The *MetaTelescope*: a System for the Detection of Objects in Low and Higher Earth Orbits

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ABSTRACT

We present a new design involving several telescopes of moderate aperture and field of view for the detection of mobiles in space over a very wide area on the sky. The system uses relatively simple and cheap telescopes associated with commercial CCD, EMCCD or CMOS cameras. The instruments can be placed in a single building ("dome") or collocated in subgroups with separation from 100m to 5km (provided the weather and accessible sky remain the same). In the later case parallax measurements and ranging are possible. We provide a simple example with a dozen of telescopes surveying and area of 800 square degrees over the sky. Thanks to its versatility the system can survey and follow-up objects in Low Earth Orbit, and be used for higher orbits, either drifting or geostationary. In one of its version, a "multiplexed" use of the telescopes allows to survey an identical area, dividing the required number of instruments needed by a factor of 2 to 3. We introduce also the *detect and blind track* procedure that can be used to get higher sensitivity and better precision for the orbit parameters.

1. INTRODUCTION

The observation of resident space objects (hereafter RSO, either active satellites or debris) in low Earth orbit (LEO) can be challenging. Radar are used widely for the observation of LEO objects, up to 2000km, but their efficiency decreases quickly with the altitude; depending on the wavelength, they can be insensitive to small sized RSOs (less than few decimeters). LADARs (LIDAR radars) are efficient to compute precise orbit parameters, but they need an accurate designation, or the use of an accompanying (hence passive) telescope. Both LADARs and radars are expensive items, they need powerful sources of energy, and usually they are manned. Unless very powerful beams are used, they cannot be used routinely for high altitude orbits, either HEO or GEO.

Passive optical systems have been developed mostly for the survey of the GEO orbit, either for active satellites and for debris (when they are in fact drifting and no longer geostationary) and a number of systems are in use in the world and have been mentioned extensively over the different proceedings of this conference series. They are usually working at optical wavelengths, though the use of infrared wavelengths has been explored [1]. Passive optical systems can detect small objects either on high altitude or low Earth orbits [2] [3], thanks to the Sun as the illumination source. Telescopes are easy to automatize [4] [5], they are economical in terms of the use of resources, they can work in full autonomy, and the data reduction methods are known, though there is a vast literature to achieve better performances [2] [6] [7] [8]. Optical telescopes of moderate size (diameter in the range 20 – 100cm) can be very efficient [3], as shown by the TAROT system [9]. The main disadvantage of optical telescopes is that they do not work when the sky is cloudy; they are restricted to nighttime (if IR is not used) while the RSO should be in the Sunshine. The later is not a real problem for GEO and high altitude objects at apogee, but gets more complicated for LEO and the perigee of eccentric orbits.

The issues for the observation of the LEO have been summarized in [7]. The main parameters are the field of view (hereafter fov) explored, the efficiency of the system, which depends critically on the size of the detection element (pixel), and on the observation strategy. Because a single site cannot detect all RSOs in LEO over the all the orbits, a complete survey should be performed from at least a dozen of sites, including low latitude locations, with the additional advantage to secure good weather somewhere.

The usual answer to the field of view problem is to design wide fov telescopes [10] [11]. Though custom designed instrument may have to a good performance, the price of the optical system, and the very large detectors usually required to map the focal plane(s) lead to technological difficulties and rocketing prices.

A telescope based on Earth sees only a small portion of the LEO orbit. As an example, a field of view of 5° correspond to 1/360 of a 1000km orbit. Designing and building such a telescope with a diameter of say 1m and f/D = 2 (a very fast speed) implies a focal plane detector larger than 15cm. If we want to survey a fov of 15° on a 3cm camera (approximately the size of the EEV 4240 CCD), the focal will be 120mm, corresponding to a small telephoto. Getting the same 15° field with 600mm focal length (e.g. a 40cm f/1.5 telescope), a 15cm focal plane is required. Though the design of very wide field optics is a very active topic [12] [13], achieving fast ratio even with moderately large apertures can lead to aberrations and high costs, plus the large cost of the detector, usually custom made, the constrains on the supporting mechanics, the data processing, etc.

