Performance index of a network of ground-based optical sensors for space objects observation and measurements

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The total number of space objects in Earth orbits is estimated to be over 600 thousand over 1 cm, while the current number of those that are constantly tracked and cataloged is around 25 thousand. In our era, where space traffic is increasing every year, and so the risk of possible collisions, there is a global need to take control of the near-Earth space environment, in particular the low Earth orbit. This is a common problem for every country, and it can be solved with a global collaboration between nations. In addition, the uncertainty associated with the measured position of orbiting objects is one of the main factors impacting performance, accuracy and timeliness. For this reason, aiming for the coordination of a multitude of sensors is one of the most important aspects targeted in the domain. This paper proposes an algorithm to estimate the performance of a globally distributed network of optical assets, equipped with off-the-shelf components, deployed in multiple sites distributed across different locations. The quantitative performance measure is calculated as the portion of total cataloged debris that is visible by the network in a 24 h time window, considering space objects of size down to 3 cm. The proposed algorithm takes as input all objects of the NORAD catalog, the whole set of objects' physical data provided by the DISCOS and SATCAT catalogs, and optical and atmospheric data. It then propagates the space object population to obtain their position in the selected time window, filters out all the objects that are not in the ground station network line-of-sight for a sufficient amount of time to guarantee a feasible orbit determination, and on the remaining ones it estimates the signal-to-noise Ratio achievable by the assets, leveraging an advanced algorithm that models their optical performance. These values are directly translated into a probability of detection, thus providing a performance index for the given ground sensor network configuration that can be used as an objective function to be optimized when evaluating different architectures.

1. INTRODUCTION

In recent years, a new space-race has started, propelled by the incredible source of resources and useful data space provides. This has already started to translate into a rapid increase of satellites put into orbit around the Earth every year, and in particular in the low Earth orbit (LEO) debris zone [1][2]. More satellites mean a higher probability of collisions and disasters for the orbit environment, as in the infamous incident involving Cosmos and Iridium in 2009, which generated thousands of new small orbiting fragments. A recent report by ESA [3] has estimated the presence of 670 thousand objects above 1 cm, and more than 1 million over 1 mm. One of the main problems is that most of these objects are not cataloged nor observed [4]. In addition, the position measurements for a given satellite are usually not available in real-time, in fact they depend on its visibility from the selected sensor as well as sensor's accuracy, both factors directly impacting accuracy and precision of satellite orbital predictions. The development of a distributed sensor network, shared among countries, would be a major improvement in this regard, allowing to better monitor space objects orbiting around the Earth. An ideal network would be made of several sensors, insensitive to any atmospheric or astronomical perturbation, such as synthetic aperture radars. Unfortunately, such radars are expensive, difficult to maintain, their installation requires several government permits and operations must be supervised by highly trained personnel. Optical technologies, although limited by weather conditions and illumination, are a cheaper solution to deploy and to maintain. For this reason, the study will focus on the implementation of an algorithm to find the best distribution at the global level of a number of telescopes given a list of possible sites and will provide as output the performance measure of this global optical network.

The state of the art on this topic is not very rich. Articles found in the literature mainly concern the study of existing and operational telescope networks [5][6] or the study of the performance of a single telescope in terms of signal-to-noise ratio or other parameters [7][8][9]. To the best knowledge of the authors, this is the first work focusing on performance estimation and optimization of a ground-based network of telescopes.

The study is structured as follows: the algorithm structure is presented in Section 2, Section 3 explains the general optical and astrodynamics theory behind the algorithm, and the two scenarios under study are described in Section 4. Finally, in Section 5 conclusions of this study are presented, together with possible extensions to be carried out in future works.

2. PROPOSED SOLUTION ALGORITHM

The main goal of this paper is the formulation of an algorithm to be used for finding the optimal placement of a number of optical passive telescopes for a global optical network, in terms of known LEO objects coverage as a function of a list of possible sites and a number of deployable sensors with the same characteristics.

