The International Space Station and the Space Debris Environment: 10 years on

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Abstract: For just over a decade the International Space Station (ISS), the most heavily protected vehicle in Earth orbit, has weathered the space debris environment well. Numerous hypervelocity impact features on the surface of ISS caused by small orbital debris and meteoroids have been observed. In addition to typical impacts seen on the large solar arrays, craters have been discovered on windows, hand rails, thermal blankets, radiators, and even a visiting logistics module. None of these impacts have resulted in any degradation of the operation or mission of the ISS. Inadvertently and deliberately, the ISS has also been the source of space debris, although these objects typically exhibit very short orbital lifetimes.

1. Threat of space debris to the International Space Station

The first element of the International Space Station was launched on 20 November, 1998, in the form of the 20-metric-ton Zarya module. During the subsequent ten years, 77 additional missions had been flown by the United States, the Russian Federation, and the European Space Agency for construction or logistical purposes. From a single unit to the largest and most complex vehicle ever assembled in space, the ISS now spans almost 100 meters across its main truss and has a mass of nearly 300 metric tons (Figure 1).

Typically, the ISS orbits the Earth at an altitude of about 350 km, but the mean altitude varies from about 330 km to 400 km, depending upon atmospheric density (influenced by the solar activity cycle) and operational constraints. Consequently, the ISS enjoys a relatively benign orbital debris environment in comparison with most robotic spacecraft operating in low Earth orbit (Figure 2). However, the much larger size of the ISS means that annual collision rates with orbital debris are significant. For example, the orbital debris flux for 1 cm particles and greater at the 700 km altitude of the international Earth Observation System (EOS) is an order of magnitude greater than that for the ISS orbit, but the cross-sectional area of ISS is much more than an order of magnitude greater than a member of the EOS constellation.

In the case of the ISS, the space debris environment, including both orbital debris and meteoroids, can be divided into three size categories. Particles smaller than

3 mm are by far the most numerous, but fortunately they also rarely cause damage sufficient to impede the mission of the ISS. Debris with sizes between 3 mm and 1 cm have the potential to cause damage on unprotected surfaces which could negatively impact the safety of the crew or disrupt the mission of the ISS. Impacts with such debris, for example, could cause a small leak in a habitable module, forcing the evacuation of the crew from that module or perhaps even a return to Earth. Collisions with debris larger than 1 cm, the smallest of the three size populations, have the potential to cause considerable or catastrophic damage to the ISS.

Since the ISS was designed for an operational lifetime of at least 15 years, the threat from space debris had to be met with a combination of design and operational countermeasures (Reference 1). Critical surfaces of ISS, *e.g.*, on habitable modules and external pressure vessels, are protected by dedicated and tailor-made, multi-layer space debris shields (Figure 3). These shields normally can withstand the impact of an orbital debris particle as large as 1-cm impacting with a collision velocity of 10 km/s and also provide protection against most meteoroids. For the Russian Zvezda module (also known as the Service Module), additional conformal debris shields have been installed in some areas during extra-vehicular activities (EVA's), and large protective wings might be attached near the docking compartment (forward end) in the future. At assembly complete, the total mass of space debris shielding is expected to exceed 23 metric tons or more than 5% of the total mass of the ISS.

Orbital debris larger than 10 cm which transit the ISS orbital regime are normally tracked by ground-based radars. Given sufficient warning, the ISS can simply maneuver to avoid collisions with such objects (addressed in more detail below). Hence, the residual threat to most critical surfaces of the ISS arises in large measure from particles between 1 and 10 cm, which are unseen and can penetrate the protective shields.

2. Evidence of space debris impacts on the ISS

The most frequent impacts on the ISS are from very small particles which cause no operational effects and often go unnoticed. The primary means of detecting such impact events are (1) crew member observations during EVA's, (2) photographic surveys of the ISS by externally-mounted cameras or by visiting vehicles, and (3) the close examination of components returned to Earth.

The multiple and expansive solar arrays represent the largest surface area of the ISS and, hence, the region where space debris impact damage would be expected. However, due to their distance from the core of the ISS and due to their high electrical potential, solar arrays normally cannot be closely inspected for evidence of small particle impacts. Figure 4 shows a segment of one ISS solar array which has apparently been damaged by a collision with a small particle. The design of the array ensures that the reduction in electrical power generation is limited to a small area. The arrays were sized such that adequate power would still be generated for the lifetime of the ISS, despite a gradual reduction each year due to space debris and other environmental effects.

Some surfaces of the ISS are painted, and over time this paint can degrade and become brittle due to the harsh space environment, including direct solar radiation and extreme thermal changes when the ISS moves from daylight to night and back again during each revolution about the Earth. Figure 5 indicates the breakdown of paint on a portion of the Zarya module and how it increased from 1998 to 2000. Once paint becomes brittle, small particle impacts can knock flakes of paint off the surface, which in turn become short-lived orbital debris.

