SPACE-BASED OPTICAL OBSERVATIONS OF SPACE DEBRIS

T. Flohrer(1), J. Peltonen(2), A. Kramer(3), T. Eronen(2), J. Kuusela(2), E. Riihonen(2), T. Schildknecht(1), E. Stöveken(1), E. Valtonen(2), F. Wokke(3), and W. Flury(4)

(1) Astronomical Institute University of Bern (AIUB), Bern, Switzerland, Email: tim.flohrer@aiub.unibe.ch
(2) Aboa Space Research Oy (ASRO), Turku, Finland, Email: juhani.peltonen@asro-space.com
(3) National Aerospace Laboratory (NLR), the Netherlands, Email: kramer@nlr.nl
(4) ESA/ESOC, Email: walter.flury@esa.int

ABSTRACT

Currently, observations of space debris are mainly performed with ground-based sensors. These sensors have a detection limit at some centimetres diameter for objects in Low Earth Orbit (LEO) and at about 2 decimetres diameter for objects in Geostationary Earth Orbit (GEO). The few space-based debris observations stem mainly from in-situ measurements and from the analysis of returned spacecraft surfaces. Both provide mainly information about sub-millimetre-sized debris particles. As a consequence the population of centimetre- and millimetre-sized debris objects remains poorly understood.

The development, validation, and improvement of debris reference models drive the need for measurements covering the whole diameter range. In 2003 ESA initiated a study entitled „Space-Based Optical Observation of Space Debris“, which was awarded to a team led by Aboa Space Research, Finland (ASRO). Besides ASRO, the Astronomical Institute of the University of Bern, Switzerland (AIUB) and the Dutch National Aerospace Laboratory (NLR) participate in this still ongoing study.

The goals of the study are to define the requirements and to develop the observation strategy for a space-based instrument capable of observing uncatalogued millimetre-sized debris objects. A system architecture is to be proposed fulfilling the requirements and appropriate for the selected observation strategy. The performance and cost of the designed instrument shall be estimated.

Only passive optical observations are considered within this study. Three mission concepts are studied, each concept focusing either on LEO, GEO or GTO (Geostationary Transfer Orbit). Cost-efficient solutions are considered important. Ideally, the proposed solutions shall be capable of determining a full set of orbital parameters for unknown objects.

In this paper we summarise the results of the completed study phase 1. Starting with a brief review of debris characteristics, the developed user requirements are summarised. We present promising observation concepts and outline the data processing steps. Options for the instrumentation covering telescope and camera design, as well as options for the onboard processing electronics and the platform are discussed and the main trade-offs are outlined. A short summary on the practical experience gained using ESA's PROOF tool (Program for Radar and Optical Observation Forecasting) for space-based applications is given.

1. INTRODUCTION

Today, the observation of space debris objects is limited to some centimetres in LEO and approximately 20 cm in GEO using ground-based techniques. The population of smaller objects (centimetre- and millimetre-sized) cannot be assessed from the ground, disregarding the few in-situ measurements and sample return analysis. Consequently, the population of centimetre- and millimetre-sized debris objects are poorly understood. Nevertheless, this population is of a great interest, as such small space debris objects can cause significant damages to active satellites. An improved knowledge of this population will furthermore provide valuable inputs to the validation and upgrade of space debris environment models.

In order to develop and improve debris reference models that include centimetre- and millimetre-sized debris objects, observations are needed that allow assessment of the size and spatial distribution. In this context, ESA initiated in 2003 a study entitled „Space-Based Optical Observation of Space Debris“, which was awarded to a team led by Aboa Space Research, Finland (ASRO). The Astronomical Institute of the University of Bern, Switzerland (AIUB) and the Dutch National Aerospace Laboratory (NLR) participate in this still ongoing study. Phase 1 of the study was completed in mid-2004. The study is expected to be completed in September 2005 with the issue of a final report.

The objectives of the study are to define the requirements and to develop the observation strategy for a space-based instrument capable of observing uncatalogued millimetre-sized debris objects. A system architecture is to be proposed fulfilling the requirements and being appropriate for the selected observation strategy. The performance and costs of the designed instrument shall be estimated. In the scope of this study, only passive optical observations are considered. In phase 1 of the project, three mission concepts were studied independently. Each of the mission concepts focuses on a special orbital region: LEO, GEO or GTO. Earlier studies already showed that passive optical observation from a space-based platform can in principle fulfil the required tasks by using a relatively small aperture telescope (Krag, 2003), (Oswald et al., 2004), (Lobb et al., 1993). With the US sensor "Space-Based Visible", there is already a running mission that is dedicated to space surveillance (Gaposchkin et al., 2000).

