A NEW TOOL TO OBSERVE LOW AND HIGHER EARTH ORBITS: THE METATELESCOPE

Michel Boër[(1)]

[(1)] *ARTEMIS (UCA – CNRS – OCA), boulevard de l'Observatoire, CS 34229, 06304 Nice Cedex 4 (France)*
Email: Michel.Boer@oca.eu

ABSTRACT

The observation of Remote Space Objects (RSOs) that are on LEO, or even re-entry of RSOs with optical means is interesting for several reasons: 1) optical telescopes, even moderate in aperture, are sensitive enough to catch RSOs in the cm range, 2) high angular precision can be achieved, 3) use of filters, or broad band spectroscopy, allows some access to the materials and physical quantities related to the RSOs, or, alternatively, photometry can give some information on quantities such as the spin, and 4) optical telescopes can be cheap, at least relatively compared to radar and lidar facilities. However, optical telescopes have a moderate field of view, especially when one wants to go to large apertures. Designing a telescope with a very large field of view, even 10° (which is small compared to a radar beam), can be difficult, expensive, and leads to very large focal plane area, and non-ideal response function. Though the problem for the illumination by the Sun cannot be resolved for optical telescopes, they can be used as a complement to large radar facilities, as they can be spread around the Earth. We propose a method, called the MetaTelescope, which uses a set of several moderate apertures, moderate field of view instruments, which is able to survey a very wide field of view for objects in non-geostationary orbits, especially LEO. With a dozen telescopes with a fov of the order of 2-3 degrees, areas as wide as 800 sq. deg. can be surveyed thanks to the MetaTelescope. In addition, as soon as an object is detected, it can be followed and studied with high precision. The system can be cheap and made robust. It is easily expandable, duplicable, with low maintenance. As it can be robotized, a network of *MetaTelescopes* can be deployed in remote locations, even with no local support, providing a round of the Earth surveillance and tracking network. Along the night, access to GEO, and surveillance of NEOs can be achieved.

1 INTRODUCTION

The observation of Resident Space Objects (hereafter RSOs), on the Low Earth Orbit (LEO) is challenging. RSOs can be active, passive (debris), and some, usually military satellites, can manoeuvre and have properties that limit their observability.

Radars are active detections systems that have several advantages: they have a wide field of view, they can perform ranging, they can observe through clouds and during the day, i.e. 24h a day. However they cannot locate a RSO in the sky as accurately as an optical telescope, even modest, the installation is often quite large and need a large electrical power, they are manned (at least remotely). Perhaps, their major disadvantage is the d^{-4} dampening of the signal, d being the distance of the RSO with respect to the observer that limits severely their capabilities to nearby RSO, unless large facilities are used. LADARs (LIDAR radars) can provide an accurate localization but they cannot be used through clouds, they have a very small field of view (fov), they suffer also from the d^{-4} response, and from a low returning signal unless retro-reflective devices are implemented on the RSO before launch.

Passive systems, such as visible or infrared telescopes, have a much more appealing response, that varies as d^{-2}, since the Sun is the source of the illumination of the satellite. Optical telescopes are easy to design and to build, they do not need strong resources, and they can be made fully robotized [1-4]: in this way they can be implemented in remote locations with the maintenance kept to a minimum [5]. Electronic detectors such as CCD, EMCCD and sCMOS of good quality can be found on the market and are easy to manage, and infrared sensors start to appear as COTS (Commercial Of The Shelf) cameras.

Telescopes have their disadvantages though: the main limitation for LEO is probably that as the Sun has to illuminate the RSO, and the sky background kept to a minimum, ideally at night. This means that for LEO observations have to take place near dawn or dusk, severely restricting the observation time. The use of infrared detectors can extend the observing hours, as the sky is far less luminous at these wavelengths [6]. However, when the orbit becomes higher (MEO, HEO, GEO…) this limitation do not apply, expected for short periods around the equinox for GEO [4].

In the following we will concentrate on LEO, but the observation problem as well as the solution we propose applies also for eccentric orbits with low perigee, to the re-entry of RSOs such as upper stages of launchers, and in general to all orbits that leads to rapid angular speeds on the sky.

