# CATALOGUING SPACE OBJECTS FROM OBSERVATIONS: CORTO CATALOGUING SYSTEM

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## ABSTRACT

This paper presents the system for cataloguing Earth orbiting objects based on the DEIMOS CORrelation Tool (CORTO) and provides information of real cataloguing activities based on optical observations. The approach undertaken in CORTO is based on a three step process: first correlation in the basis of comparison of observation with expected visibility considerations, a second orbit determination compatibility cross-check based on the filtering residuals, and a further manual processing of generated objects is executed to identify failures in the automatic correlation that could lead to duplicated objects. CORTO cataloguing system is accompanied by a set of auxiliary tools, which enhance the capabilities of the system to ensure the correctness of the cataloguing process. Two modules, CORTOHouseKeeping and CORTOEditor allow maintaining and modifying the CORTO catalogue accounting for the operator feedback. Additionally, the auxiliary tools, normally used together with CORTO, include CALMA (for calibration of observation stations) and CHOCO (which allows correlating the observed objects with those in the TLE dataset). This tool serves to assign the international ID to the CORTO objects, but is not mandatory for successful correlation of objects within CORTO. The catalogue is finally made available through a restricted web system (CAWEB) that allows the user to search objects, analyse the resulting accuracy, the evolution of the orbital information computed for each catalogued object, etc. A set of additional scripts accessing the database provide all the information to the operator to investigate the catalogue status with the aim of identifying cataloguing and tracking needs. Together with the description of the cataloguing approach, the paper provides a summary of the processing of observations from DEIMOS Sky Survey (DeSS) sensors located in Spain. Optical observations are used to feed the cataloguing system CORTO, allowing the creation of a catalogue of high altitude objects which are observable from southern Europe. In particular GEO ring longitudes covering Europe are well represented. The achievable accuracy of the observed orbits can reach values around 10-100 meters. Object manoeuvres can also be observable. Example cases of observed manoeuvres are investigated. The main results from cataloguing campaigns are summarised, describing the observation strategy and the measurement distribution. This summary highlights the main difficulties in the correlation activities.

Key words: cataloguing; correlation; orbit determination; tracking; optical.

## 1. INTRODUCTION

Most of the activities performed in the field of space debris depend on the accurate knowledge of the state of Earth-orbiting objects, particularly the inactive ones. A growing concern for the risks associated to the increasing number of Earth orbiting objects has raised the interest of cataloguing systems in the past years. In order to properly address those concerns, a cataloguing system must be able to provide a *complete* catalogue (all objects that exist in reality should be catalogued). The catalogue must be *accurate* and *precise* (an inaccuracy of a few meters in a predicted position may result in a large difference between an estimated and a real collision risk). Finally, the catalogue must be *updated* (the orbits of catalogued objects must be updated frequently, and contain, at each moment, the latest available information).

In order to achieve the objectives listed above, the cataloguing system must be constantly process information from data sources. The most relevant data sources are sensors, that provide observations of the objects to be catalogued. Other data sources include: foreign catalogues, foreign sensors, orbits computed by third parties, and miscellaneous information (predicted new launches, operational information from active spacecraft, information on past fragmentation). The cataloguing system must be able to swiftly ingest the information that is provided regularly (observations by its own sensors). It must be robust enough to allow merging of potentially contradicting data from different sources. Finally, it must be flexible enough to allow entering potentially relevant bits of information that, because of their nature, cannot

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be inserted in a regulated and fixed way. Such qualitative information may include the information that can be gathered by the cataloguing operators.

A cataloguing system must comprise, at least:

- A sensors network: Earth-orbiting objects are usually observed with ground-based sensors, such as radars, telescopes, and laser ranging systems. Space based sensors can also exist. As sensors are a critical part of the cataloguing system, their behaviour and particularities may shape the behaviour of the whole cataloguing system. An heterogeneous network is required for achieving catalogue completeness, as no universal sensors exist at the moment.
- A cataloguing nexus, that centralises all the information stored in the system, performs the computation tasks, generates the tasks to be assigned to the sensors, and disseminates the information received and/or created by the system.
- A roster of cataloguing operators. The operators must monitor the catalogue, operate the sensors, gather external information, and continuously improve the system. Their work and commitment is vital for the cataloguing system.

This paper presents CORTO (CORrelation TOol), that fills the software part of the aforementioned cataloguing nexus. CORTO was initially developed in 2011 to support optical observation campaigns, and has evolved since them into a tool that allows processing observations from ground based telescopes and radars, building and maintenance of a catalogue of objects, and archival of all the observational data.

A network of sensors is configured in CORTO. From that point onwards, CORTO maintains a catalogue with objects obtained exclusively from observations from the the aforementioned sensors. It expects the sensors to provide new tracks constantly. When new tracks arrive, it automatically performs a correlation and orbit determination process on them, and updates its current catalogue information.

It is possible to correlate the objects in the CORTO catalogue with those in the NORAD catalogue. Although this process is not strictly required for the operation of the system, it provides a extremely valuable information to the operators, as allows identifying hundreds of otherwise anonymous space based objects.

