Publication Year	2018
Acceptance in OA@INAF	2021-01-04T16:26:55Z
Title	Lighthouse: A spacebased mission concept for the surveillance of geosynchronous space debris from low earth orbit
Authors	Lupo, Roberto; Albanese, Carlo; Bettinelli, Daniele; Brancati, Marco; Minei, Giovanni; et al.
DOI	10.1016/j.asr.2018.03.005
Handle	http://hdl.handle.net/20.500.12386/29461
Journal	ADVANCES IN SPACE RESEARCH
Number	62

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 62 (2018) 3305–3317

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Lighthouse: A spacebased mission concept for the surveillance of geosynchronous space debris from low earth orbit

Roberto Lupo [a,*], Carlo Albanese [a], Daniele Bettinelli [a], Marco Brancati [a], Giovanni Minei [a], Claudio Pernechele [b]

[a] *Telespazio, Via Tiburtina 965, 00156 Rome, Italy*
[b] *INAF-National Institute for Astrophysics, Vicolo dell'Osservatorio, 535122 Padova, Italy*

Received 28 June 2017; received in revised form 20 December 2017; accepted 3 March 2018
Available online 11 March 2018

Abstract

In this paper, a new mission is proposed for space debris surveillance in geosynchronous orbit (GEO). The mission "Lighthouse", here proposed as a concept study, describes the use of a small satellite in a low polar orbit, equipped with a Schmidt telescope, constantly observing a belt across the geostationary orbit. In this way, a single instrument can sweep the whole orbit everyday regardless the light and weather conditions. Most of observations are nowadays performed by ground telescopes, which are affected by weather conditions and night time duration. Moreover, a single telescope can observe only a portion of the geostationary orbit. The mission concept arose as space application of an ESA ITI (Innovation Triangle Initiative) project designing a Schmidt telescope purposely conceived for the monitoring of NEO (Near Earth Objects) and space debris. A compact version of the telescope (50 cm diameter and 1.61 m length), particularly suitable for space applications, has been designed too. The size and the mass of the telescope enable the use of a small satellite platform, with the related advantages in term of costs and performance. Lighthouse is proposed as a new asset for Space Surveillance and Tracking sensors, complementary to the ground telescopes network.

Keywords: Space debris; Small satellites; Telescope; Spacebased; Space surveillance and tracking; Geostationary orbit; Continuous observation

1. Introduction

Space junk is nowadays one of the main threats to satellite systems, on which we depend for a multitude of essential services: from meteorology to the global transport of goods and passengers. It is estimated that more than 750 000 (7th European Conference on Space Debris, ESA, 2017, https://conference.sdo.esoc.esa.int) dangerous debris objects bigger than 1 cm are running in Earth orbit and have the potential to damage or destroy operational satellites. For many missions, the risk of losing a spacecraft through the impact of space debris is the third highest risk, after the risks related to the launch and deployment phases.

The most exploited orbits are the most polluted too. Consequently, the LEOs (Low Earth Orbits) and the geostationary (GEO) are particularly populated by space debris (IADC, 2002). The first step to deal with such threat is to know the threat itself, observing the characteristics of the space debris population, like spatial density, size, speed, material, etc. The Interagency Space Debris Coordination Committee (IADC, 2013) also reports how the objects in the GEO region are much less numerous than in LEO and reside in about seven times the volume of LEO, but this unique regime is the home to more than 400 opera-

---

* Corresponding author.
E-mail addresses: roberto.lupo@leonardocompany.com, roberto.lupo@telespazio.com (R. Lupo), carlo.albanese@telespazio.com (C. Albanese), daniele.bettinelli@telespazio.com (D. Bettinelli), marco.brancati@telespazio.com (M. Brancati), giovanni.minei@telespazio.com (G. Minei), claudio.pernechele@inaf.it (C. Pernechele).

https://doi.org/10.1016/j.asr.2018.03.005
0273-1177/

tional communications and other spacecraft which serve vital purposes for all countries of the world (i.e. civil and military communications, meteo satellites, etc.). The current number of estimated objects as small as 10 cm in or near the GEO region is on the order of 3.000.

Sensors are the first element of a Space Surveillance and Tracking (SST) system, aimed at detecting and predicting the movement of space debris in orbit around the Earth. Nowadays technological limits allow us to detect objects larger than 1 cm for LEO and 20/30 cm for GEO (Rossi, 2005). Radar sensors can be employed for lower orbits, together with laser sensors for precise tracking. However, optical sensors are the only ones capable to observe space objects from above 1000 km up to GEO. Sensors are mostly groundbased, but some mission studies are under development. An integrated use of both groundbased and spacebased is predictable for the next years (Flohrer et al., 2005; Escorial Olmos et al., 2013; Chen & Xiong, 2017), also because of the different observation conditions from space and ground (i.e. daytime, cloud coverage, atmospheric effects). Since spacebased observations are more complex because of many aspects – first the relative motion of target and observer –missions shall be designed considering both observation orbits and target orbits.

In this paper, a mission concept is proposed, specifically designed for monitoring GEO objects from a LEO position (LEO_to_GEO) with possibly lower complexity and costs than other solutions. A novel orbital and attitude configuration, purposely conceived, enables the monitoring of the complete geostationary orbit by means of a single instrument. The relatively simple configuration here proposed also reduces complexity of the sensor and the spacecraft.

It should be remarked that, though several spacebased missions for debris monitoring have been proposed so far, they usually envisage the use of complex satellites and/or of constellations. For example, the general characteristics of subGEO_to_GEO and LEO_to_LEO missions are discussed in Flohrer et al. (2005). An assessment of GEO_to_GEO optical observations, making use of typical cameras already implemented on-board of GEO satellites (e.g. star trackers) is reported in Shell (2010).

On the contrary, LEO_to_GEO mission concepts are rarely explored. Some missions currently under development make use of spacecrafts hosted in LEO, capable to collect data about several space regions, in particular up to GEO, but not purposely conceived for a specific surveillance of GEO debris. For instance, the SBSS (Space-Based Surveillance System – https://directory.eoportal.org/web/eoportal/satellite-missions/s/sbss) program is a planned constellation of LEO satellites for tracking space objects according to the needs of U.S. DoD (Department of Defense). A Canadian space mission called Sapphire (https://directory.eoportal.org/web/eoportal/satellite-missions/s/sapphire-space-surveillance) has been also designed for the monitoring of space debris from LEO as part of the Canadian Space Surveillance System (CSSS) and to contribute to the United States (US) Space Surveillance Network (SSN).

These missions are not specifically dedicated to GEO debris surveillance activity, as Lighthouse, and make use of other types of orbit (e.g. sun-synchronous), asset configuration and on-board sensors than Lighthouse. A discussion of the Lighthouse characteristics compared with other spacecraft/sensors is provided in the "Results" section.

2. Lighthouse mission overview

"Lighthouse" is a proof of concept involving a spacebased sensor on a small satellite, orbiting in low earth orbit, and looking towards the geostationary region (LEO_to_GEO). Thus, interesting advantages can rise by using a specific sideview configuration. The spacecraft flies along a perfectly polar orbit, (inclination = 90°) that means orthogonal to the equatorial plane and thus to the geostationary orbit.

The sensor is "sidelooking" oriented: the beam sensor lies in a plane orthogonal to the LEO orbit plane, with an inclination of ~81° from Nadir (Fig. 1). The inclination of the orbit and the direction of the beam allow the sensor to constantly scan the complete geostationary orbit with a field of view (FoV) of 5.6° × 5.6°, with no influence from atmosphere, weather and day/night time.

