# FROM SIMULATION TO REALITY: CATALOGUING OF OBJECTS FROM GROUND-BASED OPTICAL OBSERVATIONS

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## ABSTRACT

This paper presents the approach for building a catalogue of Earth-orbiting objects from optical observations in surveillance mode. The cataloguing is based on the DEIMOS CORTO tool (CORrelation Tool) which is described in this paper. CORTO has evolved from a simulated cataloguing system to a cataloguing software suite intended to process data from real observations. Thus, it merges the knowledge derived from simulation experience and the main constraints imposed by real observation activities. The main differences among these two approaches are highlighted in the paper. CORTO processes observations from several sensors in a sequential way. For each incoming observation, it attempts to correlate it to an existing object in the catalogue. If such correlation is possible, an orbit determination process is performed on the incoming measurement in the basis of a-priori state vector and covariance of the object. If such correlation is not possible, an initial orbit determination is carried out, and a new object associated to that measurement is created. CORTO allows a cold start of the cataloguing (i.e, it does not need any external catalogue to start) and thus, can maintain orbital information of object not included in public TLE file. The main results from DEIMOS cataloguing experience are summarised, describing the observation strategy and the measurement distribution considered necessary for achieving a proper cataloguing capability. This summary highlights the main difficulties that can be found, in the correlation activities which impose a several-step approach to correlation in order to avoid miss-correlation of objects. The approach undertaken in the CORTO software is based on a three step process: firstly, a correlation in the basis of comparison of observation with expected visibility periods and rough observation angles is carried out for every object. A second orbit determination compatibility cross-check based on the filtering residuals is performed later. Finally, a procedure for removing false objects (i.e, objects created by spurious measurements), and/or to remove objects which are observed sparsely is performed asynchronously. The system is intended to run in a mostly automated way, but allows an operator to assess the correlations performed automatically by the system, and to correct them if necessary. In addition to this, it is possible to correct errors related to manoeuvring objects. If the operator knows with certainty that a manoeuvre has taken place, information regarding that manoeuvre can be loaded into the catalogue. The operator can also infer when an impulsive manoeuvre has happened with support from the system. Finally, the system allows the user to perform an iterative process in order to estimate the area-to-mass ratios associated to each of the objects in the catalogue. The CORTO cataloguing system is accompanied by a set of auxiliary tools, also described in the paper, which complete the capabilities of the system to ensure the proper cataloguing process. These tools include: CALMA for calibration of observation stations (used to qualify a number of observatories), CORTOEditor, to support operator for operational maintenance of the catalogue, and CHOCO which optionally allows correlating the observed objects with the TLE data. 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 supports the monitoring of the catalogue. The paper presents the main results from an observational campaign executed in October 2014 focused on the cataloguing of high altitude objects. The campaign lasted 9 consecutive observing nights, providing more than 200.000 observations from three surveillance and a tracking telescopes located in Spain. Those observations are used to feed-up the CORTO cataloguing system, and have allowed creating a catalogue of objects which are observable from southern Europe. In particular GEO ring longitudes covering Europe are well represented. About 300 objects are systematically observed during several nights, eventually reaching accurate orbits. The achievable accuracy of the observed orbits can reach values around 10-100 meters. Object manoeuvres are also observable. Example cases of observed manoeuvres are reported.

***Index Terms***— Cataloguing, Correlation, Orbit determination, Telescopes, Space debris, Space Surveillance and Tracking (SST), Space Situational Awareness (SSA)

## 1. INTRODUCTION

In October 2014, a surveillance campaign spanning nine observation nights was carried out with four ground-based telescopes, all located at the same site in southern Spain. Three of the telescopes where devoted to perform a surveillance pattern focused on the observations of objects at GEO altitudes (including pure GEO satellites, as well as objects at near-GEO altitudes). The fourth telescope was devoted to the tracking of some selected objects. This turned out in an average of 20849 individual measurements per night (minimum 15636 and maximum 23652) after processing at the telescope facility.

One of the objectives of this campaign was to determine the feasibility of using the CORTO (CORrelation TOol) from Deimos Space to support the creation and the maintenance of a catalogue of Earth-orbiting objects. The CORTO tool was firstly developed with the objective of supporting the definition of optimal observational strategies for optical sensors monitoring the GEO ring. Reference [1] provides a description of that study. Since then, the CORTO tool has undergone several improvements, based on the experience gained by the team in several different projects, and the necessities of a fully-fledged Space Surveillance and Tracking (SST) system.

