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DEBRIS TELESCOPES CATCH OBJECTS IN LEO ZONE

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Carlo Gavazzi Space SpA, INAF (Istituto Nazionale di Astrofisica), DM (Dipartimento di Matematica Pisa) and ISTI-CNR (Istituto di Scienza e Tecnologie dell'Informazione), all members of an Italian Team studying Space Surveillance topics, have been awarded the ESA SSA Feasibility study of an innovative system for debris surveillance. The aim of this paper is to present the architecture of the optical network used for the monitoring of the upper part of the LEO region and to build up and maintain an object catalogue to support the collision avoidance. The proposed Optical Network can in principle increase performances with a relatively small impact on the overall system costs, compared to the radar system so far considered to be the baseline LEO observation methodology. The feasibility of the proposed approach results from an innovative optical telescope architecture with performances tailored for the detection of objects in any Earth orbit (and also of Near Earth Objects). The innovative approach will allow to demonstrate the 'observability' of an object passing above a given station horizon despite the combination of demanding interplaying factors such as light, Earth shadow and clouds. The architecture proposed is modular, flexible with a characteristics suitable for an effective industrialization and world wide, applying a good combination of both innovation and available state of the art technologies. The hardware technologies need to be complemented by equally innovative software technologies, including the image processing to extract long, low signal/noise trails, the correlation and the orbit determination to use the minimum number of detected trails to obtain an accurate orbit.

I. INTRODUCTION

The large number of debris around Earth is a risk for the operative satellites and space vehicles safety[1]. So it is very important to monitor space debris with different methods and to know their orbits in order to prevent collisions. Once the requirements concerning the development of debris catalogues (even from a cold start) for effective collision avoidance are defined, it's necessary to preliminarily estimate which objects, and of which dimensions, will be observed at different altitudes. For debris observations radar and optical stations are envisaged, but also space based sensors (e.g. optical observations from satellites) are under study. The classical approach is to use radar observations for low altitude debris and optical observations for high altitude debris. Even for LEO orbits the introduction of optical based observation stations as a support tool for radar systems, can be effective in meeting Space Situational Awareness (SSA) requirements while to contain the costs, implied by complex radar apparatuses implementation and maintenance[2,3].

In this view we implemented a detailed study to identify and validate an alternative approach based on a mixed solution constituted by a ground based radar sensor and a ground based network of optical sensors

[1] D.J. Kessler and K.S. Jarvis- "Advances in Space Research", Volume 34, Issue 5, 2004, Pages 1006-1012, Space Debris.

[2] 16407/02/D/HK – "European Space Surveillance System Study Feasibility"- Final Report

[3] 18574/02/D/HK – "Detailed Assessment of a European Space Surveillance System"- Final Report

In particular the requirements and the performances of an optical sensor based observation network for the survey and tracking of LEO orbiting objects were studied in detail.

II. OPTICAL NETWORK REQUIREMENTS AND OBSERVATION STRATEGY

The optical sensors, so far used to Medium Earth Orbits (MEO), High Elliptical Orbits (HEO), Geostationary Orbits (GEO) and Near Earth Objects (NEO) observations, can offer good performances vs. costs ratio, also for the higher part of the LEO zone. The advantage of the optical solution comes from several considerations, as below expressed. Starting from the basic principles of radar and optical observations the characteristics of a network of sensors using optical methods can be understood only taking into account the fundamental differences produced by the physics of the observation process. The possibility of a trade-off between higher performance radars and lower performance radars supplemented with a different observational technique results precisely from these differences. The main physical difference between radar observations and optical observations is not only limited to the wavelength of the received signal, but rather in the type of illumination of the observed object. In the radar sensor the target is actively illuminated by the radar signals, whereas an optical sensor is based, on the contrary, on the passive reception of light scattered from the object illuminated by the Sun. The advantage of optical observations is precisely in the possibility of exploiting the abundant radiation provided for free from the Sun. The optical sensor detects a signal characterized by an energy density, per unit cross section area, immensely superior to the one achievable even with the most powerful conceivable radar system.

The performances advantage of optical based sensors arises from the fact that the intensity of illumination of the receiving surface is inversely proportional to the square of the distance between the target and the optical observer, whereas for radar technology this is proportional to the inverse of the fourth power of the distance.

On the other hand, optical observations have other limitations, also resulting from the physics of the observation process.