In ECI (Earth Centred Inertial) coordinate frame, the sensor will orbit around Earth, looking at the GEO, while GEO satellites slide in its FoV. The sensor observes the whole geostationary belt (together with objects in the nearby orbits) in a sidereal day. Such configuration allows us to sweep the whole orbit daily with a single satellite. In this way, it is possible to perform a continuous surveillance of the GEO objects, being the satellites or space debris in the disposal orbits next to the GEO. In ECEF (Earth Centred Earth Fixed), the apparent precession motion of the LEO orbit moves the targeted area along the GEO belt, like the light cone of a lighthouse (Fig. 2).

The long distance between target and observer makes almost negligible the effect of the relative motion with regards to other conceivable spacebased sensors (i.e. from LEO to LEO/ from LEO to Medium Earth Orbits - MEO). Indeed, the speed of an orbiting item is mainly function of the orbit itself: about 7 km/s for the LEO, while in GEO the debris speed is expected to be similar to a geostationary satellite, about 3 km/s. Since the telescope is constantly targeting the geostationary orbit, the angular rate of targets is very low, also due to the distance between the target and the observer and the slow apparent precession motion of the orbit itself. The simulation of the angular rate of the object with respect to the FoV gives as maximum value about 14.4 arcsec/s.

It should be noted that this result is obtained by adopting a perfectly geostationary orbit to simulate the orbit of the debris. Considering the contribution of the peculiar velocity of debris object, the worst angular rate is about 19.4 arcsec/s.

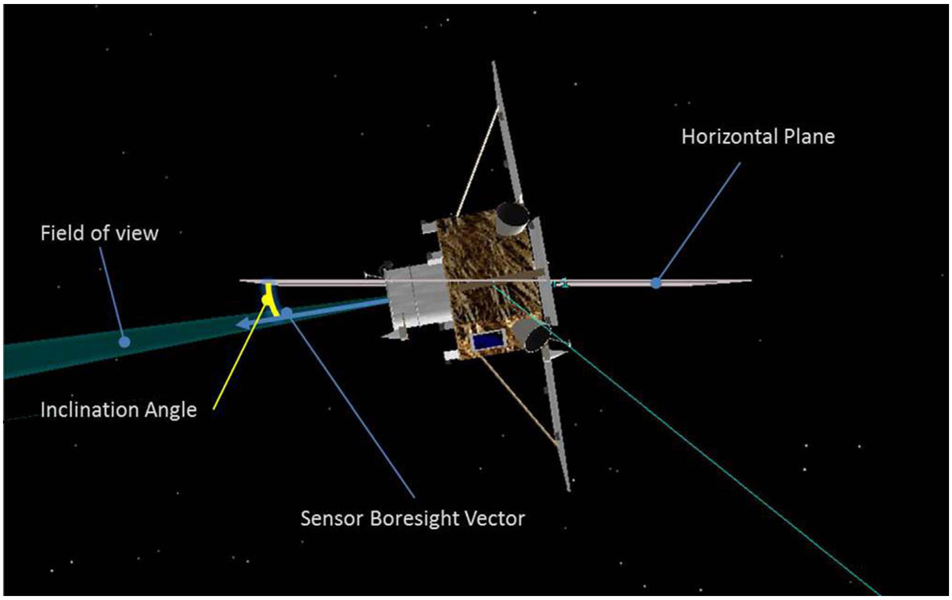

Fig. 1. Sensor inclination with regards to spacecraft.

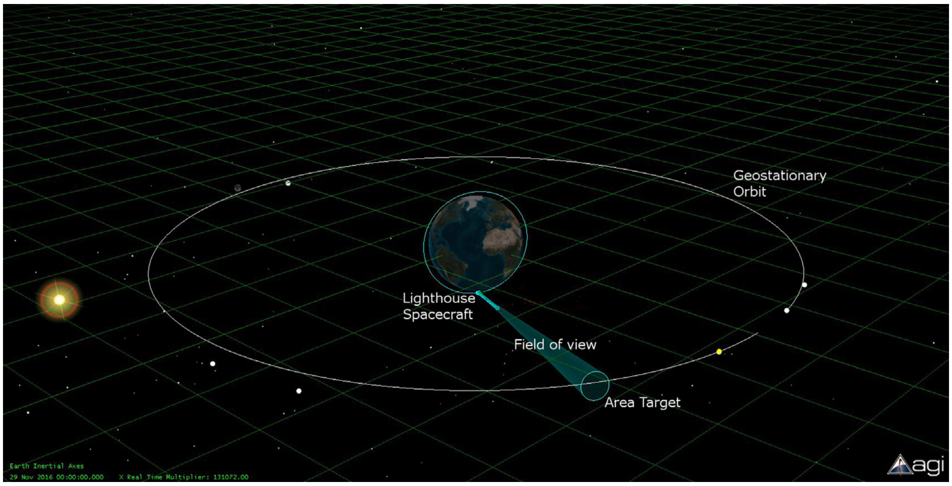

Fig. 2. “Lighthouse” mission.

It’s worth to consider that monitoring the geostationary orbit also means monitoring the close graveyard orbit, destination of most of the geostationary satellites at the end of their lifetime.

The reference sensor is a Schmidt telescope with a FoV of 5.6°. Schmidt telescopes are characterized by a homogeneous resolution over the whole FoV, due to their intrinsic symmetry, making this instrument suitable for surveillance purposes. Calculations and simulations return a limiting magnitude of 18.6, that means a capability to detect a target down to 20/40 cm diameter (best/conservative case), according to the model described in “methods”.

Since a complete satellite system is composed of a space segment and a ground segment, hence a ground segment has been simulated too in the scenario. A single ground station has been considered. Since the high inclination of the orbit, high latitude sites are expected to be more performant. The Kiruna (Sweden, 67°51′N 20°13′E) location have been considered as reference, and it was included in the scenario. Kiruna already hosts one of the four ground stations involved in the Italian radar mission COSMO-SkyMed, dealing with the data download of the radar images from the satellites (ASI, 2016). Analysing the accesses between the satellite and the Ground Station, the image size and rate, together with a data rate comparable with reference Earth Observation missions, it is possible to demonstrate how a single ground station at high latitudes (i.e. Kiruna) is more than enough to satisfy the mission needs.

3. Method

This chapter reports the approach followed in defining the main characteristics of the proposed space mission and in evaluating its performance. It should be noted that the design has not been developed in detail, however the main scientific and technological aspects have been addressed.

Here below the specific methodology (purposely developed) and its application to the Lighthouse mission are reported.

In order to define the characteristics of the proposed space platform and to evaluate its capabilities, advantages and limitations, data and assumptions are required about:

- The characteristics of the sensor (i.e. the telescope/camera optical characteristics, detector features).
- The orbit of the spacecraft.
- The orbital characteristics of the target objects.
- The physical characteristics of the target objects.

3.1. The mission – Scenario

The Orbital parameters and other simulation parameters are reported in Table 1. A LEO satellite has been created in a scenario, equipped with a sensor. The sensor cone was shaped according to the Schmidt FoV (5.6° × 5.6° full solid angle). The sensor beam was oriented towards the geostationary orbit, with an inclination angle of about 81° from nadir. The mission has been simulated by the commercial software Systems Tool Kit (STK), devoted (among others) to space mission analysis and design. Propagation has been performed by HPOP propagator for the LEO satellite and J2 Perturbation Propagator for the GEO target.

The High-Precision Orbit Propagator (HPOP) uses numerical integration of the differential equations of motions to generate ephemeris. Several different force modelling effects can be included in the analysis, including a full gravitational field model (based upon spherical harmonics), third-body gravity, atmospheric drag and solar radiation pressure. (AGI Systems Tool Kit, http://help.agi.com/stk/)

Table 1
Orbital Parameters.

