USE OF MULTI-SITE OPTICAL MEASUREMENT FOR JOINT PHOTOMETRIC AND ASTROMETRIC OBSERVATIONS

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ABSTRACT

The increasing population of space debris and NEO objects is becoming a severe threat for all the on-ground and in-space infrastructure, because of the risk of potential collisions that may seriously damage these active systems. It is therefore of paramount importance to maintain updated catalogues containing estimates of the orbital parameters of objects belonging to the whole trackable population. Space Surveillance activities, such as in-orbit collision avoidance and re-entry campaigns, are typical based on publicly available orbital parameters (TLE), accessible only for catalogued and unclassified space objects. Unfortunately, TLEs are generally characterized by a few days or even faster degradation, which makes the information provided not completely reliable: object positions may be affected by errors of the order of several kilometers, mainly in the in-track direction, making the orbital prediction unreliable both at short (few hours in the specific case of objects at the end of their orbital life) and at large term (few days).

In this paper we propose a relatively cheap resource to improve the short and large term orbital prediction using multi–site optical measurements, i.e. collecting optical data of the same objects simultaneously from two or more sites. We plan to use optical measurements for joint astrometric and photometric observations: merging the astrometric information of the multiple sites we accurately retrieve the objects positions in the 3D space, while merging the photometric information we accurately retrieve the objects attitude. On one side, by reconstructing the 3D position of the objects using multi–site measurements we drastically reduce the in-track error on the orbit parameters (from kilometers to tens of meters depending on the experimental set-up) producing accurate TLEs at epoch and as a consequence improving the quality of the TLEs predictions both at short and large terms. On the other side, using objects lightcurves from different point of views, we may retrieve their attitude which much more details than when using the lightcurve from one optical measurement only and we may figure out the shape and the orientation of the object we are looking at. These two elements (accurate 3D position and attitude) are essential for the large term prevision, where a force model estimation has to be fed with information on the orientation, on the shape and on the position of the objects.

Keywords: Debris, Observations, Multi-site, Optical.

1. INTRODUCTION

From the beginning of human space activities on 4th October 1957, approximatively 5.000 rocket launches have placed more than 8.000 satellites into Earth orbit, of which only 1.800 are still active [1]. The disruption of these satellites, together with uncontrolled collisions have produced a incredible high number of fragments, which according to the Inter-agency Space Debris Coordination Committee (IADC) are defined as space debris: *Space debris are all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional.* The number of these debris is increasing day by day, as shown in Fig.1, where the evolution of the debris number is plotted as a function of time for all the orbits. ESA estimates approximatively 29.000 debris larger than $10cm$, 750.000 smaller than $10cm$ and larger than $1cm$ and 166 millions of fragments smaller than $1cm$. These objects may reach very high relative speed ($\sim 16km/s$) and as a consequence, even objects as small as $1cm$ are characterized by a sufficient kinetic energy to severely damage or even catastrophically destroy spacecraft or active satellites after collision events, eventually causing the spreading of additional fragments, capable to produce further collisions.

The first known collision between two satellites occurred in 2009, involving the US operating satellite Iridium 33 and the non-functional Russian satellite Kosmos-2251. Beside the destruction of both satellites, more than 2000 additional objects were produced in the catastrophic collision. Furthermore, since one of the two satellites was