Because the source of light illuminating the satellite/debris is the Sun, an essential requirement is that the object is outside the shadow cone of the Earth. Moreover, the optical ground sensor cannot operate unless the ground station is inside the same shadow cone and the object elevation needs to be greater than a fixed value, such as 15 degrees, allowing for a reasonable air mass, avoiding unacceptable seeing values. Last but not least, there are meteorological constraints in that a simple cloud cover is sufficient to prevent any optical observation. These limitations must be joined to the effect of the Earth's surface curvature.

In essence, optical observations when compared to radar methods are easier for higher objects; the signal S is proportional to:

$$S \approx \frac{(d^2 \cdot D^2)}{r^2} \qquad [1]$$

where d is the diameter of the object, D is the diameter of the photon collecting area in the telescope (unobstructed equivalent) and r is the distance, which can be much more than the object altitude h. This implies that the minimum observable diameter is inversely proportional to the distance, for the same diameter D of the telescope. To decrease d the only option, besides the expensive increase of the telescope diameter, is to increase the exposure time. However this requires software technologies for image processing which are far from obvious, given the very fast rates of apparent motion of, in particular of low altitude, LEO objects.

All the above described concepts clearly indicate that for a successful implementation of the most efficient optical network, a well defined observation strategy must be adopted, taking into account the restricted conditions in which the observation of the objects produces significant results and exploiting the situations where the maximum achievable SNR values, and a space object population coverage meeting the SSA requirements on accuracy and timeliness can be obtained.

II. I Observatory Station Selection

The above described constraints pose precise limitations in the choice of the observatories locations: in fact, because of the requirement that the telescope be in full darkness, a nearly equatorial station can operate in theory only about 10 hours per day. Higher latitude stations can operate on the average for a similar time but with huge seasonal changes. However, as the night progresses from sunset to local midnight, the shadow cone grows larger and larger on the portion of the celestial sphere observable from a given station. For a nearly equatorial station at midnight, the shadow cone includes a portion of the sphere at height h which is all that could be observed, for all h < 2000 km, that is, a pass of a debris above an optical station is unobservable if it is around noon, but also if it is around midnight.

It must be emphasized that equatorial stations represent the most critical case in terms of effectively available observation time. This restriction relaxes at medium latitudes, but in this case is further complicated by the seasonal effects and by the meteorological factors. This implies that to compute if and when an object is observable from a given optical station requires to satisfy a number of rather complicated constraints, besides illumination and signal/noise ratio constraint.

Following these considerations, for the network performance evaluation, a set of seven stations was selected with three near equatorial and four at mid latitude location, operating a trade off between ideal locations and actual different geographical and geopolitical constraints.

<u>II.II Enhanced Observation Strategy and Dynamic Fence Concept</u>

The above described conditions on sunlight are quite restrictive: the orbiting objects all over the sky are illuminated only immediately after sunset and immediately before sunrise. The next figure shows the shadow cone for an equatorial station at local time 20h on Jan 1st

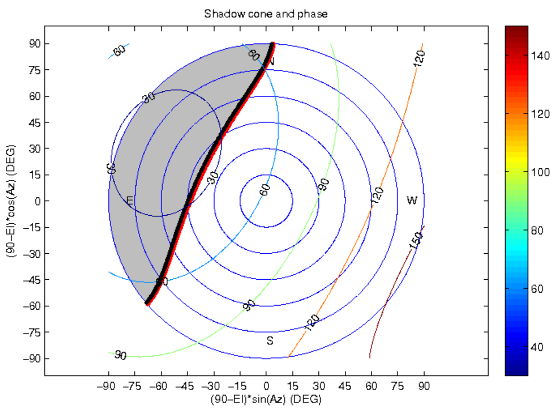

Fig 1: Sky and Earth shadow for an equatorial station at local time 20h on Jan 1st