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In the next section we will focus on the problem of the observation of the LEO orbit. In section 3 we present the design of the *MetaTelescope* system. In section 4 we discuss the operations, some management issues to improve the system while not multiplying its components, and a procedure (*Detect and Blind Tracking*) that enhances the precision of the measurements. In section 5 we discuss the use of the *MetaTelescope* for LEO, higher orbits and possible other targets and we present our conclusions.

2 THE PROBLEM OF THE OBSERVATION OF LEO

The main parameters for the observation of LEO [8] are the field of view explored, the size of the pixel over the sky that converts in pixel exposure time, and in turn will dominate the sensitivity of the system, and the observation strategy. There is a wide collection of orbits for RSOs in LEO, and even more if we include the above-mentioned eccentric orbits and re-entries, and a single site will not be sufficient. Therefore a network of about a dozen of sites, some at high latitudes, other near the equator and at moderate latitude, is needed for a complete Space Surveillance and Tracking (SST) network. We emphasize that an optical system do not replace radars, but should be seen as a complement to build a comprehensive SST system while keeping the expanses in a reasonable envelope.

The first possibility is to enlarge the fov (field of view) [7, 8]. This implies to use custom optical designs and lead to expensive solutions. Large fov telescopes have large focal planes, i.e. big and costly detectors. Large fov is also synonym of optical aberrations; even when using complicated lens correctors that have their own flaws, e.g. flux absorption, chromatism, etc.

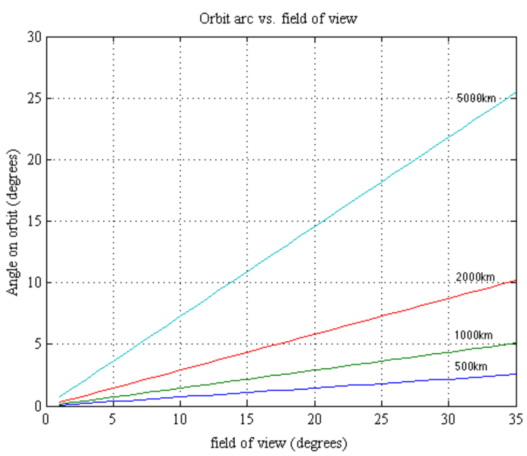

Figure 1: The portion of the orbit intercepted by a telescope as a function of its fov, for different orbits.

Lets take the example of a 5° fov, 1m telescope. This field of view corresponds only to 1/360 of a 1000km orbit (Fig. 1). If we want to build a f/2 telescope with these characteristics, the focal plane will be already larger than 15cm wide (21cm diagonal). The large E2V CCD231-84 chip is "only" 6cm wide. Commercial cameras based on it (from ANDOR or Spectral Instrument) have price tags between 200 and 300k€. Mosaic custom cameras with a 15 x 15cm focal plane are quoted around 700k€ to 1M€ depending on their specification of noise, cooling, etc.

If we want a fov of 5° on a CCD of size 3cm (approximately the size of the E2V 42-40, camera prices between 55 and 70k€), the focal length will be about 340mm, corresponding to a 10cm aperture telescope at f/3. Though fov of size 10° or more have been proposed and even achieved for telescopes ranging in the 1m size, we do not consider this option as practical, even as desirable, for an actual SST network based on optical components.

In fact the aperture of the system is only one aspect of the problem. At least for survey tasks, the telescope will be fixed, or in sidereal tracking, while the RSO crosses the field at speeds that can reach 1°/s or more (Fig.2).

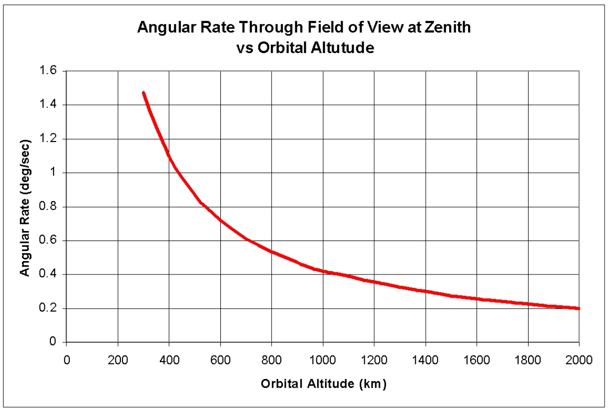

Figure 2: The angular rate of a RSO vs. its orbital altitude.

