International Space Station Program Office
Best Practices for Satellite Payload Developers

Scope

This document is intended to be used as a resource for Payload Developers (PD's) who intend to deploy satellites from the International Space Station (ISS), ISS Visiting Vehicles, or other ISS assets. This document will focus on ISS safety and Jettison Policy requirements, and what design choices PD's can make to simplify the jettison approval and authorization process and minimize risk to ISS and its visiting vehicle fleet.

The ISS Jettison Policy

Anything planned to be jettisoned or deployed from the ISS or any ISS Visiting Vehicle must show compliance with the various safety requirements documented in ISS Partner Program Directive (PPD) 1011, the ISS Jettison Policy. The ISS Program's analysis and approval process for jettison candidates typically takes roughly 3-6 months, depending on the complexity of the jettison candidate. The following sections will outline the requirements of the Jettison Policy and how payload developers can design to easily meet these requirements.

Limiting Orbital Debris

One of the primary functions of the ISS Jettison Policy is to promote the safety of the ISS and other on-orbit assets by ensuring objects jettisoned don't substantially contribute to the debris environment.

The Jettison Policy requires all candidates be trackable by the Space Surveillance Network. While trackability can be assessed on a case by case basis, the general rule of thumb is that any object with a metallic cross sectional area greater than or equal to 100 cm^2 on three orthogonal sides is trackable. The ISS Program strongly discourages deployment of satellites smaller than this. In addition to design considerations, payload developers are encouraged to establish communications with JSpOC early by registering the satellite on space-track.org and sharing contact information. This enables the 18th SPCS to communicate directly with the PD for Two Line Element (TLE) sharing, conjunction assessments, etc. These recommendations and more can be found in the 18th Space Control Squadron Cubesat Recommendations: https://swfound.org/media/205965/mckissock_cubesat_recommendations_aug2017.pdf.

In addition to trackability, the policy also requires candidates demonstrate they don't pose a significant risk of on-orbit fragmentation. The simplest way to accomplish this is for Payload developers to ensure any stored energy systems (such as pressure vessels, large batteries, etc.) will be completely depleted at end of mission. This process is referred to as passivation in the Jettison Policy. In addition to passivation, payload developers should consider the expected mission of a satellite and tailor operational altitude accordingly. Satellites with 1-2 months of science objectives, for example, may not be suitable for deployment from ISS altitudes where orbital lifetimes can be 6 months to several years (depending on solar activity). Similarly, satellites released from external deployers on ISS visiting vehicles are expected to remain on-orbit for multiple years. Satellites with 6 months to 1 year of science objectives may not be suitable for such deployments. Tailoring the satellite's altitude, and thus orbital lifetime, helps reduce the likelihood of on-orbit debris-generating collisions.

Finally, Payload Developers should be cognizant of the risk their satellite may pose to the ground population following atmospheric re-entry. The requirement to limit this risk can be found in NASA Technical Standard 8719.14. Any object which survives the harsh conditions of re-entry and maintains a kinetic energy greater than 15 Joules could potentially injure someone on the ground. Each of these surviving objects contributes toward a total ground casualty risk, which must be lower than 1:10,000 per the aforementioned 8719.14 requirements. An excellent resource for assessing ground impact risk of a satellite is NASA's Debris Assessment Software (DAS). This software, along with instructions, is publicly available from NASA's Orbital Debris Program Office (ODPO): https://www.orbitaldebris.jsc.nasa.gov/mitigation/das.html. DAS is an excellent resource since it also includes tools to assess on-orbit lifetime and compliance with other NASA Std. 8719.12 requirements.

Limit Risk of Collision with ISS and Visiting Vehicles

The International Space Station (ISS) Program considers collision between a previously deployed satellite and the ISS a catastrophic hazard. There are a number of detailed requirements in the Jettison Policy dealing with re-contact risk and how it is assessed. The following sections will provide more detail on the process of how that risk is assessed and recommend actions the PD can take to mitigate this risk.

