PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Small satellite launch capability of the Boeing Inertial Upper Stage (IUS)

Donald Platt
Christopher Antalek
Jennifer D. Bocchicchio
Dale Katz
Greg Keleshian
Paul Martin

SPIE.

Small satellite launch capability of the Boeing inertial upper stage (IUS)

Donald Platt[a], Christopher Antalek[b], Jennifer Bocchicchio[a], Dale Katz[b], Greg Keleshian[b], Paul Martin[a]

[a]Florida Institute of Technology, Melbourne, FL
[b]University of Central Florida, Orlando, FL

ABSTRACT

We present a design for taking advantage of the Boeing Inertial Upper Stage (IUS) to provide a means of launching small satellites as passengers on an Titan IV- IUS launch of a 1775 kg. communications satellite. An overview of a design to use the extra propulsive capability of the IUS to place small satellites into orbit is discussed. It is our proposal to have small satellites travel with the IUS into geostationary orbit and then release the satellites after the main satellite has been released. Alternatively, several small satellite buses could be stacked together on a dedicated mission to launch a series of small or microsatellites into any desired orbit including interplanetary missions. This design project was part of a joint space engineering class offered by Boeing , University of Central Florida and Florida Institute of Technology.

Keywords: small satellites, launch vehicles, satellite constellations, satellite buses

1. INTRODUCTION

The Boeing IUS is a two-stage solid propellant upper stage vehicle employed by the Titan IV and Space Shuttle to boost payloads from low earth orbit (LEO) to geostationary earth orbit (GEO) or interplanetary missions. The vehicle has on-board three-axis stabilization with inertial guidance. The first stage of the IUS is used to send spacecraft from LEO to a GEO transfer orbit. The second stage then burns at GEO orbital altitude to circularize the orbit.

The payload capability of the IUS from LEO to GEO is 2275 kg and quite often the full capability is not taken advantage of by launching just the main payload. Boeing requested that we look at a design for a bus to carry small satellites as passengers on missions with available payload mass.

Pending approval of the main satellite customer, small satellites could also be ejected any place along the IUS flight path prior to main satellite deployment. Aside from being carried with a main payload, it is possible to stack the small satellite buses together and launch many small satellites on a dedicated mission.

2. MISSION SCENARIOS

The object of this study was to design a system to allow small satellites to be launched piggyback on a Boeing IUS satellite deployment mission. The extra space available on the IUS and mass normally taken with ballast would now be used to provide access to space for small satellite users. The design was based around a support ring that would interface between Boeing's IUS and the main payload (see Figure 1). All hard points and connectors on top of the IUS would be replicated on the top of the support ring. The main payload would notice only a shift in the center of gravity of the entire system, but there will be no noticeable difference between the two mounting surfaces. The telemetry and launch commands for the microsatellites will be received through the IUS.

With this in mind, the support ring can easily launch two small satellites each weighing 200 kilograms. The system can also be configured to launch four satellites each weighing 100 kilograms. These satellites would be spring launched from the support ring on the IUS in multiples of two from opposite sides of the ring.

The support ring can accommodate up to twelve microsatellites. The ring can handle 2, 3, 4, 6, 8, 9, and 12 microsatellites for any given mission. This allows for the stacking of several support rings in the event of an even smaller and lighter main payload. In the future, citing programs and initiatives such as NASA's New Millennium and Motorola's Iridium, as well as the miniaturization of computers and sensors, large communications satellites of today may be replaced by dozens of microsatellites flying in a swarm or constellation around the Earth.

