LASER-BASED SPACE DEBRIS MONITORING AT DLR

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OVERVIEW

The demands of the modern society need an increased and reliable global access to outer space. Satellite-based navigation applications, for instance, require adequate data-supply. Weather and climate observations ask for satellites, which monitor cloud coverage and wind speeds as well as the thickness and coverage of polar ice caps.

However, such augmented use of orbital satellites is jeopardized by a continuous growth of so called space debris. According to ESA [1], the term space debris denotes “all non-functional, man-made objects, including fragments and elements thereof, in Earth orbit or re-entering into the Earth atmosphere”. Thus, space debris – also known as space junk – consists of payloads, rocket bodies and other mission-related objects ranging from sizes of mm to m.

The number of tracked debris objects has grown significantly over the last decades. A contributing factor to the growth of the space debris population is the steady rise of rocket launches for LEO and GEO missions. Additionally to increased use of space, the Chinese anti-satellite missile test in 2007 and the 2009 satellite collision (Iridium 33 vs. Kosmos-2251, 789 km above the Taymyr Peninsula in Siberia) increased the debris density dramatically. Such events are not the only source of the increasing amount of debris objects. Collisions of debris itself create an additional quantity of space junk, which is, due to its huge momentum, severely hazardous to space missions.

For these reasons, space faring nations seek to diminish the number of debris objects. The first step on this intention is the detection and tracking of such elements – or in other words the surveillance of space. Hence, space situational awareness (SSA) has become the generic term for the monitoring of space, addressing space debris, space weather phenomena and potential impacts of Near Earth Objects (NEOs).

In this paper, the laser-based SSA concept of the Institute of Technical Physics of the German Aerospace Center (DLR) is introduced. In this concept passive optical detection methods are combined with pulsed laser techniques allowing for precise distance measurements and orbit data determination.

1. EVOLUTION OF SPACE DEBRIS

The space debris objects originate from several sources; to mention are for instance explosions of disused rocket stages due to propellant expansion and mixing followed by self ignition, surface degradation due to the harsh environmental conditions in outer space, and the above mentioned collisions of satellites.

Figure 1 provides an impression of the temporal evolution of the number of catalogued space debris objects [2]. As can be seen, the total amount of space debris objects increased roughly linear between the years 1961 and 2007. In the year 2007, however, China conducted a so called “anti satellite test” [3], which led to an increased number of catalogued objects by approximately 40% and is referred to as “worst single debris event ever” [4]. Furthermore, the Iridium 33 versus Cosmos 2251 collision created 1500 additional space debris objects.

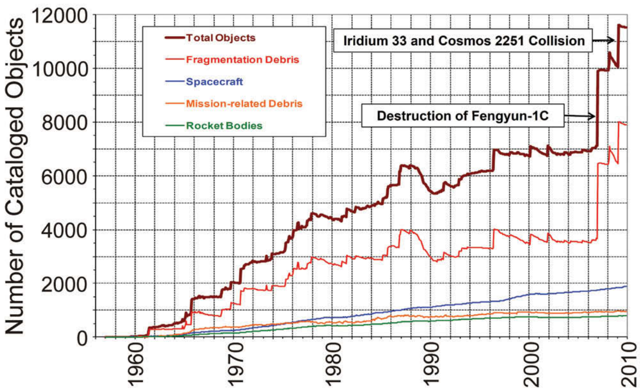

Figure 1: Temporal evolution of space debris from 1956 to 2010 (color online) [2]. The number of catalogued objects shows significant steps due to the Chinese anti-satellite test and the Iridium-Cosmos collision.

As the here shown number of catalogued objects include only objects measuring larger than approximately 5 – 10 cm in LEO and 30 cm to 1 m at geostationary attitudes (GEO), the situation worsens by taking smaller objects into account. Even objects in the size-class of one centimeter have the ability to impose severe hazard on both manned and unmanned space missions. Due to the relative velocities on the order of 10 km/s in LEO, very small and thus up to now untrackable objects hold very high kinetic energies, which are able to constrain or even jeopardize space missions.