Here we propose an innovative approach that uses mostly out of the shelf parts, or easy to design, standardization of the elements, and gives a solution to survey a very wide field without using a very wide field of view telescope, and standard detectors commonly available. In the next section we describe the solution we propose; section 3 address the operations of the system, and introduces the new *detect and blind track* procedure we propose; section 4 presents some specific modes of operation such as the *multiplexed MetaTelescope* and the *distributed MetaTelescope*; In the last section we discuss the various other objectives the *MetaTelescope* can address, thanks to its great versatility, and we conclude with some technical considerations and prospects for implementation.

2. THE SYSTEM

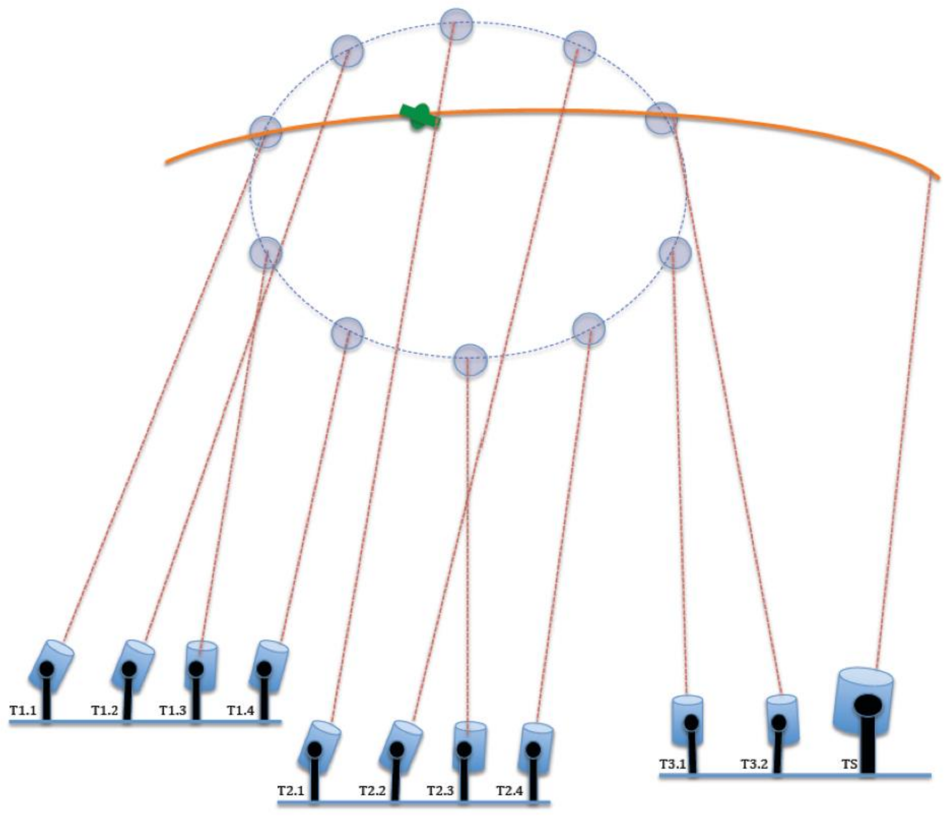

Fig. 1: Conceptual design of the *MetaTelescope*.

We base our system on the simple remark that unlike birds and fighters aircrafts (and aerobatics) RSOs usually do not change their way as they turn around the Earth. Only small maneuvers leading to changes of orbit are allowed, in which we are also interested to. Therefore it is not necessary to survey the complete region of interest; what matters is to detect and measure extensively what enters in the surveyed area, derive a first guess of the orbit to be able to recognize the RSO during a further pass, or as it flies above another station. To that purpose the best strategy is to use a telescope farm, where telescopes are operating synchronously. The *Metatelescope* consists of a set of several telescopes (say 10 – 20), with a moderately large field of view (1° - 4°), operated in such a way that they survey a crown on the sky (the figure can be a ring, an ellipsoid, rectangle, anything appropriate). They do not need to be located in the same dome and their number can be limited using some specific mode of operation (see section 4). Some telescopes (or LADARs/radars) can be added to the system for follow-up purposes.