The automatic procedure outlined above can never work with a 100% reliability. There is a handful of reasons for which it could yield incorrect results. Endogenous reasons include: limitations of the propagation and orbit determination algorithms used, insufficient or biased data from sensors, or insufficient knowledge of the orbits catalogued objects. Exogenous reasons include: maneouvres performed by active satellites (that are usually unknown to the cataloguing operators), low thrust manoeuvres, partial occlusion of observed objects and fragmentation events. In order to overcome the consequences of these incorrect results, the operator is provided tools that allow monitoring the catalogue and the automatically performed actions, and performing actions in the database in order to amend wrong results the system may have reached.

## 2. ARCHITECTURE AND ALGORITHMS

The name CORTO was used for the first version of the software, and with focus on development of correlation and cataloguing techniques (as already explained). No operational requirements existed at that time. Therefore, it comprised just a computational module that fulfilled the necessities of the study described at [2]. Along several years, a set of additional modules have been added to that core module, and all of them share the CORTO denomination. Nominally, CORTO is intended to be deployed in a single Linux machine. Figure 1 shows all the modules that comprise CORTO, along with the interactions between them.

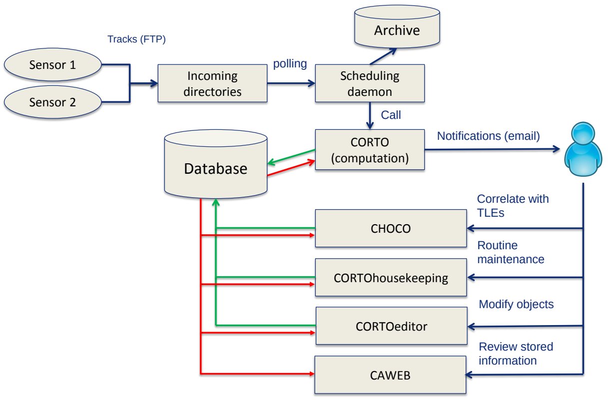

Figure 1. CORTO modules

### 2.1. Track submission

The configured sensors submit their observations (tracks) through FTP. This relies on the the widely known vsftpd daemon. Each sensor submits its tracks without being able to access the tracks submitted from other sensors.

### 2.2. Scheduling daemon

A **scheduling daemon** watches a list of incoming directories for new tracks. When a new track arrives, it is queued for processing. It is possible to configure the processing to happen as soon as tracks arrive, considering a grace time (i.e, the daemon processes the tracks only when a given amount of time has elapsed), or considering a schedule-based approach (i.e, all pending tracks are processed at a given, fixed time of the day).

For testing and development scenarios, it is possible to bypass the scheduling daemon entirely.

### 2.3. Database

All the information in the catalogue is stored in a **dedicated database**. The database is a common postgresql database, that is deployed nominally on the same host as all the other modules (although it is possible to host it in a separate machine). The information stored in the database includes:

- A list of the configured *sensors*
- A list of *Earth-Orbiting objects*.
  - Each object is given a unique CORTO id. This is defined as a unique, positive integer number.
  - Each of these objects has a list of *status updates* associated to it. These status updates can be related to an update triggered by a new track from any sensor in the sensor network, or a manoeuvre (deduced by the operator by checking the database). Each status update includes an state vector after the orbit determination (in case the status update is associated to an incoming track), or after the manoeuvre (in case the status update is associated to a manoeuvre)
- A list of all incoming *tracks*. Each track comprises one or several *measurements* of one of these types: Range, Azimuth, Elevation, Right Ascension, Declination, Visual Magnitude, Radar Cross Section (RCS), Doppler measurement. Each track is associated to a single sensor. Each track is also traced to the incoming file where it originated.

### 2.4. Archive

All the incoming tracks are archived for further reference. They are stored in a directory structure with subdirectories for each processing date (such as `year/month/day`).

### 2.5. CORTO (computation)

The core of the system is the computation module. This module works asynchronously. Each time it is started, it retrieves the past information from the database and updates it with the information contained in new tracks, that are its inputs. Figure 2 shows the top-down view of the computation carried out by CORTO.

