A MULTI-USER CARRIER STRUCTURE FOR DEPLOYING PEGASUS-LAUNCHED MICRO-SATELLITES

J. A. King, N. J. Beidleman, Dr. P. M. Stoltz[1]

Now that the viability of the Pegasus air-launched booster has been demonstrated, it is possible, and indeed appropriate, to devise methods for exploiting the launcher so that it can launch multiple micro-satellites. Such spacecraft may be launched for a single user, or the capacity of a single launcher may be divided among multiple users. In fact, not all of the satellites on a single launch need to be placed into the same orbit.

This paper describes a concept, developed by OSC, to place multiple micro-satellites into various orbits using a single Pegasus launch vehicle. The concept makes use of separable "pallets" which may be stacked, one on top of the other within the Pegasus fairing. Each pallet can have an integral propulsion system and may transport from one to six micro-satellites into an orbit modified from the reference orbit provided by the launch vehicle. Examples are given as to how the system may be used to implement a variety of mission options. If a constellation of communications satellites are deployed by this approach, global coverage can be provided at what is believed to be the lowest cost available today.

The mechanical and propulsion system designs of the pallet are discussed and user constraints are reviewed. The performance capability of the Pegasus vehicle is reviewed as it impacts the individual micro-satellite payload mass.

The successful flight of Pegasus F-1 has verified that the price per kilogram of mass to low earth orbit can be maintained even when the total mass of the satellite system being launched is low. This places options in the hands of small

[1] Members of the technical staff, Orbital Sciences Corp., Space Technology Laboratory, Boulder, Colorado

satellite designers that have never before been available. Orbit choices, launch window decisions and deployment strategies have never been choices for small satellites that have heretofore been flown as secondary payloads on large launch vehicles. For example, Pegasus has made viable the concept of a distributed LEO network of multiple satellites in multiple orbit planes in order to provide continuous global coverage. While the concept has been known and studied since the beginning of the space era, until now this approach to satellite networks has been cost prohibitive. By using a single Pegasus launch vehicle per spacecraft or per orbit plane, the aggregate cost of a network is of the same order as that of a global geostationary network. Similarly, fractions of such a network (that can demonstrate the whole network), satellites that fly in formation (clusters), and mother/daughter mission concepts can be implemented more effectively with a flexible, low cost, launch capability.

As a parallel development, micro-satellite technology has advanced so that significant communications and scientific payloads can be incorporated into spacecraft with masses as low as 10 to 20 lbm. Such spacecraft may be ideal for a thin-route global data communications network, however, it is important to observe that the value of the technique (and in a communications sense, its capacity) comes from the aggregate of the satellites, not from the value or capacity of any single member satellite in the network. This point has been frequently missed by those reviewing the design of a single micro-satellite which, for all its "cuteness," is not physically impressive. There is a tendency to think of a micro-satellite as a toy. Indeed, taken by itself, such a device is only a piece of an engine, not the car itself.

Using a single launcher to place a significant number of small satellites into orbit has only been done infrequently. Creating an entire global LEO network of small satellites has not yet been achieved by any launch means, although it has been studied may times and is now being proposed by a variety of commercial entities. Pegasus could be used to distribute multiple satellites around a single orbit plane, or it is possible to do even better. An entire global network of micro-satellites, in multiple orbit planes may be orbited by a single launch vehicle. Indeed, a number of variations in the network are possible, depending on the needs of a particular customer (or customers) and the characteristics of the orbit.

SWARMS, PALLETS AND STACKS

The following terminology will be used to explain the technique for deploying multiple micro-satellites from Pegasus:

Swarm: The entire group of micro-satellites incorporated on the launcher will be referred to as the swarm once they are deployed.

Pallet: A sub-group of spacecraft that are intended for the same specific orbit may be placed on a frame structure to be known as a pallet.

Stack: The pallets are placed one on top of the other to form a stack. The stack is the entire set of hardware launched by Pegasus.

