Astrometric Positions of Geostationary Satellites and Space Debris

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Abstract: Space debris is becoming a real problem with the constant increase of many-orbit artificial satellites. It threatens other active satellites including the ISS. Currently the best option to mitigate its effects is performing routinely observations and cataloguing them. This research aims to study the astrometric positions of HISPASAT, an active geostationary satellite constellation, in order to optimize the methodology for space debris observation. We perform a GEO optical survey with the Telescope Fabra ROA Montsec and discuss the optimal observation strategy.

I. INTRODUCTION

Space Debris has been defined by the International Academy of Astronautics (IAA) as the following:

"Orbital debris is herein defined as any man-made object which is non-functional with no reasonable expectation of assuming or resuming its intended function, or any other function for which it is or can be expected to be authorized, including fragments and parts thereof. Orbital debris includes non-operational spacecraft, spent rocket bodies, material released during planned space operations, and fragments generated by satellite and upper stage breakup due to explosions and collisions". [1]

Some small debris pieces can reenter the atmosphere, but the risk for a human to be hit by them is very low. Excluding a handful of risk objects, space debris doesn't represent any danger to humans or the biosphere.

The main hazard space debris presents is in relation to space missions, both manned and unmanned, due to debris sharing the same orbits as active satellites. Debris pieces possess a high relative velocity to other objects in orbit (up to 16 km/s), thus creating potential damage if an impact occurs [2]. It also poses a great threat to the International Space Station (ISS) as even collisions with small pieces can be devastating. This is because space debris orbits are mostly unknown, so the particles cannot be blocked nor avoided in advance. Besides from catastrophic collisions, debris can also corrupt astronomical observations and interrupt radio frequency paths.

Nowadays, according to the European Space Agency (ESA) [3], there are more than 34.000 objects in orbit with a diameter of 10 cm or more, while the number of active satellites is roughly 2000. But even worse, if we take into account smaller objects, we notice that there are about 900.000 objects from greater than 1 cm to 10 cm and about 128 million objects from greater than 1 mm to 1 cm.

Yet the total mass of all these objects is only about 8400 tonnes (10^{18} times smaller than the Earth's mass). Therefore, the main problem of debris population is not the total mass, but the number of particles that exist in a given size range (FIG.1).

There are some space debris mitigation techniques: controlling the increase of launched satellites so that the amount of debris is minimized; creating an auto-eliminating system that will be used once their lifespan is over; or carrying out an external elimination procedure. This last method could actually worsen the situation due to the possibility of breaking some parts of the satellites and thus, creating even more debris [5].

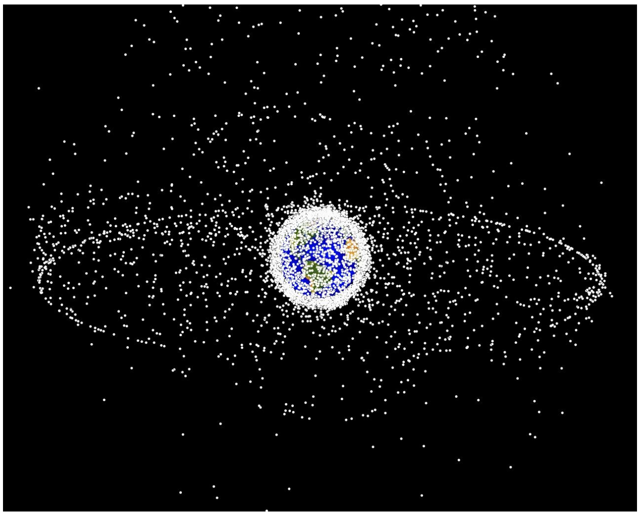

FIG. 1: Space debris' distribution in GEO orbit. Source: NASA Optical Debris Program Office [4]

Current technology is unable to eliminate space debris (due to elevated costs and lack of commercial incentive for the entity producing the debris), so the best option for now is to catalogue and determine the orbits of such objects to predict possible impacts with active satellites. However, debris observation is not a trivial task. There are many factors to take into account if a successful survey is willing to conduct.

The aim of this work is to develop an observation strategy to catalogue space debris. This will be conducted through an optical survey of the active geostationary communications satellite constellation HISPASAT. We will study its astrometric positions and optimize a method for space debris observation.

