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A Systems Approach to Select a Deployment Scheme to Minimize Re-contact When Deploying Many Satellites during One Launch Mission

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ABSTRACT

The proliferation of small, standardized/canisterized satellites and their associated adapters has made the viability of launch missions carrying thirty or more small satellites feasible. There are several missions that are pioneering an architecture where a large primary satellite drives mission requirements without utilizing all of the lift capacity of the launch vehicle. This allows the carriage of adapters containing canisterized satellites as tertiary satellites. Multi-satellite missions flying ten or more tertiary satellites require a systems approach to selecting a deployment scheme. This deployment approach eliminates the possibility of re-contact with the primary space vehicle while minimizing the possibility of re-contact between the various small tertiary satellites. This paper will summarize a systems approach to selecting a deployment scheme that meets these requirements. It will outline the use of unconventional maneuvers in the radial and anti-radial directions (straight up and straight down) to take advantage of the unique orbits resulting from these maneuvers. It allows for the separation of the primary space vehicle and all of the small tertiary satellites by treating the tertiary satellites as a "swarm." It places all tertiary satellites in similar orbits which can be managed as a system.

CONTENTS

ACRONYMS AND DEFINITIONS

1. CubeStack: Multi-payload adapter used to support up to eight 3U cubesats as tertiary payloads.
2. Hohmann Transfer Orbit (HTO): Method to transfer from one orbit to another using velocity vector and anti-velocity vector maneuvers.
3. NASA Ames NanoSat Launch Adapter (NLAS): Multi-payload adapter used to support up to eight 3U cubesats as tertiary payloads.
4. Out-of-Plane Maneuver: Using impulses normal to the plane of the orbit to change the inclination of the satellite.
5. Primary Satellite: Large satellite constituting the primary payload on a given launch. This satellite pays most of the cost of the launch, as well as defining most mission requirements.
6. Radial/Anti-Radial Maneuver: Using impulses in the radial and anti-radial directions (straight up and straight down) to change the satellites orbit.
7. Resident Space Objects (RSOs): Satellites and other objects in permanent Earth orbit.
8. Rocket Body: The last stage of a launch vehicle that deploys all primary, secondary, and tertiary satellites and remains on orbit after the deployment event.
9. Secondary Satellite: Large satellite flying as an auxiliary payload on a given launch. This satellite pays a significant part of the cost of the launch, as well as defining some mission requirements.
10. Tertiary Satellite: Small satellites flying as launch vehicle mass on a given launch. This satellite pays almost none of the cost of the launch, as well as defining no mission requirements.
11. Velocity Vector/Anti-Velocity vector maneuver: One-half of a Hohmann Transfer Orbit.

EXECUTIVE SUMMARY

The proliferation of small, standardized/canisterized satellites and their associated adapters has made the viability of launch missions carrying thirty or more small satellites feasible. Multi-satellite missions in the past generally carried no more than two or three satellites. A few, such as the inaugural Minotaur mission in 2000, carried eleven satellites. There are several missions that are pioneering an architecture where a large primary satellite drives mission requirements without utilizing all of the lift capacity of the launch vehicle. This allows the carriage of adapters containing canisterized satellites as tertiary satellites. These tertiary satellites have almost no say in mission requirements and cannot impact the primary satellite in any way. Multi-satellite missions flying ten or more tertiary satellites require a systems approach to selecting a deployment scheme. This deployment approach eliminates the possibility of re-contact with the primary space vehicle while minimizing the possibility of re-contact between the various small tertiary satellites. This paper will summarize a systems approach to selecting a deployment scheme that meets these requirements. It will outline the use of unconventional maneuvers in the radial and anti-radial directions (straight up and straight down) to take advantage of the unique orbits resulting from these maneuvers. It allows for the separation of the primary space vehicle and all of the small tertiary satellites by treating the tertiary satellites as a "swarm." It places all tertiary satellites in very similar orbits which can be managed as a system. Typically, satellites are placed in de-conflicting orbits by the use of impulses in the orbital velocity vector or anti-velocity vector directions. Unfortunately, the characteristics of a velocity or anti-velocity vector maneuver tend to result in too many degrees-of-freedom when launch missions involving ten or more satellites are involved. A simple solution, which takes into account the limitations of the deployment devices, the launch vehicles, and the small size of the tertiary satellites, is available. The unique characteristic of a radial or anti-radial maneuver is that they essentially preserve the period of the deployment orbit. An out-of-plane maneuver changes the inclination of the orbit. By recognizing the advantages of a radial and anti-radial maneuver combined with an out-of-plane maneuver, you can set up a deployment scheme for the tertiary satellites that minimizes the possibility of re-contact. It allows all of the satellites to orbit as a system—a swarm of satellites. Currently, cubesat adapters such as the NASA Ames NanoSat Launch Adapter System (NLAS) or the LoadPath CubeStack adapters allow the carriage of up to eight 3U equivalent

