Exhaustive strategy for optical survey of geosynchronous region using TAROT telescopes

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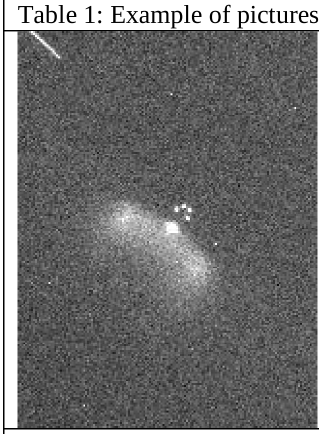
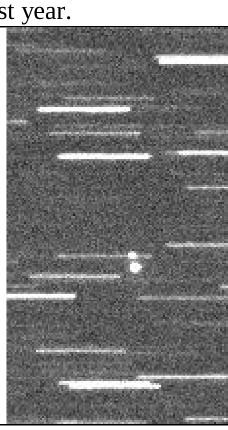
Abstract summary

CNES and CNRS has been working on Optical Space Surveillance and Tracking for many years using the TAROT telescopes network. The goal of the study presented here is to propose an exhaustive strategy for optical survey of geosynchronous region. First, constraints will be defined on perigee and apogee of the orbits for which we are looking for exhaustiveness and then solutions will be explored making the survey in one or several nights using one or several telescopes. The last part of the study proposes solutions to help maintaining exhaustiveness if some observations failed.

1. INTRODUCTION

CNES has been working on optical Space Surveillance and Tracking (SST) for many years using the TAROT telescopes network owned by CNRS. This telescope network developed and maintained by ARTEMIS and IRAP laboratories is today composed of 3 telescopes located at : La Silla Observatory (Chile), Calern Observatory (France, mainland)and Les Makes Observatory (France, Reunion Island). The primary mission of this network is the observation of optical counterpart of gamma ray bursts or gravitational waves. However, a large part of the observation time is dedicated to SST. More details about the TAROT telescope network can be found in [1]. TAROT telescopes are used by CNES to meet its SST internal needs as well as those of satellite operators, French national organisms and European Union through the EU-SST framework. The main applications are: observation of MEO or GEO satellites during launch and post-launch operations, CNES operational anti-collision service (CAESAR) and surveillance of geostationary ring. The pictures below illustrate those applications:

Table 1: Example of pictures taken by TAROT telescopes during the last year.

			
2016-11-17T17:22, TAROT Reunion: recently separated Galileo satellites 15–18 as four closely clustered dots above their Ariane 5 EPS upper stage, which is seen venting propellant as part of its passivation process.	2017-07, TAROT Calern: Tracking of electric orbit raising of Eutelsat 172B, the first European high power electric satellite, built by Airbus.	2017-07-01T04:48, TAROT Chili: A light echo near AMC-9 satellite a few days after after an anomaly.	2017-08-25T18:36, TAROT Reunion A spread echo around TELKOM-1 satellite after a technical disruption.

The repartition of the three telescopes around the planet is particularly efficient as it offers coverage of 70% of the geostationary ring. The impact of weather conditions is very limited on observation of 40% the geostationary ring as it is reachable by at least two of the three telescopes. The picture below shows reachable areas at geosynchronous altitude for elevations higher than 15 degrees above horizon.

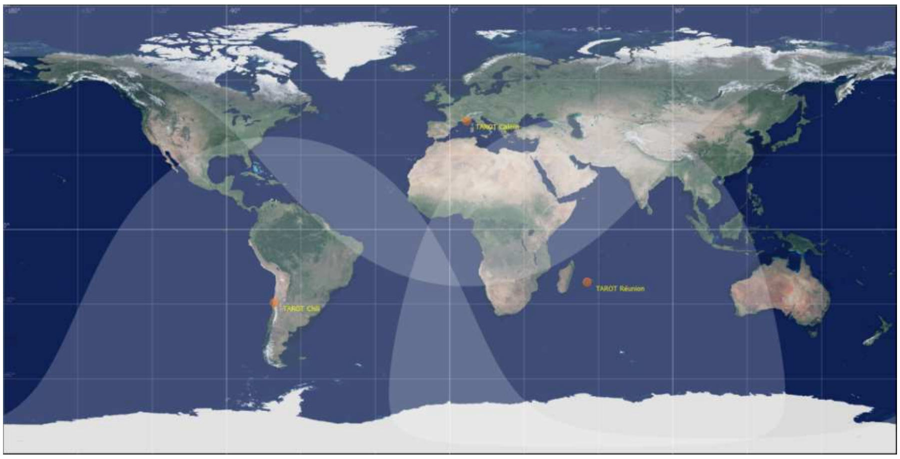


Figure 1: areas reachable by each of the three TAROT telescopes at GEO altitude.