This is quite large and means that the time spent on a single pixel will be quite small, on the order of few ms at the best. Therefore the best system will be a trade-off between aperture and fov (see e.g. [9,10]), and given the brightness of the objects in LEO, even cm sized, there is no need to compete for absolute sensitivity.

In the following section we propose a solution that solves elegantly the fov, and pixel exposure, problems.

3 THE *METATELESCOPE* SYSTEM

RSOs, even those who have some manoeuvrability, have to follow orbits, unlike birds. What matters is their detection and orbit determination over a large range of parameters. There is no need to follow them over an extended area of the sky. Therefore we propose to monitor only the border of a region, rather than the whole territory.

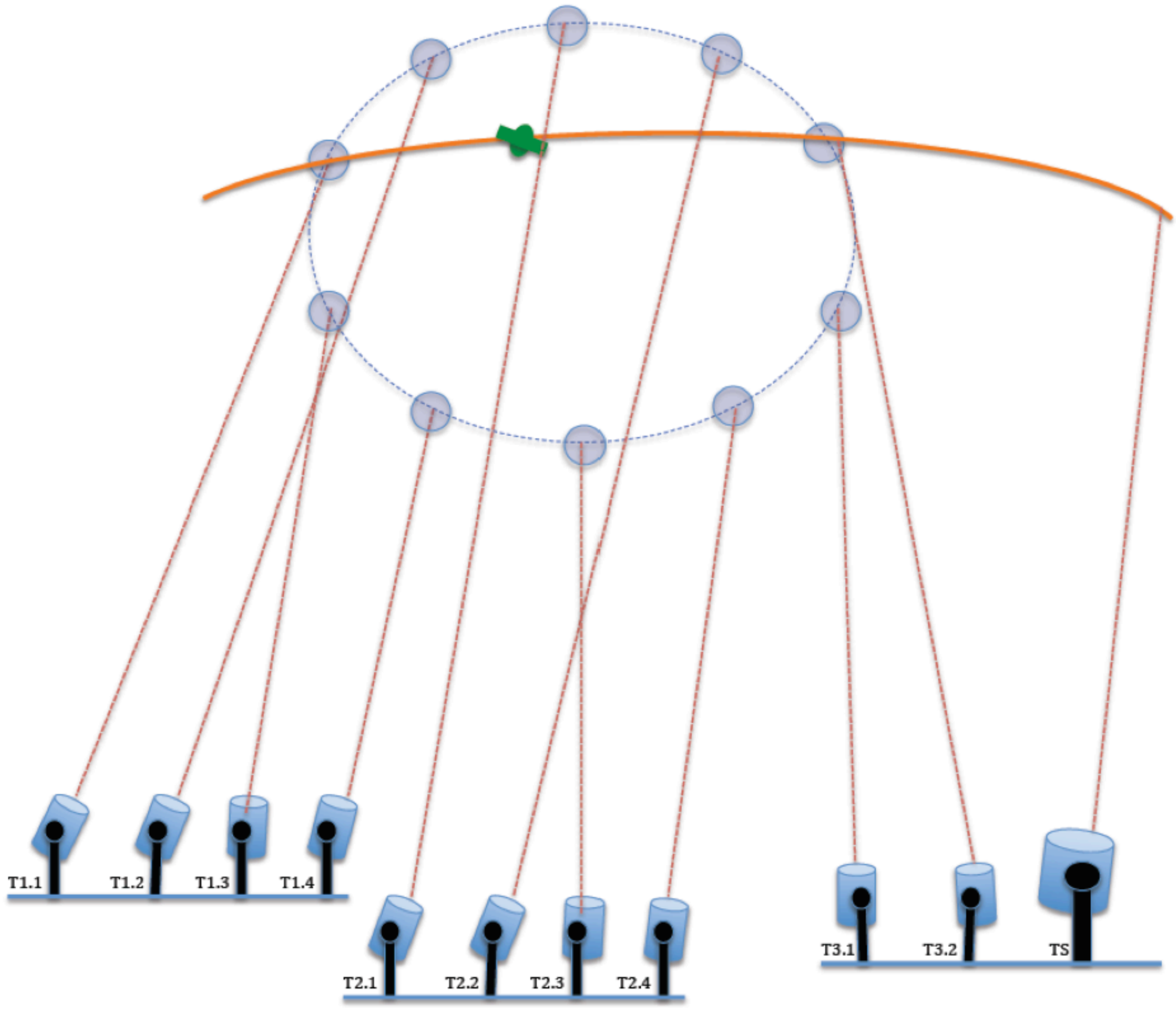

Figure 3: A possible configuration for the MetaTelescope. T1.1 to T3.2 are the survey telescopes, while TS is a follow-up telescope that can have spectroscopic capabilities for further studies.

This is depicted in Fig. 3. The *MetaTelescope* is a telescope farm. When the RSO enters the area under survey it will leave a track on one of the survey telescopes (here T1.1) and eventually on another instrument (here T3.2) as it exits it.

About 10 – 20 instruments are needed, with moderate size (say 30 – 50cm). There is no need to locate the individual instruments under the same dome: several locations can bring parallax measurements at the same time, at the expanse of more infrastructures. We have featured a follow-up telescope (TS in Fig. 3) that can be used for follow-up studies, determination of a more precise orbit (see section 4.2), spectroscopic parameters for a physical study, or even a LADAR or radar.