The design of the *MetaTelescope* is illustrated in Fig. 1: in this case we survey a cone in space that has a given direction (e.g. an altitude of 40°) and a given diameter (e.g. 30°). Each telescope surveys a portion of the periphery of the cone (the crown). An RSO will enter the surveyed area; it will be detected by the first telescope, then by a second telescope. Eventually a follow up telescope (one of the telescope of the system, on another, dedicated telescope, or a lidar…), will take additional measurements to enhance the precision of the orbit determination. As shown Fig. 1, the area is not completely covered. This point will be addressed below and in section 4.

The geometry of the system over the sky depends on the family of orbits studied (a blind search may benefit from a circular zone, while heliosynchronous or equatorial orbit searches will be optimized with a double straight line, or an ellipsoid configuration). However, for simplicity, in the following we focus on the circular geometry.

To fix the ideas we will study a circular cone centered on zenith, of 15° in diameter, as shown in Fig. 2. The 3° fov telescopes define a thick ring of 10 telescopes. A good system could be implemented with telescopes in the range 40 – 60cm; though there are no commercial optics available for this combination of diameter / fov, it cost remains reasonable. We have also drawn 3 complementary telescopes that maximize the detection efficiency, provide additional measurements for orbitography, and may be triggered for pursuit as soon as a new target is designed (see section 3.1).

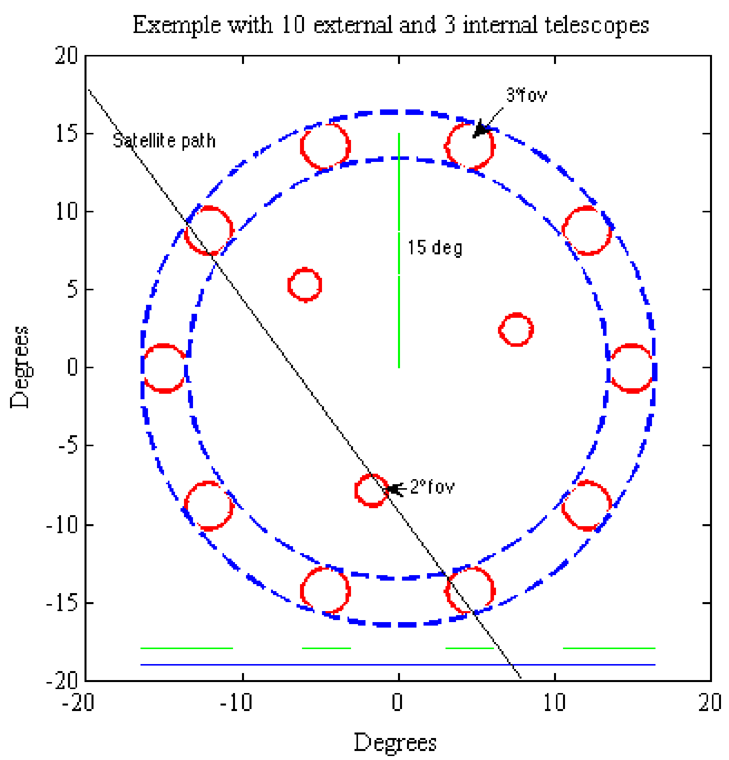

Fig. 2: The example with 10 telescopes (fov 3°); Follow-up telescopes are shown inside the cone.

In this example the perimeter is not completely covered. However, the system will intercept 60% of the RSOs entering the zone, corresponding to an equivalent area surveyed of 470 sq. deg. For a single telescope this equates to a challenging fov of 24°, especially if one wants to get a good sensitivity. Covering the whole perimeter of the cone would require 30 telescopes. In that case about 800 sq. deg. will be surveyed in all directions. Of course, we do not need to look at zenith. An appropriate geometry and an elevation around 30° leads to a larger covered area, as previously noted [7]. At zenith, the *MetaTelescope* will survey an arc of 2.5° on a 500km orbit, and almost 10° at 2000km (instead of 3° for the challenging 10° fov telescope).