As a part of a constant process of improvement of the CNES Optical SST system based on the TAROT telescopes network, we will present here an exhaustive strategy for optical survey of geosynchronous region. First, constraints will be defined on perigee and apogee of the orbits for which we are looking for exhaustiveness and then solutions will be explored making the survey in one or several nights using one or several telescopes. The last part of the study proposes solutions to help maintain exhaustiveness if some observations failed. In each section of the study, examples based on the TAROT telescopes network will be given. However, the strategies presented here could be useful to task an extended TAROT network or a larger network at the European Union level.

2. GOAL AND LIMITATIONS

Goal: The goal of the geosynchronous surveillance sub-system is to detect all the resident space objects (RSO) of the surveyed area, to associate measurements to catalogued objects and to alert the main SST system when discovering new objects. We will explore here the possibility to make this exhaustive survey in one night or alternatively to spread the survey on several nights to limit the need of observation capacity.

Limitations: A strategy scanning the target area once a night cannot establish the orbits of the observed objects. The aim here is just to alert the main SST system if an uncatalogued object is seen or if an awaited object is not seen. When receiving such an alert, the main SST system can send to the telescopes requests to explore the particular area concerned by the alert.
The objects crossing the geostationary orbit have very variable drift speeds in longitude. The extreme drift speed is attained by the objects in Geostationary Transfer Orbit (GTO) which turn around earth about twice a day.
The maximal drift speed of objects with a semi-major axis contained in the area defined by GEO altitude +/-1000km is about 15 degrees/day. The exhaustiveness of a system that does not cover all longitudes is limited by this drift: for example, the 15 degrees more east and more west of the observed portion of the ring can contain non catalogued objects that were out of this portion the day before.
To limit the domain in which we are looking for exhaustiveness, we will look for the objects whose semi-major axis is between GEO altitude+/-1000km and inclination is below 15 degrees. According to the Spacetrack catalogue, those objects represent 82% of objects crossing the geostationary ring.

Description of the TAROT telescopes used in examples: for the needs of this study, the telescopes are characterized by the side of their square field of view and by their observation cycle time. The observation cycle time is the total time the telescope uses to make an observation : the addition of the pointing time, the integration time and the readout time. An observation cycle can contain several pictures of the same field of view.

Table 2: characteristics of the telescopes used in examples.

Telescope Name	Side of the field of view (degrees)	Observation cycle time
TAROT Chili	1,8°	91 seconds (for three pictures)
TAROT Calern	1,8°	91 seconds (for three pictures)
TAROT Reunion	4,2°	71 seconds (for three pictures)

3. SINGLE NIGHT EXHAUSTIVE STRATEGY

We try here to determine the strategy to adopt in order to observe all the objects on a longitude range. For that, we study the exhaustiveness conditions of a strategy based on the observation of a latitude range centered on equator. The latitude range of the survey can either be:

- The height of the field of view of a telescope,
- The height of the combined field of view of several coupled telescopes
- The total height of a scan of the latitude range made in successive pictures.

Exhaustiveness conditions: There are two conditions to guarantee the exhaustiveness of a survey by areas centered on the GEO ring if the extend in latitude of the survey is not large enough to see the most inclined objects at their maximal elongation. These conditions are:

1. The system has to limit the time between to visits of a longitude to avoid objects to cross the observed latitude range between to visits. So, a maximal time between two visits of a longitude can be computed as the time a GEO objects with 15° of inclination takes to cross the observed latitude range. This can be done by integrating the equation 2 below.
2. The system has to continue visiting each longitude until each object at this longitude entered the observed latitude range. So, a minimal time between the first and the last visit can be computed as the time a GEO object with 15° of inclination can stay out of the observed latitude range. This can be done by integrating the equation 2 below.

Constraints on the sky scanning mode: The figure below has on horizontal axis the latitude range of the survey and the duration of intervals on vertical axis. The blue curve is the maximal acceptable time between two visits of a same longitude. The red curve is the minimal duration of a night to be sure that all objects have been seen.