MISSION HARDWARE

Mechanical Design

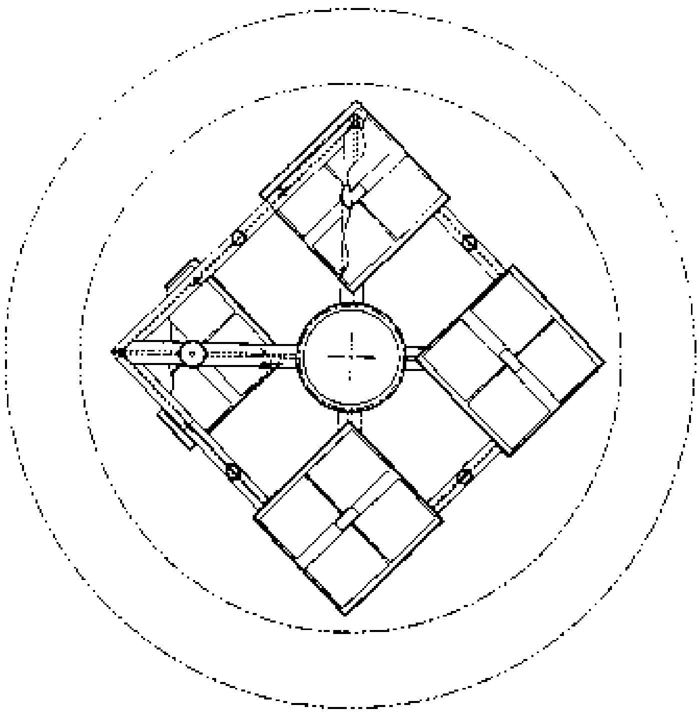
Figure 1 shows a single pallet carrying four individual satellites. The pallet structure itself consists of a lightweight aluminum frame cantilevered from a central support cylinder. The frame shown is square and supports four very small satellites. It would also be possible to have a hexagonal platform supporting six small spacecraft. The satellites shown are the same size as the AMSAT Microsats using the extended module configuration (like Webersat). Spacecraft with a larger base dimension could be used and the cantilevered platform could be extended outward, provided that the particular pallet was carried low in the stack so that it is positioned away from the Ogive portion of the launch vehicle fairing. Spacecraft that are configured as hexagonal, octagonal or circular cylinders can just as easily be flown in these same positions.

A separation system similar to that used on Microsat is also shown in the pallet design. A single tie-down bolt centrally located in the bottom surface of each spacecraft passes through a machined fitting on the pallet. A bolt cutter is contained on the pallet side of the interface. The spacecraft sits on four or more locator pins which fit into mating locator pads properly positioned on the pallet. These pins/pads also provide shear load support for the spacecraft during launch. Single or redundant bolt cutter designs are possible. A compression spring, concentric to the tie-down bolt pushes the spacecraft away from the pallet at the instant of separation.

Shown in Figure 1 are four thin walled tubes extending from the bottom side of each pallet. The tubes are connected only to the bottom side while the tube ends which separate from the pallet below are fitted onto tappered locating mounts. The tubes are intended to reduce the lateral bending (and increase the first mode resonant frequency) of the entire stack during launch.

The central support cylinder may contain a single, small solid propellant kick motor. A Thiokol TE-M-790-1 motor (STAR 6B) is shown in Figure 1. Larger motors with more propellant are also possible or the cylinder need not

