INTERNATIONAL SPACE STATION AS AN OBSERVATION PLATFORM FOR HYPERSONIC RE-ENTRY OF ITS VISITING VEHICLES

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ABSTRACT
The International Space Station (ISS) will receive an armada of visiting supply vehicles during its life in orbit. Over 500 tons of material will be destroyed in targeted re-entries of these vehicles. Because all such re-entries lie in the same orbital plane of the station, and because the visiting vehicles typically deorbit within a few hours of departure, the ISS will usually be within sight of the re-entry process, at a range of only 300-600 kilometers. This vantage point offers an unprecedented opportunity for systematically measuring hypersonic destructive processes. This paper examines the integrated operational constraints of the ISS, its supply vehicles, and candidate sensors which can be employed in the scientific observation of the re-entry process. It is asserted the ISS program has the potential to reduce the worldwide risks from future deorbiting spacecraft, through systematic experimental characterization of the factors which affect the rupture, debris survival, and footprint size of its visiting vehicle fleet.

1. PROBLEM STATEMENT
The experimental study of hypersonic phenomena is one of the most difficult branches of engineering, owing to the near impossibility of achieving sustained temperatures, pressures, molecular distribution, and especially velocities that match the region of interest in a laboratory setting. At best, certain conditions can only be obtained in shock tunnels for the briefest of times, and at great expense. The hypersonic re-entry of a spacecraft, by comparison, is a progressive event involving huge variations in Knudsen Number, Mach Number, and Reynolds Number, as the vehicle experiences exponential increases in density, temperature, and pressure. The vehicle itself progressively changes ballistic coefficient as appendages soften and fold or separate, finally reaching combinations of torque, heating, vibration, and pure dynamic pressure which combine to lead to the vehicle's structural failure, or rupture. Following the initial rupture, a new progressive phase is entered, as the remnants continue to shed yet smaller fragments.

As the spacefaring nations and private corporations of the world begin the new millennium, over one hundred boosters and a growing number of satellites will re-enter earth's atmosphere each year, thus posing an increasing threat to all inhabitants under the orbital path. The survival of the debris from these re-entry objects are for the most part only qualitatively understood. The problem of obtaining systematic experimental data on the re-entry process is compounded by the need to conduct all intentional destructive re-entries over the most remote portions of the planet, thus making scientific observation difficult and expensive. Further, there are military and/or national security implications in the majority of the previous intentional re-entries, meaning that the detailed data, when it does exist, is not easily shared among nations.

2. APPROACH
The International Space Station (ISS) program provides the potential to overcome all of the mentioned impediments to research in the field of hypersonic re-entries. Although the multinational study postulated here has not been formally agreed, members of the partner agencies are just beginning discussions of the constraints and opportunities that would shape such a study. This paper provides an interim view of the potential capabilities for ISS-based hypersonic science, and the constraints that may bound the work.

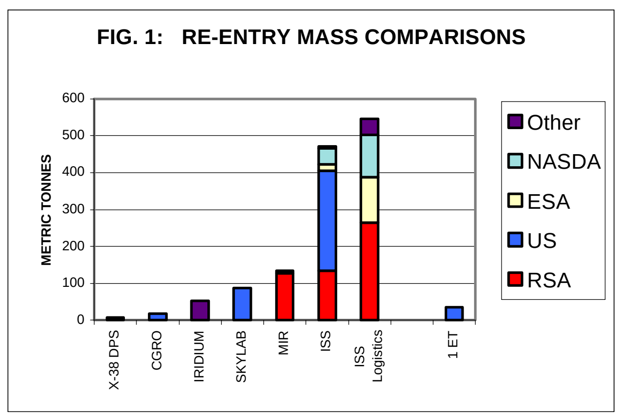

Fig. 1

The ISS will receive an armada of visiting vehicles (VV) during its life in orbit. (Fig 1). The supply vehicles that will destructively re-enter include the 7-ton Russian Progress, the orbital module and Instrument Module of the Russian Soyuz, the European Space Agency's Autonomous Transfer Vehicle (ATV), and the National Space Development Agency of Japan's (NASDA)'s H2 Transfer Vehicle (HTV). In addition, several deorbit propulsion stages (DPS) of the American