In this paper we will first summarise the characteristics of the millimetre-sized space debris population. This assessment was carried out using the ESA MASTER-2001 model. In Section 3, we will present the main user requirements that were formulated according to the space debris characteristics for the three considered mission concepts. The most promising observation concepts and processing strategies are introduced in Section 4 and the instrumentation options are outlined in Section 5. The instrumentation includes the telescope, camera, and onboard processor and the required onboard data processing software. The results of the instrument trade-off study are presented in Section 6. Finally, some short remarks regarding the experiences with the use of PROOF-2001 for space-based applications are given in Section 7. The conclusions in Section 8 give an outlook into the next project steps.

2. SPACE DEBRIS CHARACTERISTICS

There are three "obviously" prominent regions where we can suspect that small (millimetre)-sized debris are present: the LEO, GEO, and GTO. We used the ESA MASTER model, version 2001 (Bendisch et al., 2004) to analyse the spatial density of the debris objects.

Fig. 1 shows that the densest area is the LEO region. The peaks for the GEO region and (less prominent) the semi-synchronous orbits can be identified. The most promising regions for the search of small-sized debris are the LEO and GEO region.

From the observation point of view, the passive optical detection of millimetre-sized debris depends mainly on the objects' brightness and the objects' relative velocity at the detector. Hence, the optical space-based observation of faint debris objects has to search for objects at short ranges, but shall favour slowly crossing characteristics. In general only a small sample of debris objects can be observed. The observation strategy has to minimise selection effects (e.g. unrecognised multiple observations of the same object or uncovering spatial regions).

Let us look at the angular velocities of objects crossing the field of view (FOV). Estimations showed that GEO objects will cross the FOV of an instrument 1000 km below the GEO with an angular velocity typically slower than 72 "/s. In this case, a 10 mm spherical, Lambert-scattering object with a geometric albedo of 0.1 that is located in the GEO and illuminated optimally, would be observable with up to 16.5 mag brightness. On the other hand, LEO objects cross the FOV of a LEO-based satellite with a wider velocity range. If we take 2°/s as an average value, a 10 mm LEO object would be observable with brightness between 12 and 14.5 mag, depending on the observation range, and with the same assumptions as before.

With this understanding of the space debris population, we can now continue with the presentation of the main user requirements. For the user requirements definition, we consider a debris researcher as a 'user', not a spacecraft designer or operator.

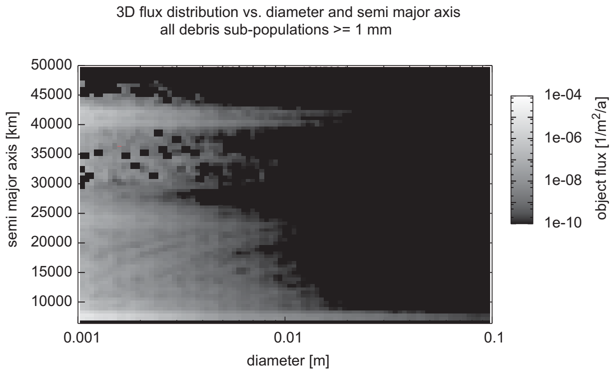

Figure 1. Debris object flux per year vs. semi major axis and diameter. Object flux cut at 1e-10 [1/m^2/a].

3. USER REQUIREMENTS REVIEW

The user requirements are grouped into system level requirements that apply to all orbital regimes (GEO, LEO and GTO), and into specific user requirements for each of the orbital regimes. The system level requirements are obtained from the study specification. The specific requirements cover the image acquisition approach and the outline of instrumental parameters of the system.

3.1. System level user requirements

The space based optical system shall be able to detect space debris in GEO, LEO, and GTO regions using passive optical observations. At least a basic statistical description of the small-sized debris orbits shall be possible. As a minimum set of statistical information, four orbital elements per object (analogues to the distance and the vector of the relative velocity) must be determined. The determination of a full set of orbital parameters is desirable, which requires three or more independent observations of the debris object.

