ON-ORBIT MONITORING OF NEAR-EARTH SPACE DEBRIS ACROSS THE SIZE SPECTRUM

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ABSTRACT/RÉSUMÉ

Near-Earth space debris is a mixture of cosmic particles and manmade trash. The LDEF Interplanetary Dust Experiment was to monitor natural dust, as a followup to Explorer 46 (MTS), but analysis of the precisely-timed impact data showed that the overwhelming majority of the particles of submicron to millimeter size at ordinary satellite distances (300-500 km) are manmade, often concentrated in clouds of hundreds of kilometers dimension. At speeds of 10 km/sec and more, these objects represent hazards to useful and expensive spacecraft, manned or robotic. Protective measures are mandatory. Unhappily, there is an information gap between what shield and mission designers know and what they need to know. There is a paucity of measured data (the only real world) on the size, spatial and temporal domains of space debris. For size, there are serious gaps in our knowledge in the 1µm to 1.5 mm range. Spatially, there are few data beyond 500 km. For the size range recorded by LDEF/IDE, there was extreme temporal fluctuation over short time scales during the period of active recording. There is surely long-term secular change also, but this is a principal crux of the problem: we do not know, because the debris environment has not been measured seriously since LDEF. We suggest that the solution is a "Debris Technology Satellite" (DTS) in the spirit of MTS, with a Sun-synchronous, perigee around 500 km, apogee 2000 km, for a duration of 10 years. Its instrument complement would include several complementary instruments to cover the size range from submicron to centimeter.

1. INTRODUCTION AND HISTORICAL

1.1 Beginnings -- Prairie Meteor Network, sounding rockets, MTS

Near-Earth space debris is a mixture of cosmic particles and manmade trash. Each has its importance and merits better understanding, which we will try to address succinctly later. Observational techniques include imaging, impact detection, and radio interference. Before artificial debris existed, the interest was purely astronomical. Other than sporadic reports of random "shooting stars", perhaps the first organized attempt to collect and codify data was the Prairie Meteor Network of the Smithsonian Astrophysical Observatory [1] intended to recover intact cosmic rocks. A bit later, Curt Hemenway [2] used upper-atmosphere sounding rockets to capture tiny grains of cosmic dust. The final act of natural particles at center stage was NASA Explorer 46, called Meteoroid Technology Satellite (MTS), so ably ramrodded by W. Kinard and Don Humes [3]. The limits of what may qualify as "space debris" are not yet well-defined. "Orbital debris" is reasonably well-defined: anything that is in Earth orbit and non-useful; almost all is manmade, despite Tony McDonnell's protestations. "Space debris" is not so clear. Evidently, on the lower dimension it includes anything that can be measured. On the upper end, Dermott *et al.* [4] have proposed a definition that includes asteroids up to a few km dimension. By pure happenstance during one of my jovian satellite patrols [5], I helped discover the 4-km asteroïd (4179) *Toutatis*, then the closest-known NEO (cosmic Near-Earth Object) and still a prime candidate for celestial mining because of its near-exact 4-yr orbital commensurability with Earth [6, 7], and I immodestly propose it as a measure. It is also one of the best examples of chaotic orbital behavior, due to other commensurabilities with both Venus and Jupiter [8], so if it is to be mined, the sooner the quicker, as Paul Herget liked to say. Last Christmas, we were strafed at nearly lunar distance by a 50-m rock designated 2000YA [9]; a much smaller rock that fell to Earth may have been a fragment. At similar distance, the object designated 2001 DO_47 was in fact the used spacecraft WIND [10]. Both the Shuttle and the International Space Station (ISS) Alpha have been forced to dodge large manmade space junk [11]. As so often repeated by arabist and diplomat Richard J. Burton in his *Thousand Nights and a Night* (1885), "were it a warner to whoso would be warned".

1.2 LDEF, Eureca, Mir -- discovery of debris clouds from on-orbit breakups

NASA's Long Duration Exposure Facility (LDEF) was launched in 1984 for a planned duration of one year; unforeseen and tragic circumstances permitted its recovery

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from orbital decay only 69 months later. The LDEF Interplanetary Dust Experiment (IDE) was conceived to monitor the lower size limit of cometary and asteroidal grains, as a followup to a similar experiment on MTS, with MOS (metal-oxide-silicon) impact detector panels facing in six orthogonal directions and impact timing resolution of about 11 sec [12]. Analysis of these data quickly showed that the overwhelming majority of the particles of submicron to millimeter size at ordinary satellite distances (300-500 km) are man-made [13]. What is more, they often are concentrated in clouds of hundreds of kilometers dimension [14]. Other impact data, though of much lower time resolution, were collected on Eureca [15], STS [16] and MIR [17, 18].