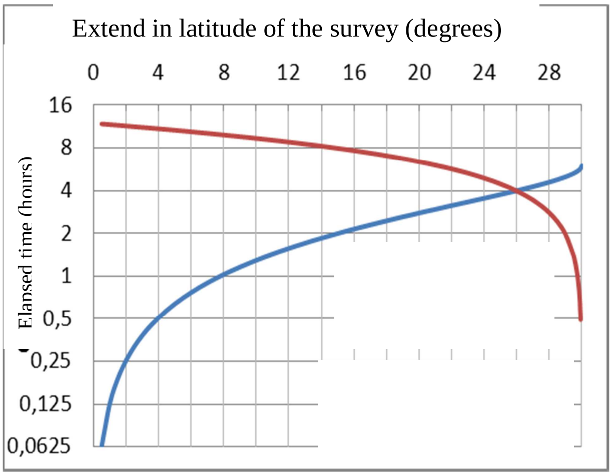


Figure 2: in blue: the maximal time between two visits; in red: minimal time between first and last visit. The analysis of this figure shows that a survey that wouldn't observe all the useful latitude range would have to do at least twice more observations.

Examples of use of the graph: In order to see all GEO objects with inclination below 15°, a survey observing a latitude range of 4° has to visit each longitude twice per hour (as read on the blue curve) and to maintain the survey during more than 8 hours (as read on the red curve).

We can conclude from this graph that the less extend in latitude the survey has, the more often and long we have to observe each longitude. Practically, a solution that doesn't cover the whole target latitude range needs at least twice the number of pictures of a solution covering the whole target latitude range.
In conclusion, to limit the needed observation capacity and as the satellites are much more bright at their optimal illumination the exhaustive surveillance system will observe each longitude on all the latitude range just once a night at its optimal illumination hour (around midnight at the local hour of longitude in a simplified model where effect of eclipse of the satellite by the earth shadow glare of the telescope by the moonlight are neglected).

Overlapping of pictures: as satellites can move between shots, we have to plan some overlapping of the field of view observed.

Overlapping during the scan of the latitudes at constant longitude: the overlapping of the fields of view when scanning latitudes depends on three parameters:

- The extend in latitude of the survey
- The time between two shots
- The velocity of the oscillations of the satellites in latitude.

The chosen strategy is to scan the latitudes from south to north. The overlapping $\Delta\varphi$ in latitude between two fields of view is given by

$$\Delta\varphi = t\,\frac{d\varphi}{dt} \qquad \text{(eq 1)}$$

where t is the duration of the observation cycle (slewing of the mount, integration, readout, possibly several pictures) and $\frac{d\varphi}{dt}$, the maximal angular velocity of a satellite is given by

$$\frac{d\varphi}{dt} = n\sqrt{i^2 - \varphi^2} \qquad \text{(eq 2)}$$

Where φ is the latitude of the object, n is the mean movement of the object and i is the inclination of the object.
This angular velocity is maximal for a 15 degrees inclination object at the equator with 20 µrad/s.

Example of overlapping scheme in latitude for a TAROT telescope with 1,8°x1,8° field of view and an observation cycle of 91 seconds for three pictures of 10 seconds integration time.
The number of fields of view to cover the 22 useful degrees of latitude is 13, the same as if there was no overlapping.

Overlapping on longitudes: the overlapping on longitudes depends on two parameters:

- The time elapsed during a scan of latitudes at constant longitude
- The maximal velocity of oscillation and drift in longitude.

The maximal velocity in longitude for objects with perigee and apogee between GEO+/-1000km when adding the effect of oscillation and drift in longitude is 6,3 µrad/s.

Example of overlapping scheme in longitude for a TAROT telescope with 1,8° x 1,8° field of view.
The duration of the observation of the useful latitude range at constant longitude is 91x13=1183seconds.
The overlapping in longitude to plan between two scans at constant longitude is 0,43°, that is 24% of the field of view.
Two follow the longitudes during the night at the sidereal rate (4,9° in 1183 seconds), it is necessary to couple 3 TAROT telescopes.

Maximal observation cycle time as a function of the field of view to scan the sky with a unique telescope:
The equation below giving the maximal observation cycle time to scan the sky with a unique telescope is based on observations from the center of earth. As the angular velocity of GEO objects as seen from the telescope is higher than the angular velocity of those objects as seen from the center of earth, the maximal durations calculated by the equation below has to be minored of about 20%.

$$t_{max} = \frac{fov}{(v_{sid}+v_{deb})\left\lceil \frac{h}{fov} \right\rceil} \qquad \text{(eq 3)}$$

where h is the extend of the survey in latitude, fov is the measure of the side of a square field of view, $v_{sid}$is the earth rotation rate, $v_{deb}$is the maximal drift rate of the objects and $\lceil x \rceil$ is first integer bigger than x.
The scheme below gives the value t_{max} as a function of fov for an extend in latitude of 22° and a maximal drift rate of 15° per day in longitude.