In these graph the black and red lines represent the Earth shadow border at 1400 km above ground; they are actually the borders of umbra and penumbra. The Earth shadow region, which is the "forbidden" region, is gray. The blue circles represent the iso-elevation regions of the sky above the horizon, being the most external one the horizon of the location. The centre of the plot is the local zenith. The coloured lines (30, 60, 90 and 120) represent the iso-phase curves for objects at 1400 km above ground, that is the regions in the sky where objects orbiting at 1400 km above ground have a specific phase angle. The graphs show that the regions where the phase angles are smaller are very close to the Earth shadow border. The best conditions to observe objects at as much smaller phase angles as possible are during the minutes just after sunset or before sunrise. Very small objects, down to some centimeters, are detectable only when they pass very close to the Earth shadow border, at minimal phase angle and thus during the small observability window after sunset or before sunrise. It is very critical to begin operations as soon as the sky is dark enough to avoid background saturation of the images and, conversely, to stop operations as late as possible By combining the orbital geometry of passages above the station with the no shadow condition it is possible to obtain objects which are unobservable from any nearly equatorial station, at least for a time span until the precession of the orbit (due to Earth's oblateness, about 5 deg/day for h=1400 km) changes the angle between the orbit plane and the direction to the Sun. On the other hand the meteorological constraint can be handled by having multiple opportunities of observations from stations at different longitudes, far enough to have low meteorological correlation.

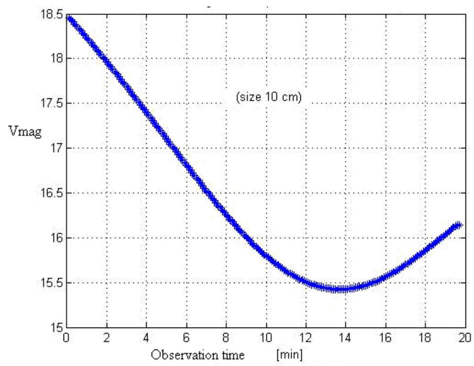

Fig 2: Example of apparent magnitude for a 10cm size object, placed at 1400 km as observed from one of the mid latitude stations, showing an evident evolution during the observation time due to a combination of the phase variation and of the distance.

The phase parameter combines with the distance of the object and strongly influences the apparent magnitude of the observed objects during observability conditions (see Fig 2).

The calculation of the apparent magnitude was derived from the absolute magnitude of the object by applying the standard asteroid model and assuming a mean 0.1 albedo value [4].

The general idea is to implement a "fence", realised by combining several telescopes that scan in a coordinated manner a well defined sky area, finally allowing the observation of the highest possible percentage of transiting objects. In this view, quick motion telescopes are a key for the implementation of a dynamic fence concept. The dynamic concept is based on the fact that the quick motion telescope cyclically scrolls the strip of sky involved in order to intercept all the particles going through it with the orbital parameters compatible for the type of observation to be carried out. This way it is avoided that the same object be observed an overwhelming number of times: further the quick dynamic motion of telescopes can be applied to observe exactly the area of the sky where the best phase condition occurs.

The debris telescope was then designed by applying mechanical components allowing a 1 second exposures every 3 seconds, with each image covering a new sky area: this way the motion of the telescope during the 2 s interval must cover around 6.7 degrees and provide stabilisation in the new position. The advantages, when compared to static concepts, where the telescopes are pointed in a fixed direction, are numerous: not only because the number of needed telescopes is reduced by a factor between 7 and 8, depending on the used strategy and tactics, but also because the dynamic positioning of the telescopes optimizes the observation and the particles are observed in the most efficient way.

In order to demonstrate the superiority of a dynamic fence with respect to a static Fence, a simulator was developed, which emulates a fence of $147 \times 14^{\circ 2}$ divided over three identical telescopes each capable of scanning a segment of $49 \times 14^{\circ 2}$. The simulator showed that three telescopes are sufficient for building such dynamic fence, since we verified the capability of observing about 98÷99% of the objects that crossed through it.

This simulation clearly evidenced the importance of a very wide Field of View (FoV), suitable to scan the most interesting portion of the sky in the fastest way.

II.III Ideal Multi Application Instrument

Once the observability conditions are satisfied a detailed analysis of the factors allowing to detect a particular object must be performed in order to assess the effectiveness of the applied optical architecture.

The possibility to detect an object and in particular to acquire an object tracklet, (the stripe of pixels illuminated by the objects during exposure time), allowing for successive orbital data elaboration, is fundamentally dependent on the object apparent magnitude along the trail, on the object speed, and on the sensitivity of the utilised optical sensor. All these factors contribute to the definition of the SNR generated in the acquired images of trailing objects tracklets. Only when this value exceeds a defined threshold then the theoretical object tracklet can be used for orbital computation (detectability condition).