The system shall be able to detect millimetre-sized debris objects originating from all possible debris sources and be capable of determining orbital parameters from a single passing event. The system is not required to acquire follow-up observations of faint debris objects. The reacquisition of very faint objects is not possible, as the required orbit accuracy for allowing reacquisition after several days or weeks (a typical period) cannot be achieved from the orbit determination based on observations of one crossing event.

The operator shall have the possibility to define the data acquisition strategy, namely to define and uplink observation plans. To save mission costs, the data processing onboard will be limited, and incorporates object detection and particle-hit event filtering. The on-ground processing of the observation data will require the downlink of the subframes containing the identified reference stars and space debris trails, and the assigned epochs. This shall allow the objects centroiding and brightness measurements as well as the astrometric reduction and orbit determination on ground.

Finally, the debris objects diameter shall be estimated from the objects' brightness and the observation range at the observation epoch. The observation range is obtained from the instrument and debris object orbits. For the estimation of the debris objects' diameter, additional assumptions about the debris objects shape and surface properties are unavoidable.

3.2. User requirements for GEO observations

The spatial coverage from GEO-based observations shall consider all debris objects in the "GEO-ring". Here, we defined this ring by all objects orbiting the Earth with a semi major axis of 42168 km+/-1000 km and an inclination <17°. The image acquisition shall be traceable to UTC with accuracy better than 10 ms to allow sufficient orbit determination, as orbit determination simulations showed.

A large pixel scale (PS) is necessary, resulting from the desired wide FOV together with the onboard processing capabilities allowing only a limited number of pixels. It was found that the background signal accumulation (reducing the signal to noise ratio (SNR)) and the orbit determination would allow a PS of up to 10 "/pixel. The point spread function full width half maximum (FWHM) shall have a diameter of about 1 pixel.

A detector with high quantum efficiency and low noise shall be used. The number of pixels shall be preferably 2048*2048 pixels. Ideally, the system shall not have a gap time due to processing issues except due to detector readout. This defines implicitly the number of exposures that should be processed during operation: all objects (debris objects and reference stars) should be detected before the next exposure is available. This allows distinguishing between stars and objects based on the combination of subsequent exposures. To allow astrometric reduction, a low number of well-distributed reference stars shall be identified in the combination. As a consequence of SNR estimations, the exposure time must be selected close to the single pixel crossing time of typical debris objects.

3.3. User requirements for LEO observations

In principle, all debris objects in the LEO-region shall be considered. The observations shall focus on an altitude region between 700 km and 1500 km. Most of the GEO requirements apply for the LEO region as well.

Compared to the GEO case the required epoch registration accuracy is more demanding: The image acquisition shall be traceable to UTC with an accuracy better than 1 ms.

As a main consequence of the fast FOV-crossing, only one exposure will be available to extract the necessary information. The processing shall thus allow distinguishing between stars and objects based on a single passing event. The orbit determination requires that several time tags are applied to the exposure.

3.4. User requirements for GTO observations

The GTO requirements are not presented here, as it was decided during the mid-term review of the project, not to study the GTO further. In GTO, the radiation environment was found to be a serious issue. One concern is the radiation tolerance of the detector and the electronic components. An even more difficult problem arises from the large number of particle hits in the detector elements, which will make the detection of faint objects in the images impossible for a major part of the orbit.

4. SELECTED OBSERVATION CONCEPTS

For the mission goal "detection of millimetre-sized debris" a relatively large aperture (and therefore heavy) instrument would be needed. The main difficulties will result from the limited FOV dwell times of crossing objects, from the limited onboard processing capacity (limiting pixel scale and FOV diameter), and from the sky background signal limiting the exposure time.

For the observation of the debris objects in the GEO region, a subGEO orbit (a circular low inclination orbit below the GEO) was selected, as this orbital scenario allows the coverage of the whole GEO ring over a reasonable scanning time, and guarantees acceptable observation ranges to the debris objects as well as valid illumination conditions at least for 12 h per day.

The GEO system shall be optimised to detect debris objects crossing the FOV with an angular velocity up to 0.02°/s. The system should also take faster crossing objects into account. Analytical estimations showed that a 20 cm aperture instrument should be capable of detecting objects down to 16.5 mag for a sky background of 21.5 mag (Fig. 2).

The LEO region should be observed from a sun-synchronous orbit close to the terminator plane with the altitude in the region with the expected highest object density. This guarantees 24 h per day of observation time and a high number of debris objects crossing the FOV at close ranges. Two possible solutions were analysed: a circular LEO and a slightly elliptical LEO. The latter allows covering a larger altitude region but leads to a lower crossing rate.