Another type of surface on the ISS on which space debris impacts can easily be detected is the windows. Figure 6 depicts a particle impact crater recorded in 2002 on one of the windows of the Zvezda module. An impact on another Zvezda window was more serious and led to the installation of a protective opaque cover over the window inside the module (Reference 2).

EVA's have revealed several areas of damage due to space debris impacts. One of the most prominent impact sites was found in 2007 on the Zarya module Reference 3). A substantial tear (6.7 cm long and 3.3 cm wide) was discovered in a thermal blanket near the forward end (Figure 7). The nature of the damage suggests an impact from an oblique angle. From laboratory tests at the Hypervelocity Impact Technology Facility of the NASA Johnson Space Center, specialists believe that the impactor probably was 0.2 to 0.3 cm in diameter and penetrated not only the thermal blanket, but also the underlying steel mesh, fiberglass, and aluminum honeycomb layers. Fortunately, the compressor immediately underneath appears to have been untouched.

Also in 2007, a crew member noticed a hypervelocity impact crater while working near a large aluminum panel (Figure 8). The following year craters were found on a handrail adjacent to the U.S. airlock and on an EVA tool which was stored externally on the Z1 truss of the ISS (Figures 9 and 10; Reference 4). Although the crater on the handrail was small (~ 2 mm in diameter), its sharp edges are now thought to have possibly been the source of cuts found previously on the gloves of crew conducting EVA's from that airlock. The particle which struck the EVA tool has been assessed to have been slightly less than 1 mm in diameter.

Very small impact features on the ISS can be difficult to detect due to their accessibility or the nature of the surface, *e.g.*, particle impacts on smooth aluminum or painted surfaces are easier to see than those on thermal blankets. A close inspection of the S-band Antenna Structural Assembly (SASA) after a 4-year exposure on the ISS revealed at least 48 space debris impacts. However, none of these collisions affected the function of the device.

Clearly, the best method of examining an exposed surface would be to return it to Earth, where not only can the number of very small impact features be determined with microscopes, but also analysis of the craters can sometimes differentiate between micrometeoroids and man-made debris. Although rarely are components of the ISS returned to Earth, the large Multi-Purpose Logistics Modules (MPLM's), which occasionally ferry equipment to and from the ISS, offer just such an opportunity. Despite their limited exposure during each mission (typically about six days), their large size (4.6 m diameter, 6.4 m length) yields a valuable area-time product.

The first five missions involving an MPLM resulted in an exposure time of more than 700 hours and two instances of penetration through the outer aluminum bumper (References 5-6). On the maiden flight of the MPLM, a paint particle with an estimated diameter of ~0.5 mm left a 1.4 mm diameter hole in one of the bumper segments (Figure 11). After the fourth flight of an MPLM, a 1.2-mm diameter hole was discovered in the space debris shield, the victim of an impact by a stainless steel particle with a diameter assessed to be 0.2 mm.

3. Collision avoidance maneuvers

At the altitude of the ISS, the satellite catalog of the U.S. Space Surveillance Network (SSN) is thought to be relatively complete for objects as small as 10 cm in size. Some debris as small as 5 cm can also be detected and tracked. Since collisions with objects greater than 5 cm could cause significant damage, calculations are made at least three times a day to determine which known objects might pose a risk of collision to the ISS within the next 72 hours. If the risk of collision is assessed to be greater than 0.0001, then a collision avoidance maneuver is planned and executed, unless the maneuver itself would pose a risk to the crew or substantially disrupt ISS operations.

Prior to 2008 on average three conjunction assessments per month initially appeared to pose a threat to the ISS. However, additional tracking of the potential impactor and higher fidelity projections as the time to the conjunction nears normally lead to updated collision probabilities of less than 0.0001. In such cases, maneuver planning is then cancelled. Collision maneuvers are normally planned for about 1 m/s in the posigrade direction, and the post-maneuver orbit is pre-screened to ensure that a new conjunction threat is not created. The maneuver is usually performed by either a Progress logistics vehicle or the Space Shuttle, if the latter happens to be docked at the time.

In the first 4.5 years of ISS operations, ISS collision avoidance maneuvers were executed on seven occasions, twice by a visiting Space Shuttle (Table 1). However, in the next 5.5 years only a single collision avoidance maneuver was necessary. This dramatic reduction in collision avoidance maneuver frequency can be attributed primarily to improved conjunction assessment processes, not an improved orbital debris environment (Reference 7).

The last collision avoidance maneuver by ISS occurred on 27 August 2008 when a fragment from the Kosmos 2421 spacecraft was projected to pose a collision risk of 1 in 72, *i.e.*, 0.014 (Reference 8). ESA's Automated Transfer Vehicle, the Jules Verne, performed the collision avoidance maneuver. This piece of debris was one of more than 500 cataloged debris released from Kosmos 2421 during three major fragmentation events from March to June 2008. At the time of these fragmentations, Kosmos 2421 was only about 60 km above the orbit of the ISS. As these debris decayed down through the ISS orbit, the number of potentially threatening conjunctions each month increased by a factor of three.