cubesats carried in four dispensers on each side of the adapter. This configuration easily allows deployment of the cubesats as deployed pairs in directions 180 degrees opposed from each other. This allows the deployment in both radial/anti-radial and out-of-plane maneuvers simultaneously. This scheme allows the orbital stacking of all of the cubesats on one side of the adapter in a cluster as well as all of the cubesats on the other side of the adapter in another cluster. Both clusters are essentially in the same orbit and both clusters comprise the swarm of tertiary satellites. The fact that radial and anti-radial maneuvers essentially preserve the period of the orbit, and the cubesats are very small enables a reasonable chance of not re-contacting with each other despite the close proximity of all orbits. This paper will examine the limitations and advantages of this scheme for de-conflicting tertiary satellites from each other as well as the primary satellite. It will outline a mission architecture which will maximize the probability that no tertiary satellite will re-contact as well as allowing the cubesats to be managed as a system as they decay.

A CASE FOR SMALL SATELLITES

At the end of the last century, several individuals of stature involved in the development of small satellites, classified satellites by their mass and volume. This was appropriate then as the capabilities of satellites were tightly coupled with their mass and volume. Satellite design is a nonlinear, complex optimization problem in which volume and mass are tightly coupled to power generation and storage, thermal dissipation, attitude knowledge and control, computing power, communication links and payload size and capability. Large satellites (about 1,000 kg) had a full range of capabilities such as precise attitude knowledge and pointing control. The smallest "fully capable" satellites massed around 150 kilograms. The smallest satellites (under 50 kg) had almost none of the support capabilities demanded by the most sophisticated experiments.

Two things changed this equation. The first was that small, containerized/standardized satellite platforms, known as cubesats, were developed by Professor Bob Twigs and others. This simplified the satellite design process for students as one of the important parameters in spacecraft design, the volume and mass, were fixed. In many ways this simplified the satellite design process and students could learn about satellite subsystems and space operations without having to resolve the complexities of optimizing this nonlinear, coupled problem. It also opened up new flight opportunities for these small, low-cost, student-built satellites because the satellite could be carried to orbit in a very strong, and secure deployment device that would contain any debris if the satellite came apart during the launch process. This reduced the risk to the primary payload and the launch vehicle in carrying these tertiary payloads. This containerized payload, or cubesat, concept has become very mature over the last decade. In conjunction, component providers have developed a variety of components such as momentum wheels, star trackers, data-handling systems, power systems, and encryption systems that are sized for these very small satellites. These components allow functionality in very small satellites that was only possible in much larger satellites only a decade ago.

Unfortunately, many members of the space enterprise view these tiny satellites as student projects or stunts of low importance when compared to the more capable satellites. Some even view these small satellites as debris and a threat to the space projects they are most interested in. We should recognize that many of our smaller satellites do have a mission to serve as training for the next generation of space professionals and do not support compelling science. We should also recognize that the proliferation of sophisticated components for these small satellites does enable the ability to perform compelling missions with tiny satellites. We can deal with the first concern by launching these training satellites into short-lived orbits.

Given the advancements over the past ten years in containerized, cubesat spacecraft, it is now probably more appropriate to classify satellites by their mission vice mass and volume. This is because the missions available that can be accomplished with tiny satellites are much greater than they were during the last part of the last century. Further, there are likely missions that can be accomplished more effectively with these cubesat spacecraft than with the larger traditional and more costly satellites; for example a global, multipoint ionosopheric measuring constellation is a very cost-effective cubesat mission. As such, the mission of the satellite should drive its significance and priority in the space enterprise. A satellite is nothing more than a tool to accomplish mission events on orbit. The launch segment and ground segment comprise the rest of the mission components. It makes sense to size the space segment to fit into the smallest satellite platform size that can accomplish the mission. This approach limits the launch costs, development costs, test costs, hardware costs, and transport costs for the satellite.

THE PROBLEM

The proliferation of small, standardized/canisterized satellites and their associated adapters has made the viability of launch missions carrying thirty or more small satellites feasible. Multi-satellite missions in the past generally carried no more than two or three satellites. There are several missions that are pioneering an architecture where a large primary satellite drives mission requirements without utilizing all of the lift capacity of the launch vehicle. This allows the carriage of adapters holding canisterized satellites as tertiary satellites.

A problem with launch missions carrying so many satellites that must be solved is ensuring that they have a reasonable chance of accomplishing their missions without colliding with the other satellites launched on the mission. Another problem that must be solved is managing the orbits of many satellites to alleviate the valid concern of collision with other Resident Space Objects (RSOs.) There is no way to guarantee that re-contact will not occur among any of the satellites launched on the same launch vehicle. This is because the orbits of each satellite change after some time on orbit due to permutations such as drag and gravitational attraction effects.