3. OPERATIONS, RSO DETECTION AND BLIND TRACKING

Lets turn now on how the *MetaTelescope* can be used during operations. We suppose that the system is completely robotic. This is not a problem, as shown by the experience gained with the TAROT/Zadko network [14] [15] [16] [17]. The down time due to technical causes is below 10%, even for the remote locations of La Silla (Chile) and Gingin (Western Australia), with no dedicated technical support on site, nor at night or at day.

A field of view of 3° can be achieved with a 400mm f/2 telescope and a wide CCD camera, such as those based on the Kodak KAF16803. Alternatively a good choice would be an EMCCD or a sCMOS: albeit there are no scientific cameras based on large (i.e. ≥ 30mm) chip, 24 x 36 sCMOS chip are available with low noise. As the time spent on a pixel is on the order of a millisecond even with the speediest telescopes, and the time to cross the fov can be as fast as 3s, it is important to achieve the best compromise between aperture and pixel field of view, which in turn will drive the effective sensitivity of the whole system (see e.g. [7]). However, methods based on the Radon and Hough transform [18] or on morphological mathematics [2] have been proposed; for that specific problems they can achieve high sensitivities within acceptable computing time, especially when implemented on GPU boards [8] or multicore machines (E. Bertin, private communication). What is important is that the exposure time should be on the order of 1 – 2s to get full tracks portions in the fov, and the readout time should be small compared to the exposure time. Modern CCD cameras achieve such speeds, but at the expense of a high readout noise. EMCCD and sCMOS are much more promising.