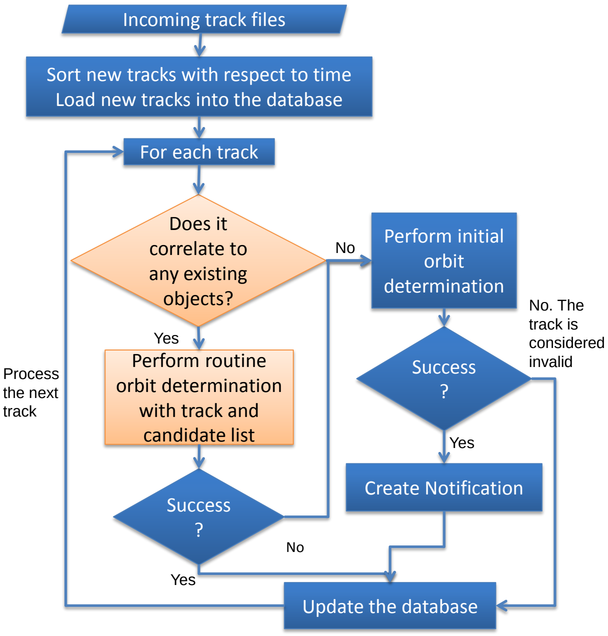

*Figure 2. CORTO main algorithm flowchart*

As the figure shows, incoming tracks are processed one by one. CORTO tries to correlate each of the incoming tracks with the existing objects in the catalogue. If this correlation does not succeed, a new object associated to this track is created inmediately. If the correlation does succeed, CORTO attempts to run the routine orbit determination (ROD) using the information stored in the catalogue as a-priori information, and the current track. In case several objects are correlated to the current track, CORTO tries the ROD with at most eight correlation candidates, from the most promising to the least promising one. Whenever one of these RODs succeeds, a new status update associated to the current track is created. If none of the RODs succeeds, it is considered that the track corresponds to a new object, so a new object is created in the database.

Whenever a new object is created, the operator is notified by means of an automatically generated email. This way, the operator can verify the process, as there are several cases in which the correlation can fail:

- The a-priori information of the object the current track corresponds to is not good enough to ensure a proper correlation and/or orbit determination

- The object has performed a manoeuvre since the last time it was observed. In this case, the correlation algorithm does not work.

It is responsibility of the operator to check the email inbox for newly created objects and to determine if some action needs to be taken about them. Each email lists information related to the creation of the new object, including: the list of correlation candidates (if any), the sensor and track that created the new object, a complete list of the measurements in the track, and a plot that allows the user to visually identify the actual and expected observations. Figure 3 shows an example of the plots that are issued to the users.

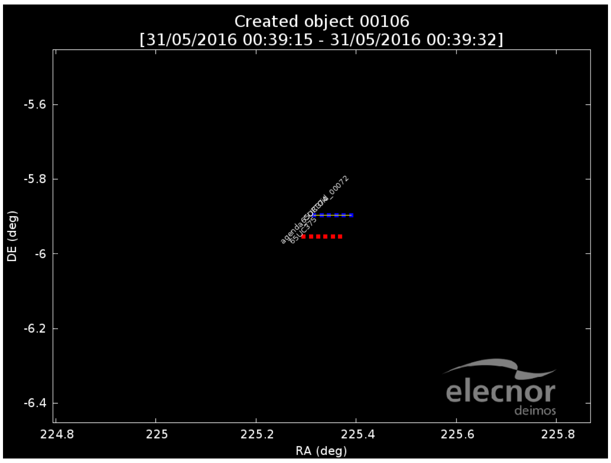

*Figure 3. Example of the plots included in the email sent to the user. In this case, a new object was discovered very near an existing one*

### 2.5.1. Correlation algorithm

The correlation algorithm implemented by CORTO is based on comparing the actual measurements in the track against the expected track. To do this, for each incoming track, all objects in the catalogue are propagated to the exact time of the measurements. Then, expected and actual measurements are compared. The average residuals resulting from this comparison are compared with an user-configurable threshold, in order to determine which correlations can be considered valid, and which ones can not. In order to reduce the computational burden associated to this, not all objects are propagated for comparison with each incoming track. Several filters allow to reduce the list of candidates of each correlation down to around 10 objects (usually).

### 2.5.2. Initial Orbit Determination algorithm

Two different Initial Orbit Determination (IOD) algorithms are implemented, depending on if there is angles and range information available (radars), or angles-only information (ground-based telescopes).

In case of radar, the Gibbs and Herrick-Gibbs methods are implemented. The implementation is based on the description at [3]. For each incoming track, three measurements (the first, the last and the middle) are taken, and Gibbs (for measurements spanning a short arc) or Herrick-Gibbs (for measurements spanning a longer arc) algorithms are applied.

CORTO needs not only the initial estimate of the orbit, as provided by the Gibbs algorithms, but also an initial estimation of the covariance. The initial covariance is computed as:

$$[C]_{[6x6]} = [J]^T_{[6x12]} \, [D]_{[12x12]} \, [J]_{[12x6]} \tag{1}$$

where:

- Dimensions of the involved matrices are explicitly expressed in subindexes.
- $[J]_{[12x6]}$ is the Jacobian formed with the derivatives of the state variables ($x$, $y$, $z$, $\dot{x}$, $\dot{y}$, $\dot{z}$) with respect to each of the individual measurements (azimuth, elevation, range, doppler), at the three times considered in the IOD.
- $[D]_{[12x12]}$ is a diagonal matrix with the squared standard deviation of each of the kinds of measurements provided by the radar.

The additional components of the covariance matrix (corresponding to the uncertainties in the knowledge of the solar radiation pressure (SRP) and drag coefficients cannot be computed by means of this method. Therefore, they are initialised with a user-configurable value.

In case of angles-only information (telescopes), a modified double-R iteration method is implemented. Again, different algorithms are available for short and long tracks. In both cases, the computation is performed with three measurements, regardless of the overall track length. Nevertheless, the remaining measurements are later used in a ROD procedure that uses the initial orbit determination as a-priori data. Therefore, although the algorithm requires three measurements, the information of all the measurements in a initial track is used.