The processing of the data from this campaign lead to several improvements focused on the real-world necessities and constraints related to the maintenance of a catalogue. The most prominent features of CORTO are:

- Allows a flexible definition of the sensors network that are deployed to feed the catalogue. Supported kinds of sensors are radars and ground-based optical telescopes.

- Allows starting a catalogue from scratch. Particularly, it does not require information from the JSpOC catalogue. One of the main goals of CORTO is to support a catalogue that is completely independent from others (i.e, all the data it contains is derived from the information provided by the sensors network). In particular, we aim to maintain objects currently not listed in the JSpOC catalogue, and to achieve a better orbital accuracy. An optional tool allows cross-correlation of objects in the CORTO catalogue with TLEs.
- Processes tracks from surveillance and tracking sensors.
- Allows the automatic processing of incoming tracks from different sensors as soon as they arrive, or with different scheduling schemes. It can be also ran manually (for example, to process past data)
- Allows the operator to supervise and correct the operations performed by the software. Particularly, correlation operations can be reviewed.
- Allows the operator to insert manoeuvres that are inferred by inspecting the catalogue data. These manoeuvres are not inserted automatically, it is responsibility of the user to detect and insert them.
- Generates ephemerides for the catalogued objects in standardised format, to allow connecting it to existing subsidiary services.

In addition to the CORTO tool, a set of auxiliary tools are built around it, in order to support the maintenance of the catalogue.

## 2. CORTO OVERVIEW

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 [1]. Now, 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.

### 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.

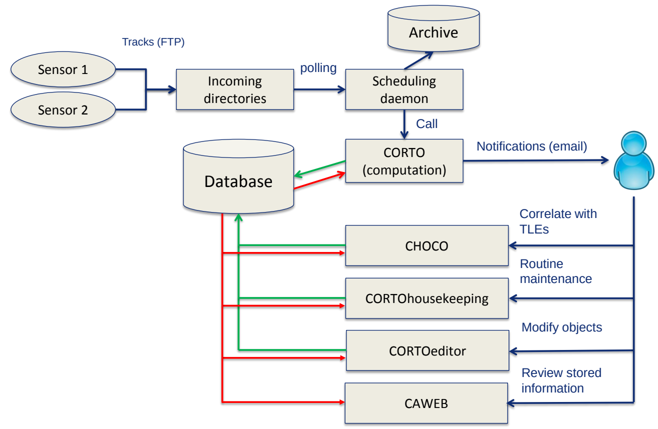



**Fig. 1**. CORTO modules

### 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.

### 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.

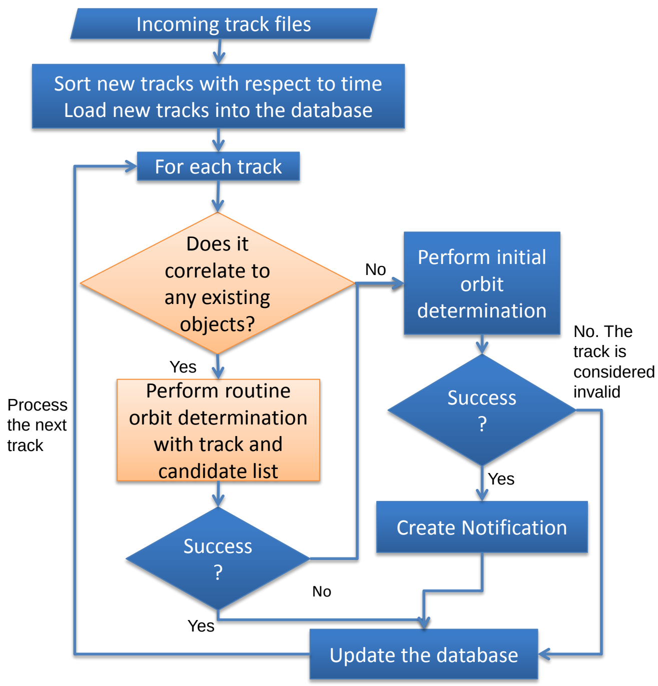



**Fig. 2**. CORTO main algorithm flowchart

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 that the correlation was correct, 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. The figures used to illustrate the cases explained in this paper (figures 7, 8 and 10 are examples of those plots, taken directly from the emails.

### 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 [2]. 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 [3].