II. SURVEYING TECHNIQUES

There are three kinds of artificial satellites depending on the orbit:

- Low Earth Orbit (LEO): up to 2.000 km
- Medium Earth Orbit (MEO): 2.000 km - 36.000 km
- Geosynchronous Earth Orbit (GEO): at 36.000 km

Space debris is mainly located in orbits with altitudes that range from 300 up to 40.000 km, with its maximum concentration in LEO and GEO and it has similar orbits to their parent objects. We are interested in GEO satellites because they have the same rotation period as the Earth (1 sidereal day), thus they appear static in the sky.

We will study the HISPASAT satellite constellation, a GEO one which belongs to the Spanish communication satellites operator carrying the same name. In particular we will track the ones with an orbital position of 30º W.

There are two kinds of tracking: following the sky (sidereal tracking) or following a certain object. In the first one the telescope is fixed on the stars, and in the second one it is fixed on the object of study [6].

Sky tracking

In this method the satellite moves with respect to the stellar background, so the stars appear as fixed points and the satellite as an elongated object with a trail. (FIG.2). The problem this method bears is that the exposure time needs to be short so that there is not a loss of precision and the trail is not too long so that the software is unable to process the image. But if the exposure time is not long enough, stars with weak magnitudes (or the actual satellite) will not be detected. If we want to conduct a subsequent observation of space debris, which can be quite faint, we will need to increase the exposure time and this method will not be the optimal. But we will also have to take into account the fact that fast moving objects, such as space debris, have a short effective exposure time due to the constant change of the pixel. Therefore it is imperative to balance the exposure times.

Object tracking

In this method the observation will be carried out in different frames in which the satellite will appear as a punctual object and the stars will present trails (FIG.3). Even though this is the preferred method of surveying, it also presents some problems. If the exposure time is too long, the trails of the stars will be so large that the software will not be able to match the sky to the catalogues, thus not finding the satellite position. There will also be a loss of accuracy due to uncertainty in the position of stars.

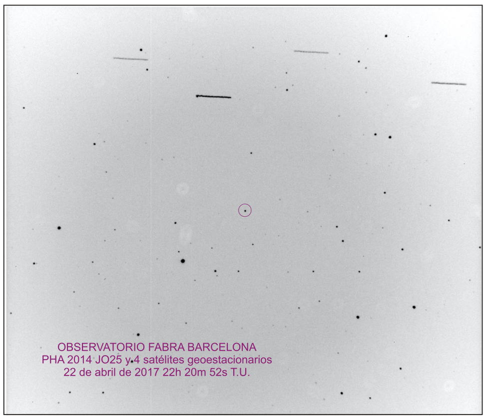

FIG. 2: Sky tracking observation of 4 Intelsat satellites. Source: Antonio Bernal, *Observatori Fabra* (2017)

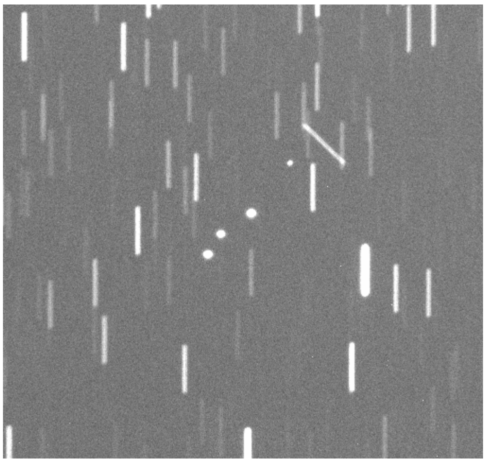

FIG. 3: Object tracking observation of the HISPASAT constellation. Source: TFRM, OAdM (2014)

III. DATA COLLECTION AND PROCESSING

LEO satellites can be tracked by radars, but when it comes to MEO and GEO satellites radars stop being effective. This is because their detectability drops as r^4, hence their ineffectiveness for high orbits. So the best sensors to track satellites in these orbits are optical telescopes with a wide field of view.

The first try was using the *Observatori Fabra*'s telescope, but the data was unable to be processed due to some problems. The first one was very bad meteorological conditions that hindered the observation and made the satellites come up very faint. Then, we had trouble with the inclination of the CCD, which caused the stars to appear tilted and fragmented, hampering the software to match them. Finally the large focal length of the telescope ($f = 4m$) made the trails too long to be handled properly. So we have performed the actual survey using the Telescope Fabra ROA Montsec (TFRM), located in the Observatori Astronòmic del Montsec (OAdM).