IDE did indeed contribute to astronomical dynamics by showing observational evidence for the existence of theoretically-predicted beta meteoroids, grains so small that radiation pressure overwhelms solar gravity [19, 20]. It also confirmed more direct LDEF measures of the craft's orientation.

1.3 Subsequent movements -- SYNMOD proposals

As a result of the LDEF/IDE discoveries and in view of the need for follow-on observations covering as much as possible of the spatio-temporal domain, the first author developed the concept christened *Synoptic Monitoring of Orbital Debris (SYNMOD)* [21]; in some manner, at some time, each co-author (plus many others) was associated with it. Proposed in several mission contexts, it was highly rated for the stillborn *Eureca 2* reflight. The "sin" of SYNMOD was that it was at once too ambitious and too narrowly-focussed. Narrowly-focussed because it was restricted to the Wortman MOS detectors and the microparticles that IDE put into evidence. Ambitious because it proposed to measure everything, everywhere.

1.4 Modern ground-based observations

Ground-based observations of space debris are of three basic types: optical, radio, and radar. Radio "whistlers" give little information beyond temporal frequency. Radar surveys were started by Dick Goldstein of Goldstone [22] and have been carried on with great success since at MIT Haystack and Arecibo. Optical patrols became possible with the USAF GEODSS telescopes, and astrophysicist/astronaut Karl Henize turned them to that purpose [23]. John Africano and his colleagues continue this work with admirable success with the LMT and other means [24], and several other such activities are underway, including both ESA/ESOC and CNES. The relatively low cost of ground operations is mitigated by their primary disadvantage: both radar and optical techniques are currently limited to detection of objects sized 5 cm and larger.

2. OBVIOUS AND ARCANE POINTS ON SIGNIFICANCE

It is surely not useful in the context of this Conference to spend much time on the significance of an improved knowledge of the space debris environment. It would amount to preaching to the believers. We will only point out the obvious. Natural cosmic trash provide pointers to solar system cosmogony. Man-made trash gives pointers to better spacecraft design and operations. Knowledge of both is necessary to hazard evaluation, counting both hazards to operational spacecraft and to terriens. Both 2000YA and WIND surprised everyone. How long, Ôh Lord ... ?

3. CURRENT MODELS AND DATA

3.1 Computer models of NASA, ESA, and others

Several models currently describe the orbital debris environment. The Meteoroid And Space debris Terrestrial Environment Reference (MASTER) model has been developed under ESA contract. The current version is limited to particles of diameter larger than 100 microns. Two other models, the Integrated Debris Evolution Suite (IDES) model and the Space Debris Model (SDM) have been proposed, but they are limited to particles larger than 1 mm. The NASA ORbital Debris Model (ORDEM96) is restricted to circular target orbits for altitudes lower than 2000 km . It is mainly based on results from observation of space debris (Haystack radar and LDEF). It offers directional flux information and is valid for particle diameters down to 1 micron. It discriminates by particles on such sources as intact satellites, large fragments, small fragments, paint flakes, aluminium oxide particles and NaK particles.

3.2 Unused but extant data

The LDEF/IDE analyses proved the existence of megameter debris clouds, and there is alleged to be support from MIR [25]. But these are data of limited spatio-temporal extent. There is an easy and relatively cheap test to fill some of the gaps -- orbiting solar coronagraphs. After LDEF was launched, the Space Shuttle continued its mission by moving only a short distance away to repair the disabled Solar Maximum Mission satellite. Indeed, LDEF's orbit was selected by NASA exactly to facilitate this "road-side service". That is to say, the two satellites had nearly identical orbits. The repair accomplished, Solar Max stayed out of service for an extended time for engineering tests. One possible reason was the unexpected detection in the near field of waves of small particles. It has been posited with serious evidence [26] that these were the same clouds of orbital debris detected by LDEF/IDE. If this hypothesis be verified by correlation of the SMM events and the IDE results, proposed but not yet attempted, then any space coronagraph is also a particle detector and their images can add to the debris database. SOHO's Large Angle and Spectrographic Coronagraph Experiment (LASCO) may show similar traces [27], in a far different orbital and temporal space. Are there other candidate sources? Think about it.