For short tracks, it is assumed that the computed orbit is circular. Therefore, the radii associated to the three observations ($r_1$, $r_2$, $r_3$) at times $t_1$, $t_2$, $t_3$ are the same. A loop in all reasonable values for these radii is performed. For each iteration of the loop, the position vectors associated to the two angles and the tested range are converted to position vectors, and the Lambert problem from $t_1$ to $t_3$ is solved. Then, the measurements obtained from the solution of the Lambert problem are tested against the input measurements at $t_2$. The radius that leads to the best result at $t_2$ is selected as the solution.

Usually, this approach is not enough to yield a correct solution, as the measurements usually span a few minutes or even seconds, and so, the mathematical problem is very badly conditioned. In order to overcome this difficulty, the algorithm is enhanced with the probability function described in reference [4].

In case of longer tracks, the assumption that the radii at the three times of the observations are the same is no longer considered. Therefore, the result of this algorithm is not necessarily a circular orbit.

Regarding the initial covariance, as it is not possible to reliably compute it for short angles-only arcs, CORTO inserts an fixed (user-configurable) initial covariance when a new object is created by means of a angles-only initial orbit determination. The initial covariance is diagonal, and the position and velocity components have all the same values.

#### 2.5.3. Routine Orbit Determination algorithm

The routine orbit determination algorithm is applied on all the tracks that are successfully correlated to an existing object. Currently, the orbit determination algorithm included in CORTO is an implementation of the Square Root Information Filter (SRIF) described in [5]. SRIF is a numerical filter, in each step, a previous estimation of the orbit, its associated covariance matrix and dissipative noise coefficents (atmospheric drag and solar radiation pressure, in this case), and a new track are processed together. This processing yields a new estimation of the orbit (defined by its state vector), covariance matrix, and dissipative noise coefficients. On success, this result is stored in the CORTO database, along with the track that yielded it.

### 2.6. CHOCO

CHOCO is a tool included in the CORTO suite that optionally allows the operator to cross-correlate the objects in the CORTO catalogue with those in the public TLE catalogue. It implements a greedy algorithm that sequentially selects the best pairs of CORTO/TLE objects based in one of these two criteria: Position of the object at the time of the latest track associated to it, or Root Mean Squared (RMS) differences of the orbit contained in the CORTO catalogue against the orbit from the corresponding Two-Line Element (TLE), obtained by using standard SGP4 propagation along a fixed time-span.

### 2.7. CORTOeditor

The bulk of the operator intervention is performed with help of the CORTOeditor tool. This tool presents a wizard that allows the user to modify some contents of the database in a safe and consistent way. This tool is in continous development: new functionalities are added whenever the necessity for them is identified during the routine use. Currently, three functionalities have been implemented:

- A functionality for *merging objects*. The tracks associated to two or more objects in the catalogue are all reassigned to a single object (the one with the lowest CORTO id). Objects that have been merged are completely removed from the catalogue. This functionality is the one that is used when the operator detects that the automated correlation has failed (because, when the automatic correlation fails, most of the times a new object is created, resulting in two objects in the CORTO catalogue which correspond to the same object in the real world). The merging consists on the following steps:
    1. The tracks associated to all merged objects are retrieved and sorted with respect to time.
    2. The operator may choose to re-execute the IOD, and modify its results or completely entering an external initial orbit. This would allow, for example, to enter an initial orbit from a TLE, instead of relying on the IOD algorithms, or to enter an operator-provided orbit, in case it is available. That orbit would then be modified by subsequent observations of the object.
    3. The operator is given the option to introduce manoueuvres. This allows to cover the case in which a manoeuvre is inferred.
    4. A routine orbit determination is performed in all the tracks, one by one.
    5. The results of this process are presented to the operator, who can choose to accept them, or to reprocess the tracks (i.e, by using a different set of initial conditions, or by inserting different manoeuvres).

6. All the involved objects are removed from the database, and a new object with the same CORTO id as the lowest of these is created, with all the tracks and status updates associated to it.

- A functionality for *removing objects*. In this case, removal means deactivation (i.e, the object is marked as invalid, and still exists in the database, but CORTO does no longer consider it a candidate for correlation, so it never gets a new status update. This is used when, for example, an object is definitely lost (its orbit is not good enough to ensure that it will be reliable reobserved), or when it vanishes (for example, if it reenters or leaves the Earth's sphere of influence, so the operator knows that there will be no future observations of that particular object).
- A functionality for *batch reprocessing*. The implementation described in subsection 2.5 always performs the orbit determination in a track-per-track basis. However, in some cases, it may be desirable to run the ROD with batches of tracks. This functionality allows this, along with the insertion of manoeuvres.

