Mem. S.A.It. Suppl. Vol. 20, 50

Memorie della
Supplementi

Wide Eye Debris telescope allows to catalogue objects in any orbital zone

L. Cibin[1], M. Chiarini[2], A. Milani Comparetti[3], F. Bernardi[4], R. Ragazzoni[5], G.M. Pinna[6], I. Zayer[7], P.M. Besso[8], A. Rossi[9], and F. Villa[10]

[1] CGS SpA, Italy, e-mail: lcibin@cgspace.it
[2] CGS SpA, Italy, e-mail: mchiarini@cgspace.it
[3] Dipartimento di Matematica, Universitá di Pisa, Italy, e-mail: milani@dm.unipi.it
[4] Dipartimento di Matematica, Universitá di Pisa, Italy, e-mail: bernardi@dm.unipi.it
[5] Istituto Nazionale di Astrofisica, Italy, e-mail: roberto.ragazzoni@oapd.inaf.it
[6] European Space Agency ESAC, Spain, e-mail: Gian.Maria.Pinna@esa.int
[7] European Space Agency ESOC, Germany, e-mail: Igor.Zayer@esa.int
[8] European Space Agency ESOC, Germany, e-mail: Pier.Mario.Besso@esa.int
[9] Istituto di Scienza e Tecnologie dell'Informazione, CNR, Italy, e-mail: alessandro.rossi@isti.cnr.it
[10] CGS SpA, Italy, e-mail: fvilla@cgspace.it

Abstract. CGS SpA Compagnia Generale per lo Spazio formerly 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 by ESA a Feasibility Study of an innovative optical system for debris surveillance obtained by applying a good combination of both innovative and state of the art solutions. This paper presents the architecture of the optical sensor used for space debris monitoring, catalogue build up and maintenance for collision avoidance, considering the upper LEO belt, the most demanding test case. The proposed sensor is the core element of an Optical Network which, for objects orbiting in the high LEO, can in principle increase performances with a relatively small impact on the overall system costs, compared to radar systems so far considered as baseline for LEO observations.

Key words. Wide Eye Telescope – Space Debris – Fly-Eye – Space Surveillance (SSA)

1. Introduction

The large number of debris around Earth is a risk for the operative satellites and space vehicles safety (Kessler & Jarvis 2004). 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 obser-

Send offprint requests to: L. Cibin

vations 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, which is the application requiring the most stringent performances, 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 implementation and maintenance of complex radar apparatuses. 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 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.

2. 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 versus 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 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 by the Sun. In particular 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. Further, an 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. 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 signal degradation. 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:

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

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 object distance, which can be much more than the object altitude h. A further element to be considered is the trailing loss (i.e. the effect of the spread of the object signal on a pixel row rather than on a single pixel) due to the object speed, which increases as the object height decreases. This element, joined to equation (1), implies that the minimum observable diameter d_{min} grows as a function of the object distance for the same diameter D of the telescope. To decrease d_{min} the only option, besides an 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 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 are verified, and a space object population coverage meeting the SSA requirements on accuracy and timeliness, can be obtained. 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 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 centimetres, 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 have 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. 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 of main interest 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 possible to avoid to observe the same object 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 emulated a fence of $147 \times 14deg$ divided over three identical telescopes each capable of scanning a segment of $49 \times 14deg$. The simulator showed that three telescopes are sufficient for building such dynamic fence, since we verified the capability of observing about $96 \div 98\%$ of the objects that crossed the scrolled area. 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. 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 lower than 1. Algorithms with this capability exist, have acceptable computational complexity and have been tested (Milani et al. 1996), 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. In a survey campaign, the maximum possible efficiency necessary to discover unknown debris is obtained by requiring a single exposure for each field, resulting in a single long trail. Starting from the trail, the astrometric reduction process can produce a tracklet, consisting of two observations taken at the beginning and end exposure times, respectively. (or equivalently, a couple of angular coordinates and their time derivatives). Anyway the information contained in such a tracklet is not enough to determine an orbit (4 equations in 6 unknown orbital elements). Hence it is essential to find correlations, which is equivalent to find multiple tracklets belonging to the same physical orbiting object (Milani & Gronchi 2010). The classical algorithms for orbit determination require three separate exposures over the same pass above the observing station. More aggressive orbit determination methods, recently developed, require only two tracklets and in particular a method is available, 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 (Farnocchia et al. 2010; Gronchi et al. 2010). 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 completely exploit the capability of the telescope and camera system to perform one exposure every 3 seconds, covering about 900 square degrees of new sky area every minute. 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: this requirement is addressed as '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 perture, 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 together with the expected SNR values as a function of the observed object magnitude and speed. 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, as requested by cataloguing requirements which need an along-the-track orbit accuracy in the order of 30 m, in the upper LEO region. 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.