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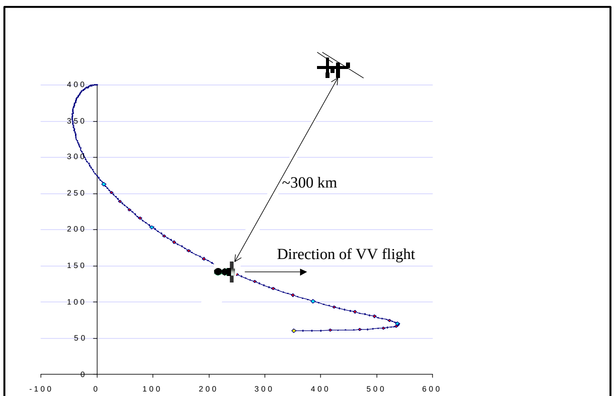
separation from the survivable lifting body, as it is periodically returned to Earth for refurbishment. Together, over 500 tons of material will be destroyed in targeted re-entries of the scheduled vehicles, and hundreds more tons will re-enter in the form of spent orbital and suborbital stages of their boosters. (Total is not shown in Fig. 1, but one Shuttle External Tank (ET) is shown for reference) These scheduled events do not include the potential future commercial transports which have yet to be incorporated into the fleet. Because all such vehicles lie in the same orbital plane of the station, and because the visiting vehicles themselves deorbit within a few hours of departure, the ISS will usually be within sight of the re-entry process, at a range of only 300-400 kilometers.

3. GEOMETRY

The ISS and its departing visiting vehicle originate at the same location and velocity, typically in a circular orbit near 400 km altitude. A coordinated separation sequence moves the VV outside of a 2-kilometer Approach Ellipse (AE). Since the ISS itself will always fly in the same basic orientation (LVLH, with X axis in the velocity vector, Z axis towards nadir), vehicles will be limited in their choice of departure direction, based solely upon the location of their docking port. (Relative to the ISS, the vehicles will need to clear radially outwards from their release point, in a direction which does not approach any other part of the ISS structure. The HTV, which is released from the nadir forward region, will therefore need to depart in a different direction than a Progress leaving from the aft docking port.). Drift rates continue to separate the vehicles.

It is currently planned that once any vehicle has departed, it should not re-cross the orbital path of the ISS, for safety concerns. Thus, ISS will likely have different views of different vehicles, unless the deorbit burn occurs shortly after departure from the AE, making the differences (fore and aft) negligible. Figures 2 and 3 show the viewing geometry of vehicles which begin their deorbit burns respectively 400 km behind the station, and 100 km in front of it.



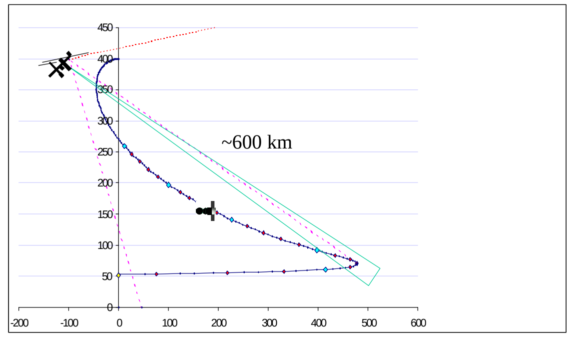


Fig. 3 Deorbit from Ahead of ISS

The relative motion plots have the same characteristic shape for the two vehicles. The VV is assumed to start from position (0,400) km in X,Y. The plots cover 45 minutes of trajectory, and trace the position relative to where the VV would have been had it not executed a deorbit burn. The ISS is positioned at some relative distance in front of (Fig. 2) or behind (Fig. 3) this initial point. Because the deorbit event is only half an orbit, the ISS stays nearly stable relative to this starting point for the duration. Viewing angles and attitudes are then easy to visualize. Diamonds mark 1-minute intervals. Post rupture, debris sweeps aft at high rate.

It is notable that the entire deorbit process, from engine ignition through subsonic debris tumble, can be visible from the station, although in a practical limit, only the region of greatest interest may be visible through any one viewing port. The ISS itself cannot be maneuvered rapidly, because it is so large (over 100 meters in width, and over 60 meters tall). Typical maneuver rates are 0.1 deg/sec, or exactly the speed of the minute hand of a clock. Maximum maneuver rate is approximately 0.2 deg/sec in any axis.

4. VIEWING

Several excellent viewing ports exist on the nadir side, including the 22-inch US *Destiny* Laboratory window, and several large windows in the Russian *Zvezda* Service Module. At least one of these Russian windows is understood to be quartz, to allow infrared observations. Together they allow high throughput of a wide range of optical wavelengths. Although approximately 80-degree fields of view are theoretically possible from the largest windows, the actual FOV will nominally be much less, because of obscuration by external modules, or even by competing observational gear in the windows. Internal geometric conflicts will be exacerbated because the optics for the cameras will be the longest and widest of the available lenses, for use in recording events over 300 km away. The US Laboratory window is the least obscured of the ISS viewing ports. However, there are other large optical instruments which will compete for this resource. The author is investigating the possible shared use of some payload optics proposed for other research in the window.