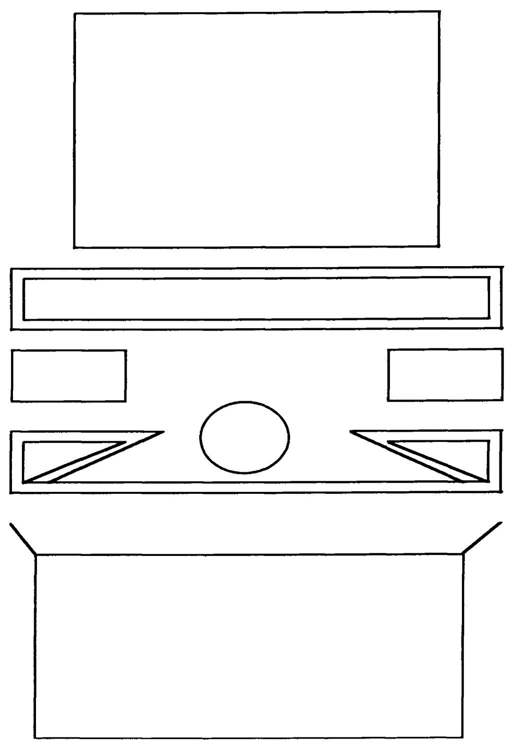

Figure 1. Smallsat AEM bus and IUS stack

Multiple small or microsatellites may be able to provide the nodal antennas in a very large array radio telescope. The baseline of such a system could be very large (as much as 2 times the radius of a geostationary orbit, 36,000 km). Several dozen of these satellites serving as radio telescope antennas could also improve the accuracy of such a space-based radio telescope array. Yet another option is to provide a very low cost *Iridium* style digital communication network that is designed for wireless internet connections for mobile computer users. The larger the swarm of satellites in such a system, the more channels of data and/or higher data rates will be available.

The IUS also allows for the possibility of microsatellites exploring other areas of the solar system. The IUS has successfully been used to send Galileo to Jupiter, Magellan to Venus, Ulysses past Jupiter and will soon be used to send Cassini to Saturn. A swarm of microsats could be launched to the moon for the establishment of a lunar communications network for a future lunar base. A dozen microsats could be boosted to Mars with the IUS to provide a communications network or remote sensing network at the red planet. Asteroids and comets could also be examined with such a network.

3. ORBITAL CONSIDERATIONS

The IUS's main mission is to take a satellite from LEO typically at 250 km altitude on either a Titan IV or a Space Shuttle launch to GEO. The IUS also does a plan change from an orbital inclination of 28.5 degrees to a zero degree orbit during its two rocket burns. The IUS then deploys the main satellite at GEO and its primary mission is accomplished.

The IUS has several advantages over other upper stages. The system is based completely on solid fueled rocket motors thereby increasing reliability and lower cost and complexity. It also has a recently upgraded inertial navigation system using ring laser gyros developed by Boeing for commercial aircraft applications. The IUS provides a circular orbit at GEO altitude as part of its nominal mission which is advantageous over the geosynchronous transfer orbit final destination of most upper stages. The smallsat adapter bus therefore provides direct access to GEO orbit for smallsat customers.

Small satellites in the class of 100 to 200 kg could be brought to GEO with the IUS and then be deployed after the main satellite. Nominally the IUS has fuel left over in its on-board reaction control system (RCS) after the main satellite deployment. This fuel could be used to maneuver the IUS-smallsat system to a location in GEO away from the main satellite and deploy the small satellites at a different longitude. Also available is room for an extra RCS propulsion tank on the IUS for addition delta-v capability.

It is also possible to deploy the small satellites any place along the IUS flight path and use on-board propulsion to place the small satellites into their final desired orbit. This would require an on-board propulsive capability to change both orbital altitude and inclination in order to place the small satellite at its desired orbit.

4. PACKAGE DESIGN AND ANALYSIS

The focus of this section of the report is to analyze the design and structural integrity of the Accessory Equipment Module (AEM) and the adapter platform that will be used to deploy the previously described small sats and communications satellite. A brief mass analysis is also included. This section closes with a description of the assumptions used, and offers possible refinements to the final design.

The AEM and adapter platform are both modeled as aluminum rings of 6 mm thickness with top and bottom connection flanges, each of 6 mm thickness. This is one of the most simple designs possible, and was chosen to minimize the work required to generate the finite element model (FEM) described later.

The AEM is designed to be attached directly to the Equipment Support Section (ESS) of the IUS. It is to attach to the ESS the same way payloads currently do. The small sats then are to mount on trusses built into the AEM with a spacer ring to provide clearance so that a communications payload could be placed on top of the AEM.

The spacer ring has the same design as the AEM. It would be attached to the AEM the same way the AEM is attached to the ESS (see Figure 2). The spacer ring then attaches to the communications payload, using the same, preexisting hardware connections (explosive bolts and springs). All connections are the same so that multiple AEMs can be stacked without changing the configuration of the communications satellite package, or the ESS attachments. The IUS is to contain all the controllers used to implement the firing procedures for deployment.