	Lighthouse
Orbit height	800 km
Eccentricity	0.000016
Right Ascension of Ascending Node (RAAN)	0
Inclination	90°
Orbital period	~97 min
Sensor beam (50 cm diameter schmidt)	5.6° (Full angle)
Sensor orientation	Y = 90° P = 0° R = -80.7°

The J2 Perturbation (first-order) propagator accounts for secular variations in the orbit elements due to Earth oblateness. This propagator does not model atmospheric drag or solar or lunar gravitational forces (AGI Systems Tool Kit, http://help.agi.com/stk/). A simple propagator has been used because geosynchronous satellite was a “dummy *target*” involved in the angular rate calculation and other simple parameters only.

The mission has been propagated for one year to consider the different sunlight conditions, including sensor blinding and area target eclipses.

Ground segment coverage has been simulated too, considering as reference a subset of the ground segment of the COSMO-Skymed mission and the state of the art of the downlink data rate for Earth Observation missions (Snoeij et al, 2013).

3.2. The sensor

In this framework, a “sensor” is the whole instrument/system used to perform observation, including optical, mechanical and electronic components, while a “detector” is the specific element that converts the radiation into an electric signal to be measured/processed (e.g. CCD, CMOS).

The sensor has been simulated taking as reference a particular Schmidt camera developed in the framework of an ESA Innovation Triangle Initiative project (references about ITI in the acknowledgements), which results suitable for NEOs (Near Earth Objects) wide survey and space debris surveillance applications. During the project, a Schmidt camera has been designed following the guidelines coming from the ESA SSA program. A Schmidt design, due to its primary spherical mirror, offers a large FoV with a low sensibility to optical misalignment. This makes it useful in spacebased debris monitoring, especially with respect to other aspherical design telescopes. Homogeneous resolution of the telescope over the whole FoV, due to the design limiting the aberrations, allows us to use this mission for surveillance purposes.

In the project, a scaled down breadboard of the telescope has been realized to validate the design methods. Real scale telescopes with different sizes have been designed, including a 0.5 m diameter version. A full implementation of the sensor is 1.610 m long, with a focal length of 0.807 m and a FoV of 5.6° × 5.6°. Such characteristics have been considered as reference for the present paper.

It’s worth to highlight that some GEO objects can also have inclined orbits up to about 17° (Flohrer et al., 2005) and a field of view of 5.6° × 5.6° is not able to fully monitor the objects on the most inclined orbits. However, Lighthouse is not proposed as a stand-alone mission, but as a sensor devoted to surveillance tasks, integrated in a global sensor network composed of both groundbased and spacebased observers (also involving different sensors technologies). Moreover, further studies could possibly address this issue, for instance by considering the adoption of different sensors (e.g. with a wider FoV), multiple sensors, slightly different configurations or observation strategies, and relevant trade-offs.

3.3. Detection capability

The complete set of parameters of the telescope enables the assessment of the capability of the sensor to detect target objects, provided that information on space debris and the environment is available. In order to do this, a general and flexible methodology is adopted, that is independent from details of design/technology of the sensor and of data processing. The approach is adapted from Shell (2010) and is briefly summarized here below.

The performance of the sensor has been assessed in terms of minimum size of detectable objects. Such assessment is based on the evaluation of the signal_to_noise ratio (SNR) achievable for a given targeted object, which in turn depends upon several parameters of target, detector, relative geometry and motion, and environment/background characteristics.

A photometric model purposely adapted from Shell (2010)) has been used to compute the relevant SNR, as described in the following. Photons coming from the target object and from the sky background radiation are collected by the telescope and converted by the detectors into electric charge, which is commonly expressed in terms of number of photoelectrons (i.e. electrons collected by each pixel):

$$e_s = QE \cdot N \quad \text{(signal photoelectrons)} \tag{1}$$

$$e_b = QE \cdot N_{sky} \quad \text{(background radiance photoelectrons)} \tag{2}$$

In the above formulas, N and N_{sky} are the number of photons collected during the time of integration T_{int}, from the object and from the sky respectively, and QE is the quantum efficiency of the detector.The SNR is expressed as:

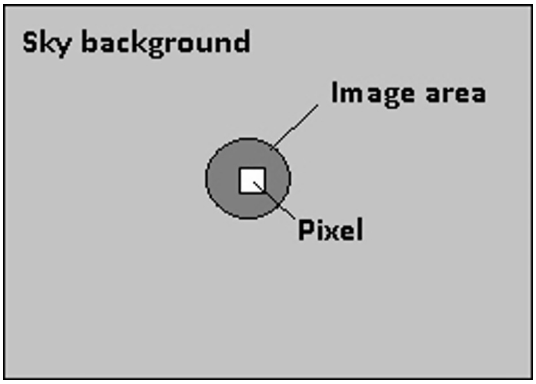

Fig. 3. Relevance of pixel size related to the image size.

$$SNR = \frac{e_s}{\sqrt{e_s + e_b + e_n^2}} \tag{3}$$

where a further term linked to e_n, i.e. the read noise produced by the detector, has been added in the noise expression.

QE = 0.8 and $e_n = 5$ have been assumed.

The values of N and N_{sky} can be evaluated on the basis of the magnitude of the object m_{obj} and the sky brightness m_{sky}. The visual magnitude system (m_v) used by astronomers is here adopted for the target object, while the sky brightness is expressed as m_v/arcsec^2, as usually done. The value of $m_{sky} = 22\ m_v/\text{arcsec}^2$ is here adopted for evaluating the sky background.

From the relevant magnitudes, the integrated flux Φ (photons $s^{-1}\,m^{-2}$) over the entire visible band[1] coming from the target object and sky background Φ_{sky} (photons $s^{-1}\,m^{-2}\,\text{arcsec}^{-2}$) can be derived (assuming $5.6 \cdot 10^{10}$ photons $s^{-1}\,m^{-2}$ for $m_{obj} = 0$, as described in Shell (2010).

Another effect to be considered is the size of the detector's pixel. The pixel size has to be properly selected: both smallest and largest sizes lead to low SNR.

Pixel smaller than the image leads to loss of part of the signal. The effect arises because of the spreading of the signal over the whole area covered by the image of a pointlike source, as shown in the Fig. 3.

It should be noted that the image of a pointlike source in the focal plane has a finite size due to several effects, i.e. optical aberrations, diffraction and seeing (not impacting in case of spacebased observations). For the considered telescope and observation conditions, the optical aberrations give the most important contribution and lead to a diameter of the image in the focal plane of about 12 µm, corresponding to 3.07 arcsec in the sky (such value has been derived from the telescope design). The value of the Airy disc diameter for the considered telescope, evaluated at a wavelength of 0.546 µm (green light), is about 2.1 µm. Thus, the impact of diffraction can be neglected compared to the effect of optical aberrations and the value of 3.07 arcsec could be considered an indication of the achievable resolution.

Due to the finite size of the image, only a fraction $\frac{A_{pixel}}{A_{image}}$ of the signal is collected by the pixel (where A_{pixel} and A_{image} are the solid angles covered in the sky by the pixel and the image respectively, in arcsec^2).

On the other hand, when the pixel is greater than the image, the noise increases because more background radiation is collected. Moreover, in this case there is also an obvious loss of angular resolution. For this reason, the use of a pixel size close to the size of the image is recommended. A reference value of 10 µm (corresponding to 2.56 arcsec) has been adopted for the pixel size, which is slightly smaller than the diameter of the image. This is also

---

[1] Considering the typical spectral response of a silicon-based detector.

the typical order of magnitude of pixel size in currently available devices.

Other signal losses can be also considered, by multiplying the number of photons by a proper reduction factor τ called transmittance, accounting all losses of photons in the path from the source to the detector. These losses are due to obscuration and partial reflection from the mirror and lenses of telescope. A reasonable value for τ is 0.8, as evaluated in the ESA ITI project.

Once considered all the above-mentioned effects, the value of N and N_{sky} is given by:

$$N = \Phi \cdot A \cdot \tau \cdot T_{\text{int}} \cdot \frac{A_{pixel}}{A_{image}} \tag{4}$$

$$N_{sky} = \Phi_{sky} \cdot A \cdot \tau \cdot T_{\text{int}} \cdot A_{pixel} \tag{5}$$

where A is the area of the entrance pupil of the telescope.

