Measuring small debris – what you can't see can hurt you

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ABSTRACT

While modeling gives us a tool to better understand the Earth orbit debris environment, it is measurements that give us "ground truth" about what is happening in space. Assets that can detect orbital debris remotely from the surface of the Earth, such as radars and telescopes, give us a statistical view of how debris are distributed in space, how they are being created, and how they are evolving over time. In addition, *in situ* detectors in space are giving us a better picture of how the small particle environment is actually damaging spacecraft today. IN addition, simulation experiments on the ground help us to understand what we are seeing in orbit. This talk will summarize the history of space debris measurements, how it has changed our view of the Earth orbit environment, and how we are designing the experiments of tomorrow.

1.0 INTRODUCTION

NASA's Orbital Debris Program Office (ODPO) is tasked with understanding and defining what the orbital debris environment looks like and how does it affect space operations. While there are a number of modeling tools employed, the "ground truth" of what is in space is done by using measurements. The orbital debris environment risk is not only due to large, tracked spacecraft, but also from very small debris only a few microns across that could potentially affect spacecraft operations. Because of the wide range of debris sizes of interest and the vast regions of Earth orbit that must be understood, there is no one instrument that can measure all types of debris. This presentation will outline the primary tools we use to measure the environment, then will conclude with a discussion of laboratory tests used to help us model the environment.

2.0 Space Surveillance Network

When most people think of orbital debris, they think of the population that is tracked. These are objects whose orbits are known well enough that we can predict where it will be tomorrow. The task of tracking objects in space is given to the US Department of Defense, and their Space Surveillance Network (SSN). This is a global network of sensors that constantly monitor the space environment. In practice, the SSN can only track objects down to about 10 cm in size in low-Earth orbit (LEO) – mostly by radar. For objects at geosynchronous orbit (GEO), SSN instruments (mostly optical telescopes) can only see intact satellites a few large debris. They have difficulty tracking and detecting smaller debris.

The tracking job of the SSN is performed to sufficient precision that the data is of sufficient quality that spacecraft operators can use it to perform collision-avoidance maneuvers – a capability that was pioneered by a collaboration between NASA and the DoD to improve the safety of human spaceflight.

Because of the global nature of the SSN, every major explosion or collision in space was first identified by the SSN. It is this near-real-time surveillance aspect of the SSN that makes it an invaluable tool to monitor and rapidly update the environment due to catastrophic events in space.

The Joint Space Operations Center (JSpOC) provides a number of tools, one of which is the two-line elements set (TLE) catalog. These are regularly-updated orbital elements useful for predicting satellite positions in the near future. However, they are of insufficient metric quality to use for collision avoidance purposes. Instead, if a spacecraft operator wishes to receive collision avoidance warnings and be given actionable intelligence on how to do that, he can subscribe to receive collision avoidance warnings for his satellite from the JSpOC. These warnings include information on the asset spacecraft and potentially-colliding object of sufficient metric accuracy to compute collision probability and determine whether to do a collision-avoidance maneuver.

Keep in mind that for every object that can be tracked, there are many objects smaller than 10 cm that cannot be tracked, but are still large enough to cause serious damage to a spacecraft in a collision. There are plans to build new sensors for the SSN that may allow the tracking of objects smaller than 10 cm in the near future.

3. Radar

While the US Department of Defense is tasked with environment characterization for objects above about 10 cm, NASA has the job of characterizing the debris environment smaller than 10 cm. While it is impossible to measure such small objects at this time with sufficient accuracy to track them, it is possible to detect them and understand much about how they are distributed in orbit and in size. NASA uses statistical surveys to sample the environment and to infer how these objects are distributed in space. This allows, in some cases, the ability to determine the sources of debris.

The primary radar tools used by NASA are the HUSIR radar, HAX radar, and Goldstone radar. The Haystack Ultrawideband Satellite Imaging Radar (HUSIR - previously known as Haystack before its recent upgrade) is an X-band radar located in Massachusetts and operated by Lincoln Laboratories. It has the capability to see objects below 1 cm in size throughout the LEO environment (below about 2000 km), and objects down to about 5 mm at ISS altitudes (400 km). The HAX radar operates beside HUSIR. It is a smaller dish, and can only see down to 1-2 cm in LEO, but it has a wider beam, and so gets better counting statistics for sizes from 3 cm to 10 cm for a given amount of time.

