INTRODUCTION

Man-made debris in low-Earth orbit constitutes a population of hypervelocity projectiles that present a substantial collisional hazard to spacecraft. The damage will range from submicroscopic impact features that can adversely affect critical subsystems to the catastrophic fragmentation of entire spacecraft. Substantial progress has been accomplished during the past decade in characterizing the current debris population and its origins (Kessler, 1996; Johnson *et al.,* 1998). However, substantial uncertainties still exist, including the detailed mass distribution, flux and origin(s) of debris particles < 1 cm in size. Such small particles are far beyond the spatial resolution of ground-based observations and can only be characterized with *in situ* observations by flight instruments. The Orbital Debris Collection (ODC) experiment, the subject of this report, is such an instrument. The objectives of ODC were to non-destructively collect debris particles in low-Earth orbit (LEO) and to return them to Earth for detailed mineralogical and compositional analyses. This information is indispensable to reconstruct the sources and origins of the debris population, and to develop strategies for their potential mitigation.

The basic instrument concept for ODC was an outgrowth of the successful analysis of hypervelocity impact features on returned materials from the Solar Maximum mission (Warren *et al.,* 1989) or the Long Duration Exposure Facility (LDEF; see Levine, 1991; 1992; 1993). Scanning electron microscopes (SEM) methods combined with energy-dispersive X-Ray spectroscopy (EDS) revealed the ability to differentiate, on compositional grounds, among man-made and natural impactors (Zolensky *et al.,* 1992). The latter derive from asteroids and cometary sources (Brownlee, 1985) and are an inevitable component of the hypervelocity particle environment in LEO. A variety of compositional subclasses were recognized among the man-made debris particles including paint flakes, human waste, steel, metallic aluminum, aluminum oxide (and others). Similarly, various natural particle types exist, including aggregate particles of chondritic bulk composition, and monomineralic silicates or sulfides (*e.g.,* Berthaud *et al.,* 1993; Amari *et al.,* 1992; Hörz *et al.,* 1993).

Of particular interest was the discovery of aluminum-rich particles on surfaces occupying the trailing edge of LDEF (Hörz *et al.,* 1993; Bernhard *et al.,* 1999), where collisions by man-made debris were not expected. These findings suggest particle sources in highly elliptic orbits, generally consistent with transfer vehicles to geosynchronous orbits and associated effluents (Al_2O_3) from solid-fuel rocket motors (Kessler, 1992). Unfortunately, these detailed observations are confined to a single LDEF tray from the "Chemistry of Micrometeoroids Experiment" (CME) that employed high-purity gold as the cratering substrate. Since most other LDEF surfaces were aluminum, it was not possible to analyze for aluminum in collection media that are themselves composed of aluminum. Using thin Be-foils of low X-ray absorption coefficient that permit for the analysis of oxygen with the above EDS methods, Bernhard *et al.,* (1999) demonstrated the presence of both metallic aluminum (Al) and oxidized aluminum (Al_20_3) impactors in the LDEF gold substrates.

The differentiation into metallic or oxidized impactors is significant, since two major source mechanisms are implied. Inadvertent collisional processes most likely produce the metallic particles from structural aluminum, while the oxidized particles are combustion products of solid rocket fuels and the products of deliberate operational design and practice. These Al-rich particles were the most abundant man-made debris type encountered on LDEF's trailing edge and, as a result, are of substantial interest. What is the relative abundance of metallic versus oxidized species? This specific objective requires the exposure of collectors that are made from materials other than aluminum, and as a consequence, the collectors exposed by ODC were made from high-purity SiO_2.