A fixed pointing strategy, either fixed away from the Sun or fixed away from the Earth, was found to be sufficient for the observation of faint space debris objects. Active pointing strategies need a priori information of crossing directions and velocities, which is not available for the unknown population of small sized debris.

The system shall be optimised to detect debris objects crossing the FOV with an angular velocity up to 2 °/s, but should also take faster crossing objects into account. Analytical estimations for a 20 cm instrument showed detection capabilities down to 14.5 mag for a sky background of 21.5 mag (Fig. 3). The observation ranges for the faint debris objects in LEO are typically up to 500 km, compared to 2000 km in GEO.

In the GEO region the image acquisition is proposed to follow a dynamical masking approach. Consecutive exposures shall be acquired with short exposure time. The exposure time shall be selected close to the single pixel crossing time of typical objects.

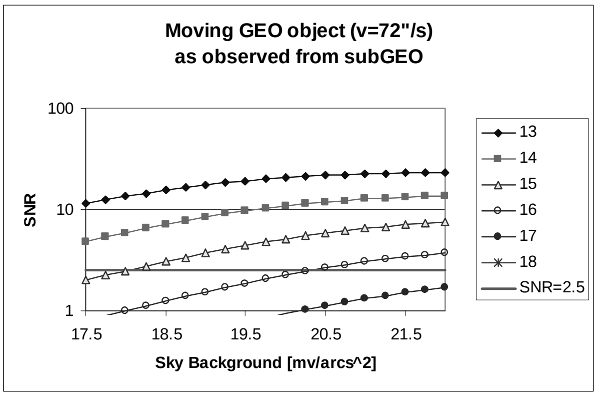

Figure 2. SNR vs. background brightness for various object magnitudes, assuming the proposed 20 cm instrument in subGEO, exposure time 0.15 s.

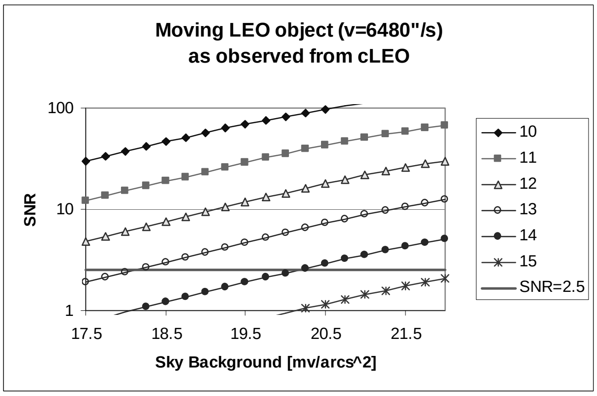

Figure 3. SNR vs. background brightness for various object magnitudes, assuming the proposed 20 cm instrument in LEO, exposure time 0.5 s.

In the LEO region the very high angular velocities of debris objects crossing the field of view do not match with the GEO image acquisition approach, as the acquisition of a series of exposures cannot be guaranteed. The image acquisition strategy in the LEO region requires the application of very accurate time stamps to a single fast crossing event. Using CCDs, applying image shifts of a few pixels in the detector can do this, while the very fast readout allows accurate epoch registration if using HyViSI (Hybrid Visible Silicon Imager) technology. The exposure time should be longer than the single pixel crossing time to allow for several position measurements within a single exposure.

It was found that it is not possible to develop a generic strategy of observation, image acquisition and processing, which is efficient in both orbital regions. Consequently, GEO and LEO observations are acquired in a different manner. However, the use of the same instrumentation seems possible.

5. INSTRUMENTATION OPTIONS

In this section we will present selected options that fulfil the user requirements best.

5.1. Telescope

The telescope shall either follow the Schmidt design or the Three Mirror design. The aperture diameter shall be 20 cm. The Three Mirror Design requires less effort to reduce the straylight, but will not be able to provide an optimal f-number. Thus, a folded Schmidt design with a folding angle of 45° without reimaging is preferred. A mechanical cover is needed to avoid camera damage in case of pointing to the Sun, to avoid contamination of the optics, and for camera calibration.

The limited practical experience with folded Schmidt design operating in space missions must be considered as a risk. The Schmidt design requires the use of a baffle. The possibly needed design of an achromatic corrector for the Schmidt design is demanding. Care must be taken while designing the telescope to fulfil the thermal requirements. These problems are understood to be solvable.