It is possible to deploy all of these satellites in a way that lowers the probability of re-contact. Typical multi-satellite missions use one-half of a Hohmann Transfer Orbit (HTO) to accomplish orbital separation. This is adequate for small numbers of satellites because "space is a big place" and the small number of objects are easy to track and manage throughout their mission and ultimate decay. Missions that involve ten or more satellites and a rocket body present a different problem. Such missions require eliminating the possibility of re-contact between the primary satellite, rocket body, and any other satellites as well as providing a concise set of orbits for the smaller satellites that can be treated as a system.

A HTO has two characteristics that limit its ability to accomplish these objectives. The first is that it changes the period of each of the satellites. The second is that the orbits are very, very close to the deployment orbit due to the small impulses available to achieve separate orbits between all objects. This results in multiple satellites in essentially the same orbit with different periods. The precession of this system, caused by the different periods, can result in a scenario where the satellites collide during a conjunction.

An unconventional, but realistic, orbital maneuver that essentially preserves the period of all orbits for each satellite involves using radial and anti-radial impulses. A radial and anti-radial maneuver results in a new apogee or perigee that is 90 degrees from the deployment point, a common node that is 180 degrees from the deployment point, a new perigee or apogee that is 270 degrees from the deployment point, and a final common node at the deployment point. This maneuver results in about twice the separation distance between individual orbits in comparison with a HTO style maneuver. This allows the orbital deployment designer to treat all tertiary satellites as a system and manage them as a system.

The approach is simple. By separating two tertiary satellites as a deployed pair and sequencing them on a reasonable timeline (30-60 seconds) with the next deployment, you can localize the risk of re-contact to each deployed pair, minimizing the possibility of re-contact with other deployed pairs, and setting up a system where all of the tertiary satellites orbit in nearly common orbits. Preserving common periods for each satellite implies that the miss distance between any two satellites will remain relatively constant from deployment until the swarm sustains large perturbations due to drag and other factors. Figure 1 shows the various types of orbital maneuvers.

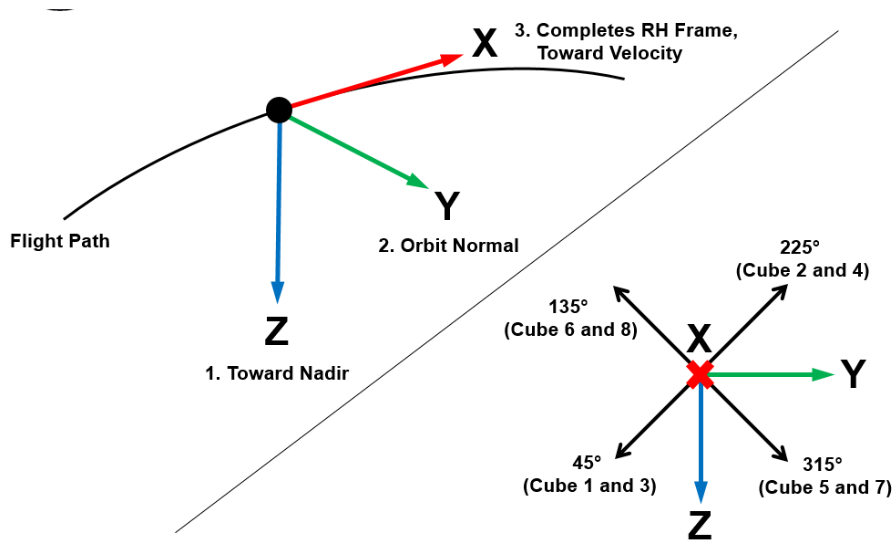


Figure 1: Orbital Vector Maneuvers (Top: Velocity Vector and Ant-Velocity Vector, Bottom: Radial and Anti-Radial Vectors)

A SYSTEMS APPROACH TO SOLVING THE PROBLEM

The complexity of launching and deploying many satellites on one launch mission requires that the mission designer treat all mission events as a system. The engineering details of the launch vehicle capability, canister/adapter capabilities, and the details of the orbital mechanics need to be synthesized into a system solution. The ideal architecture for this type of mission involves launching the primary satellite into its target orbit, accomplishing a clearance maneuver that ensures that the rocket body will not re-contact with the primary satellite, followed by the rocket body holding attitude and deploying the tertiary satellites, and finally the rocket body accomplishing another clearance maneuver to eliminate re-contacting with the tertiary satellites.