The collectors exposed by ODC also took advantage of the substantial progress that had been made during the past decade in the basic technology of hypervelocity particle capture. Specifically, highly porous, foam-like materials have been developed and introduced (Werle *et al.*, 1981; Tsou, 1995). The extremely low density (< 0.1 g/cm^3) of such materials results in only modest shock stresses being experienced by the impactor, even at high impact velocities. Indeed, the deceleration of hypervelocity particles in such highly porous media seems to be largely governed by classical continuum mechanics (*i.e.*, viscous drag forces and ablative processes), while shock-processes seem to be subordinate, following Anderson and Ahrens (1994). However, this conclusion is valid only if the thickness of the solids, such as membranes or fibers, that compose the collector are small compared to typical impactor dimensions. If the dimensions of the solids are on the order of typical impactor dimensions, the projectile will sense them as relatively massive, if not as infinite half-space targets, and severe shock become unavoidable. As SiO_2-based aerogel is made up of a network of irregular chains and clusters of SiO_4 tetrahedra ~ 40 - 60 Å thick and 200 - 300 Å long, such materials easily meet this thickness criterion and are ideal for the deceleration of micron-sized projectiles. Laboratory impacts at 7 km/s show that the total penetration depth of 50 μm glass projectiles is typically 200 - 300 times the projectile diameter in 0.02 g/cm^3 aerogel, thus necessitating collector thicknesses for flight instruments approaching centimeters (Hörz *et al.*, 1997). The technology to manufacture aerogels of such thicknesses, specifically those based on SiO_2 (Fricke, 1988; Hrubesch and Poco, 1990; Tsou, 1995), is also a relatively recent development, as is the ability to manufacture aerogels of densities as low as 0.02 g/cm^3.

As summarized by Tsou (1995) and below, $Si0_2$-based aerogel was successfully exposed in space and returned to Earth prior to ODC, yet densities were high (0.1 g/cm^3), collector size was modest, and exposure times were short. The area/time product of the aerogel exposed by ODC is more than an order of magnitude larger than all prior aerogels combined, establishing ODC as the most significant opportunity to evaluate the performance of space-exposed aerogel in capturing analyzable particle residues for return to Earth and analysis. The continued development of optimum capture media for hypervelocity particle must be viewed as an integral part of orbital-debris (and cosmic-dust) studies in Earth orbit, as future experiments will be needed to monitor the short- and long-term evolution of these particle populations to assure safe flight operations in Earth orbit.

Combining these background materials and developments leads to the following justification for the deployment of ODC as part of the MIR Environmental Effects Package (MEEP): (a) Capture and compositional characterization of orbital-debris particles and evaluation of their origins. (b) Establish the relative frequency of metallic versus aluminum-oxide particles. (c) Determine the relative roles of man-made debris and natural dust for the collisional hazard in LEO. (d) Evaluate the performance of SiO_2-based aerogel for the capture of hypervelocity particles and its utility in the long-term monitoring of the temporal evolution of the hypervelocity particle environment in LEO.

INSTRUMENT DESIGN

ODC was one of four experiments composing the MIR Environment Effects Package (MEEP), a payload designed and developed by Langley Research Center (LaRC) on behalf of the Space Station, and whose objectives were to assess the exterior environment of MIR (see http://setas-www.larc.nasa.gov/setas/meep/meep.html). This environment may be affected by different operational practices, as well as by different orbital inclination, 51° for Mir versus 28° for Shuttle. All MEEP instruments were housed in identical containers that resembled metal suitcases. Each container possessed hinges that permitted the rotation, by 360°, of the top and bottom halves, each half containing an (essentially identical) instrument tray. The inside dimensions of each half container allowed for packages ~ 62 x 62 x 8 cm in dimensions. When closed, the experiment trays were stowed face-to-face; deployment on MIR involved rotation of the two halves such that they were back-to-back exposing the two collector surfaces into opposite viewing directions. Nominally, one tray pointed in the general forward (ram) direction, paralleling the orbital motion of MIR, with the second tray pointing into the antipodal direction. Deployment and retrieval of the MEEP containers was accomplished via dedicated Extravehicular Activity (EVA).