Natural atmospheric decay & ISS re-contact risk

In the case of satellites that lack any method of controlling their orbital altitude, simple orbital mechanics analysis can be sufficient to demonstrate that the risk of re-contact with the ISS is sufficiently controlled. This orbital mechanics analysis is performed for all jettison candidates: The VIPER team provides input parameters to the Trajectory Operations and Planning Officer (TOPO) team, who perform relative motion analysis of the candidate with respect to the ISS. Alternatively, the PD themselves may provide relative motion analysis results to the VIPER and TOPO teams for review and concurrence. Input parameters include:

- ISS ballistic properties, which are consistent and predictable: conservatively the ISS Ballistic Number (BN) is approximately 100 kg/m^2 at low solar beta angles
    - The planned timeframe of jettison can be taken into account if necessary to provide some relief (beta cutouts) for candidates with BN's higher than 100 kg/m^2 since ISS BN is a function of Beta, and increases in magnitude as beta angle increases
- The planned jettison location, direction, and deploy speed

    - In cases where sufficient fault tolerance cannot be demonstrated for the deploy mechanism's deploy speed (dV), the worst case deploy speed is often assumed
- The jettison candidate/satellite's ballistic properties
    - The ballistic properties of the candidate can vary significantly: Ballistic Number is dictated by mass & dimensions of the candidate, but the flight orientation of the candidate is assumed to be an average of the smallest two faces of a satellite unless analysis demonstrates otherwise. The ISS Program considers this "worst case" BN for its baseline assessment of re-contact hazard.

The Ballistic Number referenced above is in reference to a mass/area ratio commonly used to calculate drag on an orbiting object. Drag forces on orbit are calculated the same as for aircraft:

- $F_D = \frac{1}{2}\rho v^2 C_D A$, where:
    - F_D is the drag force on any object moving through a fluid
    - ρ is density of the fluid / atmosphere
    - v is velocity of the object
    - C_D is Coefficient of Drag – almost always assumed to be ~2.0 - 2.07 based on observation for ISS applications
    - A is cross sectional area – this is the area of an object that is directly interacting with particles in the velocity vector, creating drag

For orbital drag calculations, we're most interested in the acceleration due to drag (F = ma), so we rearrange the above equation and solve for acceleration due to Drag:

- $a_D = \frac{\rho v^2 C_D A}{2m}$

The Ballistic Number combines constant characteristics of the object into one parameter:

- $BN = \frac{m}{C_D A}$

Comparing the equation for BN to the acceleration due to Drag equation above, it's simple to see the inverse relationship between BN and Drag: The higher the BN, the lower acceleration due to drag the object experiences.

Designing satellite to minimize re-contact risk:

Since BN directly influences the speed at which an object decays through the atmosphere, it is in the best interest of a satellite PD to demonstrate that the BN of their satellite is less than that of the ISS. If this can be demonstrated, the satellite will decay faster than the ISS, and there will be little or no re-contact risk with the ISS.

Some satellites are designed such that the previously described "worst case" BN already meets this criteria: the BN calculated using the average of the two smallest orthogonal areas on the satellite is already less than the BN of the ISS. In this case, verification that the passive re-contact criteria in the ISS Jettison Policy is a simple calculation using the equations above to demonstrate the satellite’s BN is less than 100 kg/m^2, which is the ISS BN under conservative environmental conditions.

Alternatively, in some cases PDs have a satellite whose total average Ballistic Number is less than ISS, but the worst case BN is not. In those cases, the PD has the option of coordinating with the ISS Program on 6 degree of freedom (6DOF) analysis to demonstrate that without attitude control, the satellite will not orient itself into this “worst case” BN orientation. This analysis is expected to be provided by the Payload Developer, with input assumptions agreed to with the ISS Program Office. Figure 1 illustrates the yaw, pitch, and roll results of one such analysis, demonstrating that random tumble is a more appropriate assumption for this satellite.