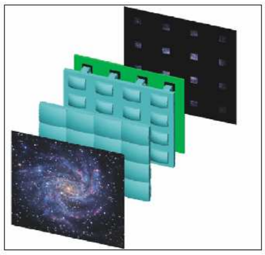

Fig. 1. Pictorial description of a FY. The image with a relatively large plate-scale is projected onto the lenslet array whose elements are field lens of the single focal reducers, and portions of the images are then imaged with a smaller plate-scale onto a number of small detectors

3. Ideal multi application instrument

The design of the telescope (Fig. 2), constituting the optical core of the instrument, was then focused to obtain the necessary resolution ($< 1.5\,arcsec$) over the needed wide FoV ($6.7 \times 6.7 deg$) of a one-meter-equivalent diameter primary mirror, to allow the collection of the amount of radiation energy which is suitable to detect 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 (Gentile et al. 2006). 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 on 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. Another fundamental advantage offered by this innovative telescope solution is that its design is modular in nature, allowing for mass production, and is therefore cheaper to produce. Due to the modular nature, the performance of the FY considered 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 $4k \times 4k$-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 $6.7 \times 6.7 deg$ square field.

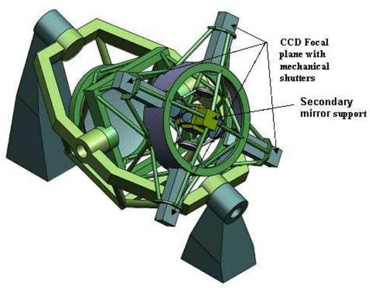

Fig. 2. Pictorial view of the debris telescope architecture

The one meter aperture equivalent telescope is characterised by a two meter effective focal length, giving rise to a relatively fast optics. Following these characteristics, a Pixel Size of $15\,\mu m$ corresponds to a Pixel Scale of c.a. $1.5\,arcsec$, as needed. The optical design of the telescope indicates the possibility to achieve subpixel resolution over the required $6.7 \times 6.7 deg$ FoV. As it can be observed from Fig. 3, the total encircled energy is greater than 80% over the whole single subFoV at sub-pixel

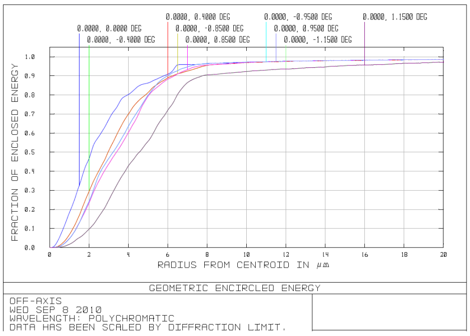

Fig. 3. Encircled energy figure of merit resulting from the FY design for a single sub-FoV

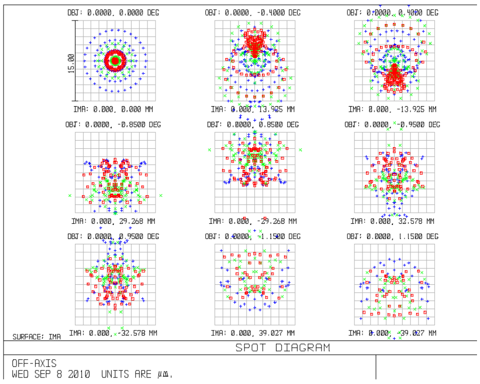

Fig. 4. Spot Diagram

level, this way, through the application of the FY concept, the same performance is obtained over the complete $6.7 \times 6.7 deg$ square FoV.

This performance is well evidenced in Fig. 4 where the achieved spot diagram characteristics are reported.

It must be observed that the optical design is performed over the entire $0.48\,\mu m \div 1.05\,\mu m$ spectral range. Finally, an important element to be remarked is that the resulting overall telescope architecture results in a very compact and relatively light structure (see Fig. 2), which allows fast and precise motion and positioning as well as reduced conditioning requirements.