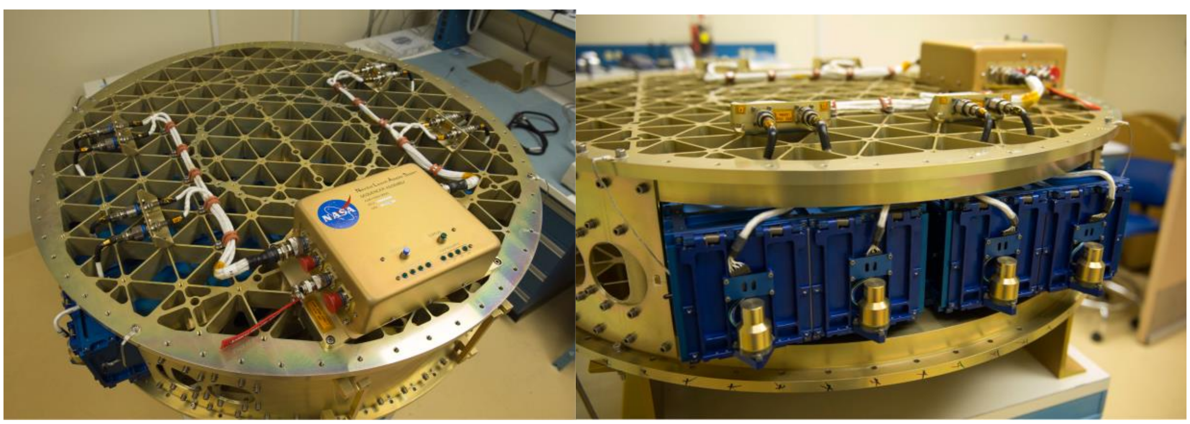
It is important to choose the proper deployment scheme that minimizes the possibility of re-contact between the primary payload, tertiary payloads, and rocket body. It is also important to recognize that the large amount of satellites deployed on this launch needs to be managed as a system to minimize the threat of re-contact with other Resident Space Objects (RSOs). The details of the engineering capabilities of the canisters, adapters, and launch vehicle rocket body can be used to design a mission deployment scheme to minimize the possibility of re-contact and maintain all objects in common orbits that can be used to define their position. This allows other RSOs to avoid the mission swarm. Let's examine the engineering details of each elements of this mission to see how they mesh together to allow for the system solution.

Launch Vehicle System Factors: Launch vehicle systems typically have attitude control and guidance on the last stage. For the purposes of this paper, I will call this last stage the "rocket body." Typically, this rocket body will have the ability to accomplish limited maneuvering and hold its attitude for several minutes. These characteristics are critical to this deployment scheme. For example, the rocket body must be able to accomplish two clearance maneuver events and hold attitude for at least ten minutes to allow for the deployment of many tertiary satellites. Small launch vehicles such as the Minotaur-I, Minotaur-IV, Pegasus, Taurus, and others have the capability to accomplish a clearance maneuver with a delta velocity of one to two meters per second and to hold attitude for up to fifteen minutes. This capability is adequate to accomplish this deployment scheme. Launch vehicles that cannot accomplish clearance maneuvers and hold attitude during the deployment of tertiary satellites cannot be used for this method. This does not mean that you cannot use these lower performing launch vehicles for cubesat missions. It just means that it cannot set up a reliable orbital system of all deployed objects without being able to accurately point each deployment.

It is also important to recognize that the size of the primary payload and rocket body are typically about three to five meters in diameter while the tertiary satellites are typically on the order of one-half meter in diameter. This is important as the larger objects need to be completely removed from the orbits of the tertiary satellites to minimize the possibility of re-contact. This requires two clearance maneuvers. The first clears the rocket body and tertiary payloads from the orbit of the primary satellite. The second clearance maneuver removes the rocket body from the deployment orbit of the tertiary satellites. This is critical because the orbits are so close together that a large object in the swarm greatly increases the probability of a collision.

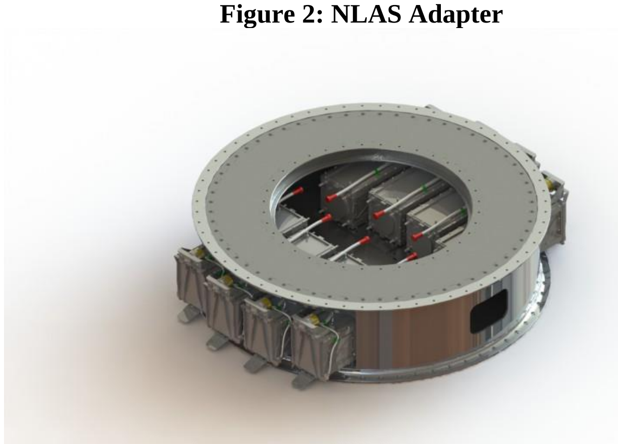
Another concern is that these rocket bodies have a limited operational lifetime on orbit after deployment of the primary satellite. Typically, the rocket body has ten to thirty minutes of battery life after deployment of the primary payload. This results in a less then optimal deployment of the tertiary satellites. Ideally, the deployment of the tertiary satellites should be accomplished at the new perigee that the rocket body achieves after the first clearance maneuver. This would provide the greatest separation between the rocket body and primary satellite. Unfortunately, this would require the rocket body to remain active for about 45 minutes after the first clearance maneuver. This would require the rocket body batteries to support rocket body operations for about 60 minutes after lift-off. Most current rocket bodies cannot reliably support operations 60 minutes after lift-off. Fortunately shorter time lines between the lift-off and the tertiary satellite deployment can readily support setting up this deployment scheme. While the separation distances will not be maximized, they are adequate to avoid re-contact until significant perturbations take effect.