ODC employed $Si0_2$-based aerogel produced at the Jet Propulsion Laboratory (JPL), Pasadena, CA (see http://eande.lbl.gov/ECS/aerogels/satoc.htm or http://stardust.jpl.nasa.gov/index.html). Preliminary impact tests with such aerogels and velocities up to 7 km/s revealed that particles residing at the terminus of long, carrot-shaped penetration tracks were essentially unmelted (Tsou *et al*., 1988; Barrett *et al.*, 1992; Mendez, 1994; Tsou, 1995; Burchell and Thomson, 1996; Hörz *et al.*, 1997). Consistent with JPL's state-of-the-art aerogel manufacture capabilities, we impact tested a series of aerogels ranging in density from 0.01 to 0.05 g/cm^3, while most previous tests utilized aerogels of higher densities, typically 0.1 g/cm^3. As documented in Hörz *et al.* (1997), track length strongly depends on the aerogel density, yet there is no clear, much less a strong relationship between track length and mass of the recovered projectile residue. Nevertheless, the particles recovered from aerogels < 0.05 g/cm^3 were generally larger than those recovered from aerogels possessing higher densities. As a consequence, we selected the lowest-density aerogel of 0.02 gcm^3 that could be reliably manufactured, in late 1995, into monolithic specimen of 10 x 10 cm surface dimension and ~ 11 mm thickness. This thickness was sufficient to terminate a (dense glass) particle of 50 µm diameter (at normal incidence at 7 km/s velocity). Aerogels < 0.02 g/cm^3 were largely experimental products in 1995 and not available in the proper thicknesses to be considered for ODC; they were also excessively cumbersome to handle and process.

Each half of the ODC MEEP package housed an identical instrument tray as illustrated in Figure 1a. The major component of each tray was the *Assembly Frame*, fabricated from monolithic aluminum, 0.5" (12.5 mm) thick, containing 36 openings or cells, each 9.60 cm square. Most of the aerogel tiles were modestly oversized (9.7 - 9.8 mm on a side) relative to the cell dimensions. In deed, vibration and shock tests performed during flight-acceptance testing revealed that modest compression of aerogel is desirable to firmly secure the tiles within the Assembly Frame via frictional forces. Aerogel is surprisingly compressible and easily handled at low-strain rates, yet becomes fairly brittle, akin to glass, at high-strain rates. Many tiles were non-planar, on occasion even wavy and upturned at the edges. However, such deviations from the nominal tile thickness of 11 mm were readily accommodated by the 12.5 mm deep assembly frame.

The tiles were press-fit into the Assembly Frame from the rear, with the frame resting face down on a flat surface to assure a flush fit, and precluding any substantial protrusion(s) of aerogel above the frame surface. Following the installation of all aerogel collectors, a solid aluminum plate (*i.e.*, *Interface Plate*; 7 mm thick; see Figure 1) was attached to the back side of the Assembly Frame, while a red-anodized, 2 mm thick aluminum *Hold-Down Grid* (see Figure 1b) was attached to the frame's front surface. The openings of this Hold-Down Grid were registered to those of the Assembly Frame, but possessed only 9.30 cm square openings. This resulted in a 1.5 mm wide overlap or shoulder around the entire circumference of each frame opening, intended to prevent any aerogel tile from slipping through the tray's front opening. Of the 21 bolts attaching the Hold-Down Grid to the Assembly Frame, nine passed completely through the frame into the Interface Plate, securing the latter to the frame. In turn, the interface plate was attached to the MEEP container via a series of aluminum standoff devices (*i.e.*, Interface-Plate Standoffs; see Figure 1), the latter threaded and accepting screws on both ends.