Figure 1 - Pallet Configuration and Pegasus Envelope



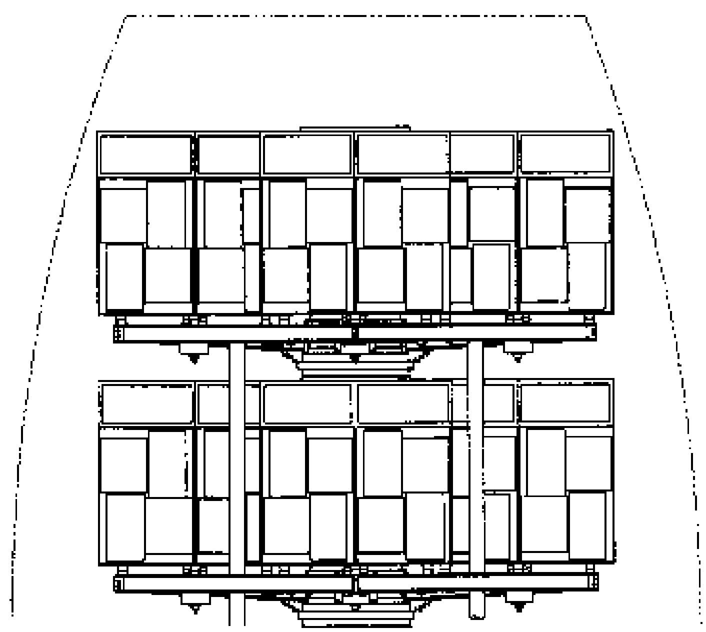


Figure 2a - Stack Configuration and Pegasus Envelope