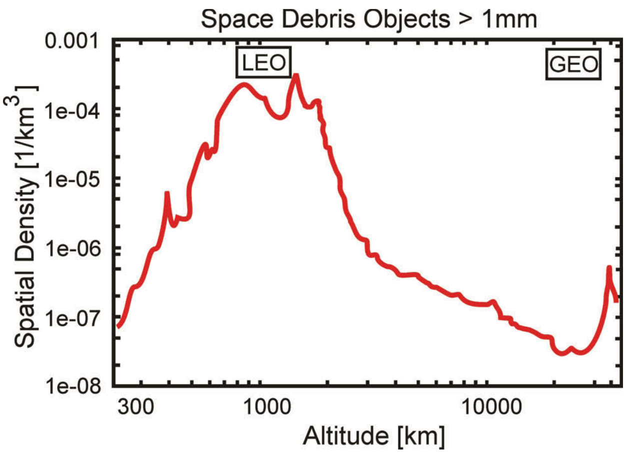

Figure 2: Spatial density of space debris objects larger than 1 mm versus altitude according to ESA's *MASTER* model.

Hence, statistic models have been developed, which allow for predictions of debris distribution of small, non-observable objects. Besides NASA's Orbital Debris Engineering Model (*ORDEM*), the Meteoroid and Space Debris Terrestrial Environment Reference (*MASTER*) by ESA provides information on debris down to millimeter scale.

As shown in Figure 2, the spatial density as a function of altitude of space debris objects larger than 1 mm shows pronounced maxima at 900 km and 1400 km, respectively. Hence, the operational infrastructure in LEO is exposed to space debris mainly at these altitudes due to the high spatial density of $\rho > 10^{-4}$ km^{-3}.

The fact that the space debris piles up in the LEO region gives rise to an additional source of space debris objects. In the late 1970s, Donald Kessler's publication on inter-debris collisions raised attention by drawing the conclusion that cascading effects of coincidental collisions between debris objects will become a (main) source of space debris [5]. This leads to an exponentially growth of debris flux over time, even in the absence of a net input in the system (*Kessler syndrome*). Despite the cascading effect, which was claimed to start in the year 2000, but does not seem to have taken place yet, the mentioned Iridium-Cosmos collision gives an impression of the need for protective measures necessary to secure space infrastructure.

2. WORLDWIDE ACTIVITIES

As was pointed out in section 1, there is an imminent danger that space debris is getting out of control. On the one hand, this danger exists due to further use of outer space accompanied by further debris, and on the other hand due to a cascading effect of collisions, which is supposed to take place after a critical threshold of space debris is exceeded. Whenever known debris objects reach the proximity of valuable infrastructure with a particular likelihood, those infrastructure, for instance the ISS, performs obstacle avoidance maneuvers. Such maneuvers will reduce the lifetime of each mission due to the consumption of fuel. Thus, a detailed knowledge of orbital parameters of the space debris objects is very valuable, both in terms of avoiding collisions and in order to prevent unnecessary evasion maneuvers. Table 1 shows typical position errors of catalogued LEO debris for different inclinations ranging from 4.32° ≤ i ≤ 98.27° [6]. The uncertainties are provided as 1σ value from a fit to data collected over 36 hours for radial, transversal and out-of plane direction, respectively (*r*, *t*, and *oop*).

position error Δ [m]			
	Δr_r	Δr_t	Δr_{oop}
i < 30°	102	419	122
30° ≤ i ≤ 60°	129	434	163
i > 60°	104	556	139

Table 1: Assessed accuracy of catalogued space debris in LEO [6]. The error is provided as 1σ value from a fit to data collected over 36 hours.

According to Klinkrad *et al*. [6], these accuracies are several orders of magnitude worse than the uncertainties of ESA's Envisat satellite, for example.

Hence, every space faring nation depends on precise information on space debris orbital parameters. However, only the USA operates an extensive space situational awareness system. This is primarily based on radar observations, which are part of the US space surveillance network (US-SSN). The US-SSN is consisting of the facilities of the so called space fence, additional contributing radar stations mainly in North America, and optical observatories in Hawaii. However, besides the catalogued and published data on space debris, 1/3 of the entries of the space objects catalogue are classified and hence are not accessible for institutions outside the US.