Every site can handle only one ground station (with only one sensor) and each sensor will have a 24 h observation interval and at least three acquisitions of the object are required to consider the acquisition feasible. Sensor opening time will be also taken into account while assuring the measures are at least 10 degrees apart one from the other. The object magnitude will be estimated and included in the visibility condition verification from the ground station.

This algorithm will evaluate each individual object in a trajectory catalog (NORAD was used in this study). The algorithm will compute a detection probability on the individual object in the catalog (which will depend on the optical configuration and how many sensors can see it) thus understanding whether that object is potentially visible from the network and with what probability. If the probability is greater than a probability threshold, in this study is the 20%, it will be considered visible from the network. At the end of the processing, the algorithm will calculate a percentage of objects that could potentially be seen by the network under the conditions mentioned before. The percentage of database objects that are potentially visible from the sensor network is considered as the performance index of the network. In other words, the percentage of all objects in the catalog that are in LOS (line of sight) and are also optically visible. The algorithm returns a list of all possible combinations of the chosen sites based on the number of ground stations selected. Each combination is associated with a performance index, which then allows the best combination to be evaluated.

The algorithm main steps can be descried as follows:

- Step 1 - All sites visibility calculations: for all the ground-station sites and using the optical asset configuration selected, the algorithm calculates the geometrical and optical visibility for all the 12 thousand objects of the catalog. How the geometrical and optical visibility are evaluated is described below;
- Step 2 - Find best configuration: uses the data inside the visibility information calculated in step 1 above and a given number of the ground station available to find the best possible locations, considering all the possible combinations and calculates the performance index for each combination. This section is independent of other sections of the algorithm.

A summary of the algorithm structure is shown in Fig. 1.

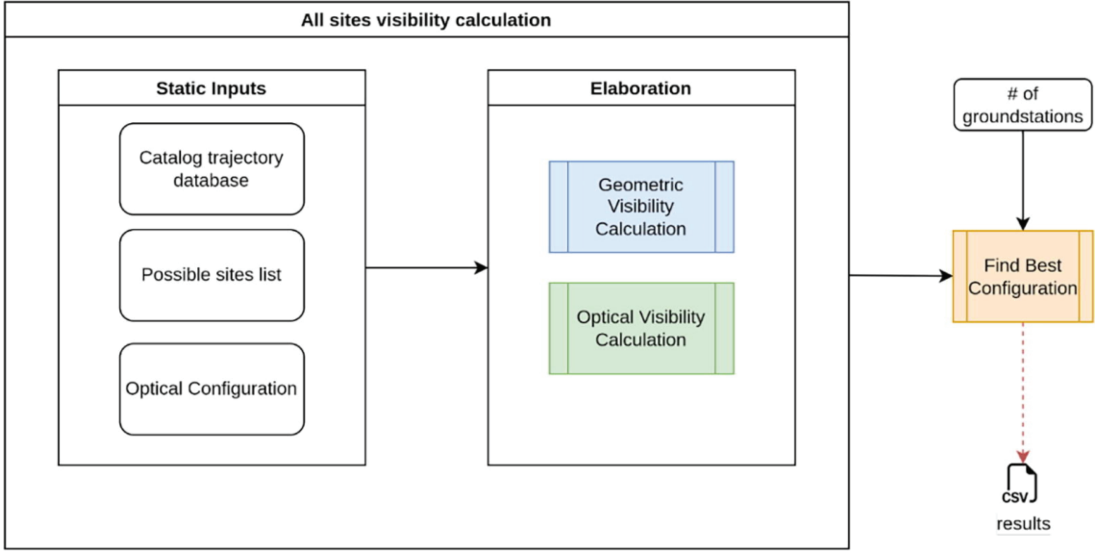

Fig. 1. General structure of the algorithm.

Geometric visibility is achieved if the following conditions are met:

- The satellite and the ground station are in line of sight (LOS) condition;
- The elevation angle of the ground station to see the satellite is greater than a certain value, in our case 30 degrees;
- The satellite is in LOS with the Sun and the ground station is in penumbra condition;
- The satellite trajectory, to be usable by an orbit determination algorithm, must have an arch longer than a certain value, in our case three sensor acquisitions separated by 10 degrees each.
- The satellite must do at least 2 passages over the ground station, a condition to improve orbit determination accuracy.