The only way of inserting manoeuvres into the catalogue is by means of the CORTOeditor tool. Therefore, the manoeuvre handling is subject to the following rules:

- Manoeuvres can only be inserted after they have taken place. It is currently not possible to insert forecast manoeuvre data (for example, provided by an operator), and let the system apply it. As we estimate that the number of previously known manoeuvres we could access would be a small fraction of all the manoeuvres that take place, we consider this approach acceptable for our objectives.
- As in the vast majority of the cases manoeuvres will be unknown, the user is allowed to enter defined manoeuvres (i.e, the time, $\Delta V$ and direction of the manoeuvre is known) or undefined manoeuvres (only a coarse time of the manoeuvre is assumed). Defined manoeuvres are implemented as directly injecting a status update in the catalogue with the operator-provided $\Delta V$s, while undefined manoeuvres are implemented by injecting an status update in which the state vector is the same as if there was no manoeuvre, but the covariance is largely increased.
- Undefined manoeuvres can also be used to solve possible errors in the ROD (convergence to a different solution)
- A current limitation of the system is the one caused by low-thrust manoeuvres. The cataloguing of objects performing low thrust manoeuvres of unknown direction and thrust is a very challenging undertaking. These objects are effectively under the effect of an arbitrary perturbation. Currently, the only way of dealing with these kind of objects is to routinely merge newly created objects.

## 2.8. CORTOhouseKeeping

CORTOhouseKeeping is a tool that performs some routine maintenance in the database. It checks for false and/or lost objects (i.e., objects which have a very small number of associated tracks, and have not been observed for a long time), and deactivates them, so they are no longer considered real objects, and are no longer candidates for future correlations.

## 2.9. CAWEB

A web application showing the information in the database has been implemented to support the daily operations. The web interface allows the operator to review every single status update associated to every object in the catalogue, as well as showing the accuracy information associated to each of the objects, and the observations processed so far.

# 3. EXAMPLE RESULTS

In this section, we present the results of a analysis campaign which was carried out from 30th May 2016 to 6th June 2016. We processed the observations from a single surveillance sensor, the CENTU 1 [1]. The surveillance strategy involved three passes of a single right ascension band, covering declinations from 0° to -18° (the GEO ring was located at approximately -6° declination), with the aim of observing GEO satellites three times per night. Figures 4 and 5 show the location of all the valid detections for a single day. Notice that objects were observed on all the covered declinations. The observed objects are mostly objects at GEO altitudes (both active and decommissioned spacecraft). Some objects with highly eccentric orbits were also observed, usually near their respective apogees. However, as the periods of the objects within this family vary greatly, they are observed very sparsely. Table 1 provides an overview of the data gathered in the campaign.

The processing was carried out with a modified CORTO version. This version addresses some of the limitations that have been detected with the development of the initial versions ([6]), and was implemented as a prototype for new functionalities that might be added in the future.

The correlation algorithm was improved with the addition of correlation of actual measurements and measurements predicted from the TLE catalogue. This allows better correlation of sparsely observed objects. Apart from that, the initial orbit determination algorithm described in section 2.5.2 was replaced for objects whose measurements

*Table 1. Statistics on the observation campaign*

| Night | #Tracks | Total time (hr) |
|---|---|---|
| May 31st 2016 | 228 | 6.05 |
| Jun 1st 2016 | 284 | 6.57 |
| Jun 2nd 2016 | 252 | 6.85 |
| Jun 3rd 2016 | 0 | 0 |
| Jun 4th 2016 | 263 | 6.68 |
| Jun 5th 2016 | 203 | 5.31 |
| Jun 5th 2016 | 238 | 6.92 |

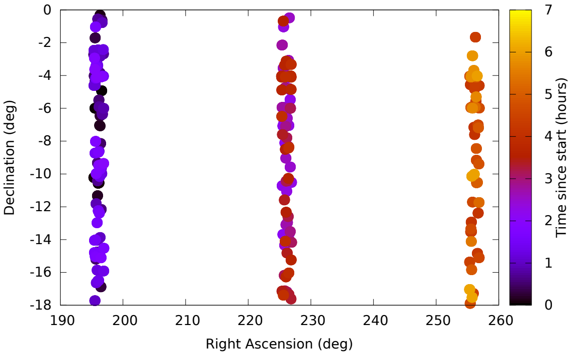

*Figure 4. Observations (Right Ascension and Declination) performed on 31/05/2016*

could be automatically associated with an object in the TLE catalogue. This approach was tried because, given the constraints of the campaign that is being analysed (a single surveillance sensor and no follow-up capabilities), highly eccentric orbits would not have been be catalogued properly (unless the operator did an extraordinary effort for manually identifying each new object based on the observations). Apart from that, the TLE catalogue can yield, most of the times, a better initial approximation to the orbit than what can be achieved with the IOD algorithm.

The processing resulted in a catalogue with 406 objects. Of those, 161 were considered valid after the housekeeping procedures. Figures 6 and 7 show the orbital elements that CORTO identified for them. As expected, the vast majority of the observed objects are GEO resident objects. Among these, most of them are within 0° and approximately 15°, with a few outliers. 22 were not assigned any NORAD number (thus we call them UFOs). They are shown in 2

In order to evaluate the validity of the orbits, we consider the average covariance in position. Figure 8 shows an overview of the covariances of all the objects, propagated to July 7th 2016. The best covariances are achieved on objects that have the most re-observations (these are mostly in the GEO resident family). It must be noticed that it is possible to use orbits with relatively high covariances

