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Passive optical detection of submillimeter and millimeter size space debris in low Earth orbit

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ABSTRACT

Understanding of the space debris environment and accuracy of its observation-validated models are essential for optimal design and safe operation of satellite systems. Existing ground-based optical telescopes and radars are not capable of observing debris smaller than several millimeters in size. A new experimental and instrumental approach – the space-based Local Orbital Debris Environment (LODE) detector – aims at in situ measuring of debris with sizes from 0.2–10 mm near the satellite orbit. The LODE concept relies on a passive optical photon-counting time-tagging imaging system detecting solar photons (in the visible spectral range) reflected by debris crossing the sensor field of view. In contrast, prior feasibility studies of space-based optical sensors considered frame detectors in the focal plane. The article describes the new experimental concept, discusses top-level system parameters and design tradeoffs, outlines an approach to identifying and extracting rare debris detection events from the background, and presents an example of performance characteristics of a LODE sensor with a 6-cm diameter aperture. The article concludes with a discussion of possible sensor applications on satellites.

1. Submillimeter and millimeter debris in low-Earth orbit

Artificial satellites, rocket bodies, and their fragments orbit the Earth in increasing numbers and present danger to operational spacecraft, especially in low-Earth orbit (LEO) and geostationary orbit (e.g., [1–7]). The United States and the former Soviet Union, now Russia, have been operating a combination of radar and optical means for cataloging and monitoring space objects since 1960s [3,7–9]. Other countries in Asia and Europe, particularly the People's Republic of China and the European Space Agency (as well as national programs in France and Germany), strive to expand their capabilities in the space situational awareness.

The knowledge of the deteriorating space debris environment and accuracy of its observation-validated models are essential for optimal design and safe operation of satellite systems. The U.S. Space Surveillance Network routinely detects, tracks, and catalogs more than 16,000 orbiting space objects larger than 5–10 cm in LEO, with 400,000 observations taken each day [10]. Much more numerous debris smaller than several centimeters also orbit the Earth. Estimates put the number of debris with sizes from 1 mm to 10 cm in tens of millions and smaller than 1 mm in trillions [3]. Properties of such objects are characterized statistically rather than individually.

A collision with a large, > 5 cm, object would likely cause a loss of a spacecraft and its catastrophic breakup [3], creating numerous fragments. Just one anti-satellite weapon test by the People's Republic of China in January 2007 [11] contributed more than 150 thousand debris one centimeter and larger in LEO [12]. Large orbiting objects are individually observed and cataloged and accidental

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collisions with them can thus be sometimes avoided. Populations of very small debris, < 0.1 mm, can be experimentally studied and statistically characterized by bringing exposed surfaces back to Earth from orbit (e.g., LDEF, SMM, EURECA, SFU, and Space Shuttle) and examining collision effects [7]. These very small debris could cause degradation of surfaces and perhaps damage unprotected spacecraft components.

This work concentrates on the population of debris with intermediate sizes from 0.1–10 mm. Such submillimeter (0.1–1 mm) and millimeter (1–10 mm) debris are typically too small to be detected by existing optical and radar means, and there are too few of them to be described by studying exposed surfaces. Because of this gap in observations [7,13,14], one has to rely on modeling of their populations based on difficult to accurately predict processes in breakup of complex bodies in high-velocity impacts. At the same time possible damage to spacecraft by submillimeter and millimeter debris ranges from surface degradation to possible loss of spacecraft capability or its components [3].

Atmospheric drag lowers orbital altitudes of space objects in LEO and causes their eventual reentry into the atmosphere. (Solar radiation pressure may also become important for some objects with large area-to-mass ratios.) Drag acceleration acting on an orbiting body is inversely proportional to its characteristic size. Consequently, the acceleration becomes higher and the lifetime in the orbit shorter with the decreasing size of the body. For example, drag would remove an aluminum sphere 1-mm in diameter from an initial 400-km altitude orbit within a couple of weeks. Such altitudes are especially important for human spaceflight (International Space Station) and atmospheric drag effectively reduces danger of small debris in such orbits.