All the objects having these characteristics are considered geometrically visible. Optical visibility is computed only for objects which are geometrically visible and is expressed by the target detection probability, based on the signal noise ratio (SNR). The detection probability is the key parameter to evaluate the performance of the entire optical configuration and its computation is affected by the object passing multiple times over a certain position and by the object being seen from multiple locations. This step of the algorithm takes as input:

- All the satellite catalog and its propagations (catalog trajectory database);
- All the ground-station positions in WGS84 (latitude, longitude, altitude) and also their magnitude at zenith taken from [9];
- Detector parameters: pixel pitch, resolution in pixel, quantum efficiency, detector readout-noise, dark noise, binning mode;
- Telescope parameters: f number, aperture diameter, optical transmittance, obscuration percentage.

Section 3 below provides details regarding astrodynamics and optics calculation implemented in the steps described above.

3. GEOMETRICAL ANALYSIS AND OPTICAL THEORY

3.1 Geometrical analysis

The geometrical analysis starts from the computation of satellites’ trajectories in Earth orbit using the 18th squadron elsets. Using the computed trajectories and the ground station positions, the celestial trajectories in terms of azimuth, elevation and range are computed with respect to each station local reference frame. However, since we are dealing with optical sensors, satellite visibility from a ground station requires certain conditions to be met, such as: line of sight between satellite and the ground sensor, satellite illuminated by the Sun and ground station in darkness. To do so, the visibility windows computations are performed by three main software modules described in the bullet points below:

- GenerateFilteredCatalog: computes the trajectories of the selected satellites batch. Satellites are filtered based on orbit altitude and physical size. An approximate batch size is around 10 thousand satellites;
- ComputeBatchScheduleMultiThread: computes the visibility windows using stations parameters (latitude, longitude, altitude, type) and windows constraints (elevation threshold, arc length threshold) for each station available on database;
- convertToStudyDataframe: converts the processed data in a format suitable for the optical performance algorithms. This is a data reduction process which keeps only the metrics relevant for the study.

Results are then stored in a dataframe of observation windows containing the following data:

- NORAD ID;
- Passage ID;
- Elevation angle;
- Distance;
- Phase angle;
- Object diameter;

These data will serve as input for the optical performance evaluation.

3.2 Optical analysis

3.2.1 From SNR to probability of detection

To estimate the detection probability is necessary to obtain the signal-to-noise-ratio of the system. Which is defined as [10]:

$$SNR = \frac{S}{\sqrt{S+BG+RN^2+DN^2}}$$

where S is the target signal component in photoelectrons, BG is the background component in photoelectrons, RN is the detector read noise component in photoelectrons and DN is the detector dark current component photoelectrons. The procedure to convert the apparent magnitude signal into photoelectrons is described in lightpollutionmap[12] and Lambert[11] as:

$$S = QE \cdot \tau_{lens} \cdot A \cdot E_{target} \cdot t_{int} \cdot \tau_{atm}$$

where *S* is the apparent magnitude signal in photoelectrons, *QE* is the detector quantum efficiency, τ_{lens} is the lens transmittance, *A* is the optical aperture area (m$_2$), E_{target} is the photon flux density from the target (ph$^{/\mathrm{s}/}$m$_2$), t_{int} is the integration time in seconds and τ_{atm} is the atmospheric transmittance, expressed by:

$$\tau_{atm} = \tau_{atm0}^{\sec(\pi/2-\phi)}$$

where τ_{atm0} is the atmospheric transmittance at the zenith as altitude dependent, and the telescope elevation angle in degrees.