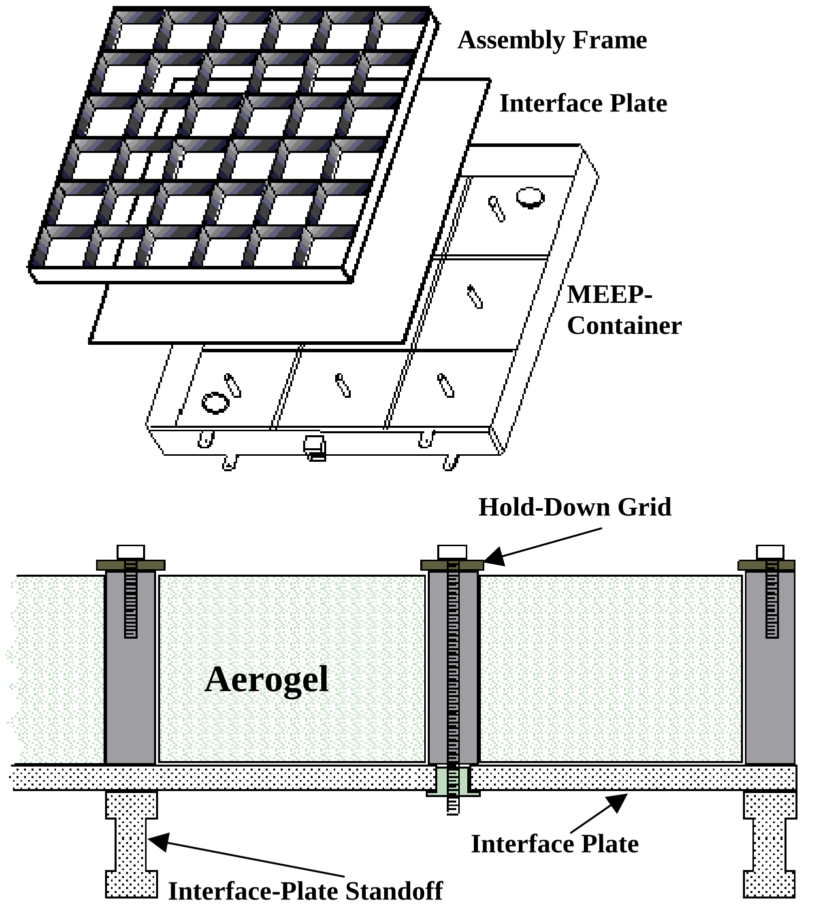

Figure 1. (A) 3-D view showing the major components for one of the two ODC trays and (B) Schematic cross-section of ODC showing the relationship of the MEEP Container, Interface Plate, Assembly Frame, and Hold-Down Grid.

The overall design aimed at firmly sandwiching the aerogel tiles between the (largely transparent) Hold-Down Grid and the solid Interface Plate. The openings within the Hold-Down Grid fixed the effective collector surface of each ODC tray at ~ 0.319 m^2. An additional, solid aluminum plate could be mounted on top of the Hold-Down Grid to protect the delicate aerogel during all ground handling and shipping of the loaded experiment from JPL to LaRC, where integration with the MEEP containers and final flight acceptance took place.