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, 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 [4]. 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 that optionally allows the operator to cross-correlate the objects in the CORTO catalogue with those in the JSpOC 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 manoeuvres. 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. OBSERVATION CAMPAIGN

A surveillance campaign was carried out by La Sagra Sky Survey (LSSS) from Thursday 23$^{rd}$ October, 2014 to Friday 31$^{st}$ October, 2014. During that campaign, surveillance, tracking, and calibration activities were carried out. There were three telescopes devoted for surveillance, and one dedicated to tracking. The La Sagra Observatory is located at 37.9823° N, 2.5656° W and 1613 m altitude. The characteristics of the surveillance telescopes were: 45 cm aperture size, 136 cm focal length, and 4Kx2.7K CCD cameras (one of them was 4K x 4K) that provide a Field of View of $1.5^\circ \times 1.5^\circ$ They were remotely controlled via Internet.

Each of the tracks provided by the telescopes comprises three measurements (a triplet). Each measurement of the triplet includes two angular measurements (right ascension and declination), and the visual magnitude. The measurements within the triplet are typically taken with a difference of a few seconds.

The observation strategy was aimed at observing the GEO ring and objects at near-GEO altitudes. Moderately high declinations (around $\pm 6^\circ$ were covered)

## 4. RESULTS OF THE CAMPAIGN

For this paper, seven of the nine observation nights of the campaign were processed with CORTO. Because the processing was not being performed in real time, the CORTO scheduling daemon was not used, and we opted for manually triggering the processing of the tracks. All the seven nights were processed following these steps:

1. Process the tracks with CORTO.
2. Verify the automatically generated emails from CORTO, check for wrongly created objects and possible manoeuvres.
3. Run CORTOhouseKeeping to remove objects with a small number of associated tracks, and therefore unlikely to be reobserved.
4. Run CHOCO to correlate the current CORTO catalogue against the JSpOC catalogue.

Between each of the steps listed above we performed a full backup of the database. This allows us to recover from errors, as well as to return to past states of the database if it were necessary.

Table 1 provides an overview of the results of the campaign. 1606 objects exist in the catalogue at the end of the processing. Of these, 1143 were considered valid. Invalid objects are:

- Those that were automatically removed by CORTOhouseKeeping. This includes those objects which were created from invalid observations (as the image reduction procedure sometimes results in false observations), and those that had observation arcs so short that there is no reasonable hope of properly correlating them with later observations.
- Those that were removed by the operator. These are objects that have a number of observations large enough to make us sure that they are not false detections, but, because of the orbital and/or observational constraints, we considered that futile to keep them in the catalogue.

**Table 1**. Summary of the results of the seven-day campaign

| | |
|---|---|
| Total created objects | 1660 |
| Number of valid objects | 1143 |
| Total number of tracks | 39676 |
| Total number of status updates | 40463 |
| Total number of manoeuvres | 29 |

Because of the set-up of the campaign, we expect most of the catalogued objects to be in the GEO and GEO transient regions. The data set we used also included secondary objects seen during the telescope calibrations, which were performed routinely. As these calibrations were made by pointing at objects in the NAVSTAR constellation, it is expectable to see some MEOs (Medium Earth Orbit) in the catalogue. However, as the surveillance strategy was focused on GEO, these observations may not provide any viable object in the catalogue.

The final number of objects with respect to the orbit type turned out to be:

- 913 GEO resident objects. Of these, 159 were automatically removed. Among the remaining 754 objects, 361 had an associated NORAD number.
- 222 GEO transient objects. This category includes the objects that have a perigee near the GEO altitudes. Although the chosen observational strategy is not adequate for this kind of objects, we might obtain reasonably accurate orbits for at least some of them. 74 of these objects were automatically invalidated by CORTO. Among the remaining, 6 were correlated to an object in the TLE catalogue. Table 2 shows some information related to these objects. It can be seen that those objects with a reasonably long observation arc allow getting an orbit similar to that of the TLE, while from those with a short arc we can only compute a coarse orbit.
- 409 MEO resident objects. During the campaign, the telescopes routinely carried out calibration measurements. All those measurements where also loaded in CORTO. With the exception of the target NAVSTAR satellites, all these tracks cover very small periods of time. This, together with the observation strategy that prioritises GEO altitudes and low inclinations, yields all these objects uninteresting. It must be borne in mind that these 409 objects do not actually correspond to 409 real objects. Due to the short observation arcs, correlation is not possible. Also, a large number of invalid measurements were found under this category.
- 4 MEO transient objects. All these objects were automatically invalidated.
- 8 LEO objects. The telescopes used in the campaign are unable to see real LEO (Low Earth Orbit) objects, as they move extremely fast. CORTO identified all these objects as invalid, and were automatically removed without any user intervention. A further check indicated that these objects were all created from invalid measurements.