ESA is currently intensifying their effort in SSA related fields. Existing radar facilities in Europe are the TIRA, operated by the German Institut für Hochfrequenzphysik und Radartechnik (FhG-FHR), and EISCAT (European Incoherent Scatter Scientific Association). Passive optical monitoring can be done with the optical Space Debris Telescope (ESA) at the Teide observatory on Teneriffe. The company EOS Technologies is using optical observation methods, too, by working on the development of techniques based on active illumination [7].

The subject of „debris monitoring“ will be picked up at the Institute of Technical Physics (DLR-TP) using laser based observation methods in the future. These methods promise an enhancement of the detection accuracy as well as detection efficiency. Both aspects are of great importance, since the debris objects in lower LEO orbit are slowed down by atmospheric friction. Thus, their orbital parameters change continuously, which necessitates so called follow-up measurements, which in particular benefit from an increased effectiveness of debris observations.

3. CONCEPTUAL DETAILS OF LASER BASED DEBRIS MONITORING

3.1. Introduction

In the field of space debris monitoring, up to now mainly angular information on the debris position is used in order to deduce its position and therefrom the orbital parameters. These orbit data are organized in catalogues, which consists of so called “two line elements” (TLE). This standardised format contains (besides the object number and other administrative entries) information on inclination, right ascension of the ascending node (RAAN), and eccentricity. Hence, the position of the object at a given point in time can be calculated based on these entries. However, since the drag of the earth atmosphere on the debris influences the orbital parameters, so called follow-up measurements are necessary in order to keep the catalogue up to date. As a consequence, known objects have to be re-monitored. Additionally, techniques which are solely based on goniometry need several round-trips of the debris object around earth in order to gain enough measuring data. Hence, these follow-up measures as well as monitoring of newly detected debris is quite time consuming and thus ties capabilities.

A lot of potential to enhance both the accuracy and effectiveness of debris monitoring lies in the detection of the debris distance in addition to angular measurements. This can be done by making use of the well established technique of laser ranging, which facilitates the ranging by using the time of flight of short laser pulses reflected by the target of interest.

3.2. Passive Detection of Space Debris

The passive optical detection of space debris relies on the reflection of solar irradiation from the debris objects itself. Examining the amount of detectable debris, the *MASTER* model provides debris density ρ as a function of altitude h, i.e. $\rho(h)$. Using an optical telescope for detection with a field of view of α = 1° defines an observation area in the shape of a cone, whose volume can be expressed as a function of altitude h, too:

(1) $$V(h) = \frac{1}{3} \cdot \pi \cdot h^3 \cdot \alpha^2 .$$

The quantity of the debris in the observed volume can be expressed by $N(h) = V(h) \cdot \rho(h)$, the total amount of debris in the ‘observation cone’ at a given point in time is

(2) $$N = \sum_{h=h_{min}}^{h_{max}} N(h) .$$

With typical LEO velocities of approximately 7 km/s, we define a time t which is necessary to transit the observed cone. In the case of α = 1°, the value of t is between 1 s (for h_{min} = 600 km) and 4 s (h_{max} = 1500 km). Using the *MASTER* model with a declination of 45° to 50° (southern Germany) and the given lower and upper bound for the observed volume yields a spatial density of debris objects ≥ 10 cm of about 10^{-7} km^{-3}. The described procedure for calculating the amount of detectable debris objects thus leads to an estimated average waiting period for detectable space debris of about 10 minutes.

Such a simplified approximation gives an impression of the estimated latencies of a passive optical monitoring system. When considering smaller debris objects of 1 cm in size the estimated holding times reduce to fractions of a minute due to the higher amount of small debris samples in orbit. Anyhow, it has to be pointed out that the given timescales only apply for constellations where the addressed ‘observation cone’ allows for solar irradiation of the debris objects.

As common in the field of detection of artificial orbiting objects, the observer has to distinguish them from natural celestial objects, such as stars and planets. This is commonly done by compensating the earth rotation by the use of the telescope. In doing so, natural celestial objects appear as dots, since their position on the telescope detector is kept constant. Besides meteoroids, artificial objects will leave a trace on the detector. This trace is firstly used to detect space debris at all, but additionally to obtain information used to implement fine tracking of the detected object. Such fine tracking is necessary to perform the mentioned laser ranging technique and will be treated in the following chapter.