The angular size of the image impacts on the calculation of the time of integration, which can be estimated as follows (in the case of image greater than the pixel):

$$T_{\text{int}} = \frac{\varphi}{\omega} \tag{6}$$

where φ is the angular size of the image in the sky and ω is its angular rate.

The values of ω and Tint have been estimated theoretically, also by means of STK simulation, on the basis of reasonable assumptions about the orbit of the target. The results are reported in the next section, describing the features of the target objects.

Moreover, the target has been modelled and analysed to estimate its faintest magnitude, according to the object size and the worst-case solar phase angle. Such value has been compared with the minimum detectable value, derived by the marginal SNR. With the above model, the assessment of the sensor performance has been done through the following steps:

- the SNR is calculated as a function of the magnitude of the target object;
- the limiting magnitude, corresponding to SNR = 3 (criterion for marginal detection), is identified (from CO-II Project, 2014);
- the magnitude (worst case with respect to sunlight conditions) of the target is calculated for several object sizes;
- the minimum detectable size is identified. To stay on a conservative side, it corresponds to a value of the magnitude well below (about two magnitudes) the limiting magnitude. An optimistic value, closer to the limiting magnitude, is also reported.

In the entire process, the conservative cases are considered. This conservative approach ensures the robustness of results, and enables to deal with the possibility of further limitation not considered in the model. Deeper photometric analyses were not included at the present stage of the study, but they could be considered in further works.

For example, the use of pass band optical filters could be considered to characterize the material properties of target objects, as already done by the ESA telescope for space debris survey at the Optical Ground Station in Tenerife, Spain (ESA Optical Ground Station, http://www.esa.int/Our_Activities/Operations/Space_Debris/Scanning_and_observing2). Indeed, the 'colour' of the objects can contribute to the identification of the potential origin of newly detected fragments, or to the recognition of known objects captured in different shots, as shown by the study performed with the MODEST ground-based telescope (Seitzer et al., 2009). The spectrum of reflected light can, in principle, give information about the material properties of the target object, although deeper researches are necessary to deal with several sources of uncertainty (Seitzer et al., 2012).

4. Results

4.1. The target objects

The first step to assess the capability of the system to detect the typical debris, is evaluating the apparent magnitude of debris as seen from the sensor (also called optical signature). Several studies have been performed to evaluate optical signature of space debris. Data and assumptions reported in Shell (2010) have been adopted in the following discussion.

The brightness of space debris is due to the sun light reflected by the object, thus it depends upon the optical reflectance or albedo of the debris. A mean value of albedo ρ = 0.175 for fragmented space debris can be used. An albedo of 0.2 is often used for payloads and rocket bodies. In this study, the value ρ = 0.175 is adopted in order to keep a conservative approach.

The optical signature is also depending upon many variables including object's size, shape, orientation and the relative geometry of the sensor, sun and object:

$$m_{obj} = m_{sun} - 2.5 \log \left[\frac{d^2}{R^2} \cdot \rho \cdot p(\psi) \right] \tag{7}$$

where $m_{sun} = -26.73$ is the magnitude of the Sun, d is the diameter of the object, R is the range to the object from the sensor, ρ is the reflectance, and p(ψ) is the solar phase angle function. The solar phase angle, ψ, is the angular extent between the sun and the sensor, relative to the object. For diffuse or Lambertian surfaces, the total reflected energy decreases with increasing phase angles, as observed with the lunar phases. For specular or mirrored surfaces, there is no such dependency. Our estimates assume equal contributions from both specular and diffuse reflectance components (this is supported by observational data). The solar phase angle function reported in Shell (2010) is adopted.

The relative distance target to sensor is about 42,800 Km, due to the geometry of the selected orbits. The relative angular rate has been calculated by simulating in STK a target object on a perfectly geostationary orbit, seen by the sensor placed in the selected polar LEO orbit. The result is a maximum value of about 14.4 arcsec/s for the angular rate.

It should be noted that this result has been obtained by using a geostationary satellite as target, to simulate GEO debris.

This hypothesis is close to a realistic situation. However, actual GEO debris objects are not geostationary, since their orbit could have different semimajor axis, eccentricity and inclination.

For this reason, the peculiar angular velocity of GEO debris should be considered.

A discussion of typical orbital characteristics of the GEO debris is reported in Shell (2010), which reports an estimation of the 5 arcsec/s for the maximum value of angular rate seen from the Earth. This debris peculiar velocity should in principle be added as a vector to the relative velocity between the target and the observer, above calculated. The maximum value corresponds to the worst case, in which the two angular velocities have same direction. In this case, the total angular rate is $14.4 + 5 = 19.4$ arcsec/s, $\varphi = 3.07$ arcsec, consequently (from Eq. (6)) corresponding to $T_{int} = 0.16$ s, and a limiting magnitude of 19.1.

The effect of the rotation of the telescope can also be considered. In order to continuously observe the target area, the spacecraft shall rotate around its axis. This leads to a field rotation (i.e. the rotation of the FoV in the focal plane), that could negatively impact on the limiting magnitude, by further decreasing Tint. The relevant impact has been estimated for a rotation period of 97 min, equal to the orbital period. The analysis show that this effect leads to a time of integration of about 0.1 s (instead of 0.16 s) and to a limiting magnitude of 18.6 (instead of 19.1).

Therefore, the value of limiting magnitude has been compared with the expected magnitude of GEO debris. In doing this, it should be remarked that the light conditions changes during the year, because of the Earth's orbital revolution. This happens since in the proposed mission, the observed area is always the same, while the apparent position of the Sun changes during the year, leading to a change in the solar phase angle and, thus, in the object visibility. The analysis shows that the sensor, even in worst light condition, is capable to detect objects down to about 40 cm (16.8 mv) as conservative lower limit. The value of 20 cm (18.3 mv), very close to the detection limit, could be considered optimistic. These objects are always visible by the considered telescope, for each solar phase angle (provided they are outside the shadow cone of the Earth). In particular, it can be easily viewed from solar phase angle spanning for 0° to about 90° mainly thanks to the amount of diffuse light, however they are detectable even in less favourable conditions, i.e. solar phase angle spanning from 90° to 180° thanks to the specular component of reflectivity. Fig. 4 reports the plot of the target brightness (reported as magnitude) with respect to the solar angle (°), calculated for target objects with a diameter of 40 cm (limiting size, conservative value) and 20 cm (limiting size, optimistic value).

4.2. Data streaming

An access analysis has been performed in STK too. A preliminary data rate assessment has been performed, considering state of the art downlink channels for Earth Observation as reference.

The generated data flow has been analysed by a preliminary simulation, in order to ensure the overall feasibility of such a mission, also in terms of ground infrastructures. The use of the ground station in Kiruna (Sweden) has been considered. Simulation returns an average value of 10 accesses of about 700 s (average value) every day.

In order to evaluate the downlink data rate availability, the state of the art of Earth observation missions can be taken as reference (Snoeij et al., 2013). Indeed, these kinds of missions share some characteristics with "lighthouse", such as the similar orbit (LEO with very high inclination, almost polar) and similar needs in terms of data production and handling (image acquisition and downloading). A typical download data rate for Earth observation missions is about 260/520 Mbps. Considering a data rate of 520 Mbps as reference for our mission, the average amount of downloadable data at each access is about 46 GB, that means 460 GB/day.

Considering the FoV of 5.6° × 5.6°, the whole GEO can be covered by 360/5.6–64 images. Since the goal of the mission is to reveal debris, comparing images among each other and aiming at the acquisition of an image of the geostationary belt, it can be supposed to have five shots in five degrees, with a good overlap among images (Fig. 5). Consequently, we have to deal with about 360 images per cycle (about 24 h), that is 1 image every 4 min.