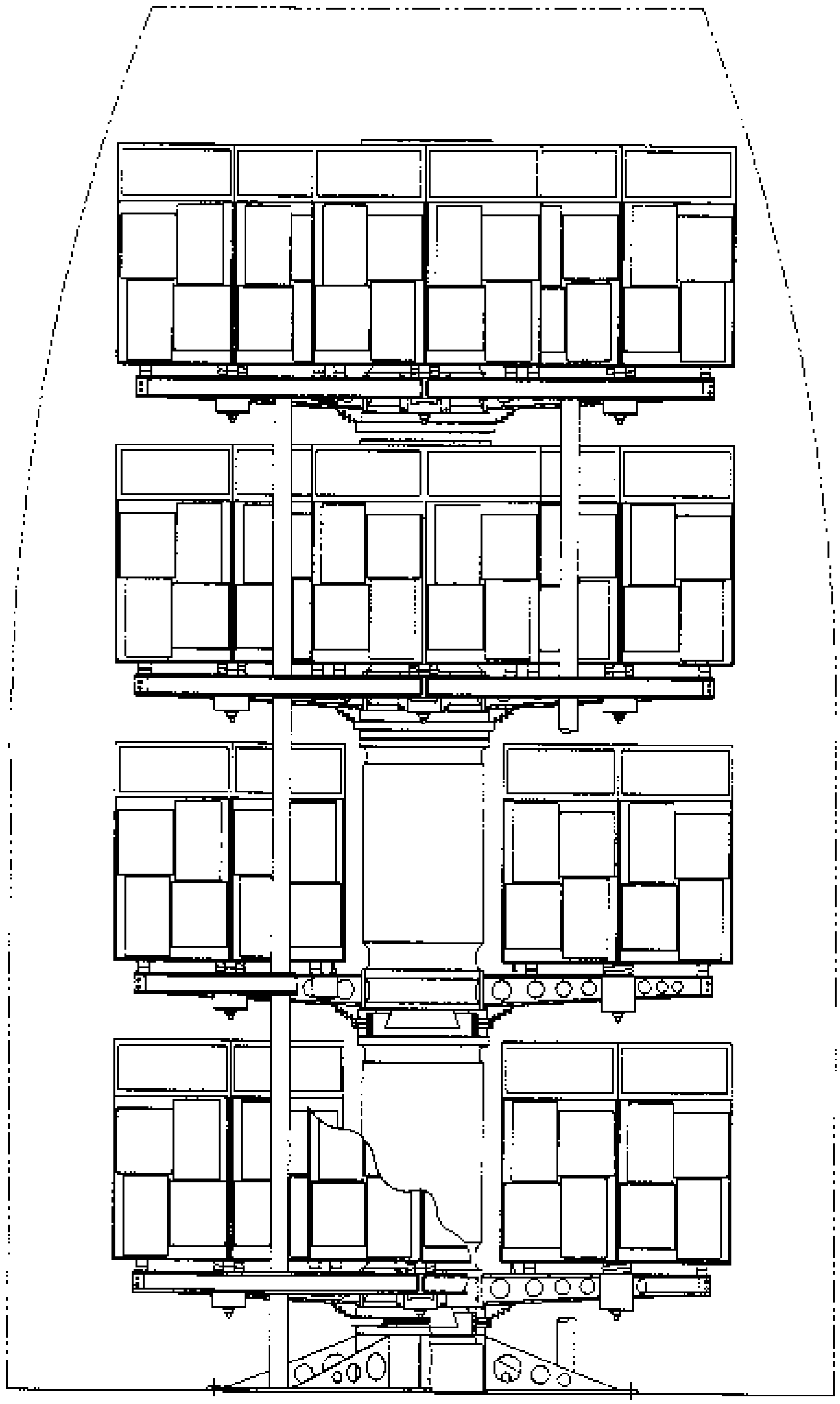


Figure 2b - Pallet Deployment Sequence

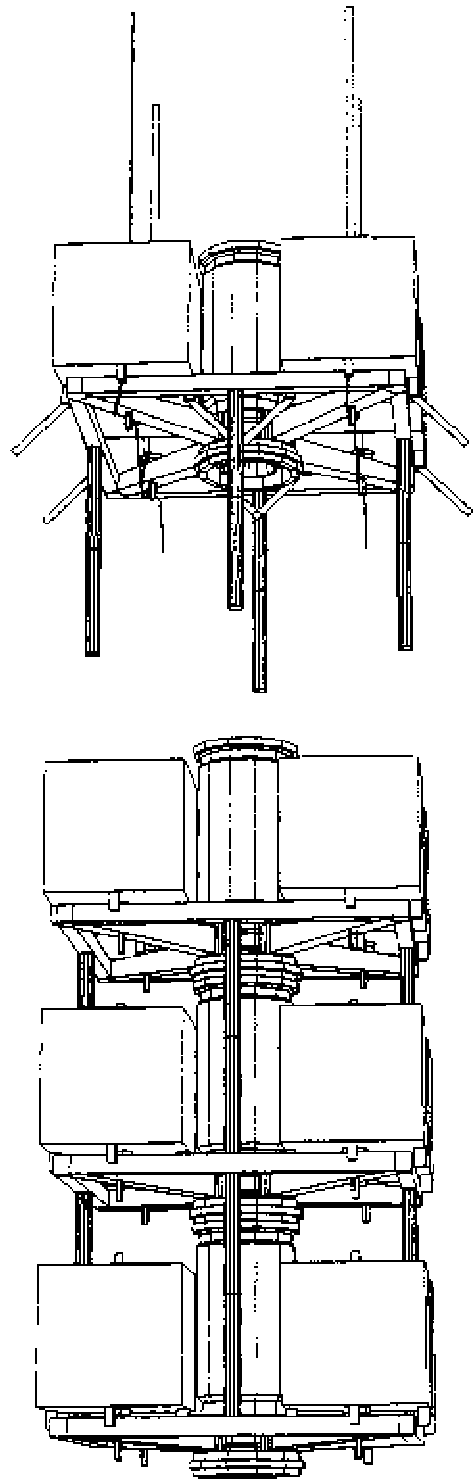