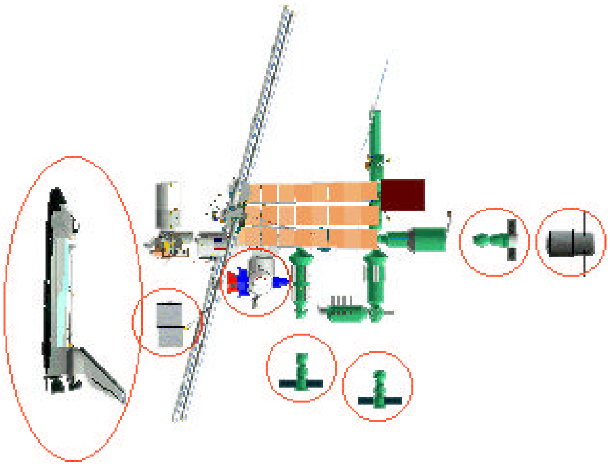


Fig 4 ISS Visiting Vehicles

4.1 <u>Operational Constraints</u>

There are flight restrictions regarding the best windows on the ISS. They are nominally covered to protect against damage from orbital debris. The Program is hesitant to open the covers if the windows are exposed to the velocity vector, out of concern for damage. Thus, the deorbit viewing as depicted in Figure 2 will require special care and resolution of competing technical desires, since the best optical configuration in this scenario would be to pitch the ISS upwards approximately 60 degrees, to put the regime of interest along the optical axis of the window for least distortion. This attitude creates a ram pointing of the windows.

The flight rules allow the ISS to maneuver to and to hold almost any attitude for a single orbit, before it is required to return to its nominal LVLH attitude or thermal and power balance. Fortunately, the deorbit event occurs over a half-orbit, and the maximum excursion (60 degree pitch) would take only 10 minutes to achieve at nominal maneuver rates, so the experiment can easily stay within the one-orbit out-of-attitude maximum. Of greater concern is the need to return the ISS to microgravity operations as soon as possible after undocking of a Visiting Vehicle (a disturbance event). These operations can only be maintained in the LVLH attitude, plus or minus 15 degrees in each of pitch, roll, and yaw. Therefore, if an off-nominal attitude is required for the viewing, it is probable that the deorbit must occur within a day of the departure or arrival of a vehicle, which is the normally scheduled time that the ISS will not be in microgravity research configuration. Note (Fig. 5) that an intentional 15-degree yaw bias can de-conflict a module obstruction of the nadir Laboratory

view from the high-gain directional antenna suite at the aft end of the Service Module, should radio communications be possible through any of the systems which share that pointing platform.

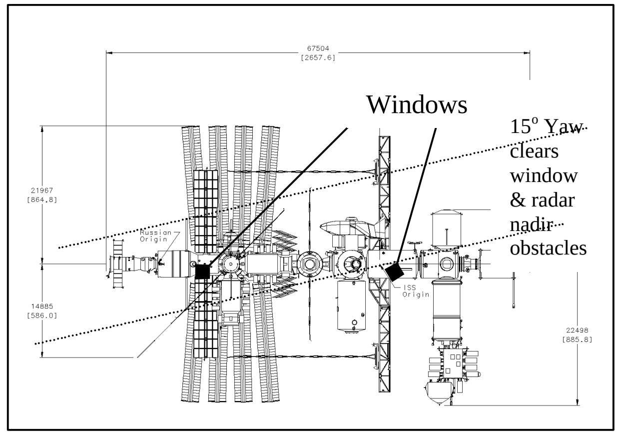


Fig. 5 Nadir View of ISS

5. STABIITY

The ISS attitude is maintained by control moment gyroscopes (CMGs), and pointing is determined by a combination of inertial systems, differential GPS, and star sensors. At assembly complete, the attitude knowledge will be 0.5 degrees (3ó) per axis, and drift rates (due to diurnal variances in atmospheric torque,etc) will be much less than 0.01 deg/sec per axis (3ó), approaching .00033 deg/sec in pitch. There will be slight variation in these parameters as the ISS grows through its various assembly stages, but these values are useful for determining relative motion with great accuracy. At least one optical payload currently includes designs to couple precise camera pointing servo-systems with attitude data from the ISS navigation system, to get absolute earth-relative pointing. Such data will ultimately be useful in resolving the details of the re-entry ballistics. If further ballistic negotiations permit a choice in event viewing, the scenario described in Fig. 3 provides the best possible situation, to optimize the stability of the view. In this case, the moment of rupture is stationary in the view, and drifts at a steady 0.2 deg/sec for nearly 20 minutes (diamond marks) before the rupture. (Fig. 6).