An evaluation of the number of pixel needed for each image can be done starting from the FoV and the angular size of each pixel, which is 2.56 arcsec for 10 μm pixel and a focal length of 0.807 m. To cover all the FoV, i.e. 5.6° = 20,160 arcsec there is the need of about 7800 × 7800–60 Mpixel CCD plate (20,160/2.56–7800).

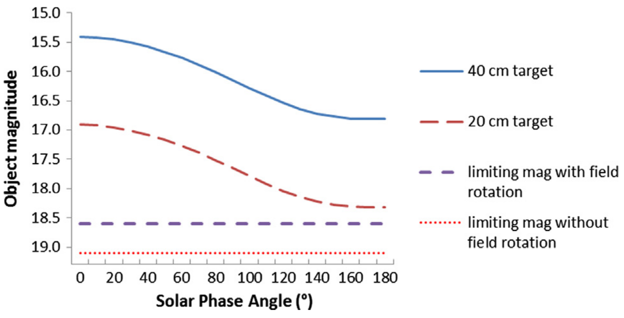

Fig. 4. Target magnitude vs solar phase angle.

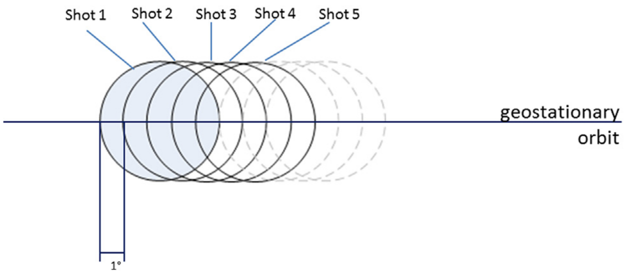

Fig. 5. Image shots overlapping. A 1_deg shot step allows a good coverage of the belt across the geostationary orbit and a the potential use of change detection techniques.

Considering a quantization depth of 2 Bytes/pixel, the size of a single image in raw format is about $60^{*}2 =$ 120 MB, producing a daily data flow of 120^{*} 360–43 GB/day. This is the worst-case scenario, no image on-board processing or compression has been considered here. Comparing with the maximum downlink capability, two accesses are enough to download all the images.

Moreover, dataflow should be further reduced by using proper compression algorithms. A deep analysis of compression techniques has not been performed; however available information about astronomical missions operating with similar types of images/data (Portell et al., 2006) suggests that reasonable compression ratios of 2.5–3.2 can be achieved.

4.3. Possible limitations related to sunlight

Some possible limitations of the proposed mission, due to the position of the sun and the motion of the Earth, have been also analysed. Indeed, since a telescope is a passive sensor, some phenomena (leading to "blind spots") can leave it useless for some periods of the year. However, preliminary simulations show that these phenomena can be avoided/mitigated by a proper choice of the orbit/characteristic of the mission. Here below some considerations about light conditions are briefly discussed. Phenomena potentially limiting the mission capabilities are described and mitigation countermeasures examined.

(1) Eclipses: if the target area goes to eclipse, due to the Earth shadow cone, no observation is possible. Not all the positions on the geostationary orbit are affected by eclipse. Since the GEO is inclined on the ecliptic plane, the points at the highest ecliptic latitude are free from eclipses. Hence, pointing the sensor (and the area target) towards the points at highest ecliptic latitude avoids eclipse problems and allows us to have our target area constantly under sunlight. Area Target Eclipses have been studied by STK and simulation confirms that eclipse never occurs (see Figs. 6–9).

(2) Direct sunlight on the sensor: if sun falls in the FoV of the observer, the sensor is to be switched off and protected, in order to avoid damages. That means to temporary lose the operativeness of the satellite. STK simulations demonstrated how the mission can be designed so that the FoV of the sensor never meet the direct sun, thus preventing the direct exposure of the sensor. Indeed, the sensor boresight is inclined of about 9.8° and the half angle of the cone is 2.8°, while the obliquity of the ecliptic is about 23.45°. The Sun always has zero ecliptic latitude and an apparent diameter of 0.5° as seen from the Earth. Thus, the Sun is outside the sensor beam. An "access analysis" in STK confirms that the sensor has no access to the sun during the entire year.

4.4. Groundbased sensors vs Lighthouse

It's worth to compare the above assessed performance with that achievable by telescopes on the ground and to discuss the possible benefits generated by the use of Lighthouse in connection with them.

First, an analysis of the general points of strength and weakness of Lighthouse with respect to a hypothetical similar groundbased sensor (i.e. with a similar design) is carried out. This analysis enable to point out the general differences between groundbased and spacebased sensors, regardless of differences in the design. Moreover, this allows assessing the theoretical performances achievable by this kind of sensor in groundbased applications. Then the characteristics of the actual sensors, already operating, are presented. Finally, some hints for possible uses of Lighthouse are discussed.

Few issues shall be considered in order to properly compare the sensors. Since groundbased sensors are not limited in size, differently from the spacebased ones, a 1 m diameter Schmidt telescope having similar design, has been considered for the comparison. This telescope has been designed in the ESA ITI project as reference for a possible ground-based application.

Moreover, the ground one is affected by the atmospheric absorption and by a greater brightness of the sky (due to diffuse light). Furthermore, the presence of atmospheric turbulence affects the spatial resolution could make a long exposure image (say greater than some milliseconds) seeing limited. On the other hand, the angular rate of a GEO target is lower for the groundbased sensor than for spacebased one. GEO objects are nearly stationary when observed from the Earth surface and the larger diameter could in principle allow collecting more light from the source, improving the capability of the groundbased sensor to detect faint objects. The photometric model has been slightly modified to take into account the effect of the atmosphere. In particular, the atmospheric transmission impacts on the SNR This effect can be taken into account

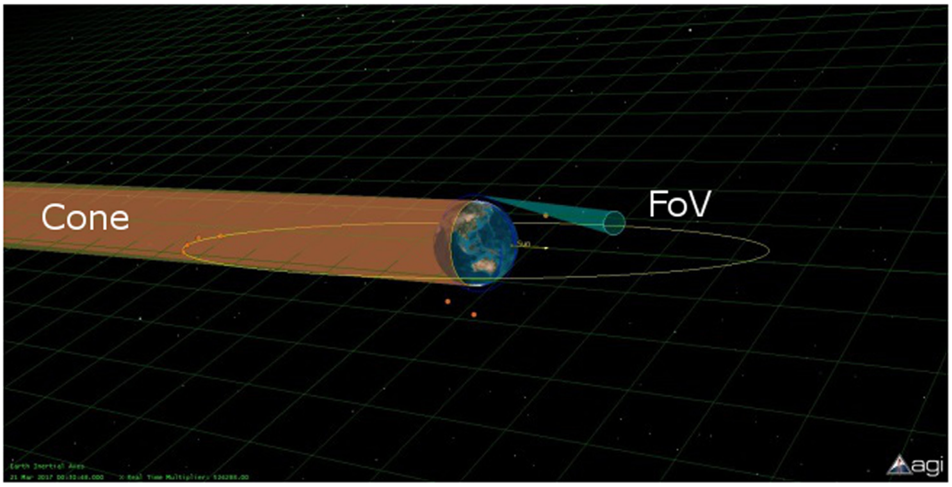

Fig. 6. March Equinox – Umbra and penumbra cones Vs FoV.