Canister/Adaptor System Factors: The development of several adapters designed to carry canisterized payloads as rocket structure has opened up an opportunity to fly multiple payloads and use up the capacity of the launch vehicle. This development; pioneered by Ames Research Center, started with the NASA Ames NanoSat Launch Adapter (NLAS) and was further refined by the LoadPath CubeStack wafer, shown in Figure 2 and Figure 3 below. Each is capable of carrying up to eight 3U equivalent cubesats. These wafers allow the carriage of canisterized satellites on top of the rocket payload interface and replicate the rocket payload interface on the top of the adapter. This allows the primary satellite to be carried in almost the exact way it would be carried if the wafer was not part of the mission.



Courtesy Ames Research Center

Figure 2: NLAS Adapter



Courtesy LoadPath

Figure 3: CubeStack Adapter

Canisters such as the California Polytechnic's Poly Picosatellite Orbital Deployer (PPoD) and the Planetary Systems Corporation 6U canister have very small deployment velocity capabilities. These are typically on the order of 1 to 1.5 meters per second. This means that the canisters are only capable of making small changes to the original deployment orbit. In fact, the orbital pathways of orbits with these small delta velocities are essentially on top of each other. In addition, electronic sequencers currently available to support deployment of multiple tertiary satellites from multiple canisters are not capable of simultaneous deployments from multiple canisters. They are capable of deploying two canisters within very short timelines (a fraction of a second) and deploying two more canisters about a second later.

Orbital Mechanics System Factors: As previously mentioned, the canisters are not capable of adding a large delta velocity to each tertiary satellite. This results in orbital pathways for each of the tertiary satellites that are essentially the same orbit. Two orbital pathways may be within two meters of each other for forty or more kilometers. These orbits may be within ten meters of each other for two hundred or more kilometers. This means that the tertiary payloads must be clustered and de-conflicted from both the primary payload and rocket body. The use of radial and anti-radial maneuvers coupled with an out-of-plane maneuver allows you to cluster the tertiary payloads based on common deployment directions.

SOME THOUGHTS ON IMPLEMENTING THE SOLUTION

This system solution is not appropriate to meet all possible mission requirements. For example, if you wish to establish a constellation of tertiary satellites in an orbit that are equally spaced around the orbit, this solution will not meet that requirement. If you wish to cluster satellites very near each other, this scheme works very well. The reason for this is that all satellites that deploy in the same direction remain very close to each other and do not re-contact each other. The separation distance between all satellites deployed in the same direction is a function of their deployment separation velocity and the timing of each deployment event. This means that the separation between the satellites deployed in the same direction is relatively stable and all satellites deployed in the same direction fly as a cluster. It is easy to achieve a separation distance of 50 meters plus or minus 10 meters and maintain this distance in a stable configuration until perturbations take significant affect. It is important to note, that each set of satellites deployed in the same direction maintains a close formation relationship with other satellites deployed in the same direction until significant perturbations take effect.

***An Example Deployment Scheme*:** In the following example we assume a primary payload is mounted on top of an adapter containing four containerized spacecraft. We assume the rocket parameters described above (the rocket can conduct collision avoidance maneuvers and hold attitude for approximately fifteen minutes after the primary payload has been deployed). We assume the containers impart 1.5 meters per second of delta velocity to each tertiary satellite as it is deployed.

The following deployment scheme is assumed:

1. Separate the primary satellite (establishes final orbit for primary satellite)
2. Accomplish clearance avoidance maneuver on rocket body
   - A. Establishes deployment orbit for tertiary satellites
   - B. Minimizes re-contact risk to primary satellite
3. Roll the rocket body to allow the tertiary satellites to be deployed out-the-plane of the rocket body orbit
   - A. A 45-degree roll of the rocket body allows one tertiary satellite to be deployed up-and-to-the-right and the other down-and-to-the-left of the rocket body
4. Accomplish series of paired deployments of tertiary satellites
   - A. Deploy on short (30 to 120 second) intervals
   - B. Establishes system of tertiary satellite orbits
   - C. Minimizes re-contact possibility between all tertiary satellites
5. Accomplish clearance avoidance maneuver on rocket body
   - A. Minimizes re-contact possibility between rocket body and tertiary satellites
   - B. Provides further separation between rocket body and primary satellite

The rough sketch in Figure 4 below indicates the first deployment of cubesat 1 and the new local apogee and new local perigee formed by the 1.5 meter per second radial impulse imparted on separation. It also shows that a common node between the new orbit (indicated by the dashed line) and the old orbit (indicated by the solid line) exists at the point of separation and 180 degrees across the orbit. (Note: this figure is not to scale and simplifies secondary effects such as the slight elliptical nature of this new orbit, it also does not illustrate the out-of-plane component of the deployment vector of cubesat 1.)