A. The TFRM

The TFRM is a telescope result of the refurbishment of an old Baker-Nunn Camera (BNC), which was located in the Real Instituto y Observatorio de la Armada (ROA), in San Fernando, Cádiz. Now the TFRM is installed in the OAdM, with WGS84 coordinates: $\Phi = 42^{o}.0516\,N$, $\lambda = 0^{o}.7293\,E$ and $h = 1570\,m$ HMSL [5].

The BNC was designed in the late 1950's to track satellites and it has been refurbished so that it can operate with a commercial CCD camera, which is able to be commanded at will during an exposure.

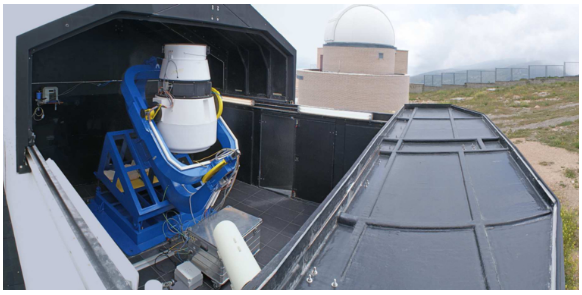

FIG. 4: *Foreground*: TFRM at OAdM with the refurbished BNC and sliding roof. Source: PASP (online version)[7]

The telescope has an equatorial mount, a wide field of view, of $4^{o}.4 \times 4^{o}.4$, a 0.5 m aperture and a focal relation (focal distance/aperture) of 0.96. Every image has 4.096×4.096 pixels and a limiting magnitude of $V \sim 19.5\,mag$ in optimal conditions and performing a stacking of images. It is fully robotized, it can track at arbitrary α, δ rates and can be operated remotely, as it has been done in our survey. All this features make the TFRM a suitable sensor to survey programs, specially due to its ability to cover the whole geostationary belt.

The telescope operates nightly and can detect about 500 GEO objects tracks per night in average. But it can track up to 3000 depending on the observation strategy. It participates in the Space Situational Awareness (SSA) and the Space Surveillance Tracking (SST) programs, regarding the survey of space debris [5] [7].

B. The survey

The survey has been conducted in a non-ideal night (partially clouded and almost full moon). Non-ideal nights are the most common scenarios, and as mentioned before, the telescope has been positioned in an Earth-fixed reference system (stopped). We have worked remotely with the TFRM and have collected data for 4 different exposure times: 1.5s, 3s, 5s and 10s.

The object of study has been the HISPASAT constellation of 30° West. As of now this constellation is composed of 3 satellites: 30W-4, 30W-5 and 30W-6. In our survey we entered the orbital elements of the 30W-6 satellite (num. 43228) [8], which are:

```
1 43228U 18023A 20010.69076108 -.00000206 00000-0 00000+0 0 9991
2 43228 0.0396 46.3869 0003321 282.6219 359.3529 1.00271504 6938
```

With this information, the TFRM is able to directly locate the object. Otherwise, we could enter the following coordinates: $\delta = -6 : 29 : 30$ and $HA = 2 : 17 : 33$.

Finally, the aparent magnitude of the 30W-6 satellite was of 14.9 *mag*. The magnitude is a variable that depends on the geometry and orientation of the satellite, the direction and intensity of sunlight and if the satellite is on the Earth's shadow (not visible). Therefore, the obtained magnitude belonged to a rather faint object.

C. Software

To perform this sort of study we need either special software, such as APEX II, or regular software with the SExtractor (Source-Extractor) function. SExtractor is very useful when dealing with the reduction of large scale data but also with crowded star fields. It works the following way: first it measures the background and its noise and subtracts it. Then it finds the objects and measures their positions and sizes. It cleans the image, classifies the objects by determining if the pixels belong to the background or to a certain object and finally builds a catalog from that astronomical image [9].

Our software of choice is PinPoint (with SExtractor) for image reduction and then SAOimageDS9 and MaximDL to visualize and study them. We cannot use Astrometrica as it is unable to handle trailed objects (stars or satellites) due to the lack of the SExtractor function.