Both HUSIR and HAX operate in a fixed pointing mode where they stare into space and measure objects moving through the beam. Both have monopulse capability, which allows some capability to determine the path of the satellite passing through the beam. They measure range and Doppler range-rate with high precision, but only get an approximate measurement of the velocity perpendicular to the beam. This limits the accuracy with which the orbits of the objects can be determined. However, both radars have operated for some time in several off-vertical modes where inclination can be determined under the assumption of circular orbits. This has proven invaluable in determining the orbit families debris occupy. Elliptical orbits are identified statistically in this range/range-rate data, but the vast majority of the detections are of circular orbits.

When Haystack was first used for debris detection in the early 1990’s, an unusual population of debris was identified in circular orbits between about 850 and 1000 km altitude and in 65° inclination orbits. These objects were too small to appear in the catalog. After a number of measurements were made, including the radar polarization that concluded that these objects were metallic spheres of various sizes, it was determined that these objects were spherical droplets of sodium-potassium liquid-metal coolant. They had presumably been released from the Russian Radar Ocean Reconnaissance Satellite (RORSAT) nuclear reactors when the reactors were jettisoned in the 1980’s. This single discovery proved the importance of using statistical measurements, because the debris source had been invisible to tracking radars of the SSN.

Today the HUSIR and HAX radars continue to monitor the orbital debris environment, giving us unprecedented information and timely analysis of the debris clouds from fresh breakup events, including the 2007 Chinese FY-1C anti-satellite test, and the 2009 accidental collision between Iridium 33 and Cosmos 2251. In both of these cases, Haystack and HAX were able to provide information on the magnitude and nature of the debris clouds in order to assess the risk to Shuttle missions scheduled to fly after the breakups.

Another useful tool is the Goldstone radar. This bistatic radar system uses NASA’s Deep Space Network 70 m dish in conjunction with a nearby 35 m dish to also monitor the LEO environment. While the system is limited, it provides data on debris objects down to about 2-3 mm at ISS altitudes to extend the debris populations below that seen by HUSIR. Goldstone has detected the remnants of the Westford needles – tiny copper needles launched in the 1960’s. Recently, Goldstone was upgraded to measure a wider range of Doppler range-rates, and allows it to point further off-vertical in order to obtain inclination estimates similar to those from HUSIR and HAX

The HUSIR, HAX, and Goldstone radars have provided critical information used to create the orbit populations in the 3 mm – 10 cm size range for NASA’s orbital debris engineering family of models (ORDEM). This represents the size range that affects much of the safety of human space flight, and the data was used to help design the debris shields on the ISS.

4. Optical

For objects in deep space, beyond LEO, optical instruments provide a useful tool. NASA has used the Michigan Orbital Debris Survey Telescope (MODEST), a 0.61-m aperture Curtis-Schmidt telescope in Chile operated by the University of Michigan, to conduct regular surveys of the GEO and near-GEO environment. As with radars, the primary purpose is not to track these objects or to create a new catalog, but to take statistical surveys of the population and understand their sources and how they are distributed. In addition, NASA has used MODEST and other telescopes to try to characterize debris, for instance to see if spectral data can identify the material type of debris objects.

NASA recently deployed a larger telescope at Ascension Island near the equator in the Atlantic Ocean to monitor the orbital debris environment. This Meter Class Autonomous Telescope (MCAT) is a 1.3 m aperture Ritchey-Chretien reflecting telescope that will be able to continue and extend the MODEST surveys to sizes near ~10 cm in GEO. In addition, special new tracking modes will be employed to try to detect low-inclination, low-altitude debris that are thought to exist in LEO but have been invisible to previous radars and telescopes.

One of the benefits of optical telescopes is that they have the capability to detect possible "optically bright but radar dim" debris, perhaps of plastic or other non-metallic materials that might be an important part of the environment, but are difficult to detect in radar.

5. *In Situ*

It is very difficult to detect debris objects smaller than about 2-3 mm from the ground. However, over the years many spacecraft surfaces have been returned from orbit with small impact craters or other impact damage. These features can be analyzed in the laboratory for evidence of the impactor residue. Some of the impact features are from meteors, but some are from orbital debris.

The Long-Duration Exposure Facility (LDEF), deployed and recovered by the US Space Shuttle, was an excellent debris impact collector, with several dedicated experiments. But it sampled the environment in the 1980's. Since then, the US Space Shuttle itself has been the primary *in situ* detector. Even though its surfaces were not specifically designed to detect orbital debris, two areas on the spacecraft proved to be excellent detectors, and were examined after each mission.

The windows provided data on small impactors – those from 10 μm to 100 μm in size. The total collecting area of the Shuttle windows was 3.5 square meters, and provided an excellent measure of the debris chemical properties, indicating the proportion of steel to aluminum impactors hitting the spacecraft. Toward the end of the Space Shuttle program, the impact damage was occurring at a rate high enough that an average of one window was being replaced each mission due to the damage.

