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Challenges, strategies and methodologies to build-up and maintain space objects catalogues

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Abstract

This paper describes the main challenges, strategies and methodologies found during the build-up and maintenance of a catalogue of (resident space objects) RSOs: a robust automated database containing information of every detected object. It does not only characterise the properties of the objects, but also provides precise ephemerides that allow Space Surveillance and Tracking (SST) products generation, including sensor tasking, collision prediction, re-entry prediction and fragmentation detection. Such a catalogue must be built-up and maintained through the processing of observation data from various types of sensors, including radars and telescopes, both ground-based and space-based, as well as satellite laser ranging stations.

1. Introduction

Human activity in space has caused the growth of a very large population of RSO. More than 20,000 objects are currently catalogued by SST networks with sizes starting around 10 centimetres in Low Earth Orbit (LEO) and around 1 metre in Geostationary Earth Orbit (GEO). They are fragmentation debris, spacecraft (both operational and not functional), mission-related debris and rocket bodies. Most space agencies and even the private sector, have their own programs to deal with this thread, both from a mitigation and operations point of view, and one of the key aspects to implement such measures is the availability of a **catalogue of RSOs**.

Since 2007 GMV has developed and used methods to identify, track and catalogue RSOs. GMV's software is capable of maintaining a catalogue of man-made Earth orbiting objects and their orbital information through the processing of measurements from a pre-defined space surveillance network of sensors.

The **SST Sensor Data Simulator** (***ssdsim***) is a software application intended to generate SST measurements (in TDM format) from several sensors for a simulated population of objects. Firstly, the simulated population is generated from one of the following sources: Two Line Elements (TLE), Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) or Orbit Mean-Elements Message (OMM) catalogues. Physical properties of the objects that might not be available, such as the area in the case of TLEs, are generated using statistical information based on the real population. Then, the orbital information and retrieved physical parameters are used by a precise propagator to generate the ephemeris, as well as to generate object visibilities given each sensor surveying and tracking capabilities (e.g.: type of sensor, field of view, pointing, location, power). Finally, the sensor measurements are generated, according to the object visibilities and several measurement generation parameters, such as measurement noise type and magnitude.

The **SST Cataloguing Simulator** (***catsim***) is a software application intended to receive simulated SST measurements from a sensor network and perform the build-up and maintenance of a catalogue of RSOs. From a global point of view, the data processing scheme (cataloguing chain) entails mainly observation correlation and orbit determination. ***catsim*** is able to manage all levels of survey and tracking data processing from both ground-based (radars, telescopes and

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SLR sensors) and space-based sensors. The use of state-of-the-art measurements reconstruction modelling and of accurate corrections has been ensured by the full reuse of the measurements generation capabilities in previous GMV software solutions. Adequate reconstruction models for the presented types of observations are then defined to optimize the accuracy of the orbital solutions and predictions obtained to support the success of the correlation process. Ground station position and reference system transformations are fully compliant with IERS standards.

The experience gained by GMV during the development and operation of its own software solution for catalogue build-up and maintenance will also be described in the paper. The strategies and methodologies presented have been applied to data from real sensors: more than 30 telescopes, radars and SLRs in five continents, covering many SST telescopes in Spain (TFRM, TJO, IAC, IAA), Airbus's GEOtracker telescopes, SpaceInsight telescopes, AIUB telescopes in Switzerland, ESA's OGS, Russian ISON telescopes network, Numerica and ExoAnalytic Solutions telescopes in USA, and radars such as TIRA in Germany, Chilbolton in UK, ESA's MSSR, LeoLabs in USA and the Spanish Navy SLR station, among others.

1.1. Cataloguing activities

There are two main catalogue related activities:

- **Catalogue build-up**, involving the detection of new objects to include them in the catalogue without any previous information. It is required not only at the beginning of an operational campaign, to build the catalogue from scratch, but also afterwards, due to new launches and fragmentations.
- **Catalogue maintenance,** entailing the update of the orbital information of existing objects. The uncertainty in the dynamical models describing the motion of an object in space, such as the Space Weather (e.g. solar flux, geomagnetic indexes), is important. Therefore, even if the object do not perform any manoeuvre, the estimated orbits should be periodically corrected.