4. ISS as a source of orbital debris

During its decade of operations the ISS itself has become a source of orbital debris, both large and small. Most large debris were released during EVA activities, many accidentally. By the 10^{th} anniversary of the ISS, the U.S. SSN had detected and cataloged 65 debris from the outpost, not including operational spacecraft releases, like the TNS-0 small sat in March 2005. Inadvertent losses ranged from a camera to a variety of tools to a complete tool bag to a foot restraint. Intentional debris releases included towels, equipment covers and carriers, hardware too large or too dangerous to return to Earth in a logistics vehicle, and an old space suit. On average, these objects fell harmlessly back to Earth in less than two months (Figures 12 and 13). The cumulative number of debris object-years is almost exactly 10, the equivalent of one piece of debris remaining in orbit for 10 years.

The international partners supporting the ISS, like other spacecraft operators, are aware of the hazards of and seek to minimize the unnecessary creation of orbital debris. In 2007 a jettison policy for ISS was approved (References 9-10). This policy limits the intentional to release of debris from ISS to only a few limited cases; the vast majority of debris created on ISS is still returned to Earth in logistics vehicles. Two objectives of the ISS jettison policy is to ensure that any object released does not experience a subsequent fragmentation prior to reentry and to limit the risk of injury to people on Earth to within standards previously set by NASA and some other space agencies, *i.e.*, the risk of human casualty should be no greater than 0.0001.

An unknown number of debris too small to be tracked and cataloged has also been generated. Very small secondary orbital debris are likely produced when the ISS is struck by high speed particles. Occasionally, the ISS crew has reported seeing and in some cases photographing objects several centimeters in size as they drift away from the station (Figure 14). Due to their low altitude and likely high area-to-mass ratios, these objects are believed to be even shorter-lived then their cataloged counterparts.

5. Conclusions

The ISS has well withstood the hazardous space debris environment during its first decade in space. This has been possible by concerted efforts in both the design and the operation of the large orbital complex. Although some minor damage has been incurred, to date the safety of the crews has not been jeopardized nor have station operations been adversely affected. With continued vigilance, the ISS should successfully complete its objectives of furthering the exploration of space and developing benefits for all mankind.

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Table 1. ISS Collision Avoidance Maneuvers.

Date	Crewed Spacecraft	Conjuncting Object	International Designator	U.S. Satellite Number	Comment
27-Oct-1999	ISS	Pegasus Rocket Body	1998-046K	25422	
30-Sep-2000	ISS	Vostok Rocket Body	1971-031B	5143	
10-Feb-2001	ISS / Space Shuttle	Elektron 1 Debris	(1964-006)	87618	Conjunctiong object tracked but not officially cataloged; Shuttle conducted maneuver
14-Mar-2001	ISS / Space Shuttle	ISS/Shuttle Debris Kosmos Rocket Body	2001-010B 1990-078B	26723 20775	Two conjunctioning objects; Shuttle conducted maneuver
15-Dec-2001	ISS	Kosmos Rocket Body	1971-119B	5730	Shuttle conducted maneuver prior to undocking and conjunction
16-May-2002	ISS	Kosmos Rocket Body	1994-061B	23279	
30-May-2003	ISS	Megsat	1999-022B	25722	
27-Aug-2008	ISS	Kosmos 2421 Debris	2006-026RU	33246	Debris originated from fragmentation of Kosmos 2421 in early 2008

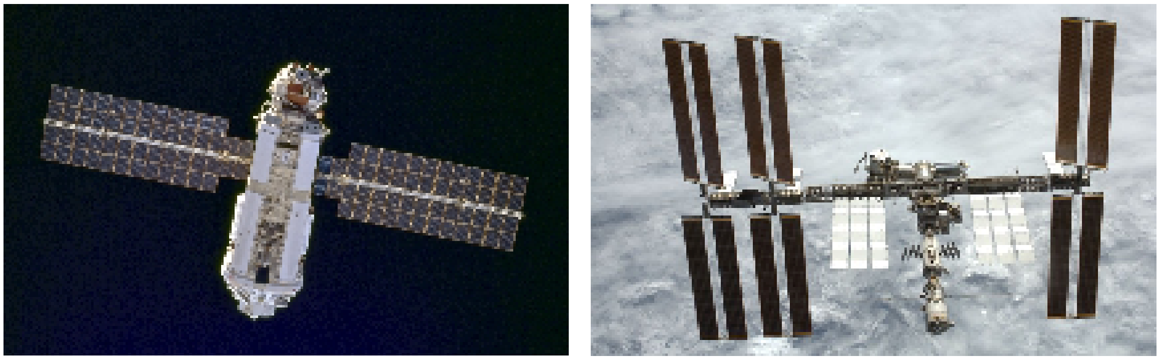

Figure 1. The first element of ISS, Zarya (left, taken by STS-88) was launched in November, 1998. By November, 2008, ISS had evolved into a complex, multinational, highly capable outpost (right, taken by STS-126).