The evaluation of the expected SNR values registered as a function of the object apparent magnitude is a key element for the definition of the optical system characteristics. For this purpose a detailed model has been developed considering the objects characteristics (altitude, relative speed, absolute magnitude, illumination conditions, etc.) summarised in its consequent apparent magnitude (i.e. photon flux available for the optical sensor) in order to define the characteristics of the optical instrument to be used. In particular the model was applied taking into account both the instrument parameters (effective entrance aperture, focal length, overall optical transmittance, CCD performances such as quantum efficiency, dark current, read/out noise, etc.) and the observation conditions (sky brightness, seeing, etc.), to evaluate the optimal exposure times to be adopted and the expected SNR values as a function of the observed object magnitude and speed (as described in paragraph II.IV).

The analysis of the different conditions allowed to evidence that a one meter equivalent entrance aperture telescope is necessary to obtain a suitable SNR value depending whether the observed object is either fixed or trailing. The objects were considered as orbiting at a 1400 km altitude, characterized by a medium 10 cm diameter size, and a 1s exposure time was adopted.

A further element to be considered is that the optical system must be 'seeing-limited' in terms of astrometric accuracy, allowing the maximum achievable precision in orbit determination: for this purpose a 1.5 arcsec astrometric resolution was considered in designing a High Resolution Camera with 256 Mpixels to guaranty the possibility of accurate astrometry, in fact the resolution of the camera must be comparable to the expected average seeing conditions.

The design of the telescope, constituting the optical core of the instrument, was then focused to obtain the necessary resolution (<1.5 arcsec) over the need wide FoV (6.7°x6.7°) of a one-meter-equivalent diameter primary mirror, to allow the collection of the amount of radiation energy which is suitable to detect

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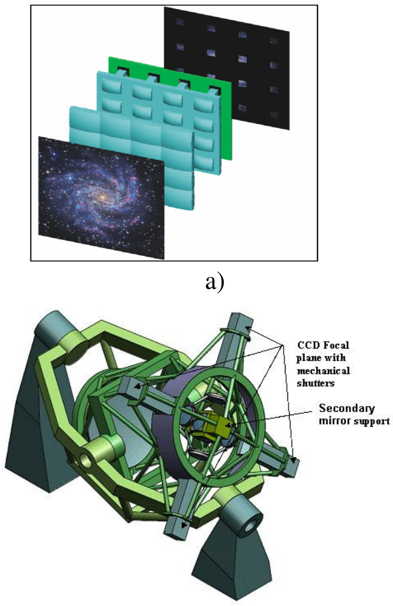
4 E. Bowell et al. 'Application of photometric models to asteroids', 1989

debris objects in the specified magnitude range. In this view an important concept was introduced, that greatly simplifies the overall optical design, namely the so called Fly-Eye (FY) structure.

This concept has been proposed for the fabrication of Fast Cameras in Wide Field imaging for very large aperture telescopes by the INAF Institute[5]. The FY design consists in splitting the overall FoV in sub FoVs on which an array of corrector elements are placed, in form of arrayed small sized lenslets, so making easier the correction of aberrations. This way the apparatus has lower weight and size with respect to any focal reducer or prime focus station of the same performance, and can be located at stations that are more accessible and do not, in general, require complicated top end changes.



a)

b)

Fig 3: a) Pictorial description of a FY. The image with a relatively large plate-scale is projected onto the lenslet array whose elements are field lens of the single focal reducers, and portions of the images are then imaged with a smaller plate-scale onto a number of small detectors; b) pictorial view of the debris telescope architecture

Another fundamental advantage offered by this innovative telescope solution is that its design is modular in nature that allows for mass production, and is therefore cheaper to produce. Due to the modular nature the performance of the FY as a whole is only limited by the performance of a single module. For example, a single unit only has to read a lot of small CCDs, maintaining a correlated fill factor equal to 1, rather than using a large buttable CCD array requiring parallel fast readout.

In our case the overall FoV is split in four subFoVs, each of which is further divided in a 2x2 portions, hence allowing the application of a total 16 4kx4k-CCD single chips, which are read in parallel by a corresponding number of dedicated processors, hence allowing very fast image read/out (two seconds red/out time are typical figures), covering an overall 6.7°x6.7° square field.

Finally, an important element to be remarked is that the resulting overall telescope architecture results in a very compact and relatively light structure, which allows fast and precise motion and positioning as well as reduced conditioning requirements.