The geometry of the system is adjustable and it will depend on the family of orbits that is under study, on the elevation above horizon, and on the latitude. A blind search can be made with a circular or ellipsoidal ring, while for the study of heliosynchronous or equatorial orbits a double straight line might be more appropriate.

Lets suppose that we study a circular cone centred on zenith, 15° in diameter, as shown in Fig. 4. We use 10 telescopes of fov 3° each, defining a 3° thick ring centred on zenith. Though, to our knowledge, there is no COTS telescope with that fov in the range of aperture 30 – 50cm, such a solution is relatively easy to design, as shown by our TAROT (Télescope à Action Rapide pour les Objets Transitoires – Rapid Action Telescope for Transient Objects) experience [5]. Several possible designs have been proposed [11 – 13], while the Newton hyperbolic configuration remains an attractive solution for speeds not exceeding f/D < 3. In Fig. 4, three additional follow-up telescopes are featured that can make additional measurements, enhance the coverage of the system, etc.

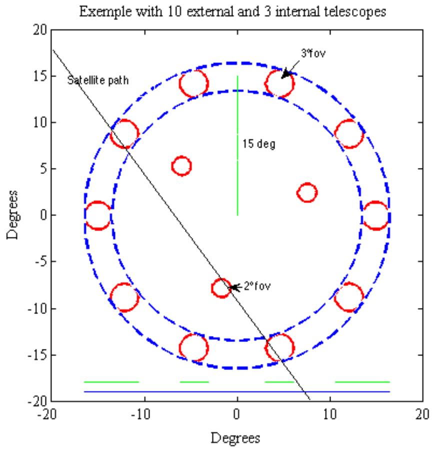

Figure 4: A 10 MetaTelescope with 10 instruments, and 3 follow-up telescopes.

As the 15+3° cone is not completely covered, only 60% of the RSOs entering it will be intercepted (we suppose random directions). This converts into an area of 470 sq. deg., or an equivalent single telescope fov of 24°, quite difficult to achieve.

If we want to cover the whole area, 30 telescopes are needed, as shown in Fig. 5. In that case, 800 sq. deg. are covered, converting into 30° fov. However this is not an optimal solution, as explained in section 4.

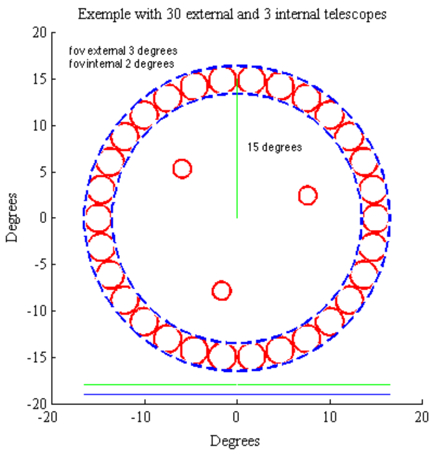

Figure 5: With 30 telescopes the 15° radius ring is completely covered.