**Table 2**. Overview of GEO transient objects properly associated with a TLE

| NORAD | Position diff. (km) | Velocity diff. (km/s) | Num. tracks | Arc length (hours) |
|---|---|---|---|---|
| 2222 | 11.93 | $7.9 \cdot 10^{-4}$ | 40 | 4.72 |
| 3292 | 9.06 | $7.3 \cdot 10^{-4}$ | 72 | 47.19 |
| 27444 | 398 | 0.73 | 20 | 0.15 |
| 38705 | 342 | $7.7 \cdot 10^{-2}$ | 3 | 0.02 |
| 13970 | 4.47 | $1.9 \cdot 10^{-2}$ | 15 | 0.39 |
| 39376 | 39.25 | $3.1 \cdot 10^{-3}$ | 40 | 0.71 |

Approximately 40000 tracks were inserted into the system. The operator actions resulted in 29 manoeuvres identified overall (notice that this figure includes actual manoeuvres, as well as auxiliary manoeuvres inserted for solving a divergence of the ROD algorithms)

It is known that some objects may not be in the TLE catalogue. In order to assess this, we have considered all the objects in our catalogue with at least 50 tracks associated to them, and no associated

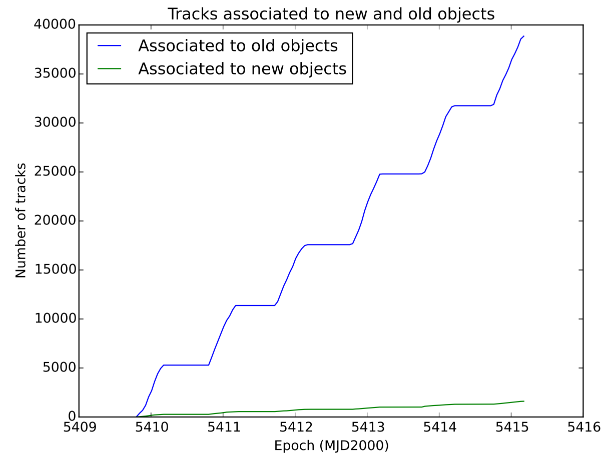
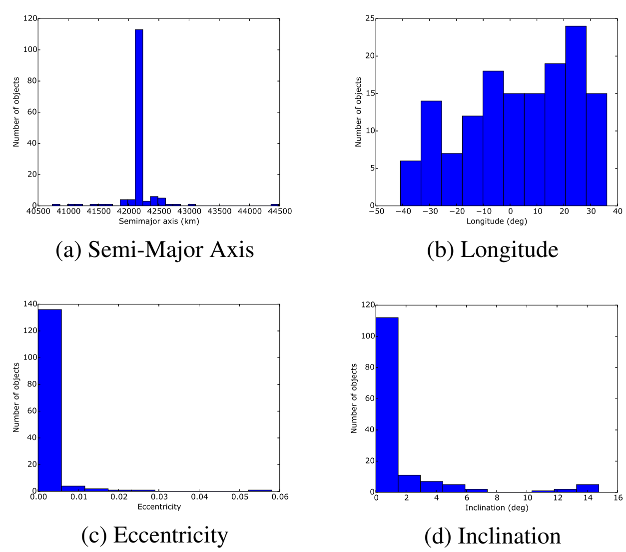



**Fig. 3**. Evolution of tracks associated to old and new objects

NORAD number. This resulted in 134 objects with more than 50 tracks and an associated NORAD number, and 11 objects with no associated NORAD number. The fact that they have been observed at least 50 times suggests that the obtained orbit for these objects should be reasonably accurate.

Most valid objects are located in the GEO ring, as shown in figure 4. It is also worth noting that there is a significant number of inclined GEO objects. Although the surveillance strategy is not aimed directly at them, it is still possible to catalogue some of them.




(a) Semi-Major Axis (b) Longitude

(c) Eccentricity (d) Inclination

**Fig. 4**. Semimajor axes, longitudes, eccentricities and inclinations of catalogued objects with more than 50 associated tracks

## 5. DETAILED INFORMATION ABOUT SOME OBJECTS

In this section we present detailed information about some of the catalogued objects that are considered of interest.