IV. RESULTS

A. Astrometric accuracy

We obtained 64 experimental valid measures: 15 of 1.5s, 15 of 3s, 14 of 5s and 20 of 10s, from which we performed an exposure time extrapolation for 34 of them. The 20 measures of 10s have been converted into measures of "false 20s", and the 14 measures of 5s into "false 10s" ones. This has been done simply by doubling the size of the image using MaximDL to obtain longer trails that mimic longer exposure times. However if the pixel size corresponding to a 10s observation is 3.88"/pix. then the one corresponding to an extrapolation of 10s (a false 20s) is 7.76"/pix. Thus we are not elongating the trail in arc-s but in pixels.

First, we plot the average RMS residual (Root Mean Square, given by PinPoint) of the measure as a function of the exposure time (FIG.5). The greater the RMS, the less accurate is the measure. The residual is in itself an error provided by the software, so no error bars are needed in the graphic. The exposure time is also managed by the telescope and the errors are negligible.

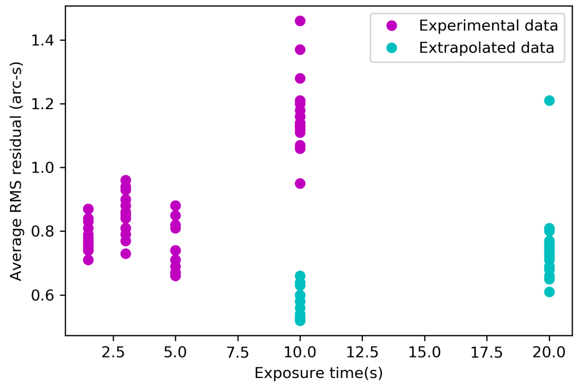

FIG. 5: Average RMS residual versus the exposure time

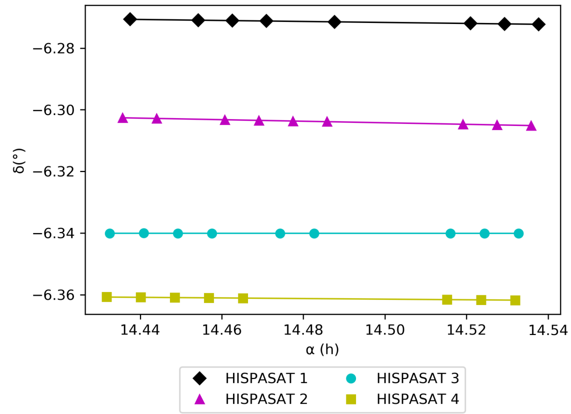

FIG. 6: Astrometric positions of 4 HISPASAT satellites

We apparently see an improvement of the accuracy for extrapolated exposure times. However when we compare the extrapolated images to the real ones, we notice that this improvement does not reflect a genuine survey since we only increase mathematical accuracy, not actual one. This is probably due to the bicubic interpolation used during the image doubling process. This means that the real accuracy should be smaller, as we are not working with real experimental data of 20s exposure time, but instead with one that has been modified. That is not what we obtain, hence we deduce the improvement in accuracy is only mathematical.

Discarding this extrapolation results, we also notice that the accuracy remains mostly constant for exposure times of 1.5, 3 and 5s, being slightly better for 5s. But for times of 10s it decreases significantly. From this results, we deduce that the best exposure time option to track geostationary satellites is of 5s, that corresponds to a 20 pix trail for the TFRM, and is preferable not to perform a time extrapolation of the experimental data if one desires to keep the accuracy to the maximum.

B. Astrometric positions

Once we know the exposure time length we can examine the satellite's astrometric positions. For the purpose of this study we have used data from another night with better atmospheric conditions (2011) and we have only considered experimental data, not extrapolated one.

First, we have used a personal software developed by Jorge Núñez, TFRMtools, that calculates the astrometric positions (using PinPoint with SExtractor) of the objects of study and groups the candidates to establish a path for each satellite. After that, we plot the positions of the 4 HISPASAT satellites that were active in 2011 (FIG.6). It is presented the declination versus the right ascension.

From this graphic we are able to identify the orbits of 4 different satellites, all of which belong to the HISPASAT constellation. The errors are of the order of 0.5-0.7 arc-s, so the error bar is so small that falls inside the points, thus not being visible (each y-axis division is 72"). The 4 straight lines are actually parabolas with a very soft curvature. If the exposure time was long enough, the trajectories would be Lissajous curves in a declination-hour angle graphic, but due to the short time we are only able to see a small portion that resembles a straight line.

This offers a method to find a certain satellite given its known positions. If we know α and δ we can easily decide to which orbit the satellite belongs, therefore we instantly know which satellite we are tracking.