*Table 2. Information on the UFOs found in the observation campaign*

| ID | #Tracks | Last covs<br>(km & km/s) | SMA<br>(km) | Inc<br>(deg) |
|---|---|---|---|---|
| 10 | 13 | $0.25; 2.164 \cdot 10^{-5}$ | 42164 | 1.93 |
| 27 | 14 | $0.16; 1.907 \cdot 10^{-5}$ | 42167 | 10.56 |
| 47 | 17 | $0.09; 1.688 \cdot 10^{-5}$ | 42168 | 7.98 |
| 59 | 16 | $0.09; 1.818 \cdot 10^{-5}$ | 42167 | 9.16 |
| 63 | 12 | $1.26; 2.928 \cdot 10^{-4}$ | 42110 | 14.55 |
| 94 | 9 | $0.28; 3.211 \cdot 10^{-5}$ | 41931 | 0.073 |
| 100 | 2 | $68.70; 1.185 \cdot 10^{-2}$ | 42410 | 12.57 |
| 126 | 5 | $17.86; 1.327 \cdot 10^{-3}$ | 42331 | 8.28 |
| 131 | 4 | $0.49; 2.918 \cdot 10^{-5}$ | 42150 | 0.07 |
| 140 | 10 | $0.15; 2.202 \cdot 10^{-5}$ | 42165 | 4.51 |
| 146 | 12 | $0.10; 2.071 \cdot 10^{-5}$ | 42176 | 0.1 |
| 159 | 4 | $389.16; 2.675 \cdot 10^{-2}$ | 43375 | 4.72 |
| 161 | 4 | $490.48; 3.425 \cdot 10^{-2}$ | 43106 | 0.03 |
| 203 | 2 | $62.27; 1.161 \cdot 10^{-2}$ | 41927 | 0.18 |
| 222 | 9 | $0.16; 2.141 \cdot 10^{-5}$ | 42165 | 12.8 |
| 244 | 6 | $0.18; 2.686 \cdot 10^{-5}$ | 41975 | 0.1 |
| 248 | 5 | $1.21; 2.267 \cdot 10^{-4}$ | 42167 | 0.077 |
| 266 | 4 | $0.54; 7.062 \cdot 10^{-5}$ | 41931 | 0.09 |
| 283 | 4 | $8.27; 1.261 \cdot 10^{-3}$ | 42402 | 8.32 |
| 289 | 5 | $0.17; 3.423 \cdot 10^{-5}$ | 42167 | 0.09 |
| 292 | 7 | $0.15; 2.548 \cdot 10^{-5}$ | 42167 | 0.08 |
| 317 | 2 | $127.77; 4.563 \cdot 10^{-3}$ | 41894 | 0.1 |

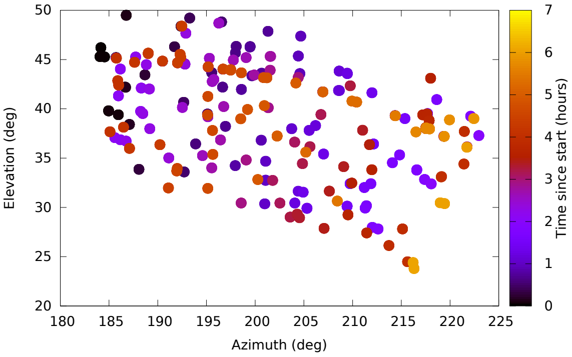

*Figure 5. Observations (Azimuth and Elevation) performed on 31/05/2016*

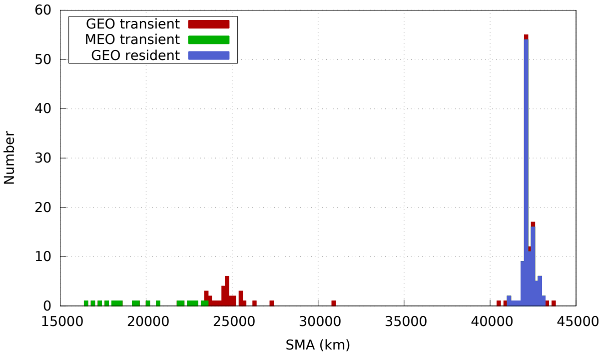

*Figure 6. Distribution of semi-major axes of catalogued objects*

(around 10 kms) for correlation and catalogue maintenance processes, even when those orbits are not precise enough to be used for conjunction assessment purposes (which would require follow-up observations in order to refine the orbits of the involved objects). In those cases, the orbits in the catalogue can be used to feed the tracking sensors.

In the following subsections we present some examples of interesting cases that appeared when performing the processing. These examples illustrate the work that has to be carried out by the cataloguing operators.

### 3.1. Object 59

The object that was assigned object ID 59 is an UFO. CHOCO was unable to assign any NORAD id to it. The object was created and maintained with no external information, and no manual intervention. It was observed every night. After the processing, the computed orbital elements were 42167 km SMA, 0 eccentricity, and 9.2º inclination. Apparently, it performed no manoeuvres during the campaign. This, together with its orbital elements, leads us to think that the object is an inactive one. Further observations would be required to determine if the object performs manoeuvres or not.