### 5.1. Objects 8 and 12

The objects with CORTO ids 8 and 12 are of interest because they where located very near the first time they were observed (and inserted into the catalogue). Figure 5 shows the tracks that were used to create these two objects (identified by the strings 4ANC001 and 4ANC005), and, overlayed in green, the expected position of those objects based on their TLEs. From the figure, it is obvious that the aforementioned tracks correspond to the TLE catalogued objects 2001-025A (ASTRA 2C) and 2012-051A (ASTRA 2F). Also, the figure suggests that miscorrelations might happen when processing the tracks of these objects. In the particular case of these objects, no miscorrelation happened, or if it happened, it was harmless. However, it is expectable that problems related with this might arise with objects flying in close formation.

These two particular objects were observed during the five processed nights, with CHOCO consistently assigning them the same NORAD number every time it was executed. Figure 6 shows the evolution of the computed orbital elements against the ones extracted from nearby TLEs (which can be considered a reference). The figure shows that the initial orbit (computed from the initial orbit determination) has a large error (mainly because the orbital radius computed by the IOD algorithm is not accurate). Subsequent routine orbit determinations approximate the orbits to the reference ones, eventually obtaining very similar results. In this particular case, these two objects where re-observed a few hours before the first initial orbit determination. This shows that the re-observation time after the discovery of a new object is critical for enabling successful subsequent re-observations.

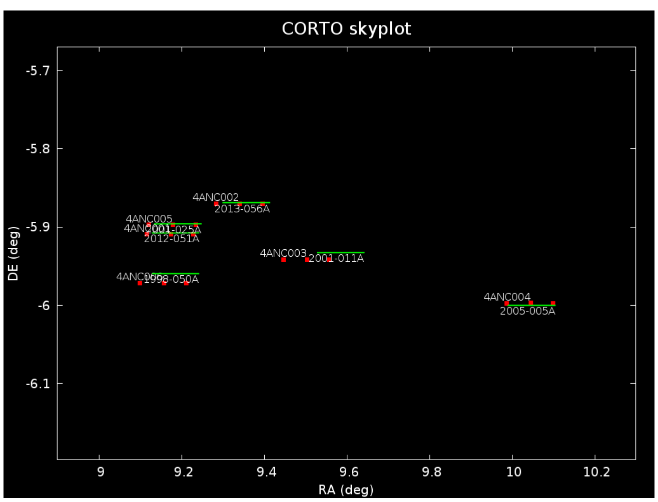
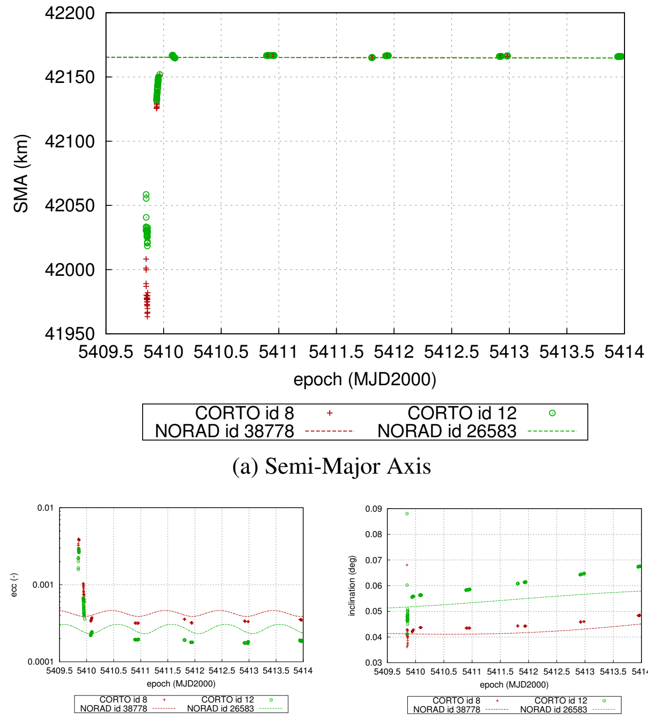



**Fig. 5**. Tracks associated to the creation of CORTO objects 8 and 12. Nearby tracks and TLEs (green lines) are also depicted

### 5.2. Objects 112 and 536

The object with CORTO id 112 was created with tracks from the first observation night. After processing the first observation night,




(a) Semi-Major Axis

(b) Eccentricity (c) Inclination

**Fig. 6**. Evolution of computed orbital elements for objects 8 and 12, an comparison with TLE orbits

it was assigned the NORAD id 29273 (2006-033B - SYRACUSE 3B). When processing the data from the next night, CORTO created a new object very near this one, with an id of 536. Figure 7 shows the plot that is issued to the system operator when the object 536 was created. By looking at this figure, our first thought was that either the orbit of object 112 at that date was not good enough, leading to a miscorrelation, or that object 112 might have performed an along-track manoeuvre. We attempted to merge the two objects with CORTO editor (described in section 2.7), as we assumed they should be the same. However, we quickly realised that object 112 had been updated at the same time as object 536. Therefore, objects 112 and 536 are necessarily different (as there are different measurements at exactlye the same times).