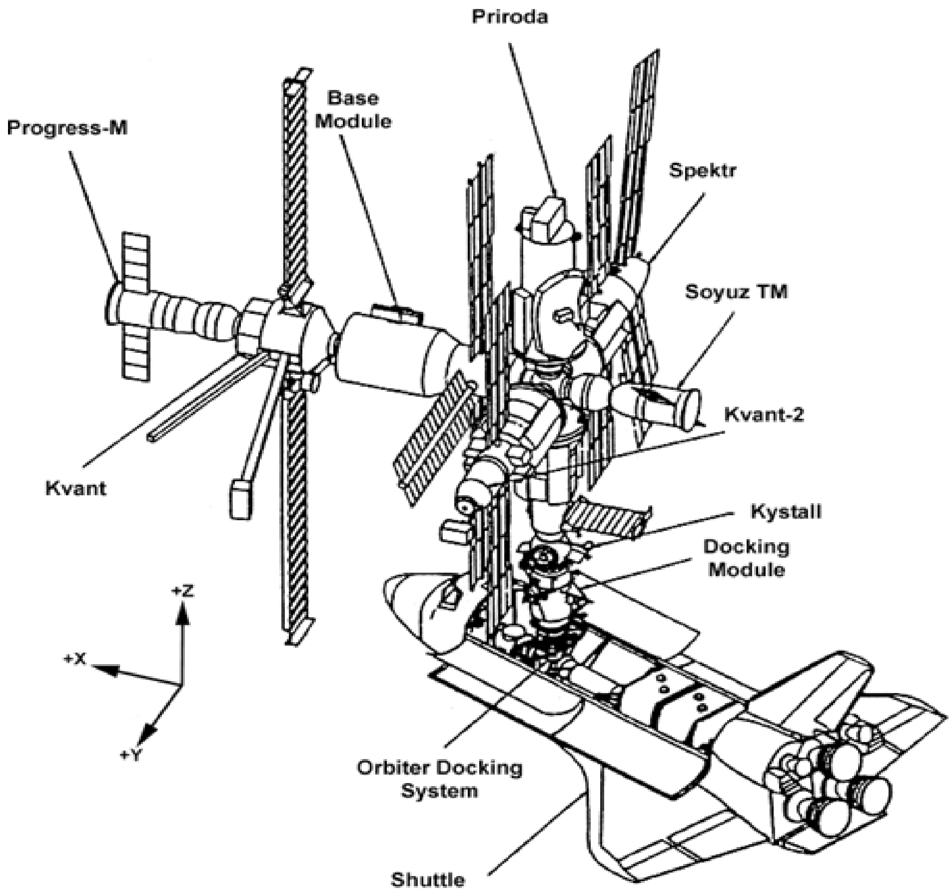

Figure 2. Overview of Mir illustrating major subsystems and a docked Shuttle. All four MEEP containers were attached to handrails on the US Docking Module, immediately above the Shuttle.

EXPOSURE ON MIR

The MEEP package, consisting of four individual containers, each housing a dedicated experiment, was launched on STS 76 on March 25, 1996. The MEEP containers were stored in shuttle's cargo bay during both launch and landing of the shuttles. Astronauts M.R. Clifford and L.M. Gooding deployed the MEEP instruments on March 27, 1996. A schematic layout of the Mir Station and its major components can be seen in Figure 2. A special clamping device allowed the MEEP containers to be mounted/attached to the handrails of the Shuttle's Docking Module on Mir. The POSA I and II instruments exposed various optical surfaces in an effort to evaluate surface desposits and/or contaminants (see http://setas-www.larc.nasa.gov/setas/meep/posa1.html and http://setas-www.larc.nasa.gov/setas/meep/posa2.html, respectively), while the Polished Plate Meteoroid Detector (PPMD) exposed gold, tin, and aluminum as cratering targets (see http://setas-www.larc.nasa.gov/setas/meep/ppmd.html). Figure 3 shows ODC and other MEEP experiments in their nominal exposure configuration on Mir. Ideally, Tray 1 of ODC faced in the forward direction, and Tray 2 into the antipodal direction; MIR's velocity vector is approximately in the plane of the paper in Figure 3, going from left to right. Figure 4 shows scenes during retrieval operations by STS 86 astronauts S. Parazynski and V. Titov on October 1, 1997. The beginning of the ODC harvesting procedure is illustrated in Figure 4a with astronaut Parazynski having unlatched and starting to rotate (360°) the Tray 2 side of the MEEP container. Note that the Tray 1 half remains stationary during this operation, as it is still connected to the mounting bracket/clamping