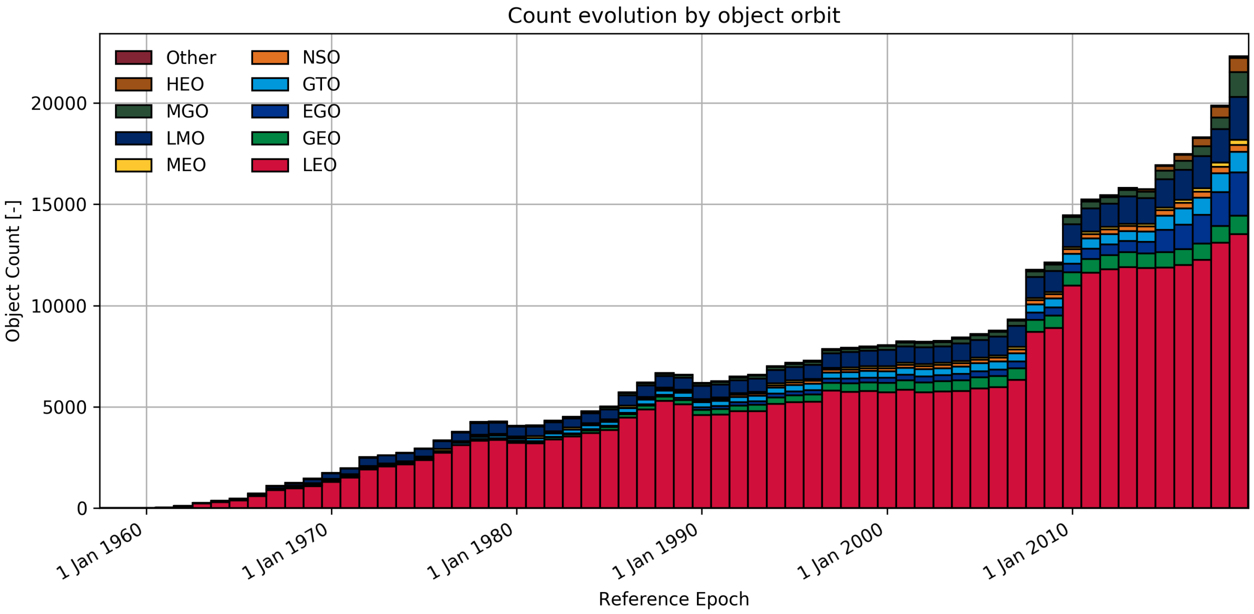

Figure 1. ***Space Debris in Numbers.*** *The number of space debris as a function of time. The plot shows the increasing number of space fragments from 1960's up to day, with colors identifying different regions. Image from the ESA'S Annual Space Environmental Report 2018 [2].*

still operative, the event had significant economic and social repercussions. More recently on 11th January 2007, China launched a ballistic missile from Xichang Space Launch Center [3]. The payload was a kinetic kill vehicle that collided, at a speed of approximately $34.000 km/h$ with a non–operational Chinese weather satellite, the Fengyun, completely destroying the satellite. This collision generated the largest debris cloud in orbit, producing more than 3.000 tracked fragments and 32.000 pieces smaller than $1cm$ that are still untracked.

It is hence of paramount importance the monitoring of the space debris population, together with the design of new strategies for debris removal and the adoption of guidelines devoted to the reduction of the produced non-cooperative orbiting objects. To this end, the United Nations (UN) released a set of recommended guidelines for the mitigation of space debris. These measures, that have been elaborated by taking into account the space debris mitigation guidelines developed by the IADC, include a 25-years limit of permanence in LEO and GEO orbital protected regions and the passivation of satellites and spent upper stages. In particular, in order for objects interfering with the LEO and GEO regions not to exceed the prescribed lifetime limit, satellites in LEO must be disposed by performing a de–orbiting or preferably a direct re-entry, whereas GEO satellites must be moved to a higher graveyard orbit. Space agencies, such as NASA and ESA, are working to design missions for the active in orbit removal of space debris. Nevertheless, performing such complex operations represents a technologically challenging task, which is requiring an important economical effort. As a matter of fact, currently the most direct and effective approach to address the space debris problem is the space debris monitoring, cataloguing and orbit determination, in order to prevent possible collision events through active debris avoidance manoeuvres performed by operational satellites.

