/m³ at an altitude of 550 km) this difference in ballistic coefficients is equivalent to 0.1 m/sec of ΔV per day and the satellites would cross within two days. The crossing can be avoided by the third (back) TechSat conducting an orbit raising maneuver, but it would probably take a day or so of checkout before the maneuver could be conducted. Therefore, it is desirable to keep the ΔV s separated by at least 0.05 m/sec and preferably 0.1 m/sec.

The TechSats have two weeks following deployment to get into formation and are planning to use the first week doing checkout before maneuvering into formation. Their

propulsion system is capable of 0.3 m/sec per day. They will be able to reverse the 0.1 m/sec increment between the middle TechSat (#2) and the front and back TechSats (#1 and #3) in less than a day at the end of the first week. During the second week they can acquire their formation, flying within a few kilometers of each other. Given these considerations then the baseline values chosen for the ΔV s are shown in Table 1.

	ΔV Magnitude (m/sec)	ΔV Direction (+ or - velocity)
NPSat-1	0.4	+
STPSat-1	0.3	+
TechSat #1	0.4	-
TechSat #2	0.3	-
TechSat #3	0.2	-

Table 1: ΔV Sizes and Directions

The ΔV s actually achievable for a specific satellite with the Lightband system is a discrete set of values that are determined by the number of springs used. This discreteness is on the order of 0.01 to 0.02 m/sec for the TechSats and STPSat and 0.02 to 0.04 m/sec for NPSat.[2] This baseline then serves as a guide for choosing a Lightband configuration for each deployment. So long as the proper separation (~0.1 m/sec) is maintained between the ΔV values, the specific value of each ΔV is not critical.

DEPLOYMENT TIMING

The original constraint on the deployments was that they

should all take place within a 45 minute period. This is after any rotations settle out following the second stage cutoff in the LEO orbit and before the preparation for the upper stage firing to take GIFTS/IOMI to GTO. This doesn't seem to pose a problem. The upper stage can rotate at up to a degree per second and the deployment alignment does not need to be terribly accurate. A 5° mis-alignment from the velocity vector only changes the along track component of the ΔV by 0.4%. Similar to the reactive ΔV s described in the previous section, each deployment will impart a torque on the remaining system of objects. But, with GIFTS/IOMI (~5000 kg) on one side of the ESPA ring and the upper stage (~10,000 kg) on the other and compensating torques from deploying in opposite directions, any rotation induced in the remaining system by the deployment should be very small and we assume can be handled in a timely manner by the attitude control system of the upper stage. It is reasonable then to expect that the deployments can take place at five minute intervals. This will be verified through the launch contractor's analysis of the complete ascent sequence.

Figure 6 shows the positions of the secondary payloads 30 minutes after the first deployment (NPSat-1 and TechSat #1) with five minute intervals between deployments. The secondaries reach a maximum radial separation relative to the upper stage one-half orbit after they are deployed. That radial separation returns to 0 at the end of an orbit. This radial separation over the first orbit (approximately 100 minutes) is shown in Figure 7 at Figure 7 suggests the desired timing of the firing of the upper stage along its velocity vector to carry GIFTS/IOMI to GTO. If the upper