Figure 2c - Stack Configuration in Fairing Half

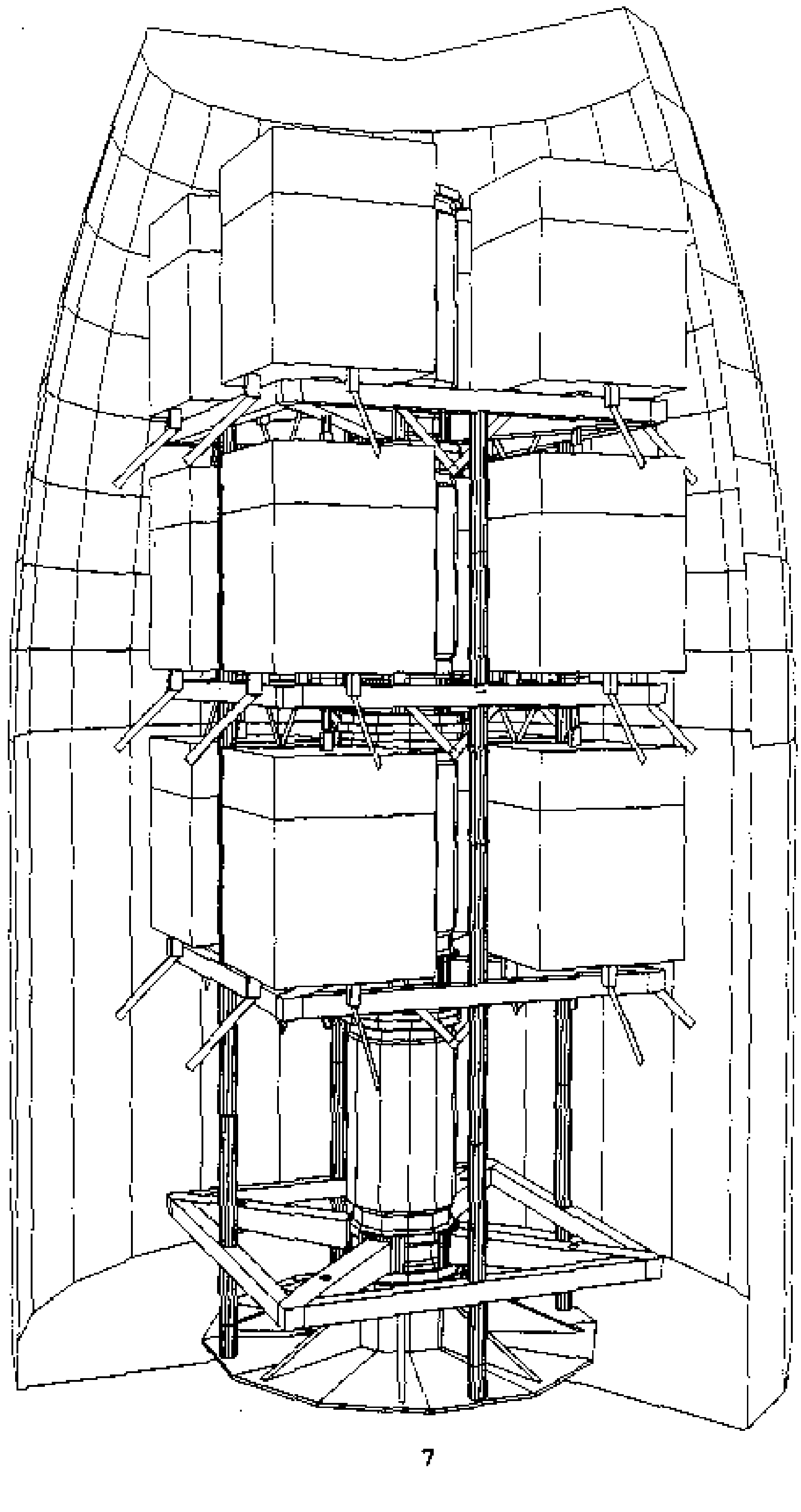
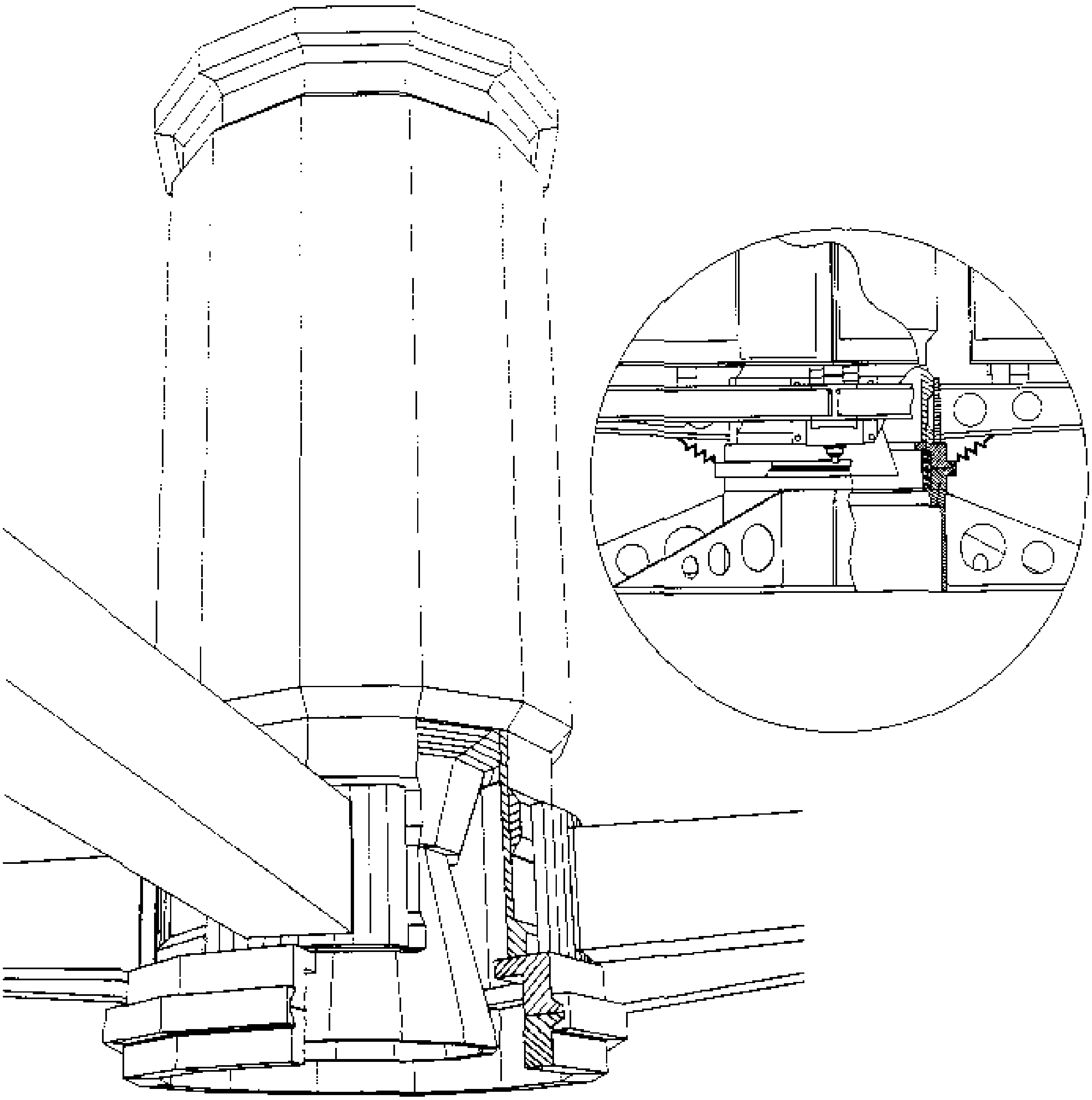