Of course, there is no requirement in pointing to the zenith. An elevation around 30° is more optimal as it enhances the area surveyed, and limits the speed of the RSOs.

4 OPERATIONS AND OPTIMIZATION

4.1 Operations

We suppose here that the system is completely robotic. This is not a problem, as shown with our expertise with TAROT [2 – 5, 14 – 15]. The down time due to technical breakdowns is below 10% [5] even for the telescopes in remote locations as La Silla (Chile), La Réunion Island (France overseas territories) and Australia, with no dedicated support on site.

The telescope – detector impairment is quite difficult to solve. We have already explored some designs that enables a 400mm telescopes to have a 3° fov on 4cm detectors, that are commercially available. Perhaps the best chips will be sCMOS, though the field is moving. To process the images, several methods have been proposed such as the Radon and Hough transform [16], and morphological mathematics [17], possibly implemented on GPUs boards [18] or on multicore machines. The dimensioning parameter here, is that the crossing time of a single field should be more than 2s to get full tracklets within the fov of individual telescopes. The readout should be small compared to the exposure time, i.e. at most 0.5s, and even less for exposure times on the order of 1- 3 s. Modern CCD cameras can achieve such speeds, but at the expense of the readout noise. EMCCD and sCMOS are much more promising, but large scientific detectors are not yet commercially available.

For the detection, the telescopes can be either at rest relative to the Earth, or in sidereal tracking. This depends essentially on the procedure and algorithms used to compute the astrometry and trajectory, and on the family of orbits under study.

As soon as the RSO is detected on a first image, a vector (position – speed) can be computed, and a simple extrapolation allows predicting the next telescope in view of the RSO. A more active procedure can be used, and a large telescope can slew to the predicted path of the RSO to capture it and look at properties such as the spin. This leads to the proposal of the specific operational procedure we are now describing.

4.2 The *Detect and Blind Track* procedure

An interesting possibility is to use a mount that is precise enough to track the RSO using the encoders alone. We have developed for TRE (TAROT – Réunion) such a mount, called RAPIDO [5]. It slews with a 20 arcsec accuracy and tracks with arcsec accuracy for several minutes, even for rapid RSOs. This has been demonstrated with the widely distributed images of the follow-up of the separation of the Galileo

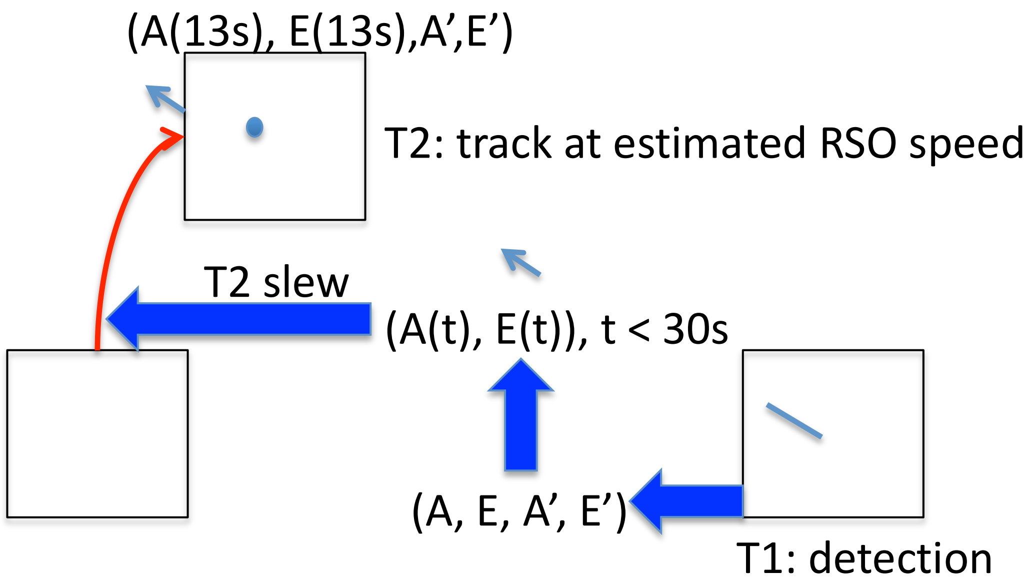

Figure 6: The Detect and Blind Track procedure.

satellites from the EPS (Etage Supérieur de Propulsion – Upper Propulsion Stage) of Ariane VA 233 (see Fig. 13 of [5]).