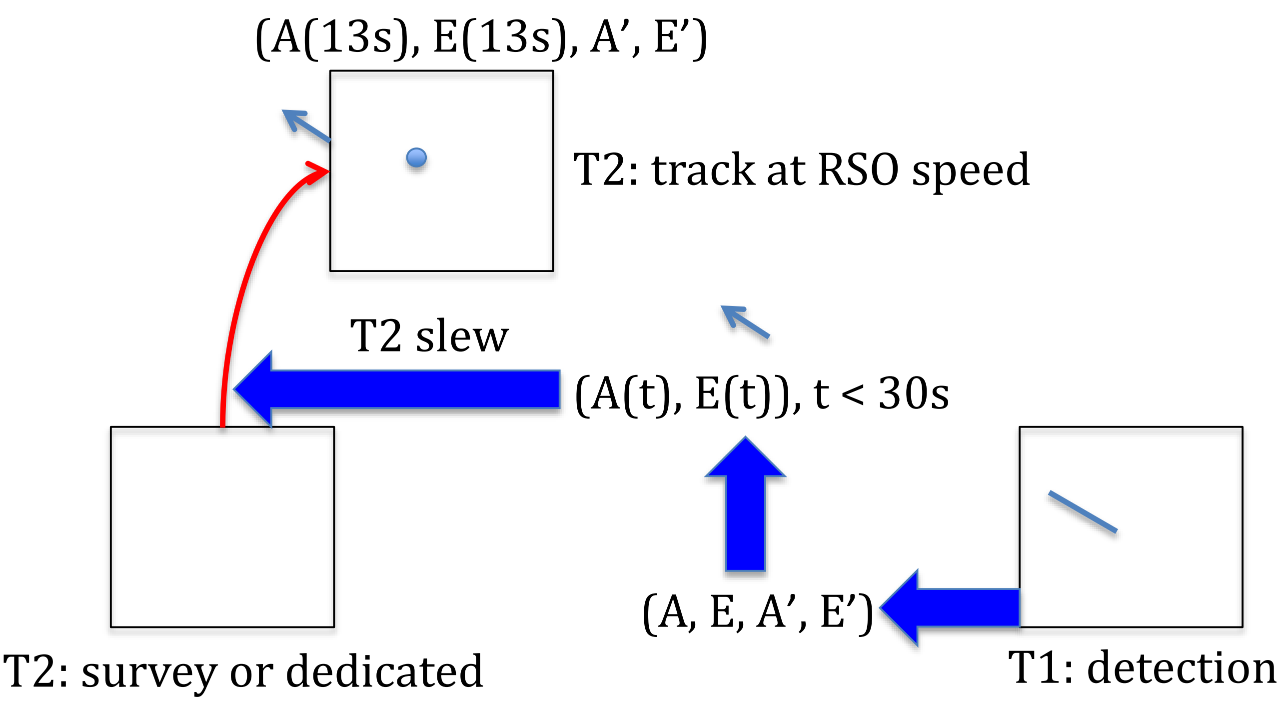

Fig. 3: Sketch of the *detect and blind track* procedure: telescope T1 detects a streak; a vector (position, speed) of the RSO iq computed that is valid locally (say <30s); a second telescope, either one from the *MetaTelescope* or another, dedicated follow-up telescope, is sent to the pre-computed position of the object, and starts tracking at the RSO speed. The RSO appears point like on the images, or can be slightly elongated depending on the errors.

For the detection the telescopes can be either at rest relative to the Earth, or in sidereal tracking, depending on the procedure used to compute the astrometry and trajectory, and the orbit observed. As soon as the RSO is detected on the image, a vector (position – speed) is computed, and a simple extrapolation is enough to derive a position that is valid locally (i.e. not a too long distance) for the large 3° fov, or even a much more restricted fov, e.g. 1°. This last options allows the use of a large (1m) follow-up telescope that can be used to confirm the detection (hence we can set a lower SNR ratio for the detection telescope), and derive a much more precise orbit, look for properties, spin…

3.1 The *detect and blind track* procedure

An interesting possibility is the use of a mount that is precise enough to be able to track the RSO using the encoder information alone. Such an instrument is currently under development (RAPIDO, A. Klotz and P. Thierry, private communication), and would offer an interesting alternative over more conventional systems. We propose the following scenario for a typical follow-up, as illustrated in Fig. 3: One of the *MetaTelescope* instruments, named T1, detects a RSO by the streak it leaves on the image. Note that in the case of a CMOS or EMCCD, the streak can be decomposed in individual images, producing a more precise trajectory. We compute the vector (position – speed), e.g. the azimuth (A), elevation (E) and their derivative (A', E') at time t_0 from that streak and the reference stars on the image (and time). Let suppose that the computation is done in 5s, and the information available in 10s (total time). This information can be used to extrapolate a position that is valid locally, say for the next 10s – 1 min. Then a second telescope, T2 slews to the expected position at time t_0 + 10s (or 13s as exemplified in Fog. 3). If the encoders are precise enough, and the motion correctly controlled, then T2 can follow the target up, which will appear as a point like source on detector of T2. The errors in the vector (position – speed) will elongate the RSO image. This allows eventually a confirmation of the source, therefore effective detection at smaller SNR, and a study of the photometry (satellite properties, Sun illumination, spin…), accurate orbit determination (because then it is followed over a large arc on the sky), etc.. T2 can be either a dedicated telescope, e.g. larger with smaller field of view (1° should be enough), and/or equipped with filters, or one of the telescope from the *MetaTelescope* farm, optimizing the system efficiency and decreasing the total cost.

If the above procedure cannot be used (because of the unavailability of proper mounts, or large errors, or high computing times…), then the RSO will cross the central part of the system, and eventually intersect the fov of a second telescope of the MetaTelescope (Fig. 1 and Fig. 2). At that stage we have already two points on the trajectory, and two velocity vectors, enabling the computation of a first orbit guess. A follow-up can be placed, either following the *detect and blind track* procedure described above, or just waiting on the path of the RSO, giving a third measurement of the RSO position – speed, hence a better orbit determination.

Finally the RSO is eventually identified in a catalogue, or added to. During later passes, or passes on another station, the objet might be re-observed and its orbit identified. We stress that as we have already a first determination of the orbit, an observation campaign can be made, even with single telescopes, as passes can be predicted with enough accuracy.

4. SPECIFIC MODES

4.1. The *MetaTelescope* Multiplexed

We address now the problem of the completion of the *MetaTelescope*. In the example above, the survey of the whole cone would need 30 telescopes. Instead we use only 10 telescopes or so, reducing drastically the cost. We propose here a procedure, called the *Multiplexed MetaTelescope*, which simulates the whole (30 telescopes) system.