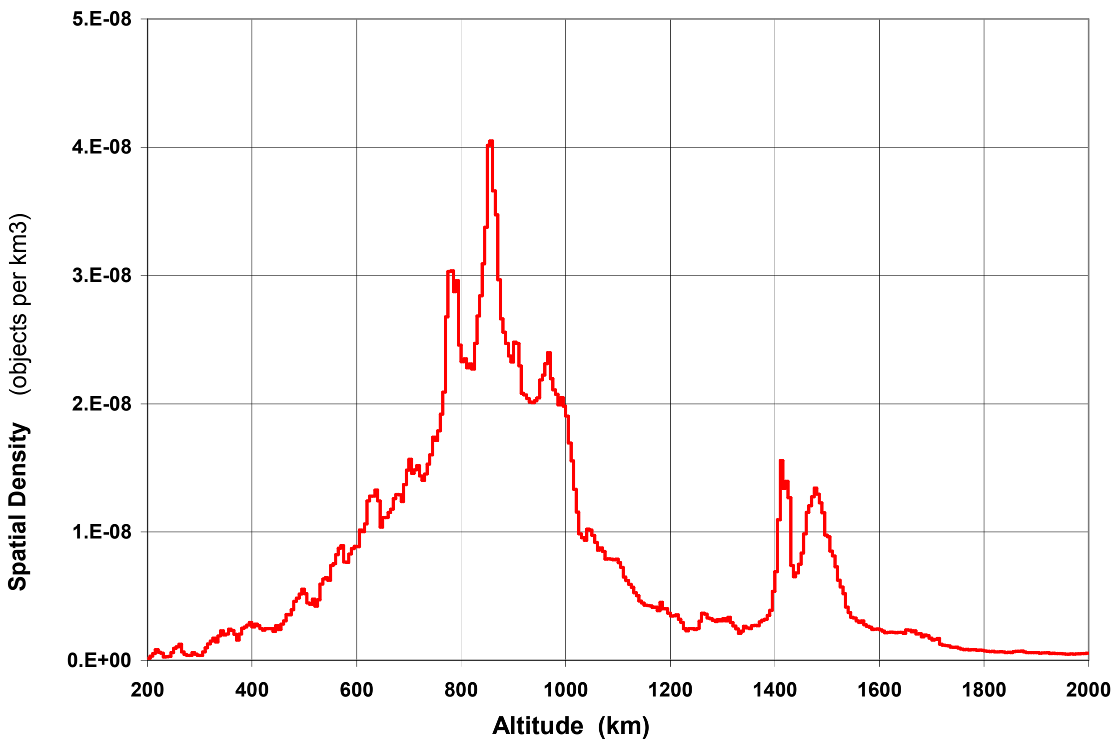

Figure 2. Average spatial density of cataloged objects in low Earth orbit at the end of 2008.

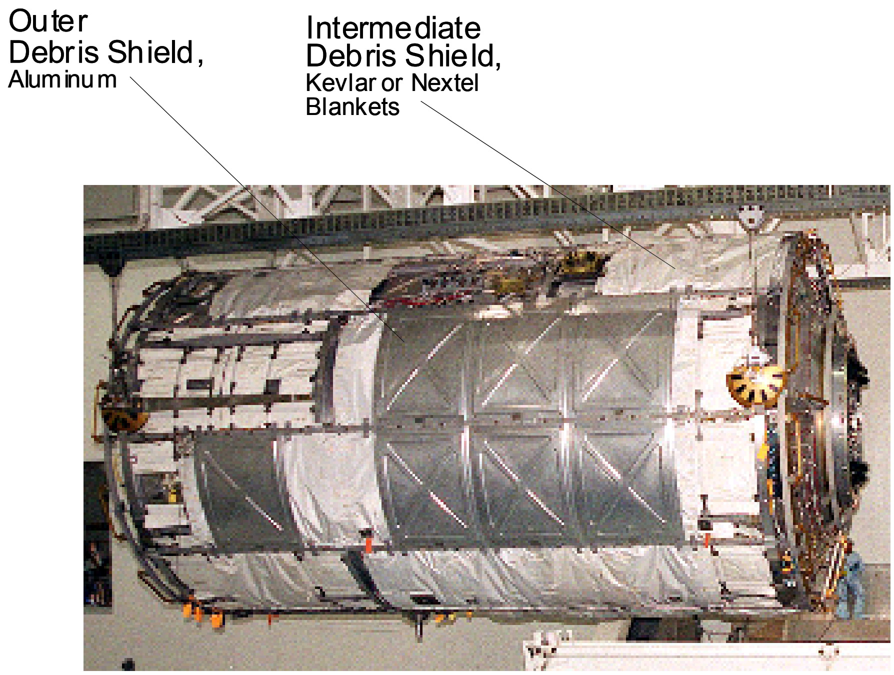

Figure 3. US Laboratory Module during installation of Micrometeoroid and Orbital Debris Shielding.