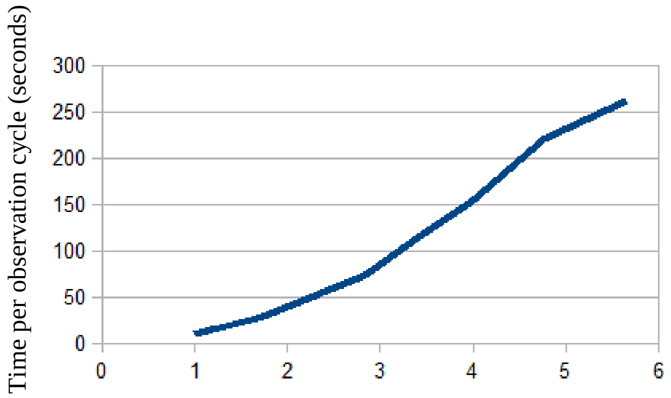


Figure 3: maximal time per observation cycle to scan the sky with a unique telescope as a function of field of view.

As an example, three 1.8°x1.8° telescopes with observation cycle time of 91 seconds like TAROT Calern and TAROT Chili would be needed to make an exhaustive survey in one night when the 4,2°x4,2° TAROT Reunion with observation cycle time of 71 seconds can make two exhaustive surveys per night.

4. SPREADING THE EXHAUSTIVE SURVEY ON A FEW NIGHTS

The goal of the present paragraph is to study how to make an exhaustive survey of the part of the geosynchronous ring visible from the telescope with a scanning rate lower to the rate needed to make the survey in one night.

Observation at constant sidereal hour: considering that on a few days, the right ascension of the ascending node (RAAN) of the objects has a very low drift, we can observe the geosynchronous ring at the same right ascension the following night (that is observing each longitude 3 minutes and 56 seconds earlier than the night before) and the latitude arguments of the objects will be the same.
Objects with semi major axis smaller than GEO will appear earlier (one hour earlier for GEO-1000km) and the objects higher than GEO will appear later, but each object will appear at the same latitude as the night before.
As a consequence, we can plan to observe a different sub range of latitudes each night to spread the scan on a few nights.

Observation with different sidereal hour: it is sometime impossible to observe each longitude exactly at the same sidereal hour as the night before as the observation can be hindered by eclipse, moonlight, clouds, Milky Way… we can even encounter nights without any observation.
The equation below gives the overlap to plan between two latitude sub-ranges observations for the same longitude as a function of the time elapsed between two observations:

$$\Delta\varphi = \frac{d\varphi}{dt}.\Delta t mod\ 86164 \qquad \text{(eq 4)}$$

where $\frac{d\varphi}{dt}$ is the oscillation velocity in latitude given by equation 2, Δt is the time elapsed during the two observations and mod is the modulo function. This equation can be used only if the time elapsed between the two observations is lower than a few days because of the hypothesis of constant RAAN of the objects and the difference of observation hour is small because of the hypothesis of constant $\frac{d\varphi}{dt}$ near the latitude constituting the boundary between the two sub-ranges.

Example of overlap calculation:
Hypothesis:
. The sub-range of latitudes [-11°,0°] is observed the first night and the sub-range of latitudes [0°,11°] is observed the second night.
. Each longitude is observed at the same solar hour each night
. The weather condition cause an outage of one night
. The survey must be exhaustive for geosynchronous objects with up to 15° inclination.
Overlapping:

$$\Delta\varphi = 20.10^{-6}.(2 \times 86400) mod\ 86164 = 9.10^{-3} rad = 0{,}54°$$

The boundary latitude chosen in this example is the latitude where $\frac{d\varphi}{dt}$ is maximal: $20.10^{-6}\ rad/s$ for objects with an inclination of 15°.

Example of observation scheme for TAROT Chili and TAROT Calern telescopes: in this theoretical case where everything works fine, cutting the 22° useful latitude range in four latitude sub-ranges, TAROT Chili or TAROT Calern can scan the visible part of the geostationary ring in 4 nights.

5. EXHAUSTIVE SURVEY IN OPERATION

During real operations, the weather conditions, the moonlight and the Milky Way often induce leaks in planned observations. The goal of the present paragraph is to study how to optimize the survey despite the missing observations.