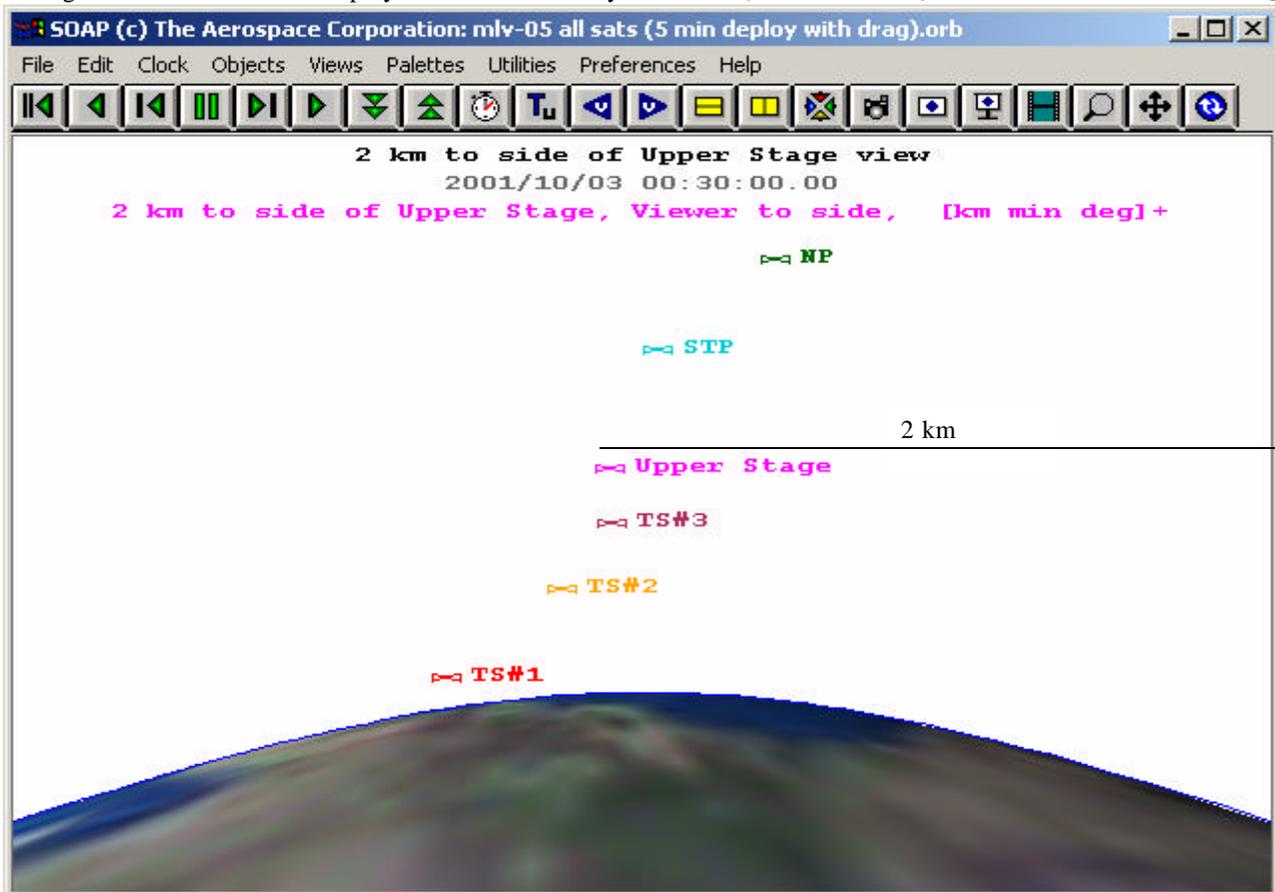


Figure 6: 30 min after deployment of secondary payloads

stage fires between 32 and 75 minutes after the first deployment all the secondaries (and in particular, the TechSats, which will be in front of the upper stage) will be at least 400 meters above or below the upper stage. Anything over 300 meters has been described as a safe distance in terms of contamination of the secondaries from the propellants of the upper stage. The exact length of the preparation period isn't known yet but is on the order of several minutes and is certainly less than an hour. As long as this is the case, the time for the first deployment can be chosen inside the 32 to 75 minute window from the upper stage firing insuring a radial separation of at least 400 meters between the upper stage and the secondaries. The upper stage burn will be done at an equator crossing so the secondaries will likely be deployed within a few minutes of the previous equator crossing.

CONCLUSIONS AND ALTERNATIVES

A baseline deployment strategy has been developed for the five secondary payloads of the MLV-05 mission. This strategy disperses the secondaries in a way that allows them to naturally separate and provides adequate separation from the upper stage when it ignites to take GIFTS/IOMI to GTO.