The widest operation of detection, tracking, and identification of space objects is managed by the United States Space Command (USSPACECOM) through the worldwide extended network of radars and optical sensors known as the U.S. Space Surveillance Network (SSN) [4]. A further task involving the organization is to hold and constantly update catalogues of all detectable space objects publishing important information in specific formats that are generally publicly available [5]. A remarkable contribution in gaining data is given from the ESA Tracking and Imaging Radar (TIRA) [6], the Haystack long range imaging radar of the MIT Lincoln Laboratory and the NASA Gladstone radar [7]. The monitoring process of a space object becomes consistently difficult, especially in the last phases of its life. The determination of the main orbital parameters related to the phase of atmospheric re-entry of a satellite, is in fact one of the essential problems concerning a program of space surveillance. The difficulties associated to the prediction are due to the great number of variables concerning the physical characteristics of the object and its interactions with environmental factors, such as the gravitational field and aero–thermodynamic interferences. The formulation of an accurate model for the re-entry phase of a satellite requires probabilistic approaches considering the stochastic nature of the gravitational and drag perturbations. These algorithms are typically computationally very demanding due to the amount of random and unknown variables to be considered [8]. Therefore, the process that leads to a complete orbit determination is particularly complex and requires numerous measures that must be processed and elaborated.

In this paper we present a novel experimental technique to space debris tracking based on multi–site optical observation, which allows an accurate estimate of objects range and angular data as well as their attitude by merging information collected from multiple sites. This new experimental technique is meant to track objects not yet catalogued and moving on unknown or unstable orbits, particularly relevant in the field of space debris tracking and collision avoidance.

2. RELATED WORKS

Space debris measurements may be performed using optical, radar or laser instruments in combination with dynamic orbital prediction models. In particular, debris in low orbit (LEO region: $200 - 2000km$) can be monitored with both optical and radar/laser systems while, due to the low sensitivity of radars at great distances, debris in high orbit (MEO region and GEO: from $2000km$ to $36,000km$) can only be detected by optical instruments.

The ultimate goal of most forms of tracking is to determine the orbit of the objects gathering range and angular information. Radar and laser instruments estimate objects range with high accuracy ($\sim 1km$ for radar and $\sim 1m$ for laser see [9]) through the measure of the light time of flight, but they are less accurate in the determination of the angular information (the celestial coordinates of right ascension and declination). On the opposite, optical instruments retrieve accurate angular information, but in principle they can not retrieve the objects range: optical experiments are performed using a photographic sensor connected to a telescope, hence they represent the projection of the three–dimensional real space into the two–dimensional space (of the photographic sensor). Because of this projection, objects on different orbits may be associated to the same image and as a result, the three–dimensional position of an object, represented by its range together with its right ascension and declination, can not be uniquely determined.

Despite this intrinsic lack of information, optical instruments still represent the cheapest and easiest resource to gather data on space debris. The efforts of the scientific community is then focused on integrating optical measurements with reliable orbital prediction models that need to take into account perturbation factors such as atmospheric drag, ellipticity of the equator, the motion of the earth poles, the effect of the Moon and Sun (effect of the third body) and the solar radiation pressure. The parameters of such a complicated models can not be set *a priori* but they must be estimated on the basis of experimental measures, from which we may retrieve information not only on the objects position but also on their attitude, i.e. their shape and orientation in the $3D$ space. Objects attitude may be direct measured using optical instruments through the lightcurve analysis, see [10] [11] [12] [13], which may give relevant information on the atmospheric drag parameters, particularly significant for objects in the LEO region.

State–of–the–art methods involve the implementation of sequential Kalman filter, see [14], a very efficient and widely used recursive technique describing the laws of evolution of dynamic systems. Such iterative algorithm needs measures of the same objects at consecutive instants on times: the position of an object at time t is obtained from the image collected at time t and it is then used to estimate the object position at time $(t+1)$ through the dynamical model, adapting its parameters to minimize the error between the object estimated and measured position at time $(t+1)$. The limit of this Kalman sequential filter is the use of local measurements over time (the measured position of the object at time t and $(t+1)$) to estimate global parameters making the method unreliable.

This limit may be reduced determining the optimal parameters of the system with a global procedure over time, see [14] where the Kalman filter is not used in a sequential mode but at a global level: the parameters of the model are not adapted over time using a single measure and iterating the procedure, but the entire object trajectory, i.e. the entire set of positions, is used to estimate the model parameters, minimizing a global cost function that takes into account the error between all the estimated and measured positions at once through the non–linear Powell method. In [14], the authors show that the global approach not only improves the quality of the parameters estimation, but also that it successfully solves cases where the sequential filter fails, i.e. the algorithm does not converge.