3.3. Fine Tracking of Space Debris

In order to track the movement of the prior detected debris object, different strategies can be pursued. The easiest approach is making use of the reflected solar radiation, which can be fed to a quadrant detector to monitor the angular position of the target. Together with the attitude of the telescope, one dataset for the given debris sample can then be recorded. However, if it is planned to use a laser ranging technique which necessitates the illumination of the debris in any case, it is self-evident to make use of the reflected laser radiation for the fine tracking as well. Since the angular position of the object is roughly known from the passive detection described above, the pulsed laser beam can be pointed onto it. The round-trip time of the photons for the upper bound of the LEO space debris distribution (1500 km, c.f. Figure 2) is approximately 10 ms, which means that debris objects travel about 70 meters within this period of time. Hence, the pointing and tracking of both telescopes for transmitting and receiving of light have to take this into account.

Fine tracking of space debris imposes tight restrictions on the used optical telescopes and the telescope mounting, which mainly result from the large distance and the high velocities of the objects. By detecting a previously unknown debris particle, the acceleration of the tracking telescopes has to be in the order of 10 °s^{-2} with fine tracking accuracy on the order of 1 µrad.

In addition to the detection and fine tracking of newly discovered space debris, catalogued objects can be re-monitored in order to render precise orbital parameters. Such procedure is referred to as *follow-up measurement*. Here, angular coordinates which have to be expected for a particular object are approached in advance in order to perform an additional monitoring. The up to here described finding and fine tracking is followed by a laser ranging procedure, which will be treated in the next section.

3.4. Laser Ranging of Space Debris

Pulsed lasers can be used for distance measurements within the earth orbit and beyond by time of flight (ToF) measurements, i.e. *laser ranging*. In first applications, the range of retroreflectors on the moon which were placed during the Apollo 11 mission, were monitored [8]. Since such technique is based on the time of flight measurement of reflected laser pulses, the spatial resolution benefits inherently from shorter pulses. Thus, in the past 40 years, the precision of this technique improved over several orders of magnitude. To achieve a resolution on the order of millimeters, the statistics of returned photons is used to distinguish between leading and trailing edges of pulses of picosecond pulses.

However, the well explored techniques of lunar laser ranging as well as satellite laser ranging deal with retro reflector equipped targets where the relatively large amount of backscattering can be evaluated in order to achieve the necessary resolution in the millimetre range. In the field of debris laser ranging, such high resolution is not required for the first instance. Here, the main challenge is the uncooperative nature of the targets, i.e. the space debris.

For large distances of space debris, i.e. small angles of emitted light rays, the received power can generally be expressed by the following equation:

(3) $$P_{rec} = P_{trans} \cdot \frac{\Theta_{trans}^{deb}}{\Theta_{trans}^{tot}} \cdot \frac{\Theta_{refl}^{tel}}{\Theta_{refl}^{tot}} \cdot \mathrm{T}\ .$$

Here, the transmitted power P_{trans} is multiplied by the solid angle of the transmitted light hitting the debris object (Θ_{trans}^{deb}) divided by the total transmission angle. Furthermore, the ratio of the solid angle of reflected light which enters the detection telescope, Θ_{refl}^{tel}, and the overall reflection angle Θ_{refl}^{tot}, respectively, is necessary to consider the detected amount of reflected photons. The parameter T contains the total transmission characteristics at the chosen wavelength, including losses in the transmission telescope as well as those due to the debris reflectivity. By assuming a distance R of a debris object, formula (3) can be rewritten as

(4) $$P_{rec} = P_{trans} \cdot R^{-4}\ \frac{A_{deb}}{\Theta_{trans}^{tot}} \cdot \frac{\frac{\pi}{4} \cdot D_{tel}^2}{\Theta_{refl}^{tot}} \cdot \mathrm{T}\ .$$

As can be seen, the received power depends linearly on the debris surface A_{deb}, but quadratically on the diameter D_{tel} of the receiving telescope, i.e. the aperture of the telescope. Additionally, the known R^{-4} dependency is clearly visible.