The procedure should be adapted to the orbit family studied, but here we just make the assumption that the RSO speed is 1°/s at most; the characteristics of the system are those described above (cone of diameter 30°, individual telescopes with 3° fov). Let N_C be the number of telescopes needed to cover the whole ring (e.g. 30), N_T the number of telescopes at our disposal, then

$$\nu = N_T / N_C \quad (1)$$

is the filling factor, and

$$\kappa = \text{int}(1/\nu) + 1 \quad (2)$$

is the multiplexing factor. We move each telescope κ times in less than the crossing time, to simulate the whole ring coverage.

In the case mentioned above, with 10 telescopes moving each second on 3 different positions, it is possible to recover all RSOs, as they cross the field in 3 seconds. Note that any geometry of the *MetaTelescope* can be multiplexed.

4.2. The *MetaTelescope* distributed

One of the advantages of the *MetaTelescope* is that it can survey a large area over the sky with a set of instruments of moderate size and field of view. The telescopes do not need to be in the same building (dome). We just require that they have to look at the same area of the sky, at the same time, with the same weather conditions. This enables to *distribute* the telescopes within a not too large area, e.g from 100m to 5km.

This way to spread the instruments in several locations allows deriving parallaxes. As an example, at 500km the parallax will be 40arcsec for 2 telescopes separated by 100m. For the geostationary orbit, 1km = 5arcec on the sky. This allows ranging RSOs with the *MetaTelescope*.

Fig. 1 shows such a configuration, with the 10 instruments distributed in 3 locations.

5. DISCUSSION AND CONCLUSIONS

We have shown that the study of the LEO can be made with telescopes of moderate size and field of view with the same efficiency as large systems with a huge field of view. The *MetaTelescope* has also some other advantages over these more complicated systems. Mostly the *MetaTelescope* is versatile and reconfigurable allowing addressing several classes of problems.

5.1. The *MetaTelescope* for high orbits

As discussed previously, for the study of the LEO the (passive) observer needs to be in the night, while the RSO should be illuminated by the Sun. This limits the observations to periods around sunset and sunrise, e.g. 4h in total. What to do during obscure hours?

High altitude orbits, such as GEO, geosynchronous, HEO, GTO (at apogee), are visible most of the time during the night. To make a complete survey of GEO, and to detect potentially hazardous drifting debris, it is needed to explore a thick belt almost 20° in elevation (Fig. 4), and at several positions around the orbit. The *MetaTelescope* has the ideal configuration for that. From our expertise on TAROT (25 cm), we expect RSOs as small as 10 cm to be detected with a 40cm instrument.

Hence the *MetaTelescope* is an ideal instrument for the observation of all orbits, from LEO to GEO and beyond. This is because it can be reconfigured dynamically along the night.