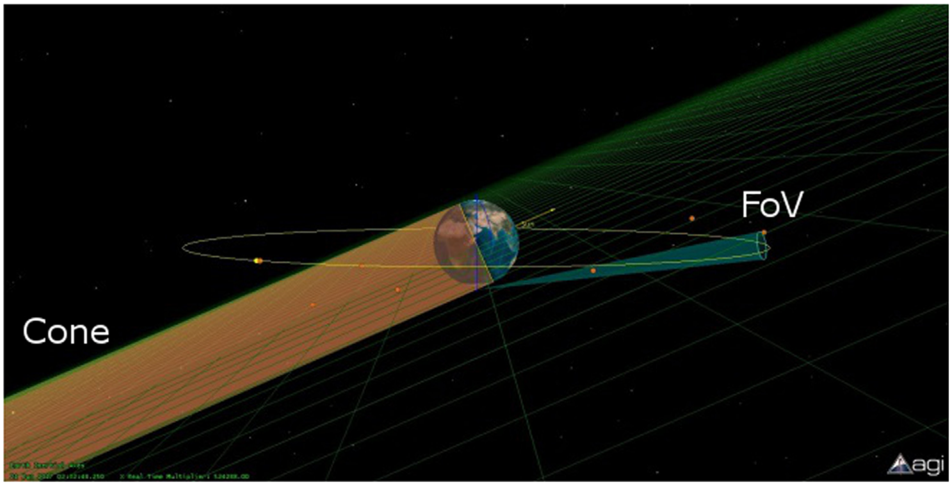

Fig. 7. June Solstice – Umbra and penumbra cones Vs FoV.

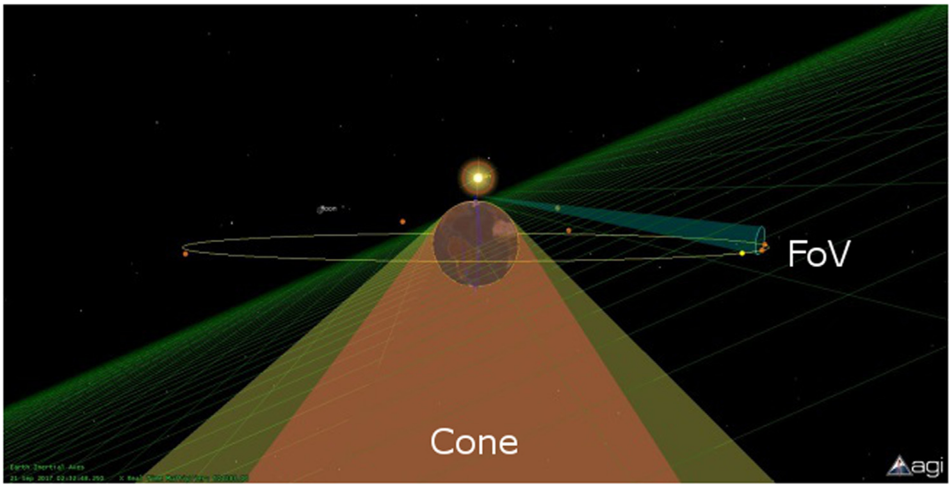

Fig. 8. September Equinox – Umbra and penumbra cones Vs FoV.

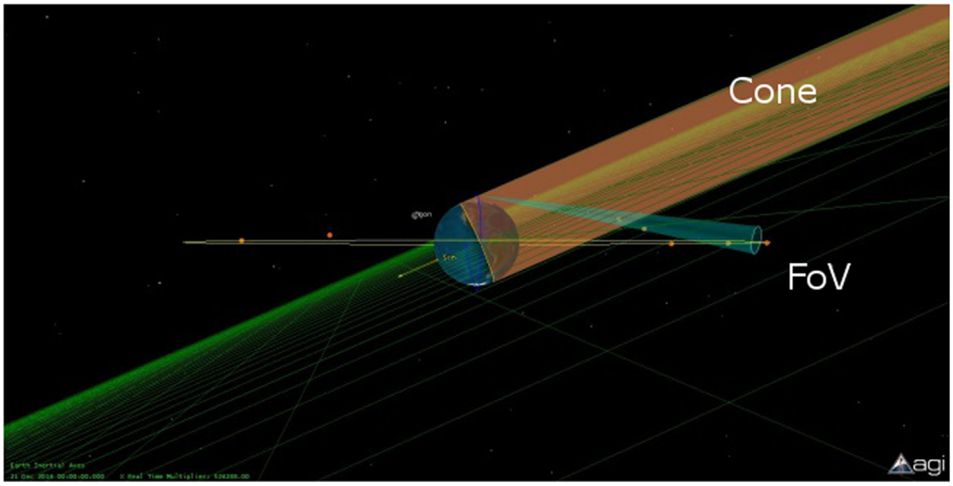

Fig. 9. December Solstice – Umbra and penumbra cones Vs FoV.

by multiplying the number of photons by a transmittance factor τ_{atm}.

Thus, the SNR Eq. (3) becomes:

$$SNR = \frac{\tau_{atm} \cdot e_s}{\sqrt{\tau_{atm} \cdot e_s + \tau_{atm} \cdot e_b + e_n^2}} \tag{8}$$

Atmospheric transmittance depends upon the elevation angle of the target object, the altitude of the observing site and the atmospheric conditions. A suitable value of $\tau_{atm}0 = 0.7$ has been identified in ESA ITI project for the evaluation of typical performances achievable by groundbased sensors dedicated to the observation of space debris.

Sky magnitude and seeing achievable in several astronomical sites have been also examined, considering the worst cases in order to be conservative. Values of msky of 21 mv/arcsec^2 and a seeing of 2 arcsec have been adopted. The most important limitation to the angular resolution for the considered design is due to optical aberrations. According to the characteristic of the reference groundbased Schmidt telescope designed in the mentioned ESA ITI project (1 m diameter), this contribution corresponds to 3.22 arcsec (25 μm in the focal plane). We consider a value of 5 arcsec/s as the maximum value of angular rate seen from the Earth.

Finally, the groundbased reference telescope features a FoV is of 4° × 4° and a 20 μm pixel size (to ensure a high SNR). These values and the angular rate of 5 arcsec/s enable to set the integration time Texp = 0.64 s.

With the above value, a limit magnitude of about 20.5 can be reached. Under conservative assumptions, such system is capable to detect GEO object down to 20 cm in size (magnitude 18.3), while an optimistic limit is about 10 cm size, corresponding to 19.8 mv.

These values can be compared with those of already existing optical telescope on the ground. ESA operates a 1 m diameter telescope at Optical Ground Station (OGS) in Tenerife, Spain, for the survey and characterisation of objects near the geostationary ring. The telescope has Ritchey-Chrétien optics, with a FoV of about 0.7°. It can detect and track near GEO objects up to magnitudes of 19 to 21 (down to 10–15 cm in size), very close to the values found for the 1 m diameter Schmidt telescope here considered. With this performance, the ESA telescope is top-ranked worldwide.

According to the results of the above analysis, the top-ranked groundbased sensors show slightly better performances than the spacebased one, with respect to the limiting magnitude and limiting size of detectable object (10–20 cm for groundbased sensors, 20–40 cm for the space sensor here considered), but with a smaller FoV. It should be also remarked that the main advantage of the proposed space mission relies on its capability to monitor the whole geostationary orbit with a single sensor, regardless of weather conditions. On the contrary, a groundbased monitoring system needs a network of sensors, worldwide deployed, to obtain such a monitoring. An example of such a network is the International Scientific Optical Network (ISON).

ISON is a large and growing open network including, at time of writing, 38 observation facilities hosting 90 telescopes in 16 countries (Molotov, 2017), mainly performing observations of the space debris. The system is also used for other scientific objectives, e.g. study of asteroids, comets and gamma-ray bursts (GRB) afterglows. ISON includes telescopes with different characteristics, different diameters and grouped into classes (also called “subsets” or “subsystems”) performing different tasks (Molotov et al., 2013). In particular, a subset is dedicated to a global GEO survey down to magnitude 15.5. The telescopes belonging to GEO survey subsystem have typical diameters ranging from 22 to 25 cm up to 50 cm. The longitude coverage of GEO belt is currently increasing, due to entering into operation of new facilities. For instance, an increase of coverage of the 40–140 W longitude occurred in 2012, with the addition of a new facility in Mexico. Another subset is devoted to the tracking of debris in GEO and GTO (Geostationary Transfer Orbit) and is capable to track objects fainter than magnitude 15.5.