The pulse energy of the ranging laser which is necessary to receive a signal well above the noise level of the detector can be estimated by using equation (4) by assuming a pulse length of 10 ns. The detection threshold was set to a signal to noise ratio (SNR) of 4, which translates into a received power of 4 nW. The transmission factor T is supposed to be 0.3 for this calculation. However, it has to be noted that the value of T strongly depends on weather conditions as well as on the particular reflectivity of the debris object under examination and the wavelengths of the laser (here: 532 nm). The value of Θ_{trans}^{tot}, which is the solid angle of the emitted laser pulses, includes both the beam quality of the laser (M^2) and the degrading effects of atmospheric turbulences. Since the latter can only be estimated, we evaluate the necessary pulse energy of the ranging laser as a function of the beam width (Figure 3). This evaluation is done for a 10 cm-sized debris object in a distance of R = 600 km. Hence, the value of Θ_{trans}^{tot} is calculated by the known relation $\Theta = 2\pi(1\text{-}\cos(\beta/2))$, with β being the half diameter of the cone divided by the distance.

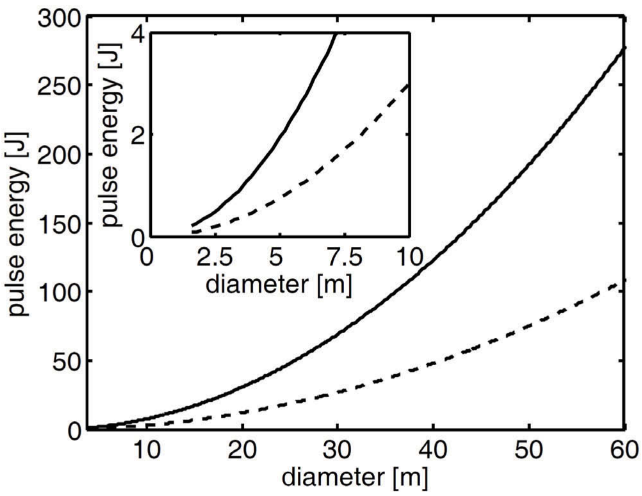

Figure 3: Pulse energy of the ranging laser which is necessary to obtain a SNR of 4 as a function of the diameter of the light cone at a distance of 600 km. The dependencies for two detection telescopes are plotted (solid line: 25 inch, dashed line: 40 inch). The inset shows the necessary pulse energy for the diameter approaching the diffraction limit of the transmitting telescope.

Figure 3 shows the necessary pulse energy of the ranging laser to achieve a SNR of 4 as a function of the diameter of the light cone at the debris distance. The aperture of the transmitting telescope was assumed to be 20 inch, which results to a diffraction limited diameter of approximately 1.6 m (for top hat profile at the transmitting telescope and at R = 600 km distance). The situation for two different receiving telescopes is analysed (solid line: 25 inch, dashed line: 40 inch). It has to be pointed out, that the diameter of 60 m represents a laser with a M^2 of 37 by neglecting any atmospheric turbulence. Hence, the estimation leaves room for atmospheric turbulences, which might distort an initially better beam quality to such values. As can be seen in the figure, the necessary pulse energy of the ranging laser increases dramatically with increasing cone diameter (i.e. increasing beam divergence). Thus, by this analysis it can be deduced that a small beam divergence of the ranging laser with pulse energies in the Joule-range is mandatory to achieve a detectable amount of reflected photons. Additionally, good atmospheric conditions are desirable in order to preserve a small diameter of the light cone and thus high photon densities at the debris object. The inset shows the necessary pulse energy for the cone diameter approaching the diffraction limit of the transmitting telescope, which is approximately 1.6 m. The necessary pulse energy for this case is 0.2 J for the 25'' telescope and 0.08 J for the 40'' telescope, respectively. These pulse energies are far below the threshold for nonlinear effects which will occur at approximately 1 kJ pulse energy.