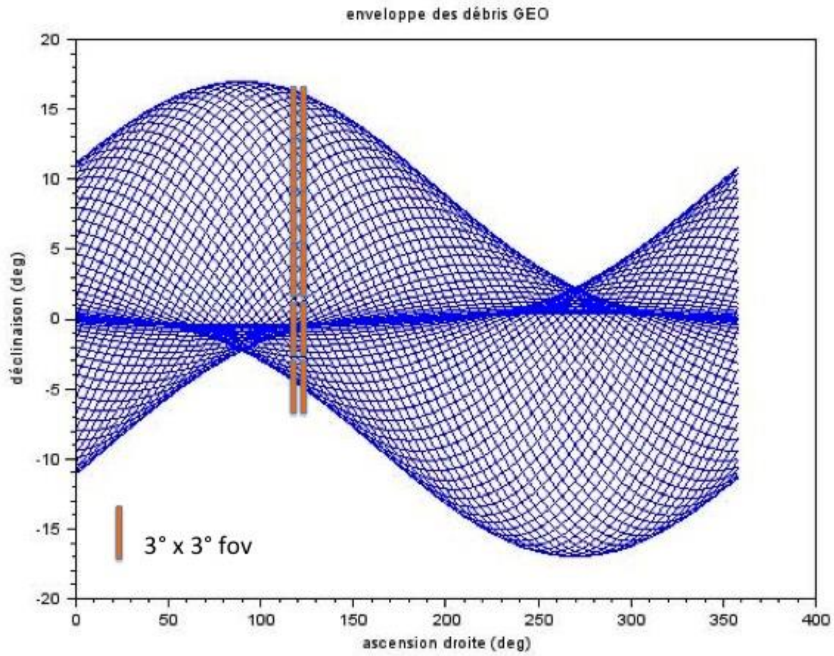

Fig. 4: The envelope of debris drifting in GEO, compared to the *MetaTelescope* field of view. Coordinates are right ascension (degrees, x-axis) and declination (degree, y-axis), (P. Richard, private communication).

5.2 Other topics of interest for the *MetaTelescope*

Many other areas of knowledge can be addressed with the *MetaTelescope*. Among them, we mention here the survey of a set of galaxies for supernova searches, the survey of GRB error boxes, especially when the accuracy of the position is low, as with the Fermi-GBM instrument. It will be specially useful for the search of counterparts of gravitational wave events in conjunction with the Advanced LIGO and Virgo instruments, as the error boxes are huge (> 100 sq. deg.), and they do not have a nice, square or circular, shape [19]. In that later case the *MetaTelescope* can be steered to cover much of the error box and follow its geometry.

Additionally, the system can be used for many usages including Near Earth asteroids, transient and variable surveys, etc.

5.3 Technical considerations

The *MetaTelescope* is a fully modular system. It is made of a dozen or so identical telescopes, with identical cameras, mounts, drives, etc. This is at the expense of the software complexity. However, building a room for theses instruments is easy, cheap, and reproducible. An estimable advantage is that the failure of an individual telescope does not stop the system, but results in a small degradation of the performance. The maintenance is also facilitated as the telescopes are redundant and identical. It can consist, preventively or after a failure, in removing a telescope, bring it to a nearby workshop (with appropriate tools), and making necessary fixes/maintenance while the array is still working. Eventually, a full telescope system (i.e. optics, mount, camera, drives and associated electronics and computers) can be on supply, either for a single or several sites.

Such an installation is shown in Fig. 5 for the RAMSES project (Robotic Advanced Multimessenger and Space Environment System). The 16 telescopes are identical, 40cm, 2.5° fov. Each telescope can be taken with a crane (shown). The maintenance is made in a dedicated workshop shown at the upper right end corner of the observing room. A 1m follow-up telescope is also shown, as well as the weather station.