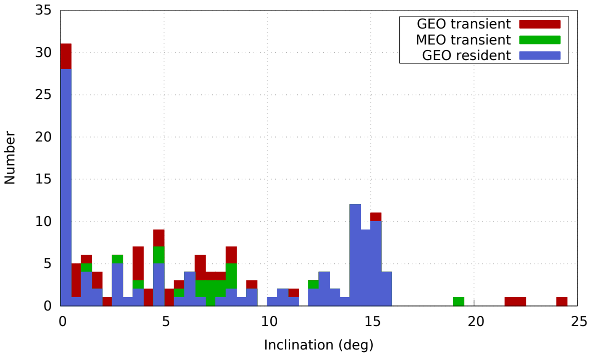

*Figure 7. Distribution of inclinations of catalogued objects*

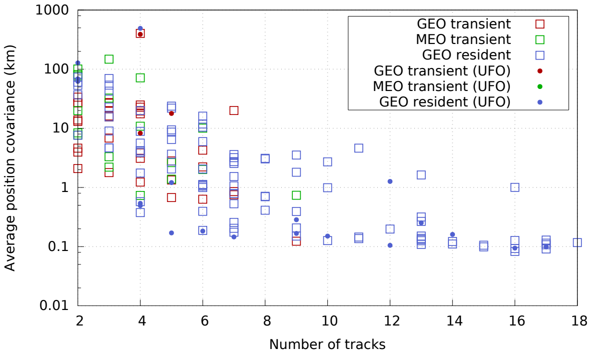

*Figure 8. Average covariances in position for all valid objects in the catalogue as a function of the number of associated tracks*

Figure 9 shows how the orbital elements computed by CORTO have evolved with each orbit determination update. It is worth noting the large initial error in the computed Semi-major axis (around 200 km). If this object was not observed three times during the first night, that initial error would not have been corrected, and CORTO would have been unable to maintain this particular object. The large initial error is because of the limitations of the initial orbit determination algorithm (described in section 2.5.2), and because of the very short time span of the tracks provided by CENTU for this particular campaign (only 18 seconds).

Figure 10 shows the evolution of the measurements residuals against the orbit CORTO had at the moment of processing each track. Therefore, the results shown there are coupled with the errors in the orbit determination (the expected performance of the CENTU telescope is approximately 1 arcsecond both in right ascension and declination).

### 3.2. Object 20

The object with CORTO id 20 was identified as HISPASAT 1B (1993-048A). At the time of the campaign

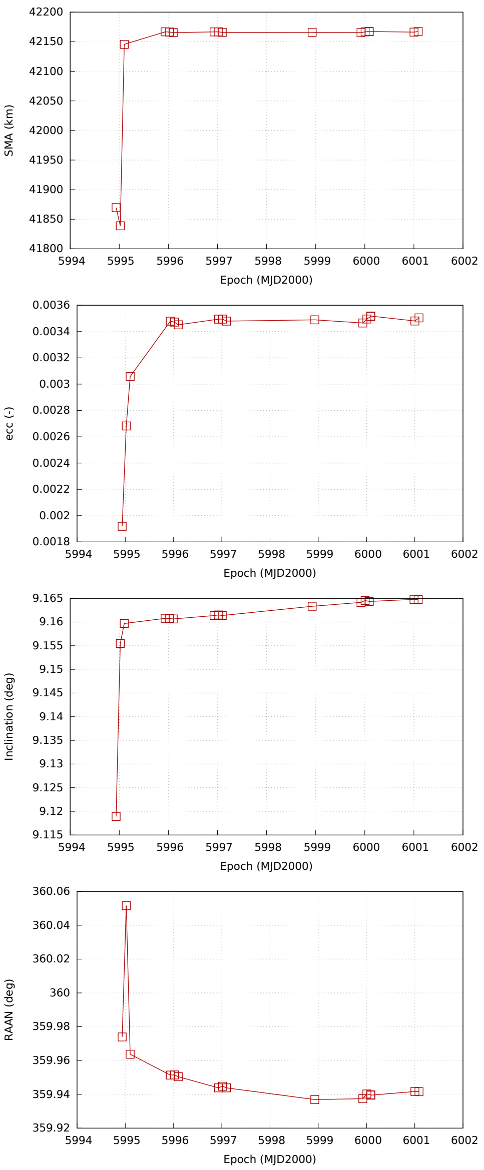

*Figure 9. Evolution of computed orbital elements for object with CORTO ID 59*

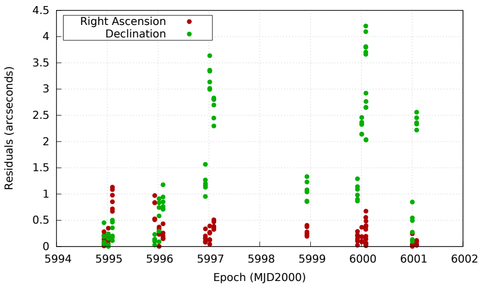

*Figure 10. Residuals of all measurements associated to object 59 against the catalogue orbit at the moment of orbital determination*

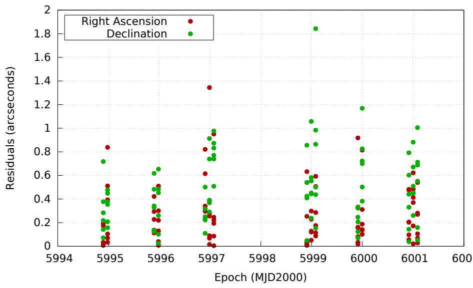

*Figure 11. Residuals of all measurements associated to object 20 against the catalogue orbit at the moment of orbital determination*

it was decommissioned and drifted at a rate of 2°/day. This object belongs to the inactive GEO resident objects, which are the easiest for the cataloguing process: they perform no manoeuvres (thus, their orbit is affected only by natural forces), and can be re-observed frequently by surveillance sensors focused on the GEO region. Figure 11 shows the residuals for this object. In this case, its behaviour is better than object 59, and suits well the performances expected from the CENTU sensor. For this case, the initial orbit determination was not executed, instead the orbit from the TLE was used as the first approximation when the first track associated to this object was processed.