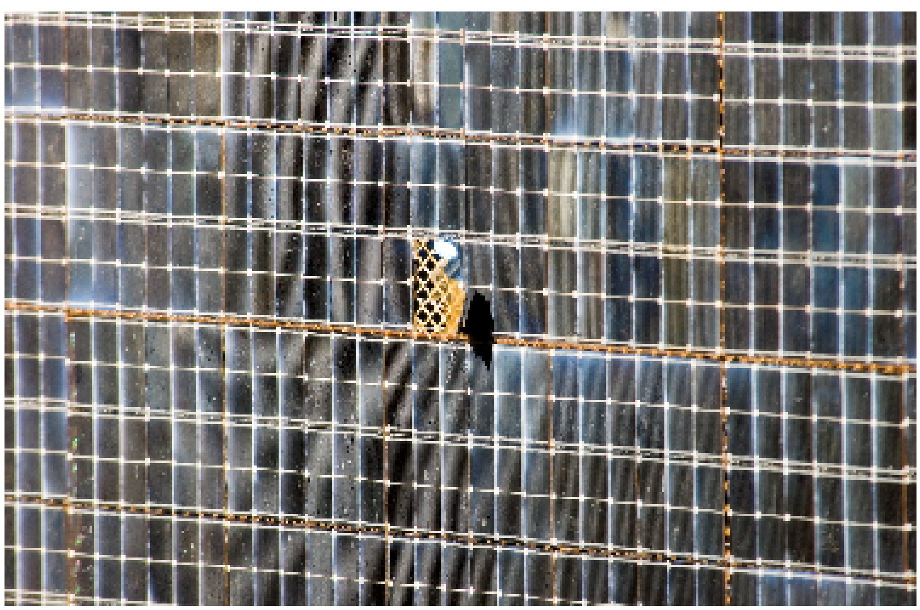

Figure 4. Photograph made in 2006 of solar array damage from an impacting particle.

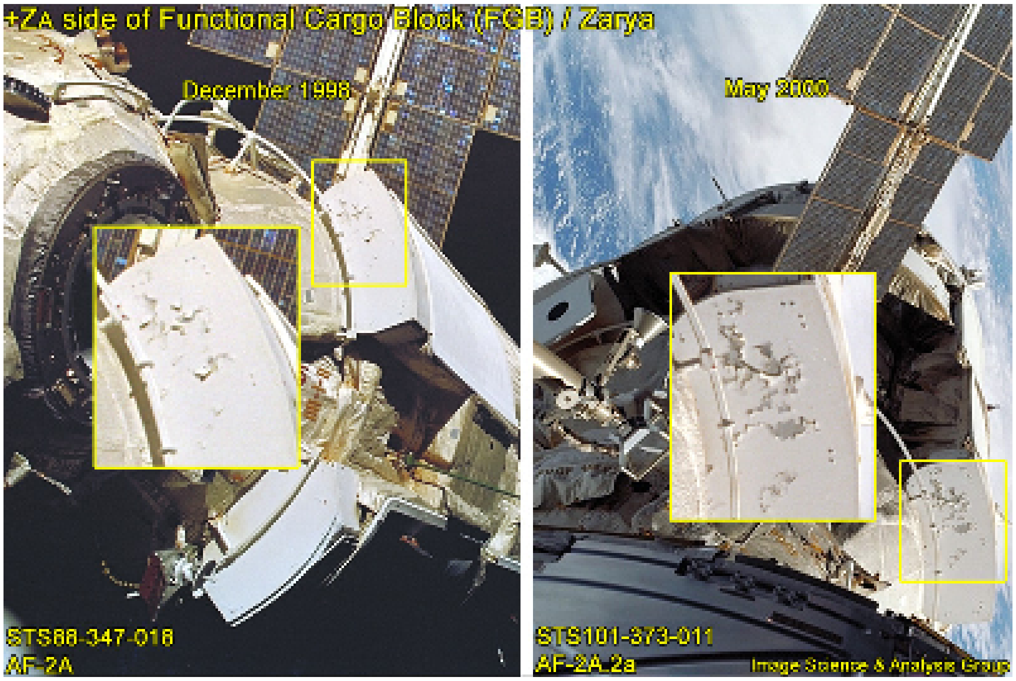

Figure 5. When paint becomes brittle from space environmental effects, small particle impacts can cause flakes to be released, becoming short-lived orbital debris.