5.2. Camera

It is proposed that the camera system will be based either on the hybrid HyViSI detector or on the more traditional frame transfer CCDs. HyViSi solves part of the difficulties in the image acquisition process with CCDs: due to the readout time limitations the fast objects in LEO can not be acquired with CCDs. In GEO the pixel illumination and background accumulation times can be chosen more freely with HyViSi. Other improvements are possible using HyViSI detectors: no blooming, higher radiation tolerance, lower power consumption and heat generation.

However, the HyViSI detectors are a new technology. There is only little information available about practical experience in using this type of detectors for space-based applications. The reduced linearity compared to CCDs will require the development of new calibration strategies. Using HyViSI detectors in the LEO region is not without problems in terms of the necessary cooling effort (passive cooling below -60°C).

5.3. Onboard processing subsystem

The processing unit should consist of two parts, an autonomous camera subsystem and an analysis unit subsystem.

The driving factor is the onboard processing power, as the image processing has to be partly performed onboard in order to limit the data downlink.

It is concluded from the estimation of required computing power that an upper low-end (<150 MIPS) processor design fulfils the needs. It is expected that a reasonable amount of work will be required for the software development. The development of sophisticated onboard processing algorithms involves high costs as well as long development and validation times.

A radiation-hardened version of the LEON processor is preferred and a relatively large-sized RAM is needed (few hundreds of MB), while the size of the ROM is not an issue (32 MB). Extra memory (25 MB in LEO scenario) is needed to ensure uninterrupted operation of the satellite during ground coverage gaps. The radiation tolerance of RAM modules needs to be confirmed and the risk of single-event upsets (SEUs) needs to be determined.

5.4. Instrument operation and data processing

After the object detection onboard, the pixels of the object trail, the reference star pixels, and the neighbourhoods of all (swaths) will be sent to ground for further analysis. The preferred object detection algorithm uses the masking technique (Schildknecht et al., 1995) together with spatial filtering applied to a series of recent exposures. This dynamical masking is preferred against a tabulated masking, which uses pre-calculated star masks, and preferred against the difference analysis algorithm used in the SBV (Harrison and Chow, 1996). Tabulated masking requires the upload of star masks once per revolution, which can become difficult in LEO, where the available upload time is about 10 minutes per revolution, and includes the mission control and observation plan upload. For all algorithms, the processing of observations, which result from pointing the instrument in the direction of the Milky Way or other regions with a high density of background stars, is expected to be impossible.

The object detection will require in total 70-85% of the onboard processing power. The total required processor power would be around 50 MIPS. The average telemetry rates are expected at 250 bps for the GEO and 7500 bps for LEO.

Considering these average telemetry rates, the LEO scenario imposes modest, but slightly more demanding than for GEO, requirements on the onboard data storage and downlink capabilities. The difference between LEO and GEO is directly related to the longer gaps in ground coverage and the higher number of detected objects expected for LEO.

From the radiation environment point of view, the circular LEO orbital scenario is preferred against the elliptical LEO orbital scenario. Shielding against particle-hit events should be provided (30 mm aluminium) and the instrument should make use of software functions for filtering, as simple pixel counting and pattern recognition techniques. The dynamical masking provides inherent advantages, too.

There are some issues of the data processing that need to be kept in mind:

- The limited epoch registration accuracy with HyViSI may lower the accuracy of the determined orbit or may only allow the determination of an incomplete set of orbital elements.
- The exposure time is limited by the background signal accumulating over the object signal. The faintest objects will thus not be detected by just extending the exposure time.
- The number of particle-hits is not constant throughout a revolution due to the changing radiation environment. The efficiency of particle event filtering is unclear.

6. INSTRUMENTATION OUTLINE

The combination of the above instrumentation options makes it possible to formulate a generic solution for the instrument:

- 20 cm aperture diameter (folded) Schmidt design telescope with 6° FOV, f/D=1.75,
- Pixel Scale ~10 ”/pixel,
- Single chip HyViSI detector, 2048*2048 pixels, 3.7*3.7 cm^2 focal plane area, 18 µm fixed pixel size, alternatively frame-transfer CCD,
- Processing unit consisting of two subsystems: autonomous camera subsystem and an analysis unit subsystem (main processor LEON, 50 MIPS), a few hundreds of MB RAM, 32 MB ROM, aluminium shielding.