II.IV Aggressive Computational Approach

To enhance the network efficiency we assumed that the image processing software, instead of being based upon the identification of the individual pixels with high enough SNR, specifically detects trailed images, by summing the readings along all possible lines in the frame. Such a software would be capable of extracting comparatively long trails, with SNR performances such that the SNR on each pixel of the trail could be even < 1.

Algorithms with this capability exist, have acceptable computational complexity and have been tested[6], however the actual implementation in operational software and field testing of the corresponding software is an assumption.

A limitation to the possibility of exploiting low SNR trails is in that the beginning and end of the trails would be poorly determined. This would result in a large astrometric error, which adversely affects the efficiency and accuracy of orbit determination.

The maximum possible efficiency in a survey to discover unknown debris is obtained by requiring a single exposure for each field, resulting in a single long trail. From the trail, the astrometric reduction can obtain a tracklet, consisting of two observations at the beginning and end exposure times; or equivalently, a couple of angular coordinates and their time derivatives. Anyway the information contained in such a tracklet is not enough to

[5] G. Gentile, A. Ragazzoni et al., "Wide Field Imaging on 8 to 100-meter class telescopes", Proc. SPIE, Vol. 6269, 62695V (2006).

[6] Milani, Villani and Stiavelli, "Discovery of Very Small Asteroids by Automated Trail Detection, Earth, Moon and Planets", 1996, pp 72, 257-262.

determine an orbit (4 equations in 6 unknown orbital elements). Thus it is essential to find correlations, which is equivalent to finding multiple tracklets belonging to the same physical orbiting object. [7] The classical algorithms for orbit determination require three separate exposures over the same pass above the observing station. More aggressive orbit determination methods, developed recently, require only two tracklets and there is one method, based upon keplerian integrals, which can compute an orbit starting from two tracklets observed at comparatively long intervals, corresponding to multiple orbital periods of the object[8].[9] By using these innovative and computationally intensive methods, it is possible to devise a correlation and orbit determination procedure requiring roughly one tracklet per day per object. In this way it is possible to exploit in full the capability of the telescope and camera system to perform one exposure every 3 seconds, covering 900 square degrees of new sky area every minute.

III. SIMULATIONS AND RESULTS

The AGI Tools Kit (STK – Satellite Tool Kit) has been used for simulated observations because it performs complex analysis of space assets and it allows to define relationship between the different objects integrated into a defined scenario. The STK computation produces simulated observations: i.e. STK simulates the data expected by the different observatory stations during an optical observation campaign. Such simulated observations (data) are then used by the ORBFIT software provided by University of Pisa for finding the correlation between different observation sets and for the orbit determination starting from the simulated observation provided by STK. The combination of STK simulated observations and the ORBFIT correlation and orbit determination allows evaluating the percentage of catalogued objects that is expected for a selected model of a space objects population. A whole series of functions has been identified to be developed in an external environment in order to integrate STK and ORBFIT work. Matlab was selected to the purpose, as both offering all the necessary mathematical and computational tools required to implement the identified functions, and being already predisposed to be interfaced with the STK.

A schematics of the simulation flow-chart is reported in Fig 4.