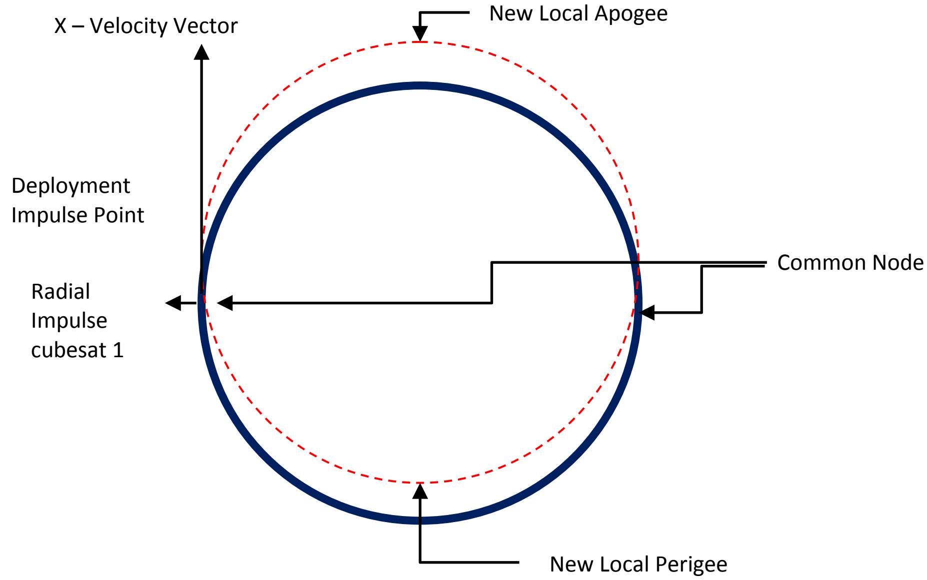


Figure 4. Effect of Radial Impulse on Circular Deployment Orbit of cubesat 1

At the same moment that cubesat 1 is deployed in the radial direction, cubesat 2 is deployed with an equal separation velocity in the anti-radial direction. This is indicated in Figure 5 below. This sketch the new local perigee and apogee of cubesat-2's orbit and the same common node at the deployment point and 180 degrees from the deployment point. (Note: this figure is not to scale and simplifies secondary effects such as the slight elliptical nature of this new orbit, it also does not illustrate the out-of-plane component of the deployment vector of cubesat 2.)

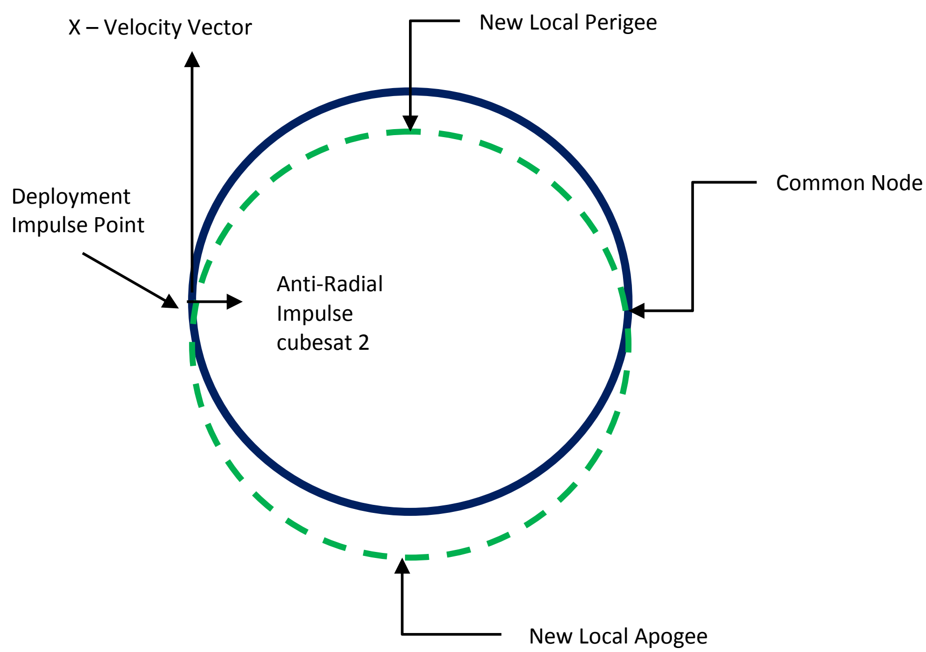


Figure 5. Effect of Anti-Radial Impulse on Circular Deployment Orbit of cubesat 2

We can overlay Figure 4 and 5 to see that this simultaneous deployment of cubesat 1 and cubesat 2 has created an orbital pair of satellites that share two common nodes with a wide separation at Apogee and Perigee.