C. Observation strategy for space debris

Once we have established the best exposure time to track satellites and we have obtained its astrometric positions, we can proceed to design the optimal strategy for debris observation using the TFRM telescope. We will sort the strategy for the 3 different kinds of orbits: LEO, MEO and GEO, and we will consider the exposure time and the type of tracking that can be applied to both bright and faint objects. For the TFRM a bright object is considered to be of a magnitude lower than 12 mag, and faint from 12 up to 15mag.

From the considerations listed above we propose a qualitative observation strategy (TABLE.I). For LEO objects there are two different procedures to be carried out depending on the brightness of the object. If the object is bright we can conduct a sky tracking with a very short exposure time, and identify the object by morphology since the object will appear somewhat trailed. The exposure time needs to be short enough so that the object trail is not too long. If the opposite happens we obtain an elongated object unable to be processed with enough accuracy. If the object is faint, we can perform an object tracking considering that the exposure time needs to be longer than in the previous case. But again, we need to make sure that the exposure time is not too long so that the trails of the stars are not very large. If this happens,

LEO (Very fast object)	
Bright Object	**Faint Object**
Very short exp. time Sky tracking	Short exp. time Object tracking
MEO (Fast object)	
Bright Object	**Faint Object**
Short exp. time Object tracking	Medium exp. time Object tracking
GEO or higher orbit (Slower object)	
Bright Object	**Faint Object**
Medium exp. time Object tracking	Long exp. time Object tracking

TABLE I: Observation strategy for LEO, MEO and GEO or higher orbit objects

as stated above, the software is unable to match the sky to the stars. Nonetheless, this kind of observation can be conducted with a radar, as we have discussed before.

For MEO objects the exposure times can be longer of those for LEO objects, but the considerations regarding long trails are the same.

Finally, for GEO objects the best strategy to follow is to perform an object tracking observation because such objects have the same rotation period as the Earth, so they are static in the sky. Therefore, the telescope can be stopped during the survey. For faint objects, as we have discussed in the "Astrometric accuracy" section, the optimal time is 5s. But for bright objects it can be even shorter, of 3s or even 1.5s, as the accuracy is not compromised. If the object were to be very bright, then we could conduct a sky tracking observation with a short exposure time, but this is not the preferred method.

Next we propose a quantitative strategy since it is clear that short trails are preferable in any kind of survey. From the experimental studies we estimate that the longest trails should not be more than 40 pixels to secure the plate reduction and the accuracy of the object.

Given the known apparent velocity of the object, we estimate the maximum exposure time that ensures a trail shorter than 40 pix ($l_{max} = 40pix$) as:

$$t_{max}(s) = \frac{l_{max}(pix) \cdot scale("/pix)}{v_{ap}("/s)} \quad (1)$$

- GEO: $v_{ap} \sim 15" s^{-1} \rightarrow t_{max} = 10s$
- MEO: $v_{ap} \sim 30" s^{-1} \rightarrow t_{max} = 5s$
- LEO:
  - high ($\sim 800km$) :$v_{ap} \sim 720" s^{-1} \rightarrow t_{max} = 0.2s$
  - low ($\sim 400km$) :$v_{ap} \sim 1500" s^{-1} \rightarrow t_{max} = 0.1s$

The scale is 3.88"/pix for the main telescope of the TFRM (GEO, MEO) and 2.90"/pix for the secondary one (LEO).

V. CONCLUSIONS

We have successfully conducted an optical survey with the TFRM to track the geostationary satellite constellation HISPASAT of 30ºW. We have studied the accuracy of a GEO object observation with object tracking finding that for times of 1.5, 3 and 5s the accuracy remains mostly constant, but rapidly decreases for times of 10s. We have also performed an exposure time extrapolation to simulate a longer survey but found that such extrapolation only improves mathematical accuracy, not actual one. Next we have determined the optimal exposure time for the TFRM in this kind of survey, with a result of a 5s exposure time. Afterwards we have plotted the positions of the 4 HISPASAT satellites active in 2011 and obtained a method to identify a satellite based on its orbit. Lastly we have discussed an observation strategy for space debris based on the orbit and brightness of the object and have estimated the maximum exposure time so that the trail is shorter than 40pix. Overall we can state that performing an object tracking survey is in most cases the best strategy to follow, as the trail errors of stars compensate themselves, but the object ones do not.

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