At higher altitudes from 700–1500 km with numerous application satellites, lifetimes of orbiting objects may exceed dozens or hundreds of years, resulting in accumulation of debris. Existing ground-based optical and radar systems have inherent limitations in measuring dangerous to satellites submillimeter and millimeter debris at these altitudes.

First, only ground-based systems near the equator can probe space objects in low-inclination low-Earth orbits, limiting capabilities of facilities in the continental United States. In addition, ground optical systems can observe LEO objects only during short time intervals at local dawn and dusk.

Second, for radar, the efficiency of electromagnetic radiation scattering, characterized by radar cross-sections, rapidly decreases for small objects, e.g., [15]. For example, the radar cross-section of a perfectly conducting sphere with a diameter at least three times larger than the wavelength approximately equals its geometric cross-section. For spheres with diameters less than one-third of the wavelength, radar cross-sections drop precipitously (known as Rayleigh scattering) with decreasing diameters.

Most existing and planned (such as the upgrade of the Space Fence in the United States) radars operate in the S-band frequencies with wavelengths 6–15 cm. For example, a perfectly conducting 1-mm diameter sphere would have the radar cross-section almost 5 orders of magnitude smaller than its geometric cross-section for a typical S-band radar operating at the 3 GHz frequency (wavelength 10 cm). For an X-band radar at the 10 GHz frequency (wavelength 3 cm), the corresponding radar cross-section would be 800 times smaller. Atmospheric absorption (e.g., [16]) fundamentally limits possible increase of radar frequencies beyond the X-band required for further lowering the upper size limit of the Rayleigh scattering region.

The German Fraunhofer Institute's Tracking and Imaging Radar (TIRA) near Bonn operating autonomously or in a bistatic mode (with the Max-Planck-Society's radio telescope at Effelsberg) could detect orbiting debris as small as 1–2 cm at altitudes up to 1000 km [5]. Most capable NASA radars today, the Haystack and Goldstone, can detect debris down to several millimeters in size at important for human spaceflight 400-km altitudes [7,17]. In recent years, the upgraded Haystack and Haystack Auxiliary (HAX) radars also demonstrated detection of such debris at 800 km altitude [18] where numerous satellites operate and where debris accumulate due to significantly diminished atmospheric drag.

Satellite-based (space-based) optical sensors offer important opportunities especially for detecting large orbiting objects as was demonstrated, for example, by the Space-Based-Visible sensor on the Midcourse Space Experiment, or MSX [19,20]. A number of feasibility studies examined capabilities of possible space-based passive optical sensors for measuring millimeter and/or centimeter size debris and larger in LEO [13,14,21–23] as well as observing objects in geostationary orbit [13,14,21,22,24,25]. (For the sake of completeness, we also note here an assessment of a space-based radar for detecting objects in LEO [26].) To the best of my knowledge no study has specifically looked at optical observation of submillimeter debris.

At the same time, a recent NASA Handbook [7] especially emphasizes the importance of such submillimeter debris by stating that “from the safety and satellite operations perspective, there is an immediate need for a large and dedicated meteoroid and orbital debris sensor to monitor and update the populations between 0.1 and 1.0 mm.” A special feasibility study sponsored by the European Space Agency specifically focused on closing “the existing knowledge gap in the space debris population in the millimeter and centimeter regime” [14]. Scarcity of experimental data leads to a one-order-of-magnitude disagreement among debris models (ORDEM, MASTER, SDPA) in prediction of fluxes of debris smaller than 1 cm [7].

This article describes a new space-based experimental and instrumental concept – the Local Orbital Debris Environment (LODE) detector – to observationally characterize 0.2–10 mm debris near the satellite path important for space system design and for mission assurance and safe operation. It concentrates on top-level system parameters and design tradeoffs, outlines an approach to identifying and extracting rare debris detection events from the background, and presents an example of performance characteristics of a LODE sensor with a 6-cm diameter aperture. Specific designs of the optical part of