We can repeat this for cubesats 3 and 4 after a short time interval (30 to 120 seconds) as shown in Figure 6 below. Figure 6 also indicates the notional position of the primary payload and the rocket body after the final collision avoidance maneuver. This sketch shows that the primary payload and rocket body are in new orbits higher and lower respectively than the pairs of tertiary satellites, thereby minimizing the potential of re-contact of these objects on orbit. This establishes a new orbital pair of satellites (cubesats 3 and 4). These satellites will be in a new orbit with a new Perigee and Apogee offset at 90 degrees and 270 degrees from the separation point (similar to Figure 4 and 5 above for cubesat 1 and 2), but offset by the number of degrees the satellites traveled during the 30 to 120 second time interval. cubesats 3 and 4 will also share a common node at the separation point and 180 degrees from the separation point, but this common node will also be offset from the common node for cubesat 1 and 2 by the number of degrees cubesats 3 and 4 travelled during the 30 to 120 second time interval between deployments. (Note: these new orbits for cubesats 3 and 4 are not shown in this sketch and this sketch does not illustrate the out-of-plane components of the tertiary satellites' new orbits).

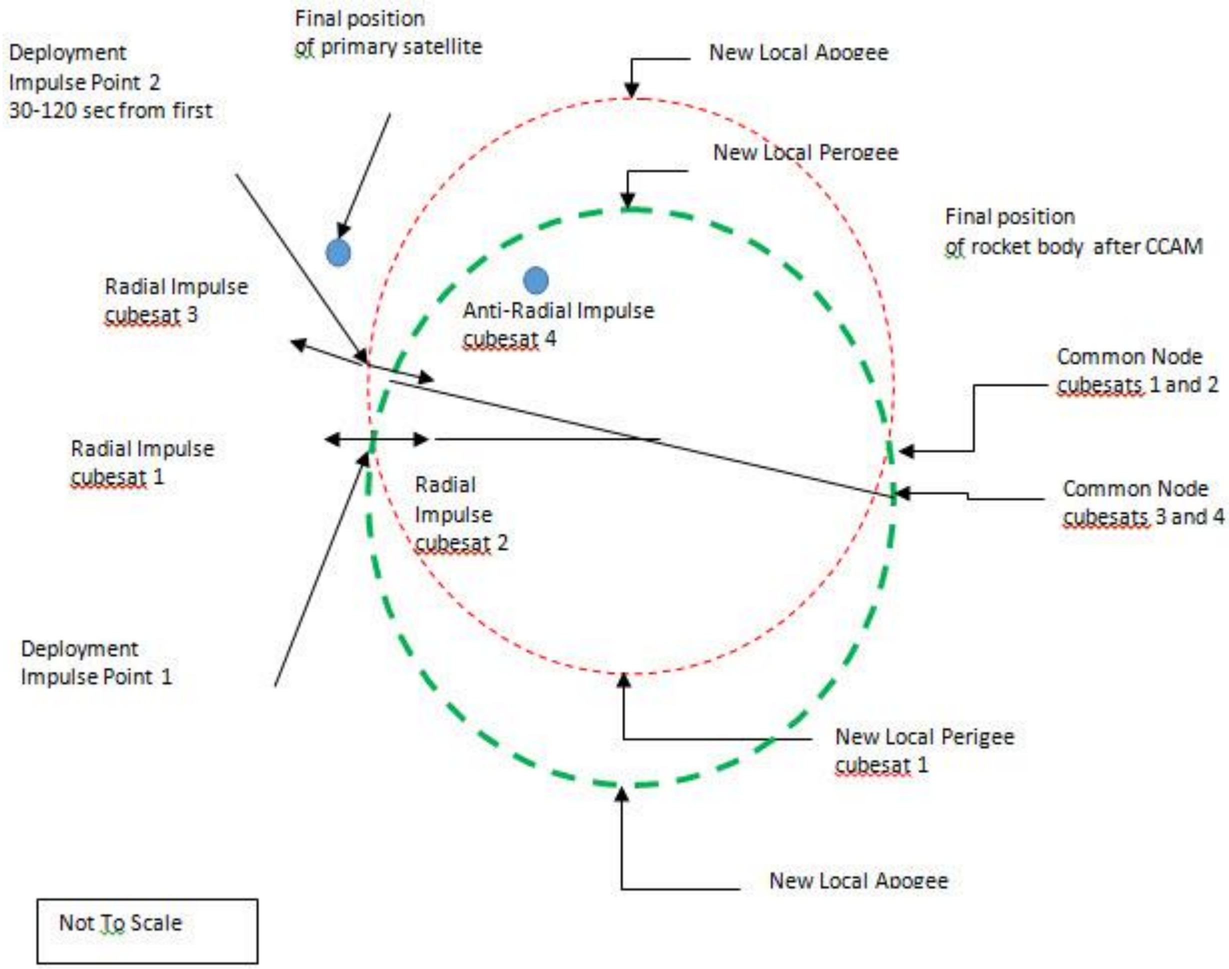


Figure 6. Effect of Combined Radial and Anti-Radial Maneuvers on cubesat 1 and 2, 3 and 4.