The global approach improves the orbital estimation of debris, but is still weak regarding the reliability of the results in terms of accuracy of the estimated trajectory, because it does not overcome the lack of objects range information from an experimental point of view, but it addresses the problem with a post-processing procedure: the object range and velocity are initially set to default values and they are considered as parameters of the dynamic model. Therefore the overall minimization method converges to the correct solution if the initial estimates of range and velocity are close to the real ones, otherwise it converges to incorrect solutions.

The future goal is then to improve the accuracy of the optical measurements, hence improving the quality of the initial state for the global method.

3. MULTI–SITE OPTICAL MEASUREMENTS

In this paper we present a new experimental strategy, very well–known in other fields of research such as collective behavior (see [16]) and in general in computer vision (see [17]), to improve the quality of the optical measurements on space debris acquiring data using a multi–site approach: two optical instruments acquire simultaneously data on the same object. Multi–site optical measurements overcome the lack of objects range estimation, intrinsic of single–site optical measurements, merging the information from different sites to accurately reconstruct the position in the real $3D$ space of the object of interest. Therefore the object will lie on the line identified by the right ascension and declination in the local reference frame of each site, see Fig.2. Knowing its projection from two points of view, we may retrieve its 3D position as the point at the intersection between the two lines, see [15] and [17], hence determining the object range. With a similar approach we may retrieve information on the object attitude by merging the photometric measurements and the relative lightcurve analysis, hence obtaining accurate data on the object orientation at a given instant of time.

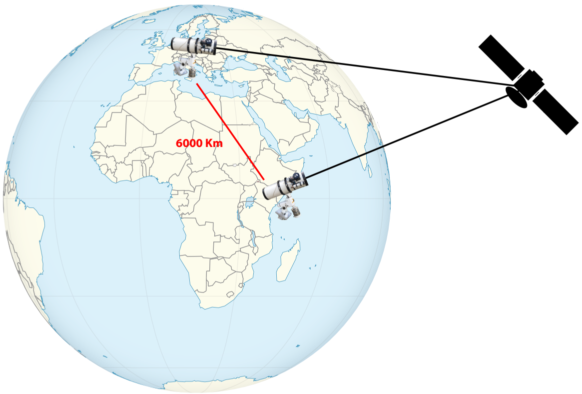

Figure 2. ***Experimental setup.*** *Multi–site optical measurements. Knowing the object projection from two points of view, i.e. the right ascension and declination in the local reference frame of each site, it is then possible to retrieve the 3D position of the object as the point of intersection between the two lines (depicted as the black lines in the figure).*

As for the single–site approach, we may now use multi–site data as the initial condition for a global method to estimate the parameters of the dynamic model. From the set of data collected at the two sites for some consecutive instants of time, we retrieve a noisy (but quite accurate) $3D$ trajectory of the object together with its attitude, we feed the model with these data and at a global level we find the parameters minimizing a cost function which takes into account the error between estimated and measured positions. Overcoming the objects range ambiguities due to the use of optimal instruments and improving the estimate of the position and orientation of the objects, we are improving the quality of the initial condition used in the global method, and hence we produce a more reliable solution.

The main benefit of using a multi–site approach is in the accurate determination of the initial condition for the global method, which may then be successfully applied to already catalogued debris on stable orbits (essentially to test the method and compare the multi–site estimate with its known TLE), as well as to objects still not present in the catalogue or to objects on unstable orbits, as for example objects re–entering the atmosphere. Note that these two latter cases are the most interesting in the field of space debris tracking because: i) objects not yet catalogued may represent a threat for all the active satellites and space systems and it is therefore relevant to discover them and make their position public to avoid collisions; ii) objects re–entering the atmosphere present not stable orbits and it is of utmost importance to accurate predict their re–entering location to avoid disasters.