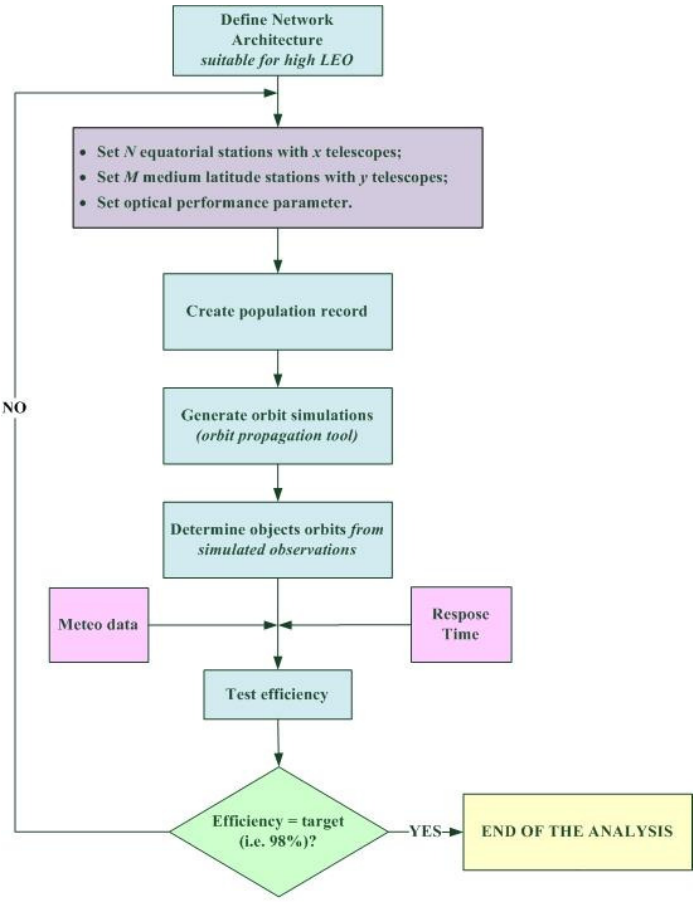


Fig 4: Schematics of the simulation flow-chart.

Two subset of objects, extracted from a MASTER2005 Population Model, which is an ESA reference model[10], updated with recently occurred fragmentation events, for objects with diameter >3cm, were selected with the following criteria:

<u>First Simulation Subset</u>
Debris count: 912
Perigee altitude: from 1301.023 to 1913.482 km
Absolute magnitude[11]: from 35.857 to 38.458
Diameter: from 8.098 to 26.828 cm
Simulation period: 28 and 60 days (from 1/1/2008)
Number of ground optical stations: 7

[7] Milani and Gronchi - "Theory of orbit determination", Cambridge University Press, 2010.

[8] Farnocchia, Tommei, Milani and Rossi, "Innovative methods of correlation and orbit determination for space debris, CMDA vol. 107, 169-185, 2010.

[9] Gronchi, Dimare and Milani "Orbit determination with the two-body integrals", CMDA vol. 107,299-318 ,2010.

[10] http://www.master-2005.net/

[11] See § II.II

Second Simulation Subset
Debris count: 1104
Perigee altitude: from 1000.26 to 1300.1 km
Absolute magnitude: from 36 to 39.5
Diameter: from 5 to 25.09 cm
Simulation period: 28 and 60 days (from 1/1/08)
Number of ground optical stations: 7

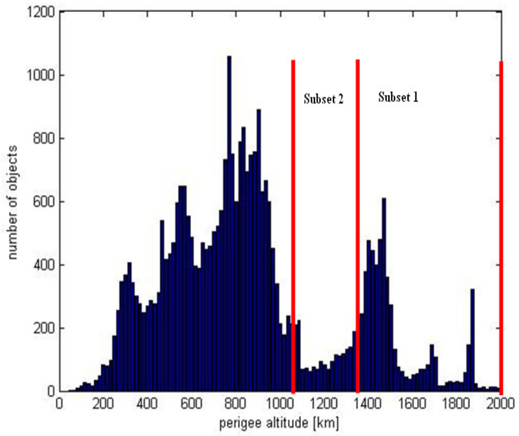


Fig 5: Population Model subsets as extracted from MASTER2005 (>3cm diameter).

The debris orbital data contained in the population subset were used by STK to simulate, in particular, the positional data in an equatorial reference frame. Other information regarding the relative position of the objects were included in the STK output, in particular the time of the observation, the range, the phase angle and the elevation angle. MATLAB was then used to process the STK simulated data to check the validity of the observation period, to calculate the apparent magnitude and SNR (applying a random error at the right ascension, the declination and the apparent magnitude).

Finally the Matlab results were fed to the ORBFIT software for orbit determination: in this phase also a random factor based on actual meteorological data of the selected observatory station was applied to take into account the incidence of the mean observed cloudiness on the simulated observations. The two debris subsets were propagated for two months and for each detected object the corresponding orbit determination was performed.

The following figure summarizes the simulation results.