The Fig. 2 scenario shows that while the event will occur closer to the ISS, the relative motion will be far more dramatic, and a would be larger challenge for tracking optics to achieve both the wide range of angular velocities and wide field of view. As a reference, the tracking payload camera that is currently being considered for other use on ISS has a total sweep of only 10 degrees. It would therefore be able to capture a far larger duration of the event in Figure 2's scenario than in Figure 3. The scenario in figure 2, as mentioned in part 4.1 above, presents a window protection issue. There is clearly further optimization work to perform.

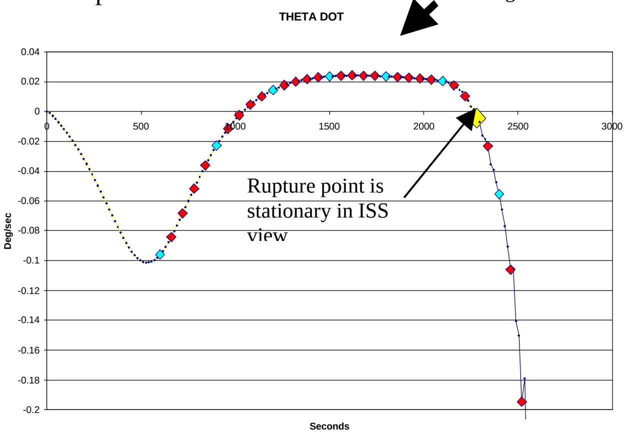


Fig. 6: dTheta/ dt of VV from ISS vantage

6. OPTICS

There will be a variety of optical recording systems aboard the ISS, including film and digital still cameras, and High-Definition Television (HDTV). HDTV is currently only planned for the interior of the ISS, although several steerable external cameras on the truss and other locations will provide NTSC video (480 line resolution). The HDTV cameras are expected to be the most useful off-the-shelf recorders of deorbit events (at 1125 lines of resolution, this is better than fine-grain 35mm film). At 16-power magnification, the resolution of HDTV at 600 km is approximately 32 meters. Larger optics and/or closer distances have the prospect of bringing the resolution of the event to equal the size of the VV. A practical limit to the lens size is the length and width of a standard launch/stowage locker, which, including packing materials, will limit the diameter of a lens to approximately 25 cm. This gives a theoretical diffraction limit of 1.8 meter resolution at 600 km range, and sub-meter resolution at 300 km. Such optics are not currently planned for the ISS, but could be a future enhancement or payload. Therefore, at typical commercial lens combinations, the resolution will be limited by the recording medium, and not by the optics path, and will remain approximately equal to the vehicle typical radius.

7. RADIO CAPABILITIES

There is no single standard for radio communications between the ISS and its visiting vehicle fleet. Each station partner has created its own radio suite to communicate with its ground control center and with the ISS. Therefore, it is difficult to characterize the "standard" suite of data that might be obtained. Further, since the VV are autonomous of ISS operations after departure from the 2 km AE, the radio sets are currently not optimized for long-range data transmission to the ISS. It is TBD whether the vehicles will maintain communications with geostationary relay satellites.

However, the proximity of the ISS to the VV rupture provides several promising possibilities, that are as of this writing only conjecture. The ISS is essentially a flying antenna farm, with dozens of frequencies at its disposal, including several highly directional systems. As an example, the Russian Ku-band system is not configured for passive radar capability, but its antenna does have an unobstructed view of the entire event. Future enhancements could theoretically adapt this or other assets on the ISS to assist in the data gathering.

One extremely promising possibility is the (currently unfunded) development of a survivable, strap-down re-entry "Black Box", similar in function and design to an aircraft flight data recorder. Such a standard device would include its own internal power, accelerometers and other sensors, thermal protection, as well as a standardized transmitter, and potentially a data input connector for deployable remote sensors (such as taped-down thermistors, positioned by the crew on the pressurized compartment walls). The black box would be built so as not to require design modifications to any VV, and would mount to existing mounts on the hatch. The crew could attach the black box to the vacuum side of the VV hatch after closeout, and before closure of the ISS side of the vestibule. (This technique has been used to attach several previous experiments to departing Progress vehicles at Russian Space Stations).

The proposed "black box" would ride down with the VV and record the accelerations and temperatures leading up to rupture. Immediately thereafter, triggered by the high accelerations of rupture as recorded by the internal accelerometers, the black box would activate its own detachment mechanism, and spring free of the hatch. At this point, the box would have a short window of time to decelerate out of the plasma cloud, and play back its recorded data to the space station, that would still be within view, only a few hundred km away. The device would not need to survive past this transmission point.