After processing the third night, object 112 was re-observed, but object 536 was not. Similarly to the first night, a new object with ID 636 was created near object 112, and there was no trace of object 536 nearby. This means that the initial orbit we computed for object 536 was not enough to ensure a re-observation after a few hours. However, at this point we already knew for sure that objects 636 and 536 had to be the same. Therefore, we attempted to merge them. After a successful merge, object 636 vanished from the catalogue, and all the tracks associated to it were assigned to object 536.

After the fourth campaign night, both objects (112 and 536) were properly re-observed, and got assigned the correct TLEs (NORAD 29273 for CORTO id 112 and NORAD 27460 for CORTO id 536). After the fifth night, both objects were re-observed.

This case illustrates how it is possible to manually recover objects that might have been lost because of the limitations of the initial orbit determinations and the correlation algorithms.

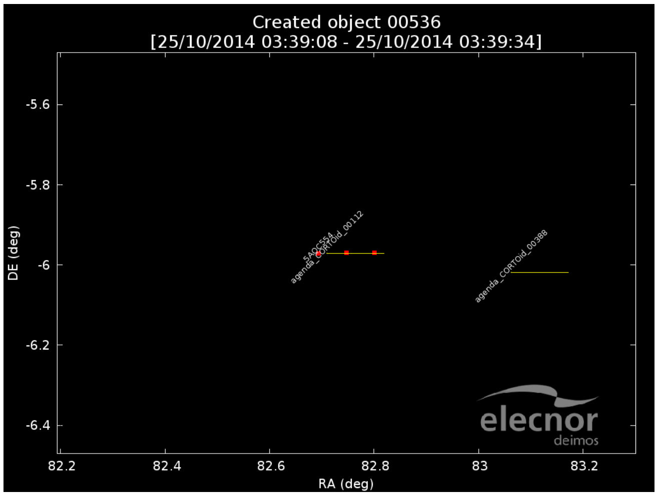



**Fig. 7**. Creation of object 536. Red dots are actual measurements, yellow lines are the expected measurements of objects already in the catalogue

### 5.3. Object 15

The object with CORTO id 15 was observed routinely during the first three observation nights, and correlated with the object 37810 in the JSpOC catalogue. A good number of tracks allowed to get a good orbit for it. However, during the processing of the fourth observation night, an object with ID 814 was created (figure 8). That figure seems to suggest that objects 15 and 814 should be the same. Considering that at this point, the orbit we had for object 15 was already consolidated, there were two possible explanations for this: the OD algorithm could have converged to another solution, or the observed object did perform a manoeuvre. In both cases, the action to be done is the same: to insert an undefined manoeuvre with CORTOeditor (section 2.7).

Inserting such manoeuvre resulted in object 15 being observed during the subsequent nights, and properly associated with the same NORAD object as before. Figure 9 shows the effect of the manoeuvre in the computed eccentricity and inclination. The figure also shows the orbital elements of the nearest TLEs for that object. The TLEs apparently show no manoeuvre.

### 5.4. Object 337

This object is of interest because it is observed routinely (every night since the second one), but CHOCO is unable to associate any TLE to it. Also, when plotting the TLEs along with the observations, there is apparently no equivalent object in the TLE catalogue that matches the observations we associated to object 337. As it has been observed for several nights, and has 95 tracks associated to it, we can conclude that this particular object is not listed in the JSpOC catalogue.