### 3.3. Object 183

The object with CORTO id 183 was identified as 2012-016C. It is a BREEZE-M Rocket Body, and orbits a highly eccentric orbit, with a perigee height of 3257 km and an apogee height of 33949 km. It is also the object with the greatest inclination of all those we were able to catalogue. It was observed 7 times during the campaign. As mentioned above, given its eccentric orbit and inclination, this was just a matter of chance. We verified that the seven times it was observed, the object was near its apogee. The lowest observation happened at an altitude of 29500 km, and the highest at 33430 km.

In this particular case (as well as in any other case with high eccentric orbit), the follow up was only possible because of the insertion of an approximate orbit from the TLEs. As previously mentioned, this is a limitation of the initial orbit determination algorithm. In order to work without the contributions from the TLE catalogue, a larger network of surveillance sensors would be required and/or immediate follow-up would need to be set up.

## 4. CONCLUSIONS AND FUTURE WORKS

In this work, the CORTO cataloguing tool was introduced. An observation campaign was carried out, processed with the CORTO software, and the outcome was

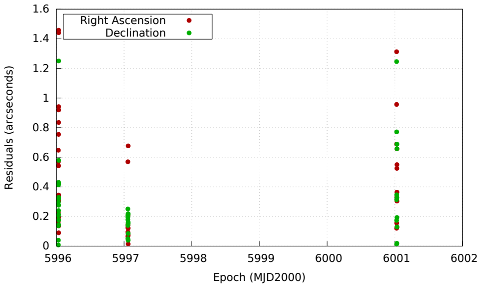

*Figure 12. Residuals of all measurements associated to object 183 against the catalogue orbit at the moment of orbital determination*

studied. The used CORTO tool included some experimental modifications that were also assessed while preparing this work.

- The campaign resulted in 161 objects that are considered valid. Of these, approximately 13% are objects that are not in the TLE catalogue. As all these objects were re-observed during the campaign, it is extremely unlikely that they come from false detections.
- As the observation strategy was focused on the GEO ring, most of the observed objects belong to that orbital regime. Among these, there are two large groups: the active objects orbiting a pure 24-hour orbit, and drifting objects with varying inclinations between 0° and 15°. The former are observed more frequently because of their low or null drift rate, the later are easier to maintain, as they perform no manoeuvres at all.
- 46 of the catalogued objects were highly eccentric ones (orbits with eccentricity larger than 0.2). They are therefore approximately the 28% of all the catalogued objects. These objects were automatically catalogued by using TLEs to determine their initial orbits.
- 245 objects in the catalogue were created and later deactivated because they had too few associated tracks. It is considered that, with such few associated tracks, it is not possible to enable later correlation without external information. Of these, 102 could be associated to a NORAD id (by means of the measurements themselves), and 143 could not be associated to any NORAD id. Among the later, it is expectable that there are measurements corresponding to actual, valid UFOs, and measurements coming from false detections. In both cases, they are data of almost no use for the cataloguing system, therefore, the objects associated to them are deactivated.
- CORTO was designed to work independently of any other external catalogues. Its aim is to be able to build and maintain a catalogue using the measurements from a sensors network only. The ability of tracking and maintaining UFOs presented in this work proves it. However, the use of foreign catalogues is an invaluable source of information (if only, for identification purposes). In the case of the eccentric orbits, the use of external information allows compensating the limitations of the sensing network (in this case, the sensing network was extremely simple: a single surveillance telescope and no follow-up capabilities).
- Manoeuvering objects are extremely challenging for a cataloguing system, as they are, from the point of view of the cataloguing system, a random force applied at a random moment. In GEO, this is often coupled with groups of active satellites flying in close formation and performing frequent station-keeping manoeuvres, making the problem significantly more difficult. Coping with manoeuvering objects requires not only a supporting software, but also a contribution of human intervention.
- The future developments that are being considered include:
  - Implementation of follow-up capabilities, including the generation and prioritisation for tracking, as well as the planning for the configured sensors. This includes immediate follow-up for newly discovered objects.
  - Use of metadata from the sensors: Information coming from the sensors, such as actual pointing directions, or lightning conditions could be used by the correlation routines in order to fill an important gap: keeping track of missing objects (i.e, objects that should have apppeared in an observation, but did not turn out)
  - Improvement of the manoeuvres module to allow a better handling of manoeuvering objects in the long term.
  - Support for extra sensors types, such as laser ranging sensors and/or space-based sensors.

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