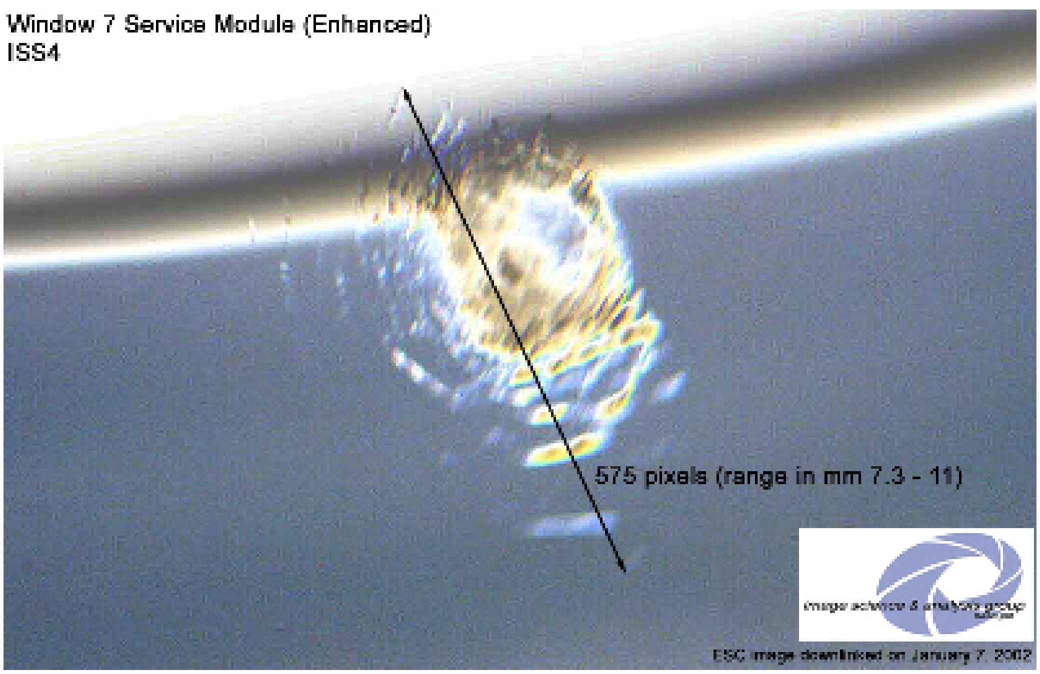

Figure 6. Impact crater found on the Zvezda module.

Figure 7. Tear in thermal blanket of the Zarya module due to space debris impact. Each square of the blanket is ~ 1 cm by 1 cm.

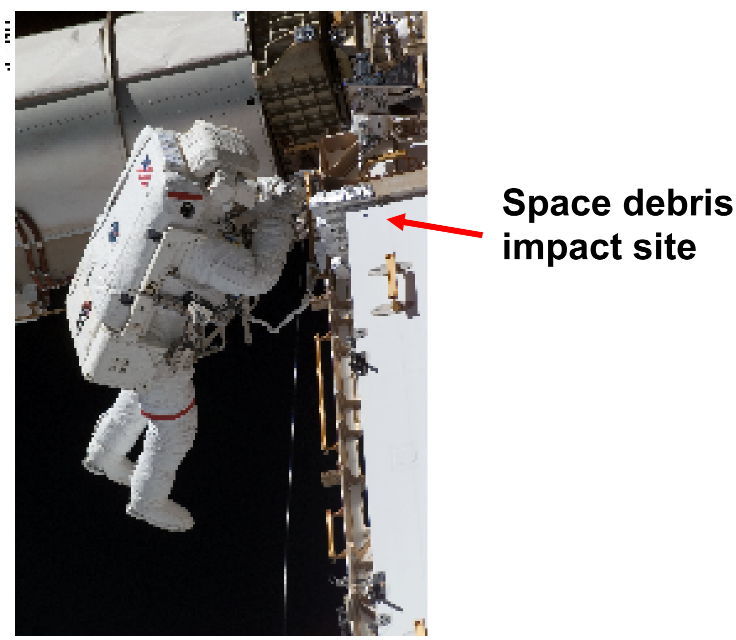

Figure 8. Space debris impact site discovered on ISS panel.