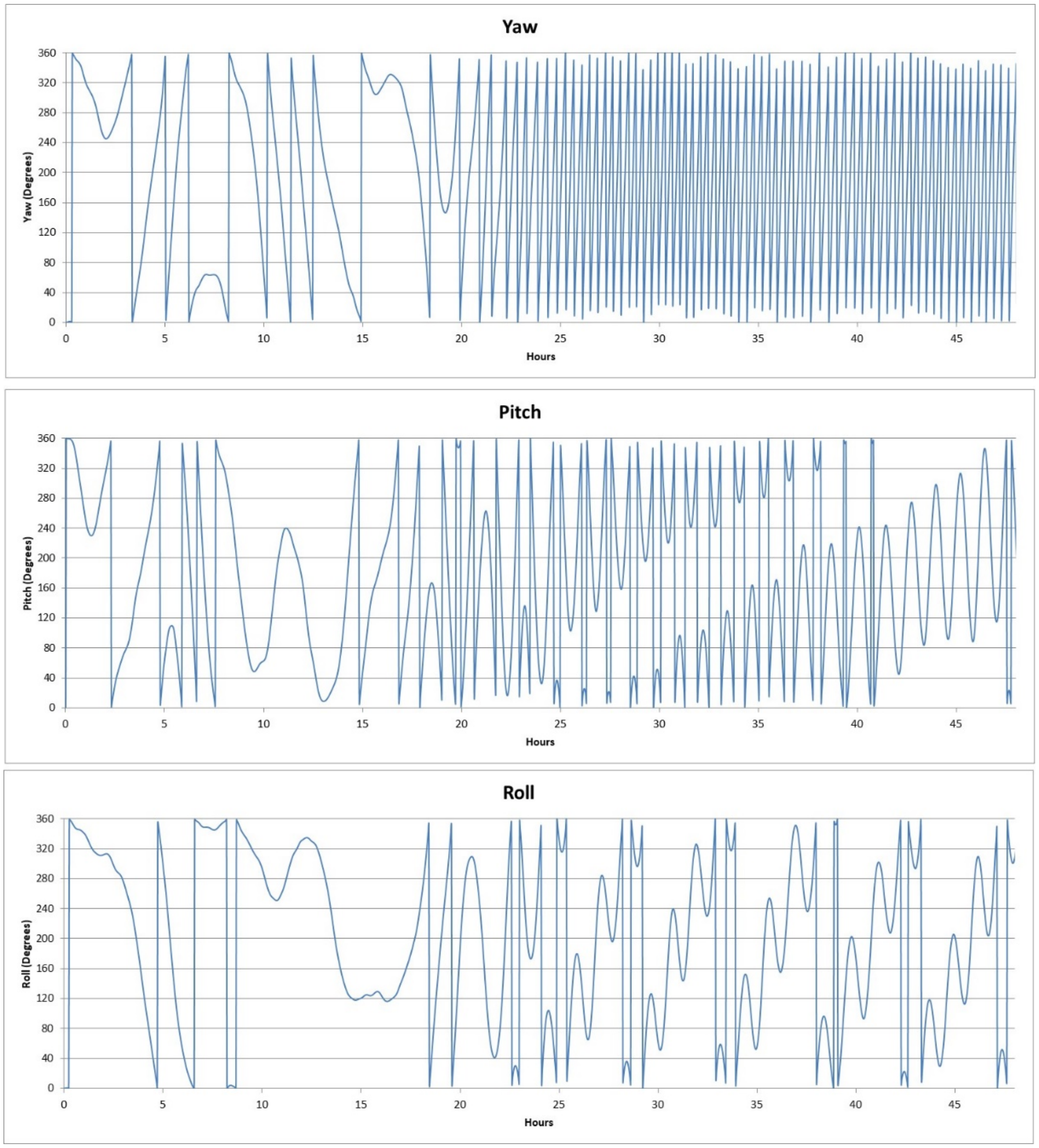

Figure 1: Sample 6 Degree of Freedom Analysis Results (Tumble)

Note that the 6DOF analysis above is actually run for 7 days; however, for clarity the data is shown here for only the first 48 hours. It can be seen that the yaw, pitch, and roll values of the payload in the analysis above continue to fluctuate constantly throughout the duration of the analysis without “settling into” one particular angle on any axis, which would indicate attitude stabilization. Based on the results of this type of analysis, the VIPER and TOPO teams are more confident using the less conservative random tumble BN for the satellite (or an operational BN, if available): This BN is calculated using the average of all 3 orthogonal sides of the satellite rather than just the smallest two.