The latest orbit determination for this object yielded a SMA of 42174.16 km, a small eccentricity, and a moderate inclination (2.2

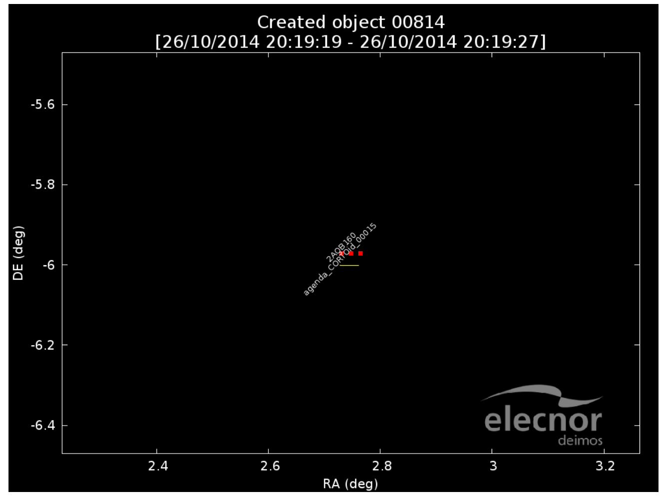
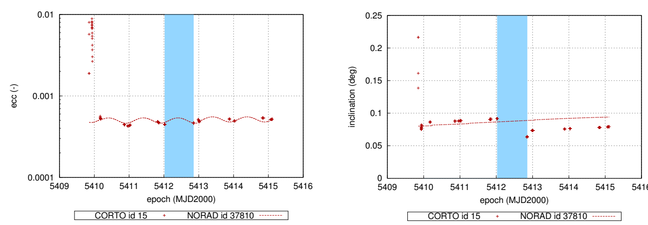



**Fig. 8**. Creation of object 814. Red dots are actual measurements, yellow lines are the expected measurements of objects already in the catalogue




(a) Eccentricity (b) Inclination

**Fig. 9**. Evolution of computed orbital elements for the object with CORTO id 15. The shaded area covers the time interval at which a manoeuvre might have taken place

deg). According to our observations, it did not perform any manoeuvre during the time it was screened. However, determining if its actually an active object or not would require an extended observation campaign and/or dedicated tracking campaigns.

### 5.5. Objects 76, 343 and 125-360-1390

The correlation with CHOCO has shown that these objects correspond to the Meteosat constellation, as listed in table 3. MSG-2 and MSG-3 where consistently observed with no particular difficulties. On the other hand, two CORTO objects for MSG-1 were created. This happened because object 125 has only observations that cover 9 minutes, and were not enough to allow correlating when MSG-1 was observed again. Therefore, it can be considered that object 360 is really MSG-1, and object 125 could be deleted or merged with 360. Moreover, the data provided in the EUMETSAT orbital information mailing list ([5]) informs that an East West station keeping manoeuvre was carried out on 28/10/2014 at 05:13:00 UTC. The last observation associated to object 360 in the catalogue is 28/10/2014 02:18:08.252 UTC, and a new object with ID 1390 was created at 28/10/2014 20:07:42.795 (as seen in figure 10). The manoeuvre mentioned by the EUMETSAT operators therefore took place between those two dates. The figure shows clearly that a manoeuvre happenend, it can also be seen that apparently was a pure along-track manoeuvre. The action taken when detecting this was to merge both objects, inserting a manoeuvre between them.

**Table 3**. Correspondence between NORAD and CORTO ids for Meteosat spacecraft

| Vehicle | NORAD id | CORTO id |
|---|---|---|
| MSG-1 | 27509 | 125-360-1390 |
| MSG-2 | 28912 | 343 |
| MSG-3 | 38552 | 76 |

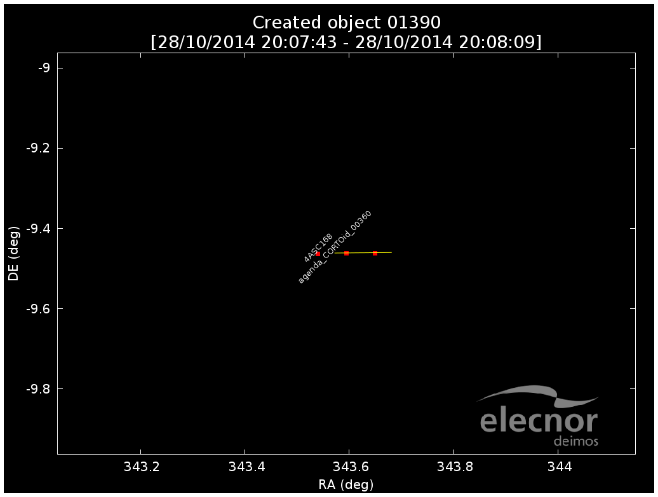



**Fig. 10**. Creation of object 1390. This could be caused by an along-track manoeuvre performed by object 360 since the last observations

In order to assess the orbits computed by CORTO, tables 4, 5 and 6 present a comparison between the EUMETSAT-provided orbits (used as reference) and the orbits obtained by CORTO and by propagating the nearest TLE (in all cases, this means the TLE was propagated backwards). In the case of MSG1, a manoeuvre took place. The table shows the accuracy of object 1390 before performing the merge operation as CORTO (1), and the accuracy of object 360 after performing the merge. It can be seen that the merge operation itself has little effect on the accuracy of the computed orbit. In this case, the accuracy obtained by CORTO is comparable to that provided by the TLEs, and further observations would be required to improve the orbit to levels similar to MSG2 and MSG3.