The other Shuttle surface was the radiators. At 120 square meters in area, they provided an excellent opportunity to study impacts of the much rarer impactors in the 100 μm to 1 mm size range. Some chemical composition information was available for the impactors, but because the radiators were made of aluminum themselves, they had trouble recognizing aluminum impactors. Nevertheless, the large fraction of "unknown" impactors (those that could not be categorized) gave a good estimate of the number of the aluminum-on-aluminum impactors.

The Shuttle data was used to generate the <1 mm debris populations in the ORDEM model. Because this data set is limited to altitudes the Shuttle flew (below about 600 km), there is a large uncertainty in how these populations change at higher altitudes. And since the Space Shuttles no longer fly, there is a concerted effort to design and deploy a dedicated sensor to measure the small particle environment in the 700-1000 km altitude range where many scientific spacecraft fly.

The Debris Resistive Acoustic Grid Orbital Navy-NASA Sensor (DRAGONS) program is an attempt to create an instrument that not only measures the flux of sub-millimeter debris on spacecraft, but also to measure a number of other important characteristics of the debris, including mass, material density, and the timing, velocity, and direction of the impacts – parameters needed to understand the orbit distribution of the debris. This is accomplished by using a series of thin layers approximately 1 m^2 in collecting area spaced some distance apart. .

The front layer a thin film of Kapton with acoustic sensors and a grid of resistive wires. These acoustic sensors will measure the time and location of a penetrating impact, while a change in resistance on the grid will indicate the number of wires broken, which will provide a size estimate of the hole. The relationship between object size and hole size will be determined by hypervelocity testing under controlled conditions. Located 15 cm behind the first layer is a second thin layer of Kapton with acoustic sensors to measure the time and location of the second penetration. Velocity is determined by dividing the distance travelled between the first and second impact points by the time it took to travel that distance. An instrumented back layer will stop the debris and measure the total amount of energy in the collision. With the information on the energy, velocity, and size of the particle, it should be possible reconstruct the particle's orbit and material density (at least to sufficient accuracy to separate steel from aluminum particles). It should provide data on particles between about 50 µm and 1 mm in size.

The sensor is planned to be deployed on the ISS mounted at an external payload site facing the velocity vector to maximize detections. It is hoped this flight demonstration will also prove the viability of the technology for future missions at altitudes between 700 and 1000 km where risks from debris to spacecraft can be greater than at the ISS altitude.

6. Ground Experiments

In addition to direct observations of the orbital debris environment, laboratory tests can be done to test certain aspects of the models used to describe the environment. Many properties of debris are difficult to observe when the particles are in orbit.

For instance, the ODPO operates an Optical Measurements Center (OMC) that simulates the lighting conditions in space in order to understand the complex relationship between debris size/shape and optical brightness. This provides "ground truth" in order to interpret the observations of the debris environment using optical telescopes.

The breakup models used to predict present and future environments are mostly based on the collected debris from the Satellite Orbital debris Characterization Impact Test (SOCIT), conducted by the US Department of Defense and NASA in 1992. The collision target was a fully functional US Navy Transit satellite. The debris pieces were collected and characterized, and the results were used to construct the NASA standard breakup model. In addition, some of the pieces were analyzed for their radar cross section signatures in order to be able to convert radar data to debris size.

However, the Transit satellite was built in the 1960s, and data from recent collisions indicate that the debris clouds from satellites built with modern materials may produce different kinds of debris clouds. Therefore, NASA and the US Department of Defense have collaborated to conduct another collision test, this time of a mock satellite of more modern design.

The target was 56 kg, with real or emulated spacecraft components. It was hit with a 6.8 km/sec, 570 g projectile (13.2 MJ total impact energy), and was completely broken up. The pieces, which number in the hundreds of thousands, were painstakingly recovered and are now in the process of being fully measured, photographed, and documented. The dataset will be the most comprehensive analysis of breakup debris ever conducted, and should shed light on how collisions will affect the environment in the future.

7. Conclusion

As can be seen in this discussion, the task of measuring the orbital debris environment is a complicated and multifaceted problem, but it provides important information on the sources and nature of orbital debris creation, as well as “situational awareness” for space operators. Because of the dynamic nature of the environment, it is critical to be able to monitor changes that are occurring, especially to identify new debris sources. Some of our data sources, such as the US Space Shuttle, are no longer available, so NASA is working to develop and deploy advanced calibrated detectors to make sure that we can observe the environment in order to identify and mitigate debris production mechanisms. New detectors, such as the MCAT telescope, will help us look in size and orbit regimes that are not well understood.