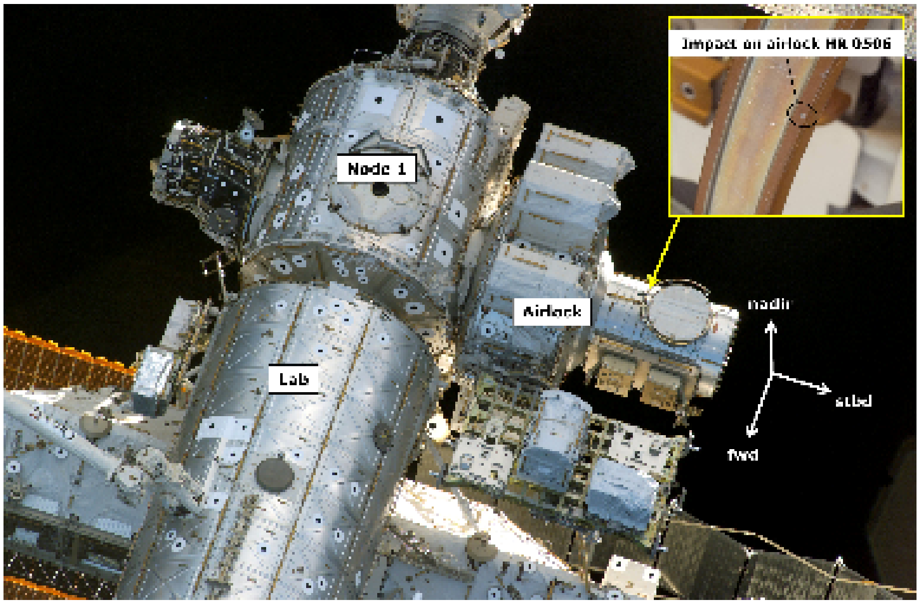

Figure 9. Impact crater discovered on an EVA handrail in early 2008 (Reference 4).

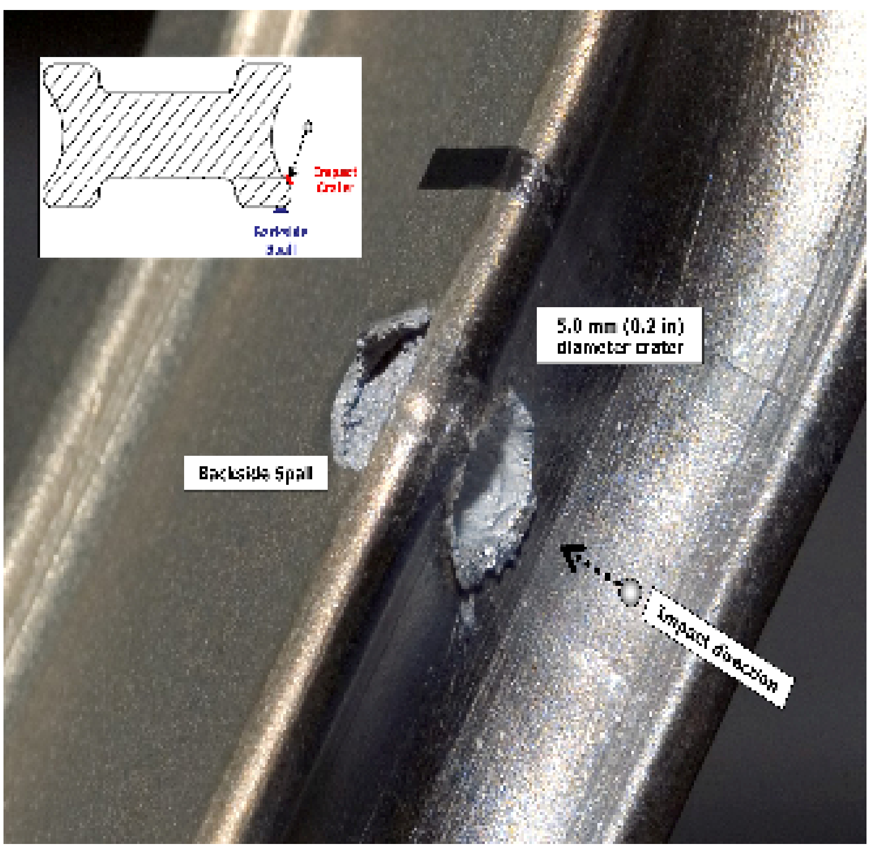

Figure 10. Impact crater and backside spall found on an externally stored EVA tool (Reference 4).