In this context a spacebased platform like Lighthouse should be tasked to provide the first level surveillance data, allowing other assets to be devoted to different observations (i.e. ad hoc observations, tracking, or monitoring of high inclined orbits -6° to 17°) or other scientific tasks.

Moreover, the use of a spacebased platform, continuously monitoring the geostationary belt, together with groundbased observations, could provide a set of complementary data, also enabling the use of parallax measurements for the orbital determination.

Lighthouse could also complete the coverage of longitude gaps and overcoming temporary unavailability of a groundbased telescopes. For instance, the dataflow from the spacecraft can be ensured in case of clouds and/or bad seeing at one or more observation sites. Finally, ground sensors are affected by the lunar phases (because of the high sky brightness in the periods near full moon).

The high sensitivity of _Lighthouse compared with those of the ISON global GEO survey subsystem (18.6 vs 15.5 limiting magnitude), suggests a possible use of Lighthouse (or similar systems) for the discovery of the faintest objects. Once detected, such objects could be followed by the ISON tracking subsystem for a better orbital determination, thus fully exploiting the ISON tracking capabilities.

Finally, Lighthouse could also be a source of homogeneous data (collected by a single instrument, instead of several different types of telescopes) for scientific purposes.

The above possibilities need to be carefully investigated, taking into account the development status of groundbased networks, the scientific needs and the requirements of a possible SST service. Such evaluation is out of the scope of this paper and could be addressed by future works.

4.5. Lighthouse vs other spacebased sensors

The use of spacebased sensors is a very recent development and few missions have been designed and implemented so far. Moreover, most of these missions are developed under military programmes and, for this reasons, detailed information about their features is often not publicly available.

For these reasons a direct comparison between Lighthouse and other spacebased solutions, is difficult to achieve. Neglecting the exploitation of sensors already on-board operational satellites (i.e. star trackers and small cameras hosted on GEO satellites, discussed in Shell, 2010), not specifically conceived for space debris monitoring, some examples of SubGEO_to_GEO and LEO_to_LEO missions are discussed in Flohrer et al. (2005). LEO-to-LEO mission capabilities are mainly limited by the high relative sensor-target velocity, while dedicated high orbit (e.g. SubGEO) should increase mission costs with regards to LEO ones, due to their orbital height.

Generally speaking, from the GEO belt surveillance perspective, the aforementioned missions aim at the detection of smallest objects, down to centimetre size or less in favourable conditions, by placing the sensor very close to the target. Objects with 10 mm size can be in principle detected by such kind of missions, with limiting size depending on the aperture of the telescope and light conditions.

The main disadvantage is the requirement of high orbits for the monitoring of the GEO belt, increasing the mission difficulty and costs.

Some missions hosted in LEO and capable to observe up to GEO have been proposed too. They typically use more complex sensors/spacecraft configurations than Lighthouse, or envisage the use of satellite constellations. Moreover, the optical characteristics of the sensor in terms of limiting magnitude, resolution and FoV are generally worst (a high effective FoV is often obtained by implementing an active pointing system, increasing the complexity of the spacecraft).

For example, the SBSS program is a planned satellite constellation developed by Boeing for the U.S. DoD (Department of Defence) to track space objects in orbit. The SBSS-1 spacecraft, which is the first spacecraft of the series, is equipped with a sensor based on an evolution of the SBV (Space Based Visible) sensor, on-board the previous MSX (Mid-Course Space Experiment) mission of DoD (launched in 1996). According to the available information (SBSS, https://directory.eoportal.org/web/eoportal/satellite-missions/s/sbss), the spacecraft is placed in a Sun-synchronous circular orbit with altitude = 630 km and inclination = 98°. The sensor is based on a 30 cm diameter TMA (Three Mirror Anastigmatic) telescope mounted on a two-axis gimbal, and can cover a high FoV by means of an active pointing system. Such on-board system is very complex if compared to Lighthouse.

However, a reference mission for spacebased debris observation is Sapphire, a Canadian minisatellite, launched in 2013, able to provide continuous optical surveillance data, located in a LEO sun-synchronous orbit at an altitude of approximately 750 km. Sapphire is less expensive than the U.S. SBSS, since it use a smaller telescope, fixed with respect to the spacecraft body. Sapphire can observe objects ranging from 6000 km to 40,000 km in altitude. The sensor has a 15 cm diameter TMA off-axis imaging optical design with a FoV of 1.4°. As for the SBSS, even Sapphire's telescope is based on the design of the SBV telescope of MSX. The system was designed to detect objects with magnitude from 6 to 15, with a required pointing accuracy of 6 arcsec (Maskell and Oram, 2008). The selected orbit enables the observation of the object with the optimal solar phase angle (anti-sun viewing) with minimal attitude changes, but active tracking of a specific object is also possible, changing the spacecraft's attitude. The Sapphire payload is smaller and lighter (about 28.5 kg) with respect to those adopted for Lighthouse but, according to the available information, it is also less performant with respect to sensitivity and FoV.

Indeed the Lighthouse telescope would have a collecting area more than 10 times larger (50 cm in diameter vs the 15 cm of the Sapphire system) and a 4 times larger linear FoV (about 16 times in area). Hence, Lighthouse would be then more sensible than Sapphire (18.6 vs 15 limiting magnitude) and able to recognize faintest debris for a given object distance.

An important point to underline is that, differently from Lighthouse, the above systems are not specialised and optimised for a specific orbital region and task. They have the advantage of being multi-purpose and equipped with active tracking systems. Moreover, they use a favourable orbit with respect to the light conditions and are also capable to actively follow the objects. On the other hand, they require more complex on-board systems and observation strategy. Once again, Lighthouse can be integrated with other missions, allowing them to be tasked for different observation out of the Lighthouse range.

4.6. Future activities

The present preliminary study did not consider many features like data processing, images compression, orbit determination performances, contamination sources discrimination. Some of these features should be deeply investigated in further studies, some others have been considered in charge of a SST ground segment rather than a single mission. Indeed Lighthouse is conceived as a sensor integrated in a SST service chain, involving global sensors networks and data processing centres.

Consequently, tasks like orbit determination, object identification (Tommei et al 2007) or the characterization of the GEO environment concerns the SST ground segment, fed by Lighthouse data, among others.

In the other hand, the possibility of some on-board preprocessing, usually adopted by this kind of systems, could also be considered in the future, on the basis of a trade-off between datalink and payload/mission requirements. The use of multiband photometric observations could be also useful for the identification of target objects with respect to contamination sources.

It is useful to remark that Lighthouse is conceived for the surveillance, thus it is optimized for the detection of faint objects. On the other side, tracking implies the follow-up of the discovered object by means of sensors with high astrometric precision, to obtain accurate orbital parameters.

However, it is interesting to note that, according to Chen & Xiong (2017), observations performed from LEO orbits with high inclination by means of a sensor orientation perpendicular to the orbital motion (similar to the configuration here considered) lead to observational arclength longer than other LEO configurations (such as small inclination orbits) with some advantages for the precision of orbit determination.

5. Discussion and conclusions

The “Lighthouse” mission concept proposes a spacebased telescope for debris surveillance purposes. The choice of the polar orbit with the sensor orientation towards the geostationary orbit, together with the features of the telescope (briefly described above), offers a set of advantages.