We propose the following procedure (Fig. 6): a first telescope, T1, detects the streak left by the RSO; a (position, speed) vector with 4 elements (azimuth, elevation, and the derivatives of both quantities) is computed at time t_0 from the comparison of the streak position and time, and the stars within the fov. This allows to extrapolate the position of the RSO and it speed at a later time (13s in Fig. 6); a second telescope, T2, slews to the position in order to be ready to observe at $t_1 = t_0 + 13s$ (as exemplified here). Thanks to the RAPIDO mount we can slew with T2 to the position and track the source at a speed based only on our simple extrapolation. The errors in the vectors, either from the measurements or from the rough approximation used, will elongate the image, allowing for a much more precise determination of the position and its derivative.

Thanks to the pseudo-point like image, the SNR (Signal to Noise Ratio) will be greatly enhanced; it allows confirming the source, and therefore detecting at smaller SNRs. T2 can be either one of the telescope of the farm, or a dedicated, larger with smaller fov (and angular pixel size) instrument.

If the *detect and blind track* procedure cannot be applied, e.g. because the measurement is of poor quality, then the RSO will cross the central part of the system and it will possibly intersect a second telescope of the MetaTelescope, leading to two points in its trajectory, and the computation of a first orbit, supposing a circular orbit. A follow-up can be launched, either using the above mentioned *detect and blind track* procedure, or just a telescope (from the farm or dedicated) placed on the trajectory and waiting for the RSO.

Then a catalogue is enriched, either with a new object or an updated measurement.

We note that as we have already a first information on the orbit, an observation campaign can be made as we can predict the apparition of the RSO over other regions, even with a single telescope network such as TAROT.

4.3 The *Multiplexed MetaTelescope*

Let address now the problem of the number of telescopes in a single farm. As shown in Fig. 5, 30 telescopes are needed to cover the entire ring of 16.5° outer radius.

We suppose that the RSO speed is at most 1°/s, though the procedure can be adapted to any, reasonable, speed. We keep the characteristics of our example system as those described in section 3 (cone of 15° radius, fov of 3°). Let N_C be the number of telescopes that are needed to cover the whole ring, and N_T the number of telescopes we can buy: then

$$\nu = {}^{N_T}\!/_{N_C} \qquad (1)$$

is the filling factor, and

$$\kappa = \mathrm{int}\left(\frac{1}{\nu}\right) + 1 \qquad (2)$$

is the multiplexing factor. If we want to simulate a full

N_T system we have to move the telescopes κ times while the RSO is crossing the field.

Though this is challenging, as already mentioned, modern CCD cameras, sCMOS and EMCCDs can already achieve such readout speeds. In the above example the telescope should move every second, meaning that the dead times should be less than 1/10 of a second.

4.4 The *Distributed MetaTelescope*

We have already mentioned that possibility in section 3. There is no requirement to place all instruments within a single dome, albeit this can be simpler and cheaper. They have to have access to the same area of the sky (i.e. the ring) at the same time and with the same weather conditions.

If we spread the instruments over a larger area, then we can derive at the same time parallaxes. At 500km the parallax will be 40 arcsec for two telescopes separated by 100m only, an angle that is easily measurable (for TAROT, accuracies of 1 arcsec are routinely attained). For the geostationary orbit, a separation of 1km leads to a parallax of 5 arcsec, again within the reach of a simple device.

We have already exemplified this configuration in Fig. 1, the telescopes being distributed in three different buildings.

5 DISCUSSION AND CONCLUSIONS

We have shown that the MetaTelescope is a viable alternative to more complicated designs. However, as already mentioned, observations of LEO orbits can take place only close to dawn and dusk, leaving ample time devoted to other targets.