4. Simulations and results

In order to verify the compliance of the optical instrument with the SSA requirements, a considerable number of simulations were performed. The AGI Tools Kit (STK Satellite Tool Kit) was applied to generate simulated observations due to its capability to perform complex analysis of space assets. Further STK allows to define relationship between the different objects integrated into a defined scenario. In particular by using STK the data expected by a set of different observatory stations during an optical observation campaign were simulated. Such simulated observations (data) were then used by the ORBFIT software provided by University of Pisa to find the correlation between different observation sets and to simulate the orbit determination starting from the simulated observation provided by STK. The combination of STK simulated observations and the ORBFIT correlation and orbit determination allowed evaluating the percentage of catalogued objects that is expected for a selected model of a space objects population. Two subset of objects, extracted from a MASTER 2005 Population Model, (an ESA reference model updated with recently occurred fragmentation events, for objects with diameter $> 3\,cm$), were selected. In particular the simulations were performed over two subsets of sample objects, the first constituted by 912 catalogued debris, with perigee altitude spanning from 1301.023 to 1913.482 and with diameter from 8.098 to 26.828 cm, and a second composed by 1104 catalogued debris with perigee altitude from 1000.26 to 1300.1 km, and diameter: from 5 to 25.09 cm (see Fig. 5). For both subsets the simulation periods were 28 and 60 days (starting from 1/1/08), whereas the number of ground optical stations was fixed at 7.

The debris orbital data contained in the population subsets 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

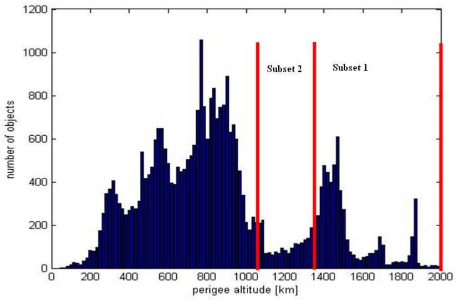

Fig. 5. Population Model subsets as extracted from MASTER 2005 (> 3 *cm* diameter).

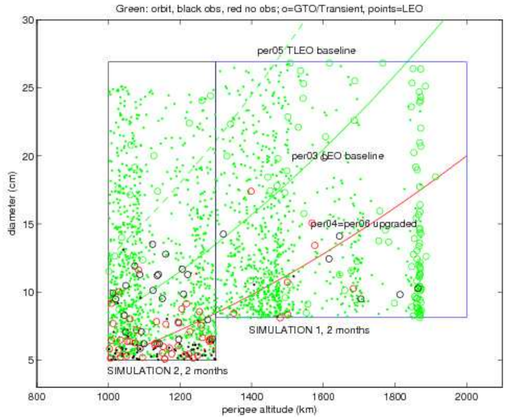

Fig. 6. **Green**: observed objects and computed orbits. **Black**: observed objects but no computed orbit. **Red**: never observed objects. Simulation 1 and 2 refer to the two simulation subsets. Baseline and upgrade refers to the requirements under study. It is clear that for perigee height above 1300 km the cataloguing phase of the debris is essentially terminated after only 2 months, while for the smaller objects with perigee between 1000 km and 1300 km the task is not complete.

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 Fig. 6 summarizes the simulation results.

5. Discussion

The results obtained are quite promising and are a consequence of the adopted approach based on innovative concepts. In particular the role of the following key items must be stressed.

5.1. Advanced optical equipment (FY 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 0.5 m diameter of entrance aperture
- Pixel scale: 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 scales.
- Wide FoV, generated by the FY 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

5.2. 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.

5.3. 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 $\sqrt{N}$-criterion in lieu of the conventional N-criterion allows for a tracklet composed by 200 pixels a $200/\sqrt{200} \sim 14$ factor gain in the limiting detectable *S/N* value. The innovative method of correlation and orbit determination requires only about 2/3 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.

6. Conclusions

This study demonstrated the efficacy and identified the system architecture that can be applied in a successful way to the optical observation of any orbital areas, such as LEO, MEO, GEO, HEO as well as NEO objects. In particular it was demonstrated the possibility to build-up an efficient optical network also as a support for radar based systems for LEO orbiting debris survey and tracking, opening a scenario of proficient cooperative synergy between radar and optical methodology. 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.

Acknowledgements. This work was possible thanks to the ESA/ESOC contracts 22750/09/D/HK SARA 'System Support for SSA Requirements Analysis' Part 1, and ESA/ESOC contract TELAD 'Co-V Telescopes Analysis and Design'.

References

Kessler, D.J., & Jarvis, K.S. 2004, Advances in Space Research, 34, 1006

Milani, A., Villani, A., & Stiavelli M. 1996, Earth, Moon and Planets, 72, 257

Milani, A., & Gronchi, G.F. 2010. Theory of orbit determination, Cambridge University Press

Farnocchia, D., Tommei, G., Milani, A., & Rossi, A. 2010. Celestial Mechanics and Dynamical Astronomy, 107, 169

Gronchi, G.F., Dimare, L., & Milani, A. 2010. Celestial Mechanics and Dynamical Astronomy, 107, 299

Gentile, G., et al. 2006. Proc. SPIE, 6269, 62695V

16407/02/D/HK - 'European Space Surveillance System Study Feasibility'- Final Report

18574/02/D/HK - 'Detailed Assessment of a European Space Surveillance System'- Final Report

http://www.master-2005.net/