At perigee and apogee each of these pairs of satellites will have a wide separation. They share a common node and at these points the satellites will be very close to one another. However, each of these satellites will pass thru this common node at slightly different times; thereby minimizing the risk of re-contact. For the example included in this sketch an orbital analysis indicates that at the common node cubesats 1 and 2 would pass within 50 meters of one another. This is quite close for typical orbital maneuvers, however the closing velocity between these two satellites at this point is approximately 3 meters per second. This is a very small closing velocity and even if drag and orbital perturbations caused these satellites to impact, it is not likely that either satellite would sustain major damage or create any additional debris (this would be equivalent to an approximately eighteen inch drop onto a hard surface).

CONCLUSIONS

PROS AND CONS OF THIS APPROACH:

Deploying pairs of tertiary satellites using these radial and anti-radial deployment schemes has several advantages of a traditional Hohmann Transfer Orbit. This includes the following:

- Relatively stable orbits are achieved at deployment
  - Satellites deployed in common direction maintain relative positions
  - Stable until perturbations take effect
- Satellites deployed in opposite directions maintain adequate separation
  - Miss distances cycle between tens of meters and kilometers
  - Stable until perturbations take effect
- Maximum closing velocities of satellites are single digit m/s (similar to 18” drop to ground)
  - These impacts would not create orbital debris!
  - Care must be taken to completely eliminate the rocket body and primary satellite orbits from the common tertiary satellite orbits

However, there are some disadvantages to this deployment scheme. These include the following:

- Not suitable for spacing satellites in a beads-on-a-string constellation
  - Rocket body does not have attitude control system life-time or accuracy to position large number of tertiary satellites on custom vectors
  - Satellites deployed in the same direction are stable with relatively close separation distances (tens of meters)
  - Satellites deployed in opposite directions come relatively close to each other at the original deployment point in the orbit
- All bets are off several months into the mission when perturbations take effect
  - Satellite perturbations of the constellation are indeterminate

***Final Considerations*:**

This paper demonstrates one scheme for a deploying a large number of tertiary satellites on a common launch vehicle in a manner that reduces the risks of re-contact, or of damaging the satellites or creating orbital debris if the satellite orbits degrade over time and cause re-contact. But as in any complex system, no solution is fool-proof. This scheme only minimizes the probability of re-contact by allowing the tertiary satellites to orbit as a disciplined system with orbiting satellite pairs. However orbital perturbations are likely and are impossible to predict.

This deployment scheme offers an opportunity to treat the tertiary satellites as a single orbital system. Thus they can essentially be treated as an “orbital swarm” allowing other objects to navigate around them.

Finally, this paper is intended to define a deployment scheme methodology that will enable the broader acceptance and use of canisterized satellites by minimizing the risks of orbital re-contact and generation of orbital debris. The mission designer must consider all hardware, software, and orbital factors when designing a custom deployment scheme for a particular mission. There is no substitute for good analysis!

ACKNOWLEDGEMENTS

I wish to thank my co-author and daughter, Heather A. Buckley, for her contributions to this paper. When I was contemplating writing this paper; a last opportunity to pontificate to the small space community, I faced a dilemma. My disability would make authoring a paper difficult. Heather, a student at the University of New Mexico, expressed an interest in publication. I saw an opportunity for a win-win solution and asked her to co-author this paper. She could help me author the paper, I could share a part of my life’s work in astronautics with my daughter, and she would be mentored through the publication process. For the record, I got the better end of the deal. She brings scholarship and polish to this paper. Heather is a brilliant student and fledgling scientist and I am sure this paper will be the smallest of her contributions to the sum of human knowledge. I would also like to thank my other co-author and friend Dr. Peter Wegner. Peter has been a colleague, mentor, mentee, and boss for nearly twenty years. He is also a friend and we have spent many days hunting, fishing, hiking, and riding in the New Mexico wilderness. He has always been there when I needed him. When I asked him to co-author this paper he immediately said yes. He brings stature and perspective to this paper. Once more, when I asked, “who has my 6?” he said, “I do.”

Finally, I'll issue a challenge to the two generations of space professionals following mine:

"Higher, Faster, Farther…Don't stop…Keep going!"

Your challenges will be great but your contributions will be greater. Those contributions will help enable the first generation of humans to be born and reared off planet. This will signal the transition of Humanity into a true space-faring species. Along the way, you will have so much fun. I envy you. So long.

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