These two activities are coupled, when a new track is received, it may belong or not to an existing object. The main sources of potential new object detections, in order of decreasing frequency are:

- **Operational satellites manoeuvres:** there are more than 400 operational satellites only in GEO [1], each of which perform orbit correction manoeuvres every week or two weeks.
- **Satellites launches:** more than 200 spacecraft are launched per year [2], if considering also small satellites and microsatellites, which are becoming popular during the recent years. This number is expected to grow as a consequence of satellite constellations, such as the 12,000 Starlink satellites.
- **Break-up events:** less than 10 break-up events happen per year [3]. One the latest events happened on 27th March 2019, when India performed an anti-satellite missile test ending up with more than 90 new fragments detected by 18th SPCS (formerly JFSCC), as shown in Figure 1.

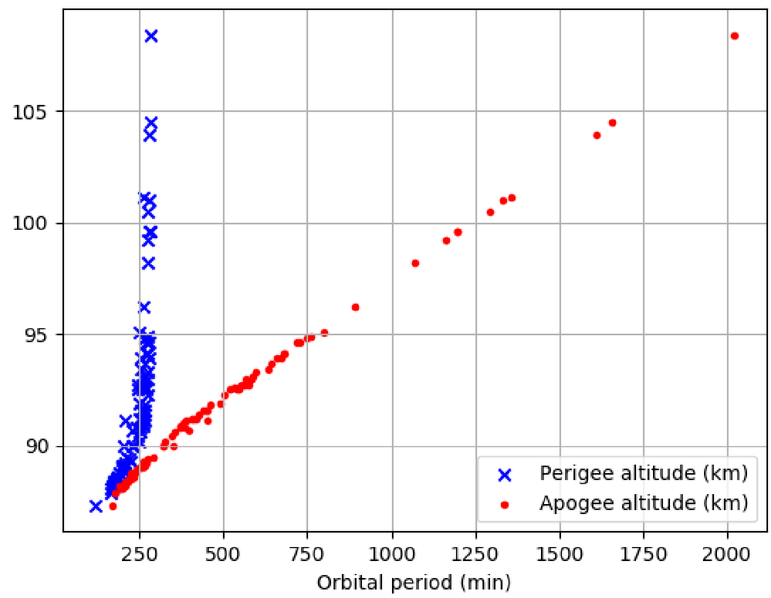

Figure 1: Gabbard diagram of India anti-satellite test performed on 27th March 2019. Generated with public data from SpaceTrack [4]

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1.2. Space surveillance and tracking

Space Surveillance and Tracking (SST) comprises the detection, prediction and cataloguing of the space debris objects orbiting the Earth. There are two main tasks related to the data generation through an SST system:

- **Surveillance**, scanning of large areas of the sky following certain strategies. It provides data for both catalogue build-up and maintenance by detecting any object passing over the sensor field of view. Prior object information is not required but due to the large field of view, the precision is limited.
- **Tracking**, following an already detected object so as to improve the precision of its orbit. A high precision can be achieved, in exchange for field of view, which is very limited. That is why the object's orbit must be known with enough precision, in order to be able to see and track the object in the small view.

2. Orbit determination

The orbits of the objects are estimated from data generated by the SST network. To do so, the orbital elements are estimated from a given set of measurements of the object, such as pairs of angles (right ascension and declination or azimuth and elevation), range or range-rate (Doppler).

It is common to distinguish between Initial Orbit Determination (IOD) and Orbit Determination (OD) depending on the a-priori knowledge of the orbit.

2.1. Initial orbit determination

Initial Orbit Determination (IOD) algorithms allow to obtain the first estimation of the orbits from very few observations and with no a-priori information. A set of initial orbit determination methods are available on the literature for different number and type of measurements.

Most IOD methods make use of a limited number of associations, e.g. Laplace, Gauss and Gooding [5] classical methods require three observations. This means that **observation fitting and selection techniques