The presented instrumentation options do, however, conflict with the previously presented user requirements at some points:

- The detection of millimetre-sized debris objects is in principle possible, but only rarely for the smallest objects (diameter<10 mm). The frequency of such smallest millimetre-size detections depends on the observation conditions, and the debris population density in the pointing direction and is thus not constant.

- The pixel scale shall be as small as possible to improve the orbit determination accuracy and to lower the background signal that in turn improves the SNR. This requires either a narrow FOV instrument, which lowers the number of crossing objects and therewith the total instrument performance, or requires increasing the number of pixels. A higher number of pixels in the detector conflicts with the available onboard processing power and the available focal plane area.
- The required epoch registration accuracy is relatively demanding. The application of precise timestamps to the exposures requires tailored image acquisition and data processing strategies for each orbital scenario.

7. USE OF PROOF IN THE PROJECT

The ESA PROOF tool (Krag et al., 2000) was used extensively for the strategy definition and performance evaluation. The experiences gained throughout the project showed that the tool is a powerful and helpful software. However, for future projects some improvements could be thought of: a more flexible output of data, more plug-in capabilities for user-controlled modules simulating the hardware as well as the detection algorithm, and more flexible instrument pointing definitions.

PROOF simulations carried out with the preliminary instrument definition showed that a 20 cm aperture, 6° FOV instrument operating in a circular orbit 1000 km below the GEO may detect at least 120 objects within 24 h observation time, assuming a constant, phase angle optimal, pointing away from the Sun. The same instrument operating in a circular sun-synchronous LEO orbit close to the terminator at an altitude of 800 km may detect at least 700 objects within 24 h observation time, assuming the same pointing direction.

8. CONCLUSION

This paper summarises the results from the study phase 1 of the ESA study “Space-Based Optical Observation of Space Debris“ performed by ASRO, AIUB, and NLR.

Starting with a brief characterisation of the small-sized debris population, we formulated the basic user requirements for the passive, space-based optical observation of small-sized space debris. A moderate instrumentation concept is outlined, for which first estimations show the feasibility to fulfil the user requirements. Intermediate results have shown that GTO is not a suitable orbit for the optical observation of small-sized debris. A generic instrument for the two mission cases LEO and GEO is studied further. The development of a generic data processing strategy was found impossible. The image acquisition is proposed to follow a dynamical masking approach to allow the object detection onboard and the further processing on ground after the downlink of the object subframes. Special techniques allow the application of precise timestamps to the exposures in the LEO case.

Currently, phase 2 of the study is ongoing. The main tasks cover the detailed system architecture concept and the performance estimation. The detection algorithm performance will be studied and after that the performance of the entire system will be estimated using the ESA PROOF tool. Phase 2 is scheduled to finish in September 2005.

9. REFERENCES

Bendisch, J., Bunte, K., Klinkrad, H., et al. The MASTER-2001 model, *Adv. Space Res.*, Vol. 34(5), 959-968, 2004.

Gaposchkin, E. M., von Braun, C., and Sharma, J., Space-Based Space Surveillance with the Space-Based Visible, *Journal of Guidance, Control and Dynamics*, Vol. 23(1), 148-152, 2000.

Harrison, D. C. and Chow, J. C., The Space-Based Visible Sensor, *John Hopkins APL Technical Digest*, Vol. 17(2), 226-236, 1996.

Krag, H., Beltrami-Karlezi, P., Bendisch, J., et al. PROOF - The extension of ESA's MASTER model to predict debris detections, *Acta Astronautica*, Vol. 47(2-9), 687-697, 2000.

Krag, H. *A Method for the Validation of Space Debris Models and for the Analysis and Planning of Radar and Optical Surveys*, Shaker, Aachen, Germany, 2003.

Lobb, D. R., Dick, J. S. B., and Green, S. F., Development of concepts for detection and characterisation of debris in Earth orbit using passive optical instruments, *Adv. Space Res.*, Vol. 13(8), 59-63, 1993.

Oswald, M., Krag, H., Wegener, P., and Bischof, B., Concept for an Orbital Telescope Observing the Debris Environment in GEO, *Adv. Space Res.*, Vol. 34(5), 1155-1159, 2004.

Schildknecht, T., Hugentobler, U., and Verdun, A., Algorithms for ground based optical detection of space debris, *Adv. Space Res.*, Vol. 16(11), 47-50, 1995.