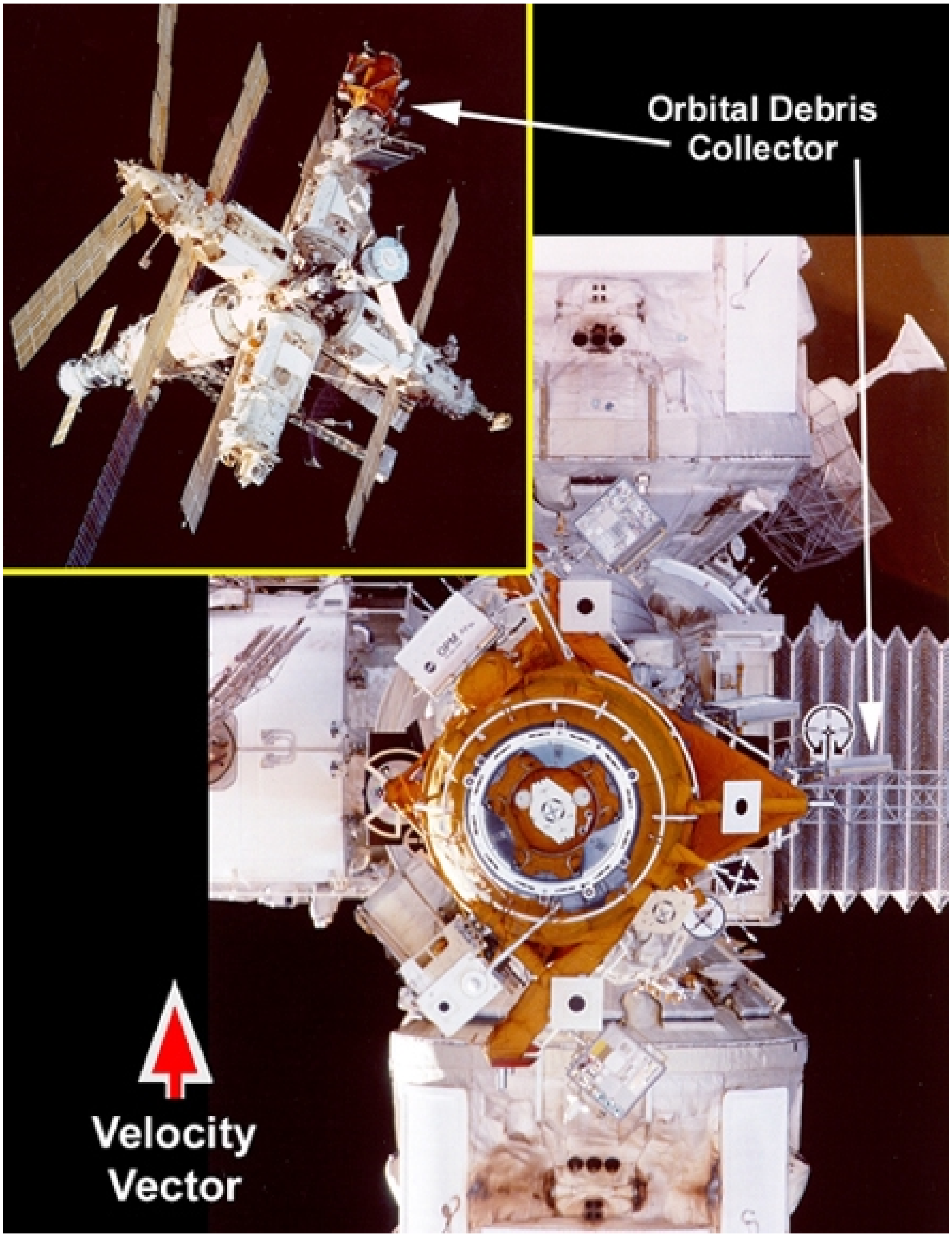

Figure 3. The orbiting MIR Station (insert) and detailed view of US Docking Module accommodating the four MEEP containers (all in the upper, right-hand quadrant relative to the center of the Docking Module. The POSA I (to the right of the 12:00 position) and POSA II (to the right of the 6:00 position) experiments point straight at the viewer, while the two remaining MEEP containers (*i.e.*, ODC and PPMD; between the 2:00 and 3:00 position) are essentially edge on. The PPMD shared a single handrail (white bar above triangular structure) with ODC.