A deeper consideration about the integration time must be done. It is obtained by summing the exposure time and the detector reading time and is valid only if the target is still in front of the lens/detector. In this particular scenario the target will not stand still on the same pixel, but it will stay inside it for a very limited amount of time. To obtain a good estimate of the signal-to-noise ratio, in this case it is necessary to consider the integration time as the time spent by the target in a single pixel. Assuming a Gaussian distribution, the probability detection can be obtained as [13].

$$P_d = \sqrt{\frac{1}{2\pi}} \cdot \int_0^{SNR} e^{-0.5(s-3)^2} dx$$

The algorithm also takes into account if a satellite has multiple passages on the same or on different ground station sites during the selected time window, and of course this affects the detection probability of the network for the single satellite. This is done considering that all events are independent and compositing probabilities so that the probability that the object has been observed 'at least once' by the entire network is obtained.

3.2.2 Chosen configurations characteristics

To achieve the best performance in terms of minimum satellite size, it is crucial to choose the right optical asset to be sure to detect the majority of cataloged objects and, last but not least, this asset must be physically realistic. To detect small objects it is necessary to use telescopes with a large aperture. These kinds of telescopes have a very high fixed focal length. The aperture and focal length are related parameters: high aperture means a high focal length. So, it is necessary to understand which focal length is suitable for a LEO object observation because a narrow instantaneous field of view (IFOV) will translate in a very short elapsed time of the target in the pixel and so into an exponential decrease of the signal and the probability detection. We take into consideration these factors to choose two possible configurations in Table 1.

Table 1. Optical characteristics for the two considered telescope configurations.

Parameter	Configuration 1	Configuration 2
Primary Mirror Diameter [mm]	800	400
Focal length [mm]	3040	1520

Parameter	**Configuration 1**	**Configuration 2**
Focal Ratio []	3.8	3.8
Linear Obstruction [%]	55	55
Resolution [pixel]	6144	6144
Pixel Size [µm]	10	9
Read Out noise [e–]	4.2	3.7
Dark Current [e–/s]	0.07	0.15
QE [%]	70	70

To evaluate the performance of each configuration, the probability detection has been calculated, related to the following conditions:

- Elevation angle from 30 to 90 deg;
- Target altitude from 200 to 2000 km;
- Phase angle of 30 deg;

The visibility altitude limit as a function of the debris size is reported in Table 2 the two configurations. Here the visibility condition is considered met if the detection probability is greater than or equal to 20%.

Table 2. Altitude visibility limits as a function of debris size for the two optical configurations selected.

Object Size [cm]	**Max Altitude Conf. 1 [km]**	**Max Altitude Conf. 2 [km]**
10	>2000	>2000
5	>2000	~1600
3	~1200	~500

4. SIMULATION AND RESULTS

In order to define the performance of the network, two scenario simulations were performed. For the first one, it was assumed to have ten different sites to place the observation assets, and twenty-one for the second scenario, which also includes the sites of the first scenario. The reason behind this is to give the algorithm a more distributed network and more possible sites to choose. It is important to emphasize that every selected location is an existing ground station, excluding the Sardinia site. The locations are chosen among the best zenith sky magnitude levels. The simulations were performed considering a filtered NORAD catalog, where objects are kept if they meet the following constraints when being propagated for 24 h observational window:

- The objects altitude must be under 2000 km;
- At least three acquisitions of the object can be taken, considering the sensor opening time;
- Acquisitions are considered feasible and completed if measurements have an angular separation of at least 10 degrees one from the other;
- Only objects with known sizes are considered. To obtain these data it has been used the SATCAT catalog assuming that all objects inside the catalog are spherical to calculate in this way the radius of the object from the RCS value. This catalog stores the RCS data of almost 12 k objects present in the NORAD catalog. For a more accurate analysis, the actual measurements of the object would need to be used; the radius obtained from the RCS was used as an estimate of what the actual dimensions might be.

The assumptions made for the algorithm were as follows:

- The object will be always centered in the field of view (FOV) and assumed as spherical;
- Clear sky visibility (>50 km) and a very dark background (>20 mag);
- Telescope Elevation (>30 deg).

To obtain a more accurate representation of the network performance, a weekly temporal mean of the algorithm results was performed, considering that each day has its own results. Observation window from 29/05/2022 to 05/06/2022 was taken into account for simulations, propagating 12129 objects from the Norad catalog. So the results of the algorithm will be valid for this specific window of observation. The considered possible sites are reported in Table 3.