Beginning any time between 32 and 75 minutes prior to the firing of the upper stage (preferably about 50 minutes prior):

First,

Deploy NPSat-1 with a ΔV of approximately 0.4 m/sec in the positive velocity direction.

Simultaneously, deploy TechSat #1 with a ΔV of approximately 0.4 m/sec in the anti-velocity direction.

Five minutes later,

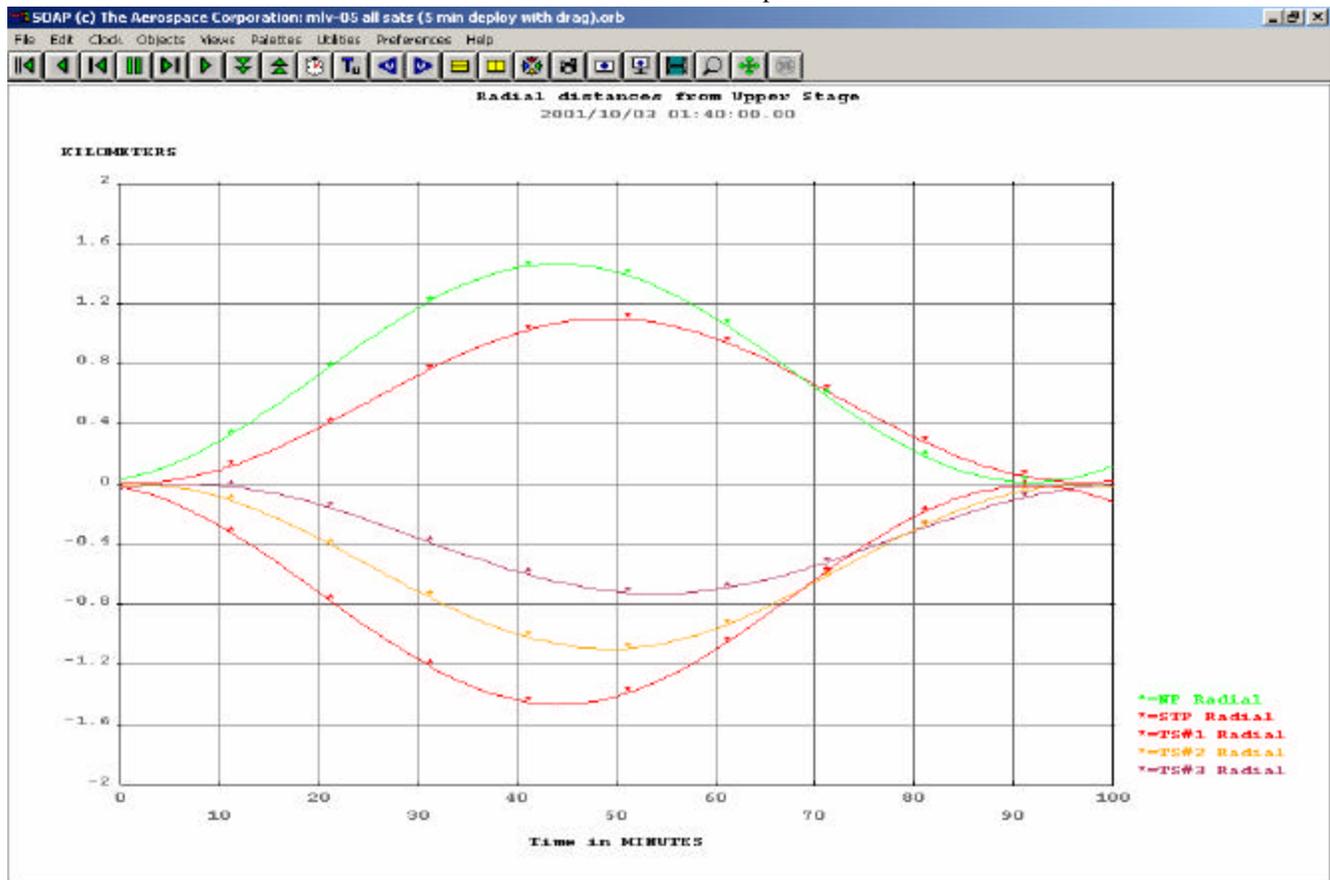
Deploy STPSat-1 with a ΔV of approximately 0.3 m/sec in the positive velocity direction. Simultaneously, deploy TechSat #2 with a ΔV of approximately 0.3 m/sec in the anti-velocity direction.