The model described above was rendered using Pro-Engineer release 16.0 and then exported as an IGES file and imported into Master Series Ideas version 2.1, in order to do the stress and deflection analysis. Master Series uses NASTRAN calculations to generate results. Figure 3 illustrates the finite element model.

For the individual elements, a tetrahedral shape was chosen in order to provide a better representation of stress distribution than a more simple shell design. To further improve the analysis, the center points of each element were also chosen as nodal points, as opposed to only using the endpoints.

Loads were evenly distributed across the top surfaces of the AEM and its trusses. A factor of safety of 1.5 was chosen with a maximum "G-force" of 6.5. Table 1 lists the masses used for the distributed load analysis. This total equivalent mass was then used to calculate the distributed load upon the top flange of the AEM.

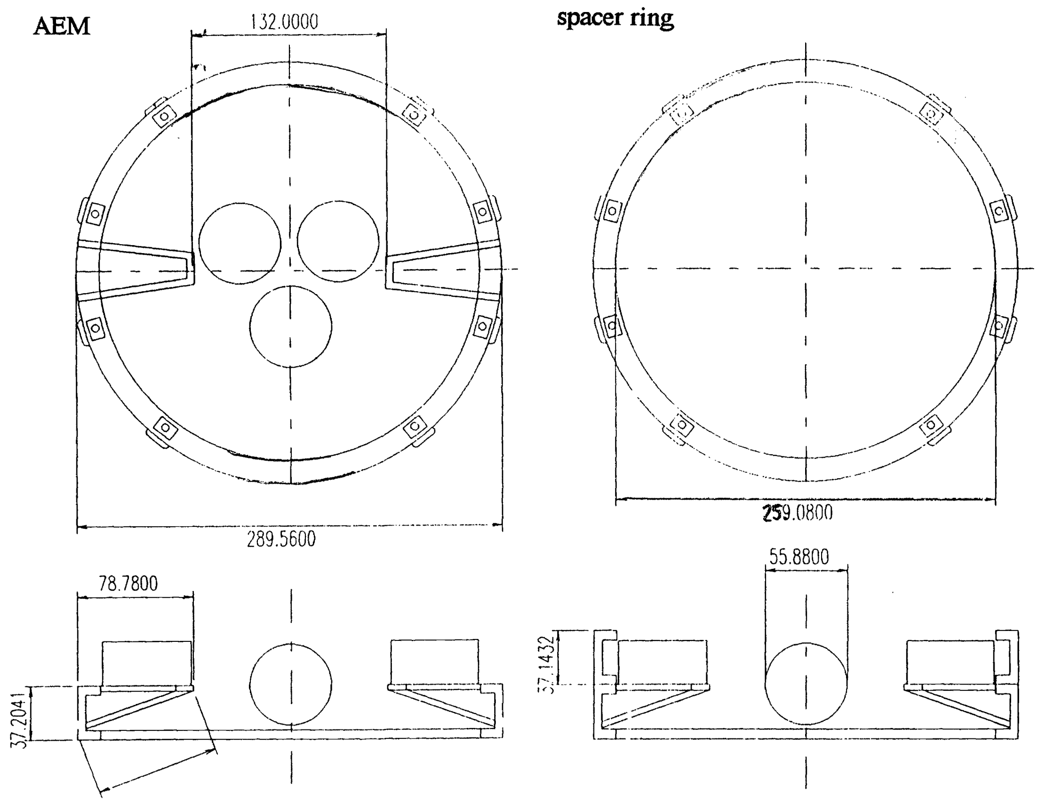

Figure 2. Payload Support Structure (all dimensions are in centimeters)