Since the aperture of the receiving telescope appears squared in equation (4), the requirements on the laser can be in general reduced by increasing the diameter of the telescope. However, the mentioned demands on agility impose a trade-off between acceleration, mechanical stability, pointing and tracking accuracy on the one hand and size on the other hand.

For the fine tracking mentioned in section 3.3 as well as for the laser ranging procedure discussed here a high spatial resolution is preferable. As argued above, the diameter of the illumination cone should be as small as possible to receive a large detection signal. Due to the high velocity of the debris objects, a high repetition rate of the laser is necessary to receive enough data required for fine tracking. Additionally, the claimed enhancement of accuracy and efficiency of space debris monitoring by the combination of passive optical detection, fine tracking and laser ranging is enabled by a repetition rate of the laser on the order of 1 kHz.

4. SUMMARY

To tackle the threat of space missions by space debris, the Institute of Technical Physics of the German Aerospace Center (DLR) has developed a concept for laser-based monitoring of these objects. This concept relies on

1. passive optical detection of space debris,

2. fine tracking of these objects,

3. and laser ranging to achieve distance information.

Whereas for all of these three steps the general technical approach can be more or less adapted from other methods (e.g. satellite laser ranging, optical free space communication), the fact that the monitoring system has to react *instantaneously* on appearing debris objects as well as their uncooperative nature imposes specific requirements, which have to be considered in the development. Namely, these requirements are high accelerations of the tracking telescopes of approximately 10 $°s^{-2}$ to acquire and follow the object with fine tracking accuracy on the order of 1 µrad and a sophisticated pulsed laser system (pulse energy ~ 1 J, repetition rate ~ 1 kHz). In order to perform fine tracking and laser ranging, all relevant components have to be harmonised to be able to detect backscattering from the debris, which enables the time of flight measurement. Since the telescope aperture size is limited by manageability and the detector sensitivity by commercial availability, the characteristics of the pulse laser (beam quality and pulse energy) is of crucial importance for the functionality of a space debris monitoring system. Accordingly, parallel to the development and integration of other parts of the system, a suitable pulsed disk laser will be developed at DLR-TP, which delivers pulses in the range of several Joules with a repetition rate of ~1 kHz at a good beam quality (M^2 < 3).

Monitoring of space debris by making use of laser ranging is a promising approach to increase the accuracy and the amount of catalogued entries. In principle, the longitudinal resolution is in the order of the pulse width (here: $c \cdot 10$ ns ≈ 3 m), but can be improved by using information of the particular pulse shape. In addition to high precision angular data obtained by fine tracking, the range can be used in order to supplement known sets of two line elements and to effectively establish European catalogues of orbital data of space debris objects.

5. LITERATURE

[1] “Space debris - Frequently asked questions”, prepared by the ESA Space Debris Office team, http://www.esa.int/esaMI/Space_Debris/SEM2D7WX3RF_0.html, visited on Oct., 26th, 2009

[2] “Update on Three Major Debris Clouds”, Orbital Debris Quarterly News, NASA, **14** (2), 2010

[3] C. Covault, “Chinese Test Anti-Satellite Weapon,” Aviation Week & Space Technology, http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=space&id=news/CHI01177.xml, online post on Jan. 17, 2007 (first public report of China’s ASAT test);

[4] F. Morring, Jr., “China Asat Test Called Worst Single Debris Event Ever”, Aviation Week & Space Technology, http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=space&id=news/aw021207p2.xml, visited on May, 10th, 2010

[5] D. J. Kessler and B. G. Cour-Palais, “Collision Frequency of Artificial Satellites: The Creation of a Debris Belt”, Journal of Geophysical Research, **83** (A6), 1978

[6] H. Klinkrad, J. Alarcón, and N. Sánchez, “Operational Collision Avoidance with Regard to Catalog Objects”, chapter in: “Space Debris – Models and Risk Analysis” by H. Klinkrad, ISBN 3-540-25448-x, Springer 2006

[7] B. Greene, ”Laser Tracking of Space Debris”, Proceedings of the 13th International Workshop on Laser

Ranging, 2002
[8] A. L. Hammond, “Laser Ranging: Measuring the Moon's Distance”, Science, **170** (3964), 1970