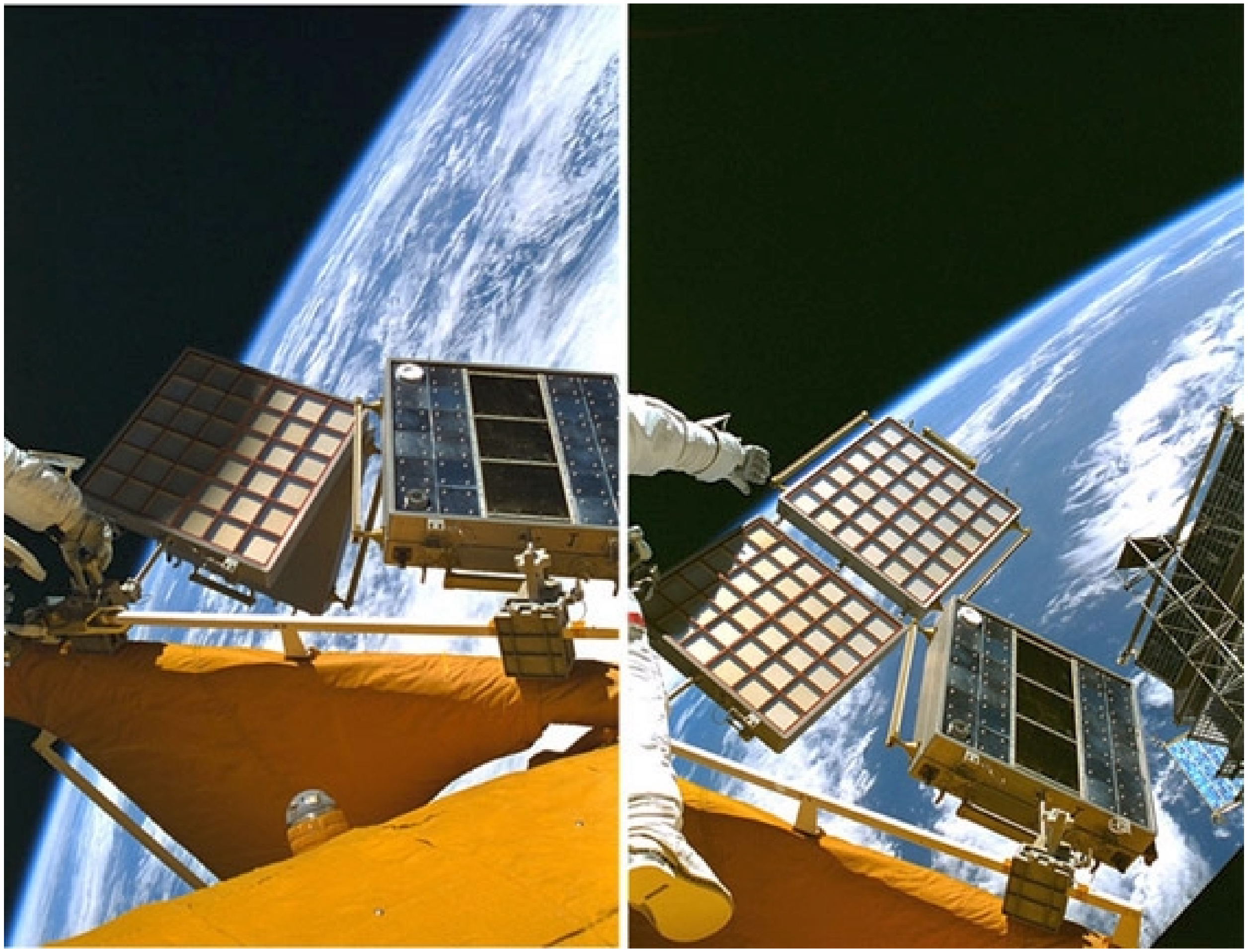

Figure 4. On-orbit scenes during retrieval of the ODC experiment with the PPMD experiment in the foreground. Tray 2 has been rotated ~ 10° (left) and ~ 180° (right) about hinges that permit the collectors to be stowed face-to-face for the return to Earth.

device, which can be more clearly seen in association with the neighboring PPMD experiment. Figure 4b depicts the closing operation at ~ 50% complete, with Tray 2 just rotating past the 180° mark relative to Tray 1. Both deployment and retrieval operations were nominal and observations by the STS 86 crews did not reveal any anomalies with ODC after ~ 18 months of exposure. None of the delicate aerogel tiles seemed damaged, much less missing.

Due to a wide variety of unscheduled and — in part — poorly documented orbital maneuvers precipitated by a number of operational anomalies on Mir, the detailed orientation of ODC relative to the station's orbital motion remains poorly understood, as are geometric shielding factors by neighboring structures. Only recently has the detailed attitude data for Mir become available, but the time consuming evaluation and analysis of this data have not been initiated. The neighboring PPMD experiment (see Figure 4) included a pinhole camera, which registered the impingement of atomic oxygen on an Ag-containing sensor surface, and thus, the relative movement of the instrument about MIR's ram direction (Peters and Gregory, 1991). PPMD and ODC pointed into essentially identical directions, which was accomplished by means of registered fiducial marks that had been inscribed on the mounting brackets at Kennedy Space Center (KSC) during fit tests of the flight hardware. The PPMD pinhole camera yielded a substantially diffuse footpad of atomic-oxygen impingement rather than a single, sharp spot. This indicates that the orientation of PPMD (and ODC) relative to MIR was highly variable throughout the entire exposure period, and that there was no long-term (or cumulative) exposure in any well defined pointing direction (Kinard, 1998).

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