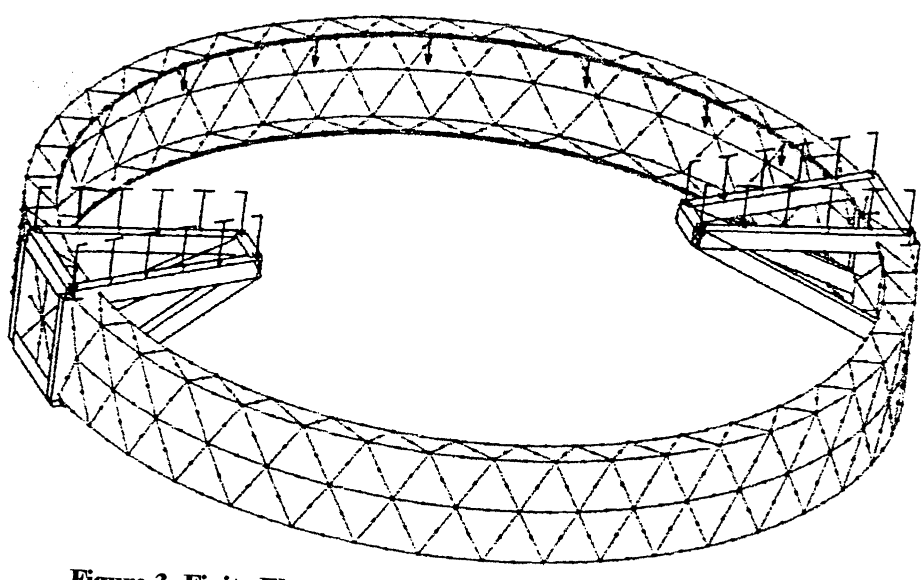

Figure 3. Finite Element Model of the AEM truss structure

Mass (kg)	Item
1814.36	Main Payload
79.42	Spacer Ring
1893.78	Subtotal
6.50	g-force
12309.593	Equivalent Mass w/ g-force
1.50	Factor of safety
18464.39	Total Equivalent Mass

Table 1 - Mass Equivalent for Distributed Load Analysis

The stress analysis was done in two phases. First a complete model of the AEM was converted to a finite element model (FEM) in Master Series' Ideas software. The only boundary condition applied was the containment of the entire bottom face by a fixed support.

The first phase of the analysis was done as follows. The complete model was generated using 0.5 inch thick walls. The loads applied did not include a safety factor or g-force loads. This was done in order to quickly find hot spots in the model. The stress distribution was modeled through the tetrahedral elements and calculated using linear functions in the NASTRAN packages. In doing this, actual stress calculations can be made by using the fact that the ratio of the small load to load with g-forces and a factor of safety is the same as the ratio of the generated stress to the larger actual stress. In using this analysis, the following calculation (equation 1) can be made for the actual maximum Von Mises stress. Only the Von Mises stress will be looked at, because in this case, they are the maximum stresses.

$$\frac{stress_{generated}}{stress_{actual}} = \frac{load_{generated}}{load_{actaul}} \tag{1}$$

Stress generated is 2780 psi, load generated is 4193 lbf and load actual is 40900 lbf yielding an actual stress of 27.117 ksi for a 0.5 inch thick ring. This value is well within the strength properties of aluminum alloy 7075-T6, with a conservative yield strength of 70 ksi.

Now that the results of the 0.5 inch model are known, we can break down the model into more simple components to make a more detailed analysis. The attachment points of the trusses to the ring impose difficulties in mesh design, therefore the trusses were removed from the AEM. In doing this, another FEM can be generated using smaller tetrahedrons, which will provide more accurate results. The new FEM has a wall thickness of 0.25 inches, with tetrahedrons approximately half the size of the previous model.

From the first model, the stress on the top flange is known, as is the maximum stress at the attachment points of the truss. From results of the new 0.25 inch thickness model, the compressive stress on the flange is calculated. This analysis is purely linear so ratios can again be used to calculate the maximum stress at the attachment points of the trusses on the 0.25 inch model (see equations 2.1 and 2.2).

$$\left(\frac{\sigma_{flange}}{\sigma_{attachment}}\right)_{0.5inch} = \left(\frac{\sigma_{flange}}{\sigma_{attachment}}\right)_{0.25inch} \tag{2.1}$$

The values of sigma can be substituted into the equation:

$$\left(\frac{5.414ksi}{27.117ksi_t}\right)_{0.5inch} = \left(\frac{7.870ksi}{\sigma_{attachment}}\right)_{0.25inch} \tag{2.2}$$

The maximum stress that occurs in the 0.25 inch thick model is at the attachment point of the flange is denoted by $\sigma_{attachment}$ and is calculated to be 39.418 ksi.