First of all, a spacebased sensor enables the continuous monitoring of the whole GEO and the next graveyard orbit, h24 every day of the year with a single satellite, regardless of the weather conditions, the seeing of the sky, the day/night time. Since target eclipses or sunblindness phenomena are avoidable by a proper mission design, a single spacecraft can provide the whole coverage. The data rate is not huge, compared with Earth observation missions, also considering the low need of images and the potentialities of a compression rate (not analysed in this paper). Even if the FoV can observe a “belt” along the GEO, the mission could in principle partially monitor also the population of objects having more inclined orbits, since they will cross the equatorial plane during their orbit.

Detection capabilities of such kind of sensor are comparable -slightly worse- with those of the top-ranked groundbased telescope (i.e. the ESA telescope at OGS in Tenerife), but with the advantage of a much wider FoV.

Moreover Lighthouse sensitivity results greater than those achievable by typical telescopes for space debris surveillance, e.g. the current GEO global survey subsystem of ISON. Moreover, the use of a LEO observer fits better the needs related to the observation of GEO targets rather than LEO objects, because of the lower relative angle rate.

Of course, differently from ground telescopes, realtime observations are not available with spacebased assets; however, realtime is not needed for operative purposes of Space Surveillance and Tracking.

It should be remarked that Lighthouse is not proposed as an alternative to ground telescopes, but its aim is to integrate ground stations networks, providing a wide surveillance service, while leaving to them part of the surveillance and the tracking activities.

Compared with other spacebased solutions, Lighthouse shows some points of strength to be considered/evaluated. It is simpler and cheaper than a subGEO_to_GEO or a LEO_to_LEO mission considered in Flohrer et al. (2005), even if not so performant with respect to the smallest detectable size object.

Since the main limit of a spacebased sensor is the cost of the mission, the choice of a compact Schmidt telescope (about 80 kg mass), allow the use of small satellites spacecraft thus reducing the costs of the launch and the operativeness of the mission, also using small vectors or multipayload launches. Other kinds of sensor with other characteristics (e.g. smaller or having a wider FoV) could be also considered in future work, depending on the scientific needs/user requirements.

Moreover, the oversized downlink capability will allow sharing the ground segment assets among different missions, contributing to the cost reduction.

Compared with other solutions hosted in LEO, such as SBSS and Sapphire, Lighthouse is more specialised, since it is optimized for the surveillance of the geostationary belt. Moreover the larger telescope adopted by Lighthouse, and its design, enable a greater sensitivity and a wider FoV. The peculiar orbit and attitude configuration purposely conceived minimise the need for a complex on-board tracking system.

On the other hand, more complex systems can be multi-purpose and flexible. In general, a trade-off between the point of strength and weakness, and between different needs, has to be performed in the design of such kind of space missions. The most probable scenario for future developments is the deployment of networks of sensors, both on the ground and in space, with different features and performing different tasks, feeding the same SST ground segment and its services.

Acknowledgments

The design of reference telescopes mentioned in this paper has been developed under the ESA ITI Project “An innovative approach for camera/telescope optical system design” (ESA contract No. 4000114150/15/NL/CBi/GM) aimed at demonstrating the feasibility of an innovative approach in the design of optical telescopes, and funded by the European Space Agency.

The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

The authors wish to acknowledge the role of the project partners not involved in the paper, for their contribution to the definition, the design and the validation of the Schmidt telescope: Dr. Atul Deep from ESA, Technical officer of the project; Prof. Antonio Romano, from University Federico II in Naples and founder of OPTIMATH s.r.l. for the design of the telescope. Mr. Ernesto Pecchioli and Pecchioli Research for the design validation through the implementation of the reduced scale breadboard used in the project.

References

7th European Conference on Space Debris, ESA/ESOC, April 2017, Darmstadt, Germany https://conference.sdo.esoc.esa.int/.

AGI Systems Tool Kit, online help, http://help.agi.com/stk/.

ASI, 2016, COSMO-SkyMed Mission and Products Description, Italian Space Agency Website, ASI-CSM-PMG-NT-001 (http://www.asi.it/sites/default/files/attach/bandi/cosmo-skymed_mission_and_products_description_update_2_1.pdf).

Chen, B., Xiong, J., 2017. The Platform Design of Space-based Optical Observations of Space Debris. Chinese Astronomy and Astrophysics 41, 109–124.

CO-II Project 2014, Design Justification File – NEO Segment: Phase 2, Issue 1 Rev.2, 17/04/2014 ESA Ref: SSA-CS-RS-DJF-0011.

ESA Optical Ground Station (OGS), http://www.esa.int/Our_Activities/Operations/Space_Debris/Scanning_and_observing2.

Escorial Olmos, D., Alemán Roda, F.E., Middleton, K., Naudet, J., 2013. Space-based space surveillance operational and demonstration missions. In: Proc. ‘6th European Conference on Space Debris’ Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013).

Flohrer, T., Peltonen, J., Kramer, A., Eronen, T., Kuusela, J., Riihonen, E., Schildknecht, T., Stöveken, E., Valtonen, E., Wokke, F., Flury, W., 2005. SpaceBased Optical Observations of Space Debris, Proceedings of the 4th European Conference on Space Debris (ESA SP-587). 18-20 April 2005, ESA/ESOC, Darmstadt, Germany. Editor: D. Danesy, p.165.

IADC Space Debris Mitigation Guidelines, 2002, IADC Action Item number 22.4.

IADC, 2013, IADC Assessment Report for 2011, IADC-12-06.

Molotov, I., 2017. ISON network development in 2015 – 2016. IADC 35th Darmstadt, Germany—WG1, April 24–26, 2017, www.astronomer.ru/data/0235/ISON_2016.pptx.

Molotov, I., Agapov, V., Khutorovsky, Z., et al. Current status and developments of the ISON optical network. In: Proc. ‘6th European Conference on Space Debris’ Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013).

Maskell, P., Oram, L., 2008. Sapphire: Canada’s Answer to Space-Based Surveillance of Orbital Objects“, Proc. of the Advanced Maui Optical and Space Surveillance Technologies Conference, Maui, Hawaii, September 17–19, 2008, S. Ryan Editor, p. E5.

Portell, J., García-Berro, E., Luri, X., Villafranca, A.G., 2006. Tailored data compression using stream partitioning and prediction: application to Gaia. Exp Astron 21, 125–149. https://doi.org/10.1007/s10686-007-9078-1).

Rossi, A., 2005. The earth orbiting space debris. Serb. Astron. J. 170, 1–12.

Sapphire. https://directory.eoportal.org/web/eoportal/satellite-missions/s/sapphire-space-surveillance.

SBSS. https://directory.eoportal.org/web/eoportal/satellite-missions/s/sbss.

Seitzer, P., Cowardin, H.M., Barker, E., Abercromby, K.J., Foreman, G., Horstman, M., 2009. Photometric studies of GEO debris. In: Ryan, S. (Ed.), Proceedings of the AMOS Conference, Wailea, Maui, Hawaii, September 1-4, 2009, The Maui Economic Development Board., p. E23, https://amostech.com/TechnicalPapers/2009/Orbital_Debris/Seitzer.pdf.

Seitzer P., Lederer S. M., Cowarding H., Cardona T., Barker E S., Abercromby K. J., “Visible Light Spectroscopy of GEO Debris”, AMOS 2012 Conference, 2012

Shell, J.R., 2010. Optimizing orbital debris monitoring with optical telescopes. US Air Force, Space Innovation and Development Center Schriever AFB, CO, September 2010.

Snoeij, P., Geudtner, D., Torres, R., Davidson, M., Bibby, D., Lokas, S., GMES Sentinel-1 System Overview. POLinSAR 2013 Workshop Presentations, January 28–February 1, 2013, ESA ESRIN, Frascati, Italy, https://earth.esa.int/c/document_library/get_file?folderId=408536&name=DLFE-5605.pdf.

Tommei, G., Milani, A., Rossi, A., Orbit Determination of Space Debris: Admissible Regions. Celestial Mech Dyn Astr (2007) 97: 289. https://doi.org/10.1007/s10569-007-9065-x.