5.1 High orbits

The GEO, HEO and GTO (at apogee) orbits are visible the whole night (at least for GEO). If we want to detect all potentially hazardous objects in GEO, we need to explore a thick belt of 20° in elevation at several position around the orbit, and centred on the countries (e.g. Europe) in view of the satellite (for telecommunication / remote sensing satellites) with +/- 6h in longitude (Fig. 4). The MetaTelescope can make a complete survey of the GEO belt within the night, and repeat it for new potentially dangerous objects, or for RSOs, either active of passive, that can lead to a potential collision, in support to anticollision activities, such as the CAESAR centre of the CNES (Centre National d'Etudes Spatiales – National Centre for Space Studies, French Space Agency).

At a distance of 36000km, a moderate aperture 40cm telescope can detect RSOs that are 10cm or less in size (supposing an albedo of 0.2).

We conclude that the MetaTelescope is an ideal instrument for all orbit families, thanks to its high throughput, and dynamic reconfiguration capabilities along the night.

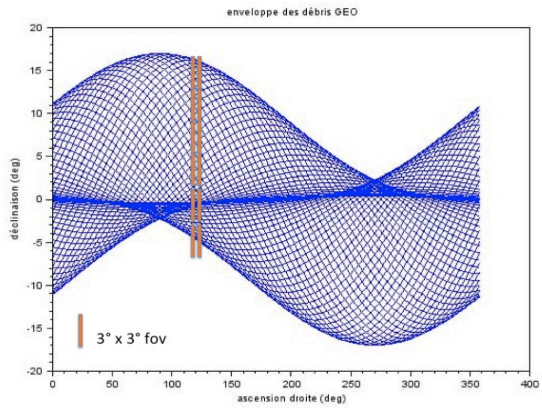

Figure 7: The envelope of debris drifting in GEO, compared to the MetaTelescope fov. Note that the apparent elongation of the MT fov is due to different scales in the x/y axes. Courtesy P. Richard, CNES.

5.2 Technical implementation

The MetaTelescope is a fully modular system. It is made of a dozen identical telescopes. They are equipped with the same mounts, the same cameras, drives, etc. Building such a facility, and the dome(s) to host it is simple and inexpensive compared to complicated large instruments.

The failure of an individual telescope will lead to a slight degradation of the overall system performance, but it will still be operational.

As the elements of the system are identical the maintenance is facilitated, and the redundancy is high. It can consist, preventively or after a breakdown, in simply removing the faulty telescope, in moving it to a nearby workshop, and working on it in a comfortable environment while the *MetaTelescope* is working safely. Possibly a cold redundant system can be in stock for a small increase of the overall system price.

We present in Fig. 5 the implementation proposed for the RAMSES (Robotic Advanced Multimessenger and Space Environment System) facility to be installed at the National Aurès Observatory (Algeria)[19]. The system features 16 40cm telescopes, each with fov of 40cm. A dedicated workshop is located inside the building, and a 1m telescope provides an additional deep sensitivity and spectroscopy capability.