Maximum deflection also has to be considered in order to find out how closely components can be packed into the AEM without deflecting into each other. The deflections also allow the mechanical frequencies occurring throughout the system, especially at the trusses, in order to make sure they are compatible with the payload. The same approach described above was taken to find the maximum deflection and where it occurs. It was determined from a deflection plot of the 0.5 inch thick AEM that the maximum deflection is 0.0132 inches without g-forces or a factor of safety. This maximum occurs at the ends of the trusses. With g-forces and a factor of safety the maximum deflection becomes 0.1287 inches.

The maximum deflection was not calculated for the 0.25 inch AEM, but some generalizations can be made. The same truss construction is used for both models, and the maximum deflection occurs at the end of each truss. Assuming that there is not a significant change in the deflection of the outer ring of the AEM, it should be acceptable to assume that maximum deflection also occurs in the truss members. Therefore, the maximum deflection of the 0.25 inch AEM is the same as the 0.5 inch model.

Mass calculations were then done using the Pro-Engineer software, and verified by the Masters Series software. Pro-Engineer calculates the mass by multiplying the density 0.098 lbm / in^3 by the volume of the part. the volume is calculated internally, using the dimensions of the model. Table 2 contains the payload mass breakdown.

2 Smallsats @100kg ea.	200.00
1 Main Payload	1814.37
Total Payload	2014.37
Payload Spacer Ring	79.42
AEM	87.36
2 Trusses @ 28.35 kg ea.	56.70
Total Payload Support	223.48
Total without ESS	2237.85
ESS	650.00
Total Without SRM-2	2887.85
3 Extra Hydrazine Tanks	170.00
Total With Hydrazine	3057.85
SRM-2	3040.00
Total with SRM-2	6097.85

Table 2 Payload Mass Summary (masses in kg)

There are several areas of this design with room for future study and perhaps improvement. The one area under closest scrutiny is reducing the mass of the system. The walls of the support and spacer rings are solid aluminum, much of which is dead weight and can be eliminated through a variety of designs. A good possible solution would be to machine out triangular sections of the walls of the rings, leaving a thin amount of aluminum (perhaps 0.06 inches) instead of cutting holes all the way through the walls. This should help to provide some rigidity, while providing very little excess mass. Another solution would be to use a support ring made entirely of hollow aluminum trusses. A more innovative solution to the weight problem would be to construct the entire structure out of carbon fiber layers. The weight would be nearly half that of aluminum, losing no strength, and having a stiffness advantage over aluminum.

5. OUR EXAMPLE MISSION

As part of our design project we were required to develop a trajectory to use the IUS to deploy two small satellites with the IUS and put them in a final 12-hour semi-synchronous orbit. It was our proposal to have the small satellites ride with the IUS into GEO orbit to get into the required zero degree orbit and then use propulsion on board the microsatellites to fly them back to the semi-synchronous orbit. The satellites should be deployed two at a time in order to keep even balance on the IUS. Once the satellites are deployed, the IUS can fire its RCS system to maneuver out of the way.

The small satellite will then be able to be fired into its transfer orbit at the point that is required to get the satellite into its desired final orbital position. The first burn will send the spacecraft into its transfer orbit to semi-synchronous orbit. A second burn will then be done to circularize the orbit at semi-synchronous orbital altitude.

The GEO to semi-synch transfer was the most fuel-efficient approach to placing the microsatellites into their final semi-synchronous zero-degree inclination orbit. A plane change maneuver is very energy-intensive with a delta-v to complete such a maneuver can be calculated from Larson and Wertz:[1]

$$\Delta v = 2v_i * \sin(\theta / 2) \tag{3}$$

where v_i is the velocity before and after the burn. In addition to having to use the microsatellite's propulsion system to do its plane change, if the microsatellites are deployed before they reach GEO on the transfer orbit at semi-synch, the microsatellite will have to do a burn as soon as they are deployed to circularize the orbit. The energy and instantaneous velocity of a transfer orbit from LEO (R_1 = 6628 km) to GEO (R_2 = 42164 km) can be calculated:

a, semi-major axis of transfer = $(R_1 + R_2) / 2 = 24396$ km
ε, orbital energy = $-\mu / 2a$ ($\mu = 398016\ km^3/sec^2$)