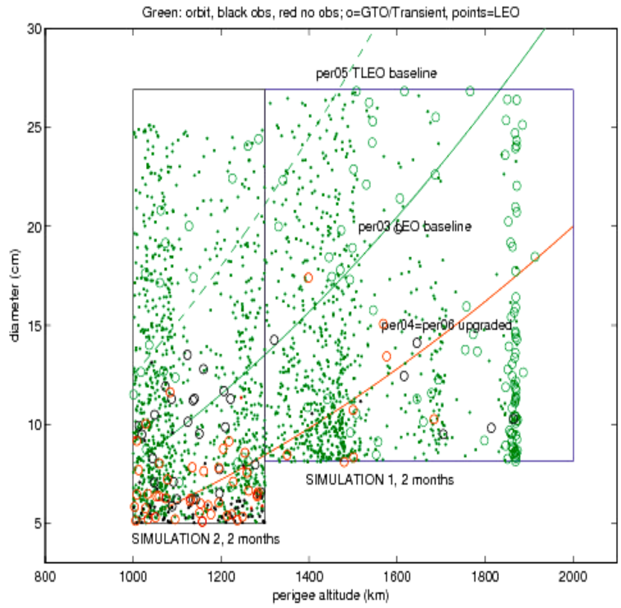


Fig 6: Green: orbits computed. Black: objects observed, no orbit. Red: not observed. Simulation 1 and 2 refer to the two simulation subsets. Baseline and upgrade refers to the requirements of study. It is clear that for perigee height above 1300 km the cataloguing phase of the debris is essentially terminated after only 2 months, while for the smaller objects with perigee between 1000 and 1300 km the task is not complete.

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IV. DISCUSSION

The results obtained are quite promising and are a consequence of the adopted approach based on innovative concepts. For what concern accuracy aspects and the timeliness of the catalogue build up and maintenance, the activities are still on going. and will be presented in a forthcoming work

In particular the role of the following key items must be stressed:

Advanced optical equipment (Debris Telescope Solution):

this aspect is particularly important offering numerous advantages with respect to the application of most traditional technologies. The main aspects of the innovation which render the optical equipment adequate to the challenge are:

- Entrance aperture: though imposing a more elaborate optical design allows the collection of a consistent amount of radiation energy, increasing the accessible object magnitude: a one meter equivalent entrance diameter generates a factor 4 in terms of photon flux impinging on the CCD sensor when compared to more traditional telescopes with 0.5m diameter of entrance aperture

- Pixel size: the 1.5” pixel offers a factor >5 in terms of noise reduction when compared to more conventional systems based on c.a. 5” pixel sizes
- Wide FoV, generated by the Fly-Eye concept: an increased FoV allows a slower scanning of the sky, offering a more efficient schedule in terms of image acquisition (exposition time) and read/out noise

Enhanced observation strategy:
this is another important aspect of the adopted approach which allows to focus the observations in the sky areas where the observed objects show the most suited illumination conditions: just to fix ideas the phase angle by itself was evidenced as a key element for observing an object in its maximal luminosity conditions with respect to the observatory during its sky trail.

Aggressive computational strategy:
this allows the treatment and the recognition of tracklets characterised by S/N values inaccessible by means of conventional image processing techniques allowing a >10 factor gain: just to fix ideas the application of the √N-criterion in lieu of the conventional N-criterion allows for a tracklet composed by 200 pixels a 200/√200 ~14 factor gain in the limiting detectable S/N value.

The innovative method of correlation and orbit determination requires only about 1/3 of the observations of the traditional methods, resulting in a corresponding decrease of the required sensor resources.

It must be stressed that only the concomitant application of all the above reported strategic elements can allow the implementation of an effective optical observation network, anyone of these not being available would cause a strong degradation of the expected performances.

A further element to be remarked is that the same optical network architecture allows not only the successful observation and catalogue build up of the objects interesting the higher LEO orbital belt but, by exploiting the remaining operative time not suitable for LEO, also the efficient observation of GEO, HEO, MEO and NEO fields, without lack of efficacy due to the reduced speed shown by the objects populating these orbital zones.

V. CONCLUSIONS

This work demonstrated the possibility to build-up an efficient optical network as support of radar based systems for LEO orbiting debris survey and tracking.

The main result of the study was the identification of all the elements optimising the performances of the optical network: in particular from our analysis it was clear that a good combination of both innovative concepts and off-the shelf technologies can allow the achievement of good performances in a time earning and cost effective way. In particular the innovative Debris Telescope Solution, implying the application of the fly-eye concept, appeared as a mandatory approach to obtain the optimised performances. From the study it was also clear that the identified system architecture can be also applied in a successful way to the observation of other orbital areas, such as MEO, GEO, HEO as well as NEO objects.

VI. ACKNOWLEDGMENTS

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