Grab one of EG’s 6DOF results that show at least one axis stablizing

Figure 2: Sample 6 Degree of Freedom Analysis Results (Stable)

If a satellite’s BN is still higher than ~100 kg/m^2, additional risk mitigation techniques may be used to reduce risk of re-contact with ISS, but often rely on deployment constraints on the satellite. In these cases, verification of Jettison Policy re-contact requirements is accomplished via relative motion analysis coordinated by VIPER and performed by the TOPO office. In all cases, Ballistic Number and re-contact analysis is presented to the ISS Program and International Partners for review and jettison authorization.

The re-contact analysis described thus far assumes either 1) The satellite jettison candidate does not have attitude control or 2) The satellite’s attitude control has failed to activate. In cases where a satellite possesses attitude control, the PD must provide the planned flight orientations of the satellite for additional re-contact analysis to be performed by TOPO. These additional cases assume that attitude control is activated and functional, and check the operational BN of the satellite for any ISS re-contact concerns.

Altitude Control and Propellant Mechanisms

The aforementioned re-contact analysis does not take any altitude control methods possessed by the satellite into account; however, propulsive re-boost capability also creates a risk of ISS re-contact risk that must be controlled.

There are two requirements in the ISS Jettison Policy specifically written for satellites with propulsive capability:

Requirement 3.2-3: Satellite Controllability:

All jettison candidates with systems capable of modifying or adding energy into the candidate’s orbit must demonstrate that they do not pose a collision hazard to the ISS or visiting vehicles.

a. Jettison candidates shall provide an operations and flight plan demonstrating that all systems shall be operated such that no part of the jettison candidate enters a ±2 km radial by ±25 km down track by ±25 km cross track rectangular keep out zone centered about the ISS and does not follow a flight path which interferes with nominal ISS operations.
b. Jettison candidates shall demonstrate that within credible systems failure scenarios as defined by the payload developer and ISRP, the candidate cannot maneuver itself into a ±2 km radial by

±25 km down track by ±25 km cross track rectangular keep out zone centered about the ISS within 10 days of failure occurrence.
Note: It is the responsibility of the payload developer to demonstrate sufficient fault tolerance in the aforementioned systems to the ISRP in accordance with their respective requirements documented in SSP 30599, Safety Review Process.

Part A of requirement 3.2-3 is an operational requirement. Compliance can be achieved by the PD making agreements with ISS flight operators at NASA that the satellite plans to operate in a way that will not impact ISS operations. It is recommended that satellites plan to operate well below or well above (for satellites released from external deployers mounted on ISS visiting vehicles) the operational altitude range of the ISS, which is roughly 395 km to 425 km. Actively maneuvering to cross the ISS operational altitude range should be avoided whenever possible, unless the satellite can demonstrate 2 fault tolerance and must work functionality in the propulsion systems.

Compliance with part B of Requirement 3.2-3 is related to satellite design and fault tolerance. ***The most straight forward way to show compliance with part B is to demonstrate 2 fault tolerance against inadvertent thruster firing once the satellite has been activated***; however, many satellites do not have the resources for 3 fully redundant computer systems. If 2 fault tolerance cannot be demonstrated, full relative motion analysis, which includes differential drag between the ISS and satellite and the "worst case" thruster firing scenario as agreed to with the ISS safety community, is an acceptable way to demonstrate compliance with this requirement. The following sections will provide recommendations that will minimize re-contact risk to the ISS.