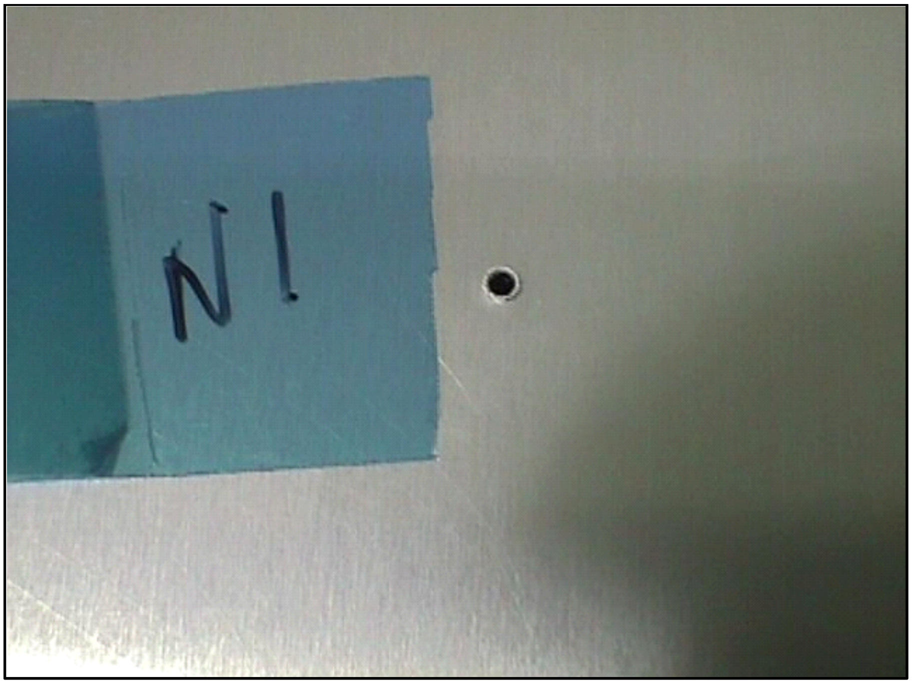

Figure 11. Hole found in the space debris shield after the first flight of the MPLM to the ISS in 2001.

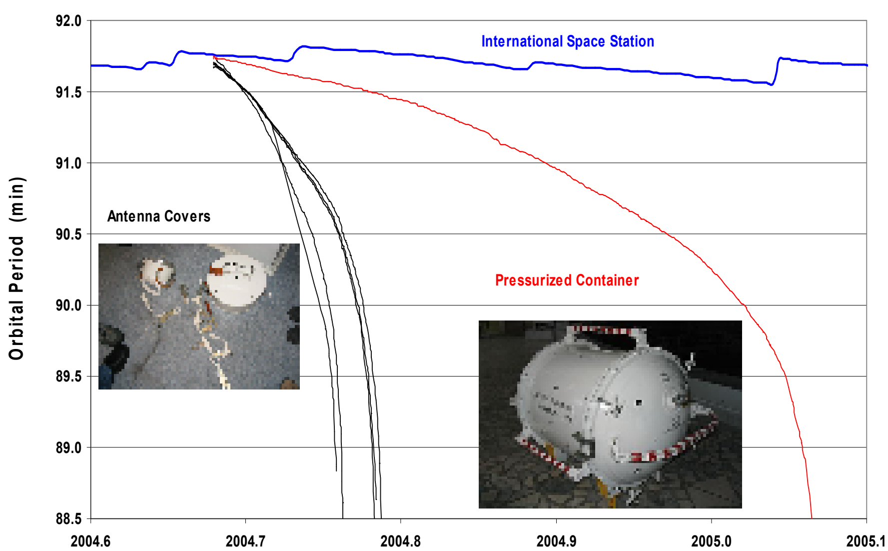

Figure 12. Orbital decay histories of sample debris from the ISS.

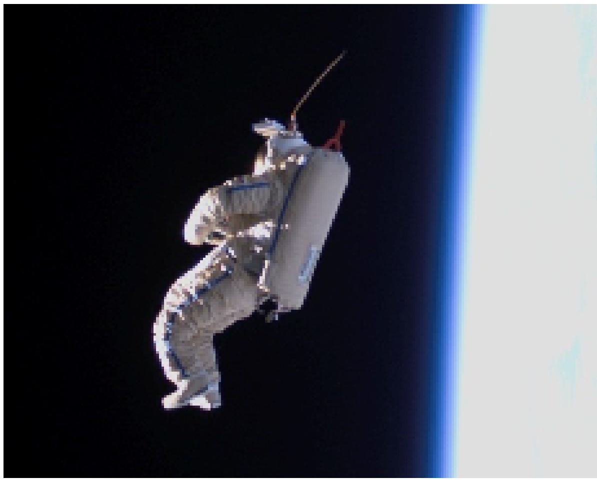

Figure 13. Discarded EVA suit released from ISS in February 2006.

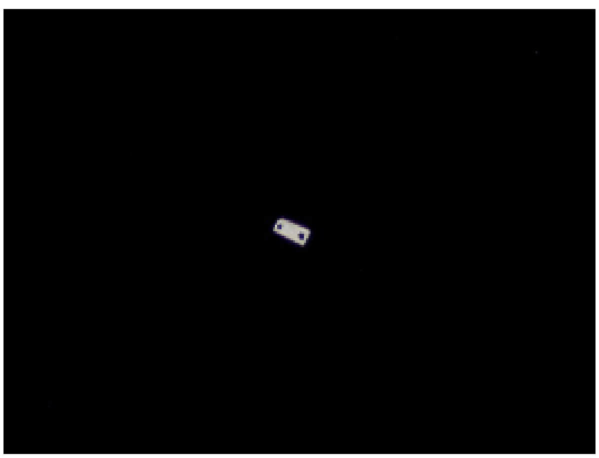

Figure 14. Small debris observed from ISS in June 2003.