This on-board instrumentation of the rupture process would be a first, and could easily be standardized, for there are only two types of docking/berthing mechanism hatches for the entire fleet, and a common receiver platform in the form of the ISS. The prospect of large production runs of the sensors for use on the scores of ISS visiting vehicles could bring the cost per unit to just a few percent of the cost of an airborne observation expedition, with better (directly measured, onboard) data from the event.

8. EXPERIMENT PARAMETERS/VARIABLES

The VV fleet is optimized to deliver cargo to the ISS. Therefore, there is nominally little flexibility in the delta-V budget (and in some cases, *power* budget (HTV, CRV), and even *life support* budget (Soyuz, CRV)) during the disposal process. However, within the margin, each vehicle will have a small range of possible re-entry angles, vacuum perigees, etc. Tumble, spin, and/or entry attitude are relatively simple parameters that can be varied without significant impact to the vehicle's propellant budget. Other factors are possible, but will require further discussion. Such factors include entry latitude, vacuum perigee, and TBD specific passivization techniques. Each of these measures may require trades of ISS cargo needs for VV propellant or for deorbit specific hardware, that have not been negotiated.

The chance to directly record re-entry of insertion stages will occur approximately for one in every fourteen launches, based upon pure statistical chances of the event occurring within the 1/7th of the ground track visible from the station's 400km altitude. This assumes that the ISS can be maneuvered to direct at least one sensor on the event. Per the discussion on microgravity in section 4, this may not always be possible, even when the event is within the line-of-sight of the ISS. Conversely, a much larger fraction of the insertion stage events will be visible if one considers that the station will arrive over the decelerated debris cloud within minutes after the rupture, even when the event occurs beyond the ISS forward horizon. Radar capabilities would be most appropriate to this type of post-rupture viewing, but as mentioned above, such a capability has not been developed yet. Some useful data might be gathered from smoke or residual plasma trails. Experience with this sort of observation may suggest enhanced techniques that could routinely and inexpensively gather post-rupture debris spread. The insertion stages of the H2 and the Ariane 5 rockets are understood to include controlled deorbit capability. The constraints on this capability have not yet been explored, but the controllability of the event may open increased opportunities for optimized observations.

9. PROGRAMMATICS

The physics of the deorbit viewing provides a relatively simple engineering integration challenge. However, the financial and political factors will require special attention if such a systematic deorbit study is to be conducted.

First, outside of the approach envelope, operations planning and control of the VV is under the exclusive authority of the visiting vehicle provider. Integrated operations of the ISS vehicle are under NASA's control. Because of this agreement to partition responsibility, no formal discussions have yet occurred to document cooperative work outside of the Approach Envelope. For a deorbit science campaign to be properly coordinated, new areas of international cooperation will need to be explored, and agreed by the partners.

Further, NASA's current agreements with each ISS partner are bilateral. In order to maximize the scientific return, it will be necessary to work multilaterally, and to overcome the potential issues with export and sharing of sensitive technological data on the performance of the individual visiting vehicles, which are national assets of the ISS partner agencies. Multilateral cooperation may also need to expand to financial commitments, if ISS radio, optical, or other instrument enhancements are developed for common use by the partners in characterizing their vehicle's deorbit performance. Examples of such financial cooperation would be the potential cost savings from large production runs of deorbit "black box" recorders, and the development of associated common radio receiver gear or of radar tracking capability for the ISS.

Finally, the safety of the ground population is paramount. While parametric variation is key to any scientific endeavor, deorbit experimentation must remain within the certified, safe operating capabilities of the visiting vehicles and of the ISS. Efforts to systematize the data gathering must be tempered with the need to conduct every deorbit event in the safest possible manner. As with any flight test program, the operating envelope must be expanded with caution. Thus, clear guidelines must be jointly accepted by all partners sharing in the study for any increased liability or risk that results from expanding the operating envelope of any deorbit event, done under the auspices of an international deorbit science campaign.

10. CONCLUSION

It is the author's hope that all technical and legal obstacles can be overcome, and that the ISS program partners will be able to take advantage of the unprecedented opportunity that lies ahead. The International Space Station's proximity, vantage point, stability, and remarkable instrumentation suite offer the potential to expand hypersonic re-entry science to the same extent that space-based observations have advanced the field of astronomy, and at negligible additional expense.. Through such experimentation, the Visiting Vehicle fleet offers a chance for the world's space powers to make major advances in the scientific understanding of (and the control of the risks from) the re-entry process.