DFMR

Design for Minimum Risk (DFMR) parts and components for propulsive systems, when possible, can be considered to provide additional fault tolerance toward the required 2 fault tolerance for systems which present a catastrophic hazard to ISS.

Inhibit scheme

VIPER recommends that payload developers design their satellites with additional inhibits between satellite activation and propulsive system activation. In the past, satellite developers have been unable to demonstrate sufficient control against inadvertent thruster firing after satellite activation (even without any commanding to begin thruster firing), thus the ISS safety community has constrained satellite activation itself (or required removal of all propellant on the satellite) in order to control the ISS re-contact hazard. A physical inhibit between satellite activation and propellant system activation could allow the satellite to activate and begin science objectives much sooner, without need for an entire satellite activation inhibit against ISS re-contact.

It is for this reason that the VIPER team strongly recommends PDs develop fault trees for their propulsive control systems. It is critically important during the safety review process for the PD to be able to identify credible failure scenarios and determine the number of faults necessary for them to happen. Similarly, payload developers that successfully perform CBCS or use hardware that has been reviewed through Computer Based Control System (CBCS) analysis can more confidently be shown to meet the safety criteria of the NASA Safety community.

Command Encryption

As a general rule, satellites with propulsive systems should have command encryption. It prevents possible issues with signal interference, and can help provide assurance that commanding to the satellite is intentional.

Low Maximum Satellite dV

Robotic deployment mechanisms available on the ISS generally deploy satellites at speeds between 0.5 m/s up to 2 m/s. It's straight-forward trigonometry to determine the effective retrograde departing speed of the satellite taking into account robotic deployment angles. Knowing the effective deployment dV can provide a bounding condition for the worst case thrust needed to create a re-contact risk: the thrust of the satellite would have to be greater than that initial effective departing speed (assuming the satellite meets the aforementioned Ballistic Number requirements of the Jettison Policy). If the total dV available on the satellite is lower than the effective departing rate, it becomes trivial to demonstrate risk of re-contact is controlled.

Thruster layout

Thruster layout is another way that ISS re-contact risk can be reduced. One method of limiting the worst case dV that could be applied to the satellite is orienting multiple thrusters such that they are individually pointed offset from the c.g. of the satellite, but provide a total force which acts through the c.g.. These thrusters individually do not provide dV to the satellite, and thus any failure scenario which considers only a single thruster inadvertently firing cannot present a re-contact risk to ISS. Because such a configuration requires multiple thrusters fail 'on' to achieve dV, additional fault tolerance against ISS re-contact is achieved (assuming there isn't a single failure which would lead to all engines firing simultaneously).

Figure 3 shows one such satellite thruster configuration:

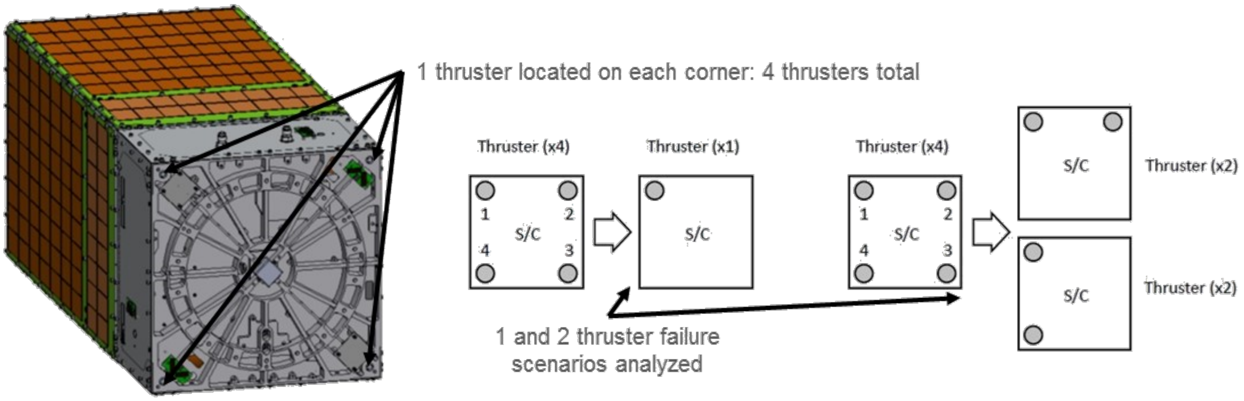

Figure 3: Satellite Center of Gravity (c.g.) Offset Thruster Configuration

Note that the thruster configurations shown in the figure above are not actually comprehensive: two thrusters failed on diagonally could contribute to a total thrust still applied through the c.g. of the satellite. It's for this reason that the ISS Program office recommends early coordination of analysis assumptions between PD and VIPER/TOPO/the safety community to ensure that the appropriate cases have been assessed.

Attitude Control

Because re-contact with the ISS requires specific orientation when burning thrusters, fault tolerance in a satellite's attitude control systems can be used as rationale that a satellite cannot realistically pose a re-contact risk with ISS. Even without 2 fault tolerance, attitude control can still add a level of fault tolerance when the satellite does not nominally intend to orient itself into a "reboost" attitude.

Thruster on-time limitations

Thruster on-time limitations can be an effective method of limiting re-contact risk with the ISS. Many thrusters are only capable of firing for a limited amount of time, often a shorter timeframe than would be necessary to expend all available propellant on the satellite. Alternatively, inhibits designed into the propellant system that limit the dV that can be applied to the satellite for each commanded use of the thrusters also reduces the total effective dV that can be achieved in a particular failure scenario.

These thruster limitations, if verifiable to the ISS safety community, can be used as rationale to reduce the overall "effective dV" applied to the satellite in the worst-case inadvertent thruster firing analysis scenarios. Reducing the worst case effective dV will allow satellite propulsive systems to activate and begin operation sooner: If a thruster system cannot fire long enough in a single burn to achieve a total dV greater than the departing dV from the ISS, re-contact with ISS is controlled.

Low impulse thrust systems

Similar to thruster on-time limitations, satellites using engines that provide low impulse (such as ion thrusters) dramatically reduce the risk of re-contact with ISS since they do not quickly change the orbit of the satellite. Since significant dV takes so long to achieve for such systems, a failure would have to be stable (attitude control consistently incorrect, for example) to actually put the satellite at risk of conjunction with ISS. Additionally, in the worst case ISS would be aware of and able to respond to a failure in such a low thrust system well ahead of time if necessary, essentially eliminating the actual risk of conjunction. If the impulse of the thrust system is so low that it would take > 10 days to generate the dV required to create a re-contact risk, Requirement 3.2-3.b can be shown to be met.

Note that the end goal of many of these recommendations is to define an "effective dV" that could be applied to the satellite in the credible worst case inadvertent thruster firing scenario. This effective dV is then used to determine whether any additional activation constraints should be applied to the satellite to control the re-contact hazard with ISS, taking into account the satellite’s BN and retrograde departing rate from ISS (deploy dV). Any method of reducing the “effective dV” a satellite could achieve in a failure scenario could potentially mitigate the re-contact risk with ISS and demonstrate compliance with the Jettison Policy.

Resources

- Publicly Available Satellite Tracking Data
    - www.Space-Track.org
- CubeSat 101:
    - https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf
- NASA Debris Analysis Software and Resources
    - https://www.orbitaldebris.jsc.nasa.gov/mitigation/das.html
- NASA Technical Std. 8719.14: Process for Limiting Orbital Debris
    - https://standards.nasa.gov/documents/nasa-std-871914pdf
- JSpOC Recommendations for Optimal Cubesat Operations:
    - https://www.space-track.org/documents/Recommendations_Optimal_Cubesat_Operations_V2.pdf
- 18th Space Control Squadron CubeSat Recommendations:
    - https://swfound.org/media/205965/mckissock_cubesat_recommendations_aug2017.pdf