After another five minutes

Deploy TechSat #3 with a ΔV of approximately 0.2 m/sec in the anti-velocity direction.

There is still some flexibility within this baseline. The time between the deployments could be shortened or lengthened by a few minutes if necessary. NPSat-1 could be given a larger ΔV up to about 0.9 m/sec but that seems unnecessary in the baseline option. There is not much flexibility in the ΔV s of the TechSats in the baseline since going below 0.2 m/sec would reduce the radial separation of TechSat #3 from the upper stage when it fires and going above 0.4 m/sec would impact the design and/or the testing of the Lightband. A sixth secondary could be added opposite TechSat #3 on the ESPA ring. The order of the paired deployments would then depend on its ballistic coefficient relative to that of the other secondaries.

Option 2 could be considered if, for instance, there were a problem having the TechSats in front of the upper it fires. In this option all the secondaries would receive ΔV s in the



positive velocity direction causing them to rise above and then fall behind the Upper stage before it fires. The ΔV for NPSat-1 could be increased, but then the ΔV s for STPSat-1 and the TechSats would need to be distributed between 0.4 and 0.2 m/sec in the positive direction which would reduce the separation rates somewhat. It would also be necessary to deploy the secondaries in sequence (according to the natural ordering: NPSat-1 through TechSat #1) which would increase the time overall time interval for the deployments.

Option 3, with all the ΔV s in the anti-velocity direction does not hold much promise. NPSat-1 would have to be deployed last with the least ΔV , losing the flexibility of giving it a ΔV greater than 0.4 m/sec. Then all five secondaries would have ΔV s between 0.4 and 0.2 m/sec further reducing the rate of separation.

As mentioned previously, crosstrack and radial components to the ΔV s were not used in their deployment strategy because they do not change the along track locations of the satellites. Also, for a given ΔV magnitude, if some of the energy is directed crosstrack, less is directed along track reducing the separation rate between that satellite and the upper stage. However, if it were necessary to deploy the satellites in a shorter period of time simultaneous deployments with one or more of the satellites receiving a crosstrack component are possible. Note also that though the secondaries are deployed in the same plane, by the time one has done an extra orbit and re-encounters another (after several weeks or months) solar pressure will have rotated their orbit planes slightly relative to each other. Also, the different orbit decay rates will cause the faster decaying satellite to pass below the other. This has been confirmed by analysis with SOAP.

ACKNOWLEDGEMENTS

This work was conducted under contract # F0401-00-C-0009 between The Aerospace Corporation and the United States Air Force Space and Missile Center.

Special thanks go out to Lisa Berenberg, Jim Farmin, and Gary Green who reviewed the paper and provided many useful suggestions.

REFERENCES

[1,2] Correspondence with Walter Holemans, Planetary Systems Corporation



Don Keenan is a Senior Project Engineer at The Aerospace Corporation. He is currently a member of the Space Test and Experimentation organization in Albuquerque, NM supporting the Space Test Program. Previously he has been involved in a range of space oriented projects including orbit dynamics, signal processing, radar tracking, and mission design. Prior to coming to Aerospace, he taught mathematics at Texas A&M University and the U.S. Naval Academy. He received a BS and a Ph.D in mathematics from Caltech.