$\varepsilon = -398016 / 2*24396 = -8.1694\ km^2/sec^2$

At any point, r, in the transfer orbit the velocity, v, can be calculated from:

$$v = \sqrt{2\varepsilon + 2\mu / r} \tag{4}$$

v at semi-synchronous (r = 26610 km) altitude would be equation 5.

$$v = \sqrt{2 * -8.1694 + 2*398016/26610} \tag{5}$$

v = 3.6905 km/sec

The circular velocity at semi-synch would be:

$$v_{cs} = \sqrt{\mu / r} \tag{6}$$

v_{cs} = 3.8703 km/sec

The Δv would then be $v - v_{cs} = 0.1798$ km/sec.

The IUS will be at some inclination at the point of deployment which can be designated by θ and its value would be approximately 20 degrees. A combined circularization and plane change burn could be accomplished. The required Δv for this maneuver would be:

$$\Delta v = \sqrt{v * v + v_{cs} * v_{cs} - 2 * v * v_{cs} \cos\theta} \qquad (7)$$

for a θ of 20 degrees this Δv would be 1.3248 km/sec.

The best alternative was found to be dropping the microsatellites off at GEO after the main satellite has been deployed. The Δv for this scenario can be calculated as a simple Hohmann transfer from two co-planar orbits. R_A would be the radius at GEO (42164 km) and R_B would be the radius at semi-synch (26610 km). The total Δv can be calculated using the template on page 145 of Larson and Wertz (Table 3):

$a_{tx} = (R_A + R_B)/2 = 34387$ km
$v_{iA} = 631.3481(R_A)^{-1/2} = 3.07467$ km/sec
$v_{fB} = 631.3481(R_B)^{-1/2} = 3.87032$ km/sec
$v_{txA} = 631.3481(2/R_A - 1/a_{tx})^{1/2} = 2.70473$ km/sec
$v_{txB} = 631.3481(2/R_B - 1/a_{tx})^{1/2} = 4.28568$ km/sec
$\Delta v_A = \lvert v_{txA} - v_{iA} \rvert = 0.36994$ km/sec
$\Delta v_B = \lvert v_{txB} - v_{iB} \rvert = 0.415368$ km/sec
$\Delta v_{total} = \Delta v_A - \Delta v_B = 0.785309$ km/sec

Table 3. Total Δv for a smallsat to get from GEO to a 12-hour semisynchronous orbit

6. CONCLUSION

We present a design for an accessory equipment module to adapt to the existing IUS upper stage while keeping costs low and modifications to the existing IUS system to a minimum. The ring design permits up to twelve microsatellites to be carried on one bus with the provisions for stacking more than one adapter together for a greater capability if mass constraints allow.

The IUS is a unique upper stage with many advantageous features for the small satellite customer. Its low-cost, reliable solid motor design, inertial navigation system, on board telemetry and RCS propellant expandability make it an attractive upper stage. The direct GEO capability also offers easy access to GEO for small and microsatellites.

Many smallsat missions could be accomplished with the help of the IUS. Included in these are a constellation or swarm of microsats for communications or remote sensing networks, university student-based space experiment missions, or even interplanetary missions. The IUS has a proven track record in launching interplanetary missions and could be used for similar smallsat missions.

Boeing has expressed an interest in using the IUS for smallsat customers and ours is a preliminary design to convert the system for this capability. With the growing demand for small and microsatellite systems, this design could give the industry a new bridge to space for such satellites.

ACKNOWLEDGEMENTS

The authors wish to thank Professors Roger Johnson of the University of Central Florida (UCF) and Mark Moldwin of the Florida Institute of Technology (FIT) for their technical support and advise. Also we would like to express thanks to the US Air Force, Cape Canaveral Air Station and the Boeing Titan IV-IUS contractor team. This work was a group project for the joint Boeing, UCF, FIT Space Launch Processing class, fall 1996.

REFERENCES

1. W. Larson, J. Wertz, *Space Mission Analysis and Design*, Chapter 6, Microcosm, Inc., Torrance, CA, 1992.