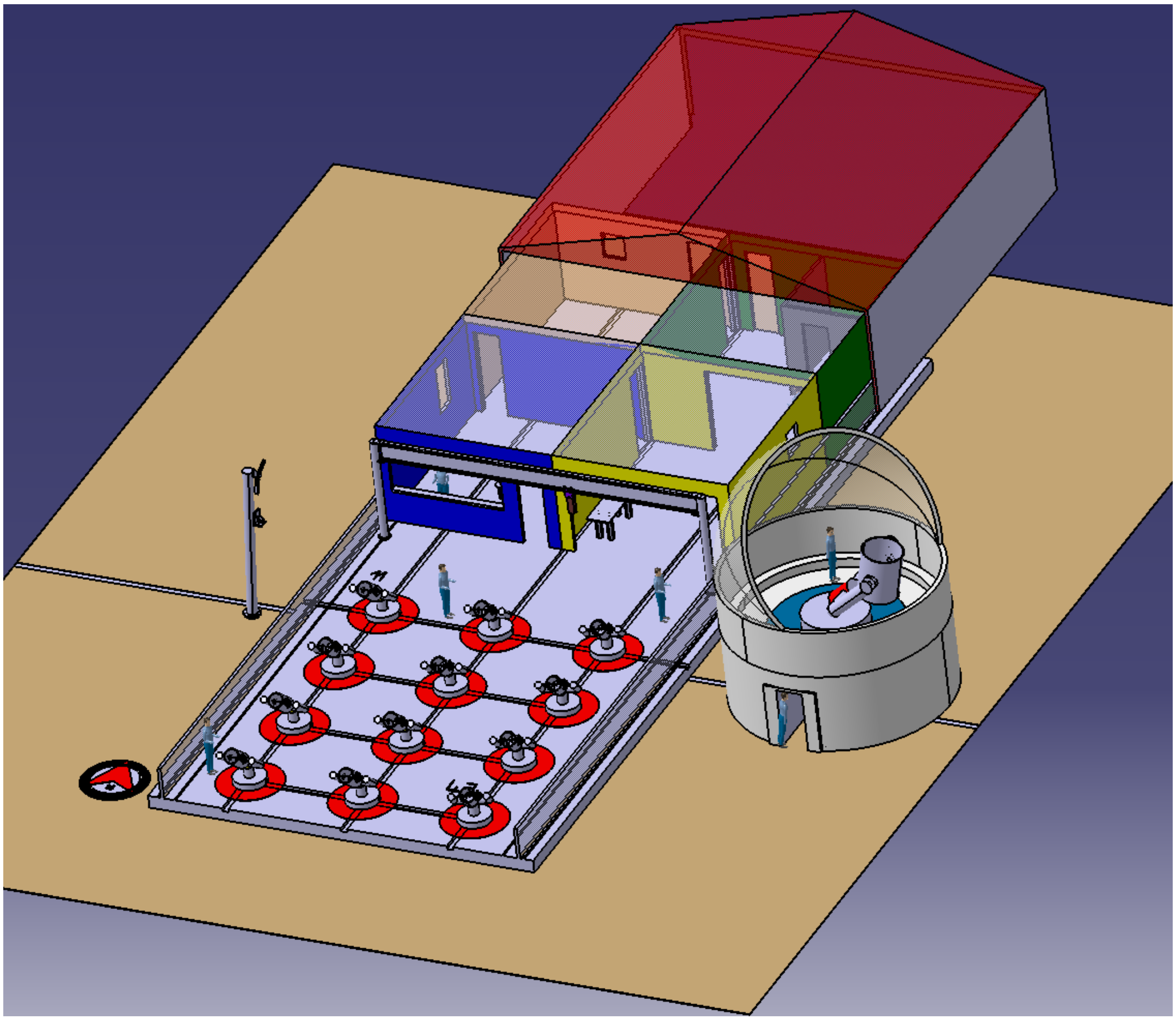

Fig. **4**: The RAMSES project, a [16]MetaTelescope; each 40cm, 2.5° fov instrument is identical, and a crane can bring them in a workshop located at the upper right of the drawing. A 1m follow-up is shown, as well as the weather mast, and technical rooms (design, Mourad Merzougui, Observatoire de la Côte d'Azur).

As noted already, a complete survey of the Low Earth Orbit would require about 10 *MetaTelescopes* installed around the globe. Additional instruments may be used for other topics. Not only the present design is easy to reproduce at low cost, but also the maintenance, consumable etc. are limited. Electricity can be produced by solar panels, and satellites can bring the Internet. Such a redundant array would need only a yearly on-site maintenance (actually, TAROT-Chile is maintained only once a year), without the risk of complete failure. It can be also monitored from a central server, as it is already the case with the TAROT/Zadko network and its central data archiving, scheduling and processing facility, called CADOR, located in France at the Haute-Provence Observatory.

5.4 CONCLUSIONS

We have proposed a new system that is particularly efficient for the survey of the Low Earth Orbit at low cost. This system has a high factor of reliability and it can work in remote places. Moreover, it is versatile and it can handle several targets over the night, such as higher orbits (e.g. GEO) that remains visible most of the time. Though the software is relatively complex, its operational costs are minimal. We have shown that a specific mode of operations, the Multiplexed *MetaTelescope*, allows reducing by a factor 2-4 the number of individual telescopes required. The *MetaTelescope*, if we use adequately precise mounts, open the possibility of a powerful mode of detection and follow-up that we call the *detect and blind track* procedure.

We believe that the *MetaTelescope* is an adequate alternative for Space Surveillance and Tracking of RSOs at low altitudes.

ACKNOWLEDGMENTS

The author thanks Pascal Richard (CNES) and Alain Klotz (Université Paul Sabatier Toulouse) for useful discussions about the *MetaTelescope*.

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