Complementary observations the same night: if an observation or a group of observations failed, it is possible to make a new visit of the same area a bit later. Two things have to be noted for this:

- The area to revisit is larger than the original one as the satellites present in the area during the missed visit can have moved because of their drift, their eccentricity or their inclination. Typically, for a second visit of an area one hour later, the boundaries in longitude have to pushed back of 1.3° ; the boundaries in latitude has to be pushed back of a value that depend of the latitude of the boundary and can be up to 4° near equator.
- The nominal survey is designed to observe each longitude at favorable illumination. In order to get a detection threshold comparable to the nominal survey, the second visit has to be done at an hour with favorable illumination of the area.

Spreading an exhaustive survey on a few nights despite of missing observations: in the case of an exhaustive survey on a single night, there is no use of taking into account the night before. However, in the case of an exhausted survey spread on a few nights, the system can take into account the failures of the preceding nights to plan the following night. If each longitude is planned each time at the same solar hour, the area to observe to make up for the missed areas increase with the time:

- in longitude: the boundaries of the areas to revisit move at about 13° per day for objects at 1000km from GEO altitude.
- in latitude: the boundaries wouldn’t move if we observed always at the same right ascension. However, the difference between sidereal day and solar day impose to change regularly the observed right ascension of about 1° per day. So, the boundaries of the area to revisit move at a velocity depending on the latitude and that can attain 0.27° per day near the equator.

The missing observations are not the only cause of the loss of exhaustiveness: new drifting objects can enter the surveyed portion of the GEO ring at about 13° per day (for objects at 1000km from GEO altitude) by the extreme longitudes.

Continuous update of a survey with dating of the area:
A missed observation does not cause a total loss of exhaustiveness on the missed area but a miss of update. Better than considering the missed area as unknown, the system can register the date of last update of each area.

In order to maintain the knowledge about the surveyed part of the GEO ring, the system can use a grid in longitude and latitude with a small step, e.g. 0.1° and store in each cell the date when it has been last updated. The unknown cells (never observed or outside the surveyed part of the ring) get a zero as last observation date.
After each night, the system increases the area of the oldest dates by moving their boundaries at the speed presented in the preceding paragraph. This system is illustrated by the figure below.

Map at the end of the third night: the blue area has been observed during the night 3, the red area has been observed during the night 2 and the green area has been observed during the night 1. The black area has never been observed.

Map at the beginning of the fourth night:
1.The unknown area of extreme longitudes has been extended as drifting objects can have entered the surveyed sky.
2. Each boundary between areas of different date has been moved to extend the oldest area. This take into account the fact that new objects appeared since the last visit of the area can have gone in neighboring areas.

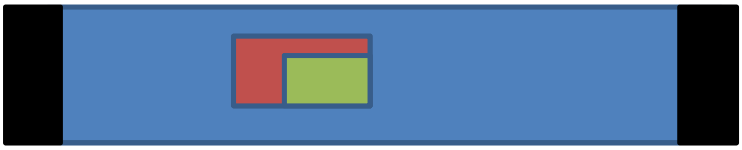


Figure 4: longitude-latitude map for continuous update

Strategy to maintain the continuously updated grid: the main strategy is to work at the first level of priority on the unknown areas (black on the above figure) to discover all the objects entering the surveyed part of the GEO ring. At the hours when no unknown area is reachable or if all the unknown area has been observed, the system try to find the new or displaced objects. To meet this goal several priorities has to be taken into account:

- Observation of the oldest areas
- Observation of the areas where the probability of detection is maximal
- Observation of the area where known objects have not been seen on preceding nights. A good way for this is to consider as unknown the place where the object has not been seen. So the unknown area will extend at the maximal drifting velocity of the object or the potential fragments.

6. CONCLUSIONS

This theoretical study aimed at finding possible strategies to maintain an exhaustive knowledge of objects resident in the part of the geosynchronous ring reachable by a telescope or a network of telescopes. After an introduction on the TAROT telescope and their use for SST, we presented in the second section the limits of the orbital domain for which we look for exhaustiveness. The third section gave a method to evaluate the capacity of a telescope or set of telescopes to make an exhaustive survey in a single night. The fourth section explained how the needed capacity can be reduced by spreading the survey on a few nights and, finally, the fifth section proposes a strategy to maintain a partial exhaustiveness of the survey when operating a real telescope or network of telescopes. Future works will concern the optimization of the strategy under real conditions and its use on a large network of telescopes.

7. REFERENCES

1. Michel Boër, Alain Klotz, Romain Laugier, Pascal Richard, Juan Carlos Dolado Pérez, et al.. TAROT: a network for space surveillance and tracking operations. 7th European Conference on Space Debris ESA/ESOC, Darmstadt/Germany, Apr 2017, Darmstadt, Germany.