Figure 3 - Marmon Clamp Assembly Detail



contain a kick motor at all. A desirable property of the STAR 6B is that the motor casing may be used as the central support cylinder itself with only slight modifications. This reduces the mass of the overall pallet. The pallets are separated from the stack, one at a time, starting from the top. A marmon clamp separation system with spring is envisioned for this task. The clampband assembly is located at the lower end motor interface. Figure 2-a shows a stack of four pallets. Figure 2-b shows the separation of the first pallet from the top of the stack. Figure 3 shows the detail of the proposed marmon clamp assembly.

Electronic Design

The design of the electronics (or avionics) to support this approach is somewhat a function of individual mission requirements. In all cases, however, it has been assumed that there is more than the average amount of interaction between the spacecraft and the launch vehicle. In the simplest case, the launcher and the pallet structures are used as a carrier until orbit is achieved. No propulsion from the pallets is necessary. It is only necessary for the launcher to issue separation commands. Initially, the first four spacecraft are separated, then the empty pallet is jettisoned. This is followed by the second four satellites and the second pallet. And so it goes until "everyone is off the bus." In between pallet separation events it is possible for Pegasus to perform a re-orientation maneuver that will maximize the miss distance of the individual satellites. In this simplest of cases, no roll-up of the launcher would be required. The sequencing operation is accomplished by the launch vehicle flight computer and a ordnance box known as the Pyrotechnic Driver Unit (PDU). Each PDU is capable of 12 outputs to fire standard initiators (5A for 75 mS). The input to the PDU is a serial bit stream from the flight computer. If each of 16 spacecraft takes two redundant ordnance lines for separation and if each pallet takes two more, then the total ordnance count is 24, thus two PDUs must be added to the third stage electronics to support the mission.

For other types of missions, however, the situation is more complex. For missions where each pallet has propulsive capability and the satellites are separated considerably after separation from the launcher, each pallet must carry its own PDU. This, in turn, implies that power and sequencing signals must be supplied by electronics on-board the pallet. It may even be necessary for some attitude control capability to also be added. Since each pallet contains several spacecraft, none of which are likely to be particularly busy, it is proposed that power and serial communications interfaces be created between the spacecraft electronics and the PDU. Continuous power is likely to be available since the solar arrays on each spacecraft will be illuminated, even though shadowing will be more frequent. The spacecraft (one or more for redundancy) may be used to sequence separation and kick motor ignition. This may be done via a timer initiated by one of the spacecraft computers or via ground command to one or more of the satellites.

Normally, the pallet and its spacecraft would comprise a stable spinner. Spin would be provided to each pallet by executing a pre-programmed launcher roll-up maneuver. In some multi-mission scenarios the pallets may keep their spacecraft for a long period of time. In this case, re-pointing of the spin vector may be required. Two methods of accomplishing this have been considered. In the best case (lightest weight solution), if sensors and torquer coils or small momentum wheels are already available for attitude control on one to several of the spacecraft, they may be used to orient the pallet. If this is not the case then a single torquer coil, a flux gate magnetometer and possibly a simple sun sensor may be added to the pallet. In any case, it has been assumed that the "loop will be closed" by making use of one of the spacecraft computers. Both the spin rate and the direction of the spin vector of the pallet can be controlled with a single torquer coil in a LEO spinning body. While details must be worked out, the principle is straight forward. OSC has developed various forms of light weight, low cost serial data and power interfaces for use across the separation plane between spacecraft and pallet.

SOME APPLICATIONS FOR THE MULTI-USER CARRIER STRUCTURE

With a pallet and stack approach to launching micro-satellites, there are truly many ways in which this capability can be exploited. The possibility exists to divide the capacity of the vehicle among multiple customers each with multiple satellites or it might be used to put an entire network of satellites in place for a single customer.

In order to provide estimates of capability, it's necessary to provide mass estimates for the pallet hardware. A mass budget for the pallet shown in Figure 1 is given in Table 1. The values are for the pallet without motor propellant but, with the motor casing (acting as a structural member). The pallet can take larger motors with different casing masses so one needs to keep track of this factor. The pallet masses then must be subtracted from the total mass available to the micro-satellites.

A study orbit has been picked that is good for demonstrating the usefulness of this concept. The orbit is 460 km X 1000 km X 55 degrees inclination. The perigee of the reference orbit is high enough to be out of the serious part of the drag region, the apogee height is "about right" for various LEO communications and earth observation missions and the inclination is high enough to provide coverage of most of the earth. In some cases it is desirable to circularize this

o Mech. Arms	2.68 lbm
o Support Struts	2.60
o Clamp Band	1.85
o Motor Hardware	2.00
o Motor Casing (STAR 6B)	9.17
o Separation Spring	1.50
o Other Hardware/ Misc.	5.20
o Total Pallet Mass	25.00 lbm = 11.33 Kg.

Table 1 - Pallet Mass Estimate

No. Pallets	No. S/C Per Pallet	Mass Per Pallet
2	2	259 lbm (117.6 Kg)
2	4	"
2	6	"
3	2	165 lbm (74.7 Kg)
3	4	"
3	6	"
4	2	118 lbm (53.5 Kg)
4	4	"
4	6	"
4	8	"

Table 2 - Possible Pallet Configurations

orbit. For example, if four micro-satellites each weigh 11.3 Kg (25 lbm) then, counting the pallet mass, about 3.0 Kg of solid propellant in the STAR 6B motor is required to circularize the above orbit (delta-V applied at apogee). Table 2 provides some of the options for the pallet and stack system. The masses shown in the third column must be treated with some care. First of all, they are based on trajectory analysis runs using Pegasus data provided prior to our F1 flight. Adjustments to the vehicle performance need to be made based on F1 information plus upgrades presently being made to Pegasus which improve performance over the F1 version of the vehicle. The net sum of these may be close to or even above the values given in the table but, the table should be considered preliminary.