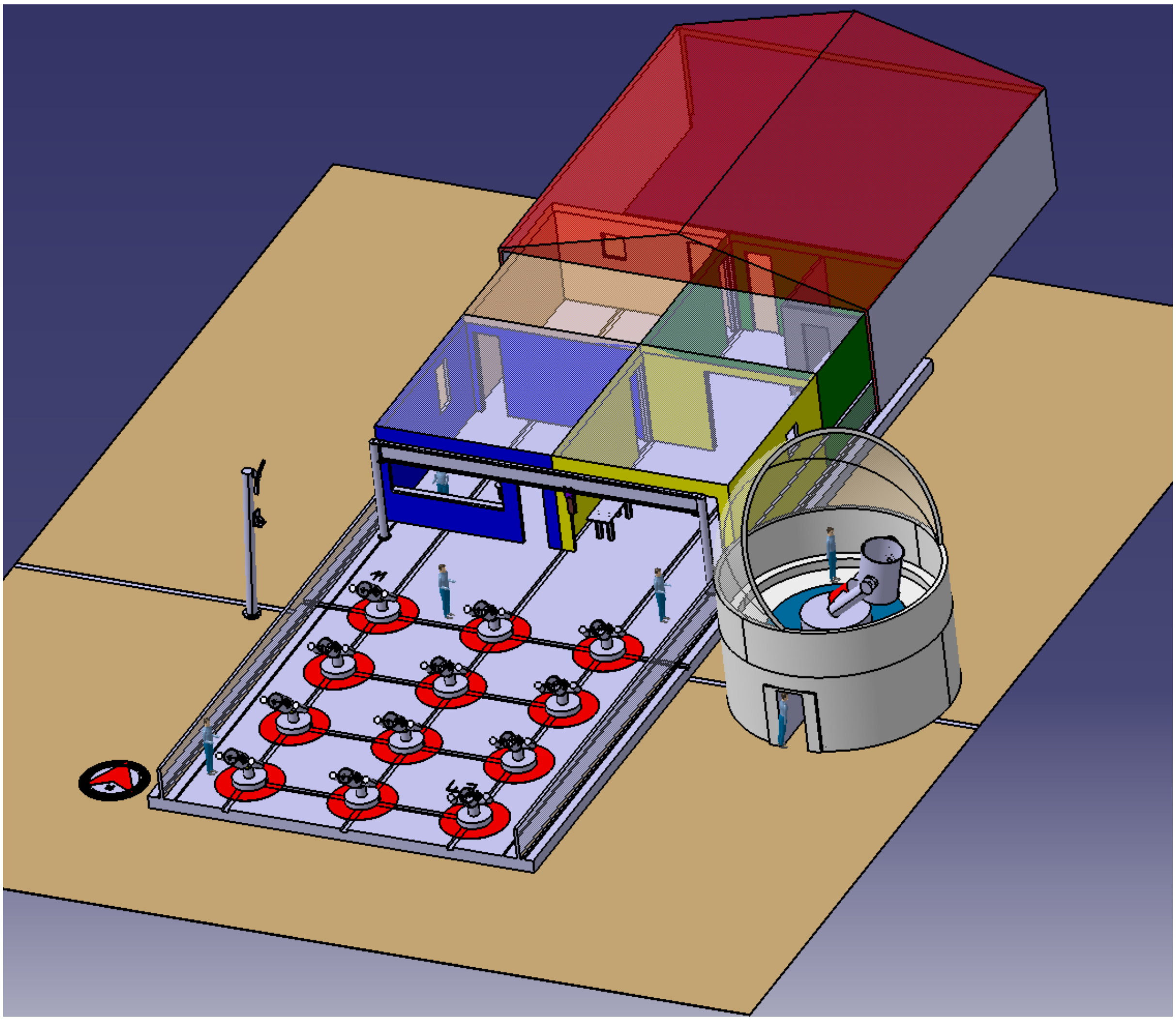

Figure 8: The RAMSES facility planned for the National Aurès Observatory

A complete SST systems for the LEO would require about 10 such system installed around the globe, in addition to radar facilities that are usually located in Europe, in the USA or similar countries. For that purpose the MetaTelescope has the advantage of being easily reproducible and agile. The needs in maintenance are low, as well as the consumables are reduced to a minimum, and the risk for a complete breakdown reduced to almost zero. A small solar plant can provide the power, and the INTERNET can be provided by a satellite constellation. The network can be managed from a central facility, such as the CADOR (Centre d'Accés aux Données des Observatoires Robotiques – Data Access Centre for Robotic Observatories) system installed at the Haute Provence Observatory in France [5].

5.3 Conclusions

We have proposed a system that is able to monitor the LEO at low cost. At the same time, the *MetaTelescope* can take on all the tasks needed by a SST system covering all orbits (from re-entries to GEO and beyond). Though the scheduling, management, data processing and archiving software is relatively complex, the operational costs are very low. Specific modes of operations, such as the *Detect and Blind Track* procedure or the *Multiplexed MetaTelescope* provide powerful means of detection while reducing the number of individual telescopes by a factor 2 to 4.

We note finally that beside the SST, the *MetaTelescope* can be used to monitor Near Earth Asteroids to avoid potential hazards resulting from the fall dawn of a large asteroid on Earth.

We believe that the MetaTelescope is a credible alternative for a comprehensive Space Surveillance and Tracking Network.

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