**Table 4**. Comparison of CORTO, TLE and reference orbits for MSG3. The TLE was propagated 20 minutes backwards

| Source | Dif. Pos (km) | Dif. Vel (km) |
|---|---|---|
| TLE | 4.68 | $8.4 \cdot 10^{-4}$ |
| CORTO | 0.60 | $4.9 \cdot 10^{-5}$ |

The tables show that for the cases in which no manoeuvres have been performed, the accuracy of the obtained orbit improves over the accuracy provided by the TLEs, because of the frequent re-observations. The case with the manoeuvre shows that the level of accuracy obtained by CORTO is of the same order of magnitude

**Table 5**. Comparison of CORTO, TLE and reference orbits for MSG2. The TLE was propagated backwards 4.8 hours

| Source | Dif. Pos (km) | Dif. Vel (km) |
|---|---|---|
| TLE | 4.82 | $2.5 \cdot 10^{-4}$ |
| CORTO | 0.46 | $2.9 \cdot 10^{-5}$ |

**Table 6**. Comparison of CORTO, TLE and reference orbits for MSG1, after a manouevre took place

| Source | Dif. Pos (km) | Dif. Vel (km) |
|---|---|---|
| TLE | 33.82 | $2.6 \cdot 10^{-3}$ |
| CORTO (1) | 35.19 | $2.5 \cdot 10^{-3}$ |
| CORTO (2) | 35.12 | $2.3 \cdot 10^{-3}$ |

as the TLE. The insertion of the manoeuvre as an undefined one had the effect of correctly associating the older object to the newly created one. But, after the manoeuvre, the orbit of the target is effectively a new one, so subsequent re-observations are required to reach the accuracy levels that where obtained before the manoeuvre.

## 6. CONCLUSIONS AND FUTURE WORKS

The CORTO cataloguing software was tested with data from an optical surveillance network, covering seven days of observations. This allowed us to build a catalogue that covers objects in the GEO region that is observable from southern Spain. The observation strategy was tailored to maximise observations in the GEO region, so the best results were obtained there. Additional inclined GEO objects were observed and successfully catalogued, although it is assumed that a non-negligible number of them are not properly catalogued.

The success of the buildup and maintenance of the catalogue not only depends on the processing software. Choosing an adequate observational strategy that fits the strengths of the sensors and allows adequate re-observations of the observed objects is vital. Objects that cross the field of view but do not get adequate re-observations are challenging, and can be dealt with by means of additional tracking campaigns. CORTO does support processing data from tracking sensors, so that additional information could be added effortlessly.

A large effort was made in order to make the system independent from JSpOC TLEs. The only step in which TLEs are used is in the CHOCO correlation, which is an optional process. The orbits stored in the catalogue come exclusively from the processing of the observations from the sensors network, and the operator inputs. For the future evolution of the software, we intend to maintain this independence. TLEs could be used as help for improving, for example, correlations when there are large gaps between observations. Our aim is however, to keep every step requiring TLEs as optional.

Future developments of the CORTO tool will rely on simulated and real data. Simulated data allows us to simulate large workloads, and global coverage (radar sensors included). We will be using also real data from Deimos Sky Survey (DeSS). DeSS comprises three telescopes: one developed for surveillance tasks, another one for tracking, and an experimental telescope focused on tracking of LEO objects. We aim is to maintain a catalogue based solely on these sensors and on CORTO.

The future evolution of CORTO will also address the following points:

- Include additional kinds of sensors to the already supported radars and ground-based telescopes. Particularly, laser ranging sensors are being considered.
- Address objects with low-thrust propulsion.
- Consider adding a module for issuing tracking requests.
- Optionally allow entering third party data orbits.
- Include an additional fragmentation alert module, which would warn the operator in case a large number of objects appear unexpectedly in a given region, and issue tracking requests for those fragments.

## 7. REFERENCES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