Single Orbit Plane - Twelve to Sixteen Spacecraft

As discussed above, the simplest approach is to use pallets as carriers to place all satellites into the same orbit. The separation sequence has already been described. The satellites will all separate out slowly within the same plane. The final orbit is 460 km X 1000 km X 55 deg. Orbital velocities of the spacecraft should differ only by the "delta-V" of the separation springs. If four pallets are used as shown in Figure 1 and if no mass is used for propellant, then the satellites can each weigh 13.4 Kg (29.5) lbm. Similarly, if three pallets are used with four satellites per pallet then the satellite mass goes up to about 18.7 Kg (41.2 lbm). The volume available for each spacecraft is approximately consistent with the current values for the mean density of electronics and the available mass per spacecraft.

The satellites on each pallet, or on different pallets need not be of the same mass as the spacecraft are deployed from a non-spinning Pegasus. Gross imbalance, however, should be avoided.

Single Launch Satellite Network - Multiple Orbit Planes; Twelve to Sixteen Spacecraft

This scenario is similar to the first, however, each pallet now makes use of the STAR 6B motor as shown in Figures 1 and 2. OSC has developed a proprietary method for placing each pallet and its associated satellites into a different orbital plane. The planes may be equally spaced or staggered relative to one another. The final orbits of the satellites are a function of the quantity of propellant loaded into the STAR 6B motors and the final satellite masses, however, it is assumed that one of the more useful final orbits (per this example) would be circular at 1000 km altitude and 55 degrees inclination. By making use of this unique feature, it becomes possible to launch an entire global LEO network with a single Pegasus launch vehicle. It is believed that this is the lowest cost method of providing global communications coverage via satellite available today.

The satellites on each pallet should have balanced mass properties so the pallet is is a stable spinner. It must act as a spinning body until after motor burn-out and spacecraft separation.

Mix and Match - Eight Spacecraft

In this scenario it is assumed there are two different customers each with multiple spacecraft but with different orbit requirements. User A wants to place four spacecraft into a circular orbit at 1000 km and 55 degrees inclination while User B wants a 460 km circular orbit at 55 degrees inclination and also proposes to carry four satellites on his pallet. Each user shares a ride to the common reference orbit given above and each has a total mass of 117.6 Kg or 259.5 lbm. User A is spun up and released first and at the apogee of the orbit fires his kick motor. The Pegasus vehicle has given the pallet an orientation so that the motor is fired aligned with the velocity vector, increasing the velocity of the orbit at apogee. If the mass of the propellant is trimmed to 6.62 Kg (max. propellant for the STAR 6B is 7.11 Kg) and the mass of the four spacecraft are each 27.75 Kg (61.2 lbm) then the delta-V provided by the motor is 141 m/s which circularizes the orbit at 1000 km altitude. User B is also spun up and released but, is aligned by Pegasus with the motor aimed against the velocity vector of the orbit. This motor is fired by User B at the perigee of the orbit. The propellant for this motor must be trimmed to 6.75 Kg and each of the satellites must weigh 27.71 Kg (61.1 lbm). This will result in a delta-V of -144 m/s ("-" indicates velocity is subtraced from the orbit) which will circularize the initial orbit at 460 km.

Mother/Daughter(s) Mission

For some science missions it is useful to launch two or more spacecraft together on a single launcher and then split the spacecraft apart. One spacecraft may go into a highly elliptical orbit while the other may stay in a lower circular orbit. The satellites then perform correlative scientific experiments using orbits that provide very different vantage points. The NASA/MPI mission known as APEX and the earlier NASA/ESA International Sun/Earth Explorer mission are two notable examples of this approach. In this example, suppose that a single spacecraft weighing 90 Kg (198 lbm) is to be placed into an orbit 460 km X 10,000 km X 55 degrees inclined. The other spacecraft (four micro-satellites) are then to be placed in a circular orbit 460 km in altitude. The initial reference orbit is 460 km X 1100 km X 55 degrees as before. If a STAR 13A motor is used on the first spacecraft and fired at perigee (motor aligned with the orbit velocity at perigee) then the 33.1 Kg of propellant (Isp = 286.5 sec) will place that spacecraft in the correct 460 km X 10,000 km orbit. A single pallet containing the four micro-satellites is then aligned against the velocity vector of the orbit at perigee, spun up by Pegasus and released. The motor on the pallet is then fired at the perigee of the orbit. The delta-V required for the maneuver is -144 m/s (the same as in the previous example). In this case, we need slightly more propellant than can be accommodated by a STAR 6B motor. Instead, we assume that an off-loaded STAR 10 motor is used. The normal propellant loading for this unit is 11.9 Kg while the fuel required for the circularization burn is 8 Kg. It has been assumed that the dry pallet mass has now increased to 16 Kg in order to provide some additional stiffness for the added spacecraft plus motor mass and to account for a heavier motor casing. The mass remaining can then be divided equally among the four micro-satellites (which are not so "micro") giving a mass per spacecraft of 33.25 Kg (73.3 lbm). The initial elliptical orbit has now been circularized at the perigee altitude of 460 km and the four small scientific satellites are deployed from the pallet.