3.3 Data that lack

A basic principle amongst astronomers is that an observation taken lasts forever, but an observation not made can never be recovered and is lost forever. For space debris, groundbased radar and optical techniques are pushing the size limits down. The basic problem with modelling the centimetric and smaller space debris environment is that so many observations have not been made. We continue to lament the gaps in our data, but we have done precious little to fill the gap. Mitigation measures are surely helping, but who has measured to what degree? This can only be done on orbit. And once does not suffice, because of the temporal aspect. Clouds come and go, so should be monitored. It has to be done continuously and over a large spatial domain to be meaningful.

4. A KEYSTONE SOLUTION -- DEBRIS TECHNOLOGY SATELLITE (DTS)

4.1 Generalities

The main problem of the space debris data base is the paucity of data on sub-centimeter objects. Asteroids create meteor craters, but they are rare and observable; 2000YA could have obliterated the village in which I live, but it missed. Gravestones are made by sandblasting, which is the fate of solar panels, optical devices and heat exchangers on-orbit, subject to the largely unmeasured clouds of microscopic debris. Unmeasured, but not unmeasurable. We have suggested [28] that its solution is a "Debris Technology Satellite" (DTS) in the spirit of MTS. Like MTS, LDEF, and Eureca, it should bear a complement of diverse instruments. Unlike LDEF and Eureca, those devices should be chosen for a single integrated goal: to better characterize the space debris environment. Unlike MTS, it should avoid the illusion that we know what to expect and it must use the maximum possible of what has been learned since LDEF recovery.

4.2 Solar coronagraph

Submicrometer-sized particles scatter light forward. Every automobile driver has experienced it when driving into the setting Sun. For that reason, any orbital coronagraph is a prime detector of the smallest sandblast component of space debris, whether cosmic or manmade [26]. Such a device is a necessary complement of the DTS concept.

4.3 MOS, PVDF and other surface-mounted impact detectors

These devices have each proven their worth on orbit, for detection of 0.1-200 μm particles. They have different advantages and weaknesses, being therefore in some measure complementary. Discussions of combined MOS/PVDF instruments were already undertaken between Mulholland and Tuzzolino several years ago. The Wortman MOS disks are sensitive to smaller particles and capable of higher time resolution, while the Simpson PVDF provide directionality and a measure of energy, available only by implication on MOS.

Jim Wortman has designed multi-segment versions of the MOS detector, and we have tested them in hypervelocity accelerators at Canterbury and Heidelberg [29]. They did not perform well, and we estimate that the problem was related to the geometry, with sharp points that could compromise the electrical integrity. We recommend that the original circular configuration used on LDEF be retained for DTS and other applications.

Another alternative is presented by impact foil cassettes, used on LDEF [30], Eureca [15] and MIR [31]. We suggest that these devices are less suitable than either MOS or PVDF, for reasons both of mechanical complexity and timing resolution. But it remains an open question, because they are sensitive for up to a few mm.

MOS devices are being developed for ISS Alpha [32].

4.4 Anti-solar optical telescope

The millimeter and larger size ranges are not appropriate to either the coronagraph or surface-mounted impact detectors. If the spacecraft be stabilized for the coronagraph, then an opposite-pointing Schmidt (or other wide-field) telescope could profit from backscatter to detect such larger objects, d>100μm.

4.5 Piezoelectric or other extended film impact detectors

If such devices are feasible as large-area deployable wings, then even larger particles could be detected. The detector definition depends on the flux one wants: for one impact per year of size 1 cm, one needs about 400x400 m detector area.

4.6 Orbital geometry and mission duration

Such a craft might have a Sun-synchronous orbit with perigee around 500 km, apogee 2000 km, for a duration of 10 years This idea has been considered by NASA/JSC following our 1998 presentation, but apparently abandoned for budgetary reasons. It is still not a bad idea.

5. CONCLUSION -- A CALL TO ACTION

When a "road-side repairman" throws an enormous solar panel into the orbital void because he couldn't fold it into the STS bay -- as happened with Hubble Space Telescope -- at least it can be tracked by ground radar. But what happens to the sandblast cloud when some machine simply blows up? What happens to all the crud that is left over from solid rocket exhausts? One can't know without measuring it. Past assumptions have too often been shown wrong, once tested. Observation is the only real world. Burying one's head under the tent doesn't make the optics last longer or the budget go farther. It is time for the world's space agencies to convince their governments that it is time to start monitoring the microscopic debris environment, with one or more devices such as DTS.

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