The counterweight of such an improved accuracy with multi–site measurements may be found in a more complicated experimental procedure, in terms of: i) calibration of the system; ii) time synchronization of the data acquisition; iii) design of the set–up. All these three factors contribute to the accuracy of the final measurements, therefore calibration/synchronization procedures and set–up have to be carefully tested to keep the reconstruction error under control and produce high quality data.

There are two kind of calibration parameters of a multi–site experiment: i) intrinsic parameters - they are characteristic of each sensor and include: focal length, optical center position and distortion coefficient. These parameters strongly affect the determination of right ascension and declination of objects from each single sensor; ii) extrinsic parameters - they are characteristic of the optical systems and they are essentially the 5 angles, which describe the mutual position and orientation of the optical instruments used, and a metric baseline measure. These parameters strongly affect the accuracy on the object range estimation.

Intrinsic parameters do not depend on the specific position and orientation of the camera, but only on the optical sensor, therefore intrinsic parameters of each sensor may be calibrated only once, when the experimental campaign starts. On the opposite, extrinsic parameters do depend on the position and orientation of the sensors and hence their calibration has to be performed for every data acquisition. Calibration of both intrinsic and extrinsic parameters may be carried out using the fixed stars. In particular, for the calibration of the intrinsic parameters, we can shoot several images at different portions of the sky, i.e. rotating the telescope, identify the stars and from their well-known mutual distances, in terms of right ascension and declination, determine focal length, position of the center of the sensor and distortion coefficients. Instead, for the calibration of the extrinsic parameters we need to take a single picture from both optical sites, identify the stars in the common field of view and use their mutual distance to determine the mutual position of the two optical sites. The baseline of the system, i.e. the distance between the two sites, may be instead measured using the GPS coordinates of the two sites.

As for the intrinsic and extrinsic parameters, the time synchronization between the two sites is of crucial relevance. Indeed the accuracy of the $3D$ reconstruction is based on the estimate of right ascension and declination of the same object from two different points of view. A shift in time would correspond to an error on the angular information in one of the sites and hence in a object range error, which grows linearly with the time shift but quadratically with the actual range of the object, see [15]. In order to check the accuracy of the time synchronization between the two sites, we can not use fixed stars but we need to use moving objects such as satellites with a very well–known position and check on those object the reconstruction error.

The last and extra complication of the multi–site is the need of a large baseline between the observatories used. The accuracy of the reconstructed object range, see [15], is indeed linearly dependent on the ratio between the object range and the baseline of the system. This means that depending on the objects of interest, we may use different pairs of sites, checking that the fields of view of the two sites share a portion of the sky. For objects in the LEO region an acceptable baseline could be $\sim 100km$, while for objects in MEO and GEO regions the baseline should be much larger, $\sim 5000km$. In the next future we plan to perform an experimental campaign collecting data on objects in LEO region using the two following observatories: MITO (Mid Latitude Italian Observatory) in Rome and SCUDO (Sapienza Coupled University Debris Observatory) in Collepardo, both located in Italy at a mutual distance of $110km$. We are also planning to perform an experimental campaign on objects in MEO e GEO regions using the two sites: MITO in Rome (Italy) and EQUO (Equatorial Observatory) in Malindi (Kenya) at a mutual distance of $6000km$. For this intercontinental experiment, we will have a good temporal window to collect the data (telescopes looking at the same portion of the sky) of 11 hours per day during winter and 7 hours per day during summer for objects in MEO and GEO region, while we could collect data on objects in LEO only a bit earlier than dawn during summer and a bit later than dusk during winter.

4. CONCLUSIONS

We presented a novel experimental technique based on multi–site optical measurements that, together with an effective tracking algorithm, allows the accurate reconstruction of the $3D$ position of the objects of interest. With this new method we propose to use trajectories as initial values to a global minimization problem adapting the parameters not only on object range and angular information but also on the object attitude retrieved by merging data from lightcurve analysis of the data. In this way we introduce a stereoscopic experimental procedure that guarantee the global minimization problem convergence, providing accurate tridimensional initial data.

The method is meant to successfully work on objects not yet catalogued and on objects re–entering the atmosphere, moving on unknown or unstable orbits, particularly relevant in the field of space debris tracking and collision avoidance.

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