PROPOSED SPACECRAFT/PALLET INTERFACES

Since the pallet and stack approach to launching multiple satellites on Pegasus has never before been done, it is perhaps a bit early to be proposing specific standards. Clearly, considerable mission analysis and mechanical and structural design work needs to be completed before a configuration could be finalized. Nonetheless, a few useful inputs are in order.

Mechanical Interfaces

Attachment of the micro-satellites to the pallet should conform to some standard interfaces, if for no other reason than to reduce costs and shorten integration schedules. For mechanical attachment of the spacecraft to the pallets it is proposed that:

1) For S/C > 20 Kg Mass: Use Standard Delta/STS 9" Marmon Clamp.

2) For S/C < 20 Kg Mass: Use Single Tie-Down Rod/ Compression Spring Separation System (See Above).

A marmon clamp is a very reliable, secure separation system. One of two redundant bolt cutters will separate a single spacecraft. A 9" clampband will support up to 200 Kg and is almost overkill for this application. Marmon clamps when used on micro-satellites consume considerable vertical height, which is in short supply within the Pegasus fairing. For this reason marmon assemblies are suggested for missions requiring three pallets or less where more height per pallet would be available.

The specific method proposed, using a tie-down rod or bolt, is an old but, well proven concept. It was originally used for Agena-launched secondary payloads back in the early 1960's. The approach is simple, low cost and can be made very reliable by using two bolt cutters and a single tie-down rod.

Electrical Interfaces

Standards for electrical separation of the spacecraft are also important to review. Ordnance devices using standard NASA initiators are strongly recommended. It is proposed for both marmon separation systems and for the lighter weight tie-down rod system, a cutter/power cartridge like the Hi-Shear SL-1034/PC19-19, be used. For a typical mission, OSC would furnish the cutters and perform the mechanical and electrical operations associated with mating the spacecraft to the pallets.

In order to achieve compatibility between spacecraft and pallet electronics (for more complex missions requiring the pallet to fire kick motors and orient itself in space) significant electrical interfaces between the spacecraft and pallets will have to evolve. While it is too early to be specific, two general comments are offered here:

1) Small spacecraft frequently benefit from having lower voltage power busses. The mass of even smaller capacity battery cells becomes significant when a 28 volt bus is used. It is suggested that battery strings that produce voltages in the range from 10 to 14V would be best. If this can be agreed upon, then the pallet electronics can be designed for the same range.

2) Serial data interfaces should be used to communicate data to and from spacecraft via umbilical lines or for data intended between pallet and spacecraft. A standard such as RS-422 or the multi-drop version of same, RS-485, should be adopted.

SUMMARY AND CONCLUSIONS

A typical argument raised against deploying multiple satellites with a single launcher is related to the risk of launch failure (the old problem of putting all of your eggs in one basket). One must remember, however, that these are small eggs (both physically and fiscally). A rule-of-thumb which is sometimes used for space missions is that the cost of the payload should not exceed the cost of the launch vehicle itself. Larger launchers like Ariane, however, carry payloads valued in excess of two times that of the launcher. If we apply this sort of rule to Pegasus, then the aggregate payload should not be valued at more than say $8M to $16M, depending on one's willingness to take risk. This amount can, in fact, cover the costs of a network of micro-satellites. Further, using the pallet concept, mixing and matching is possible so that the risk of failure taken on any one launch can be shared by several groups.

A low cost technique has been presented for users to share a Pegasus launch vehicle or alternatively, use it to deploy a variety of different satellite networks. Certainly, the concepts presented are not exhaustive and OSC would like to hear others thoughts on how this idea can be expanded. Perhaps, most importantly, this approach to launching secondary payloads provides flexibility that has never before been available to a "lightsater." It's also worth noting:

-- on Pegasus, every spacecraft is a primary payload.

ACKNOWLEDGEMENTS

Our thanks to members of the small satellite community for suggesting several of the concepts contained in this paper.

BIBLIOGRAPHY

1. Space Rocket Motors, Thiokol Inc., Aerospace Group, Elkton, MD, June, 1987 or latest revision.

2. Delta Spacecraft Design Restraints, DAC 61687D, McDonnell Douglas Corp., Huntington Beach, CA, July, 1980 or latest Rev., pp 3-6 to 3-11.

3. Microsat Launch System/Spacecraft Interface Control File, DCI/393 00, Issue 2, Rev. 1, Arianespace, Evry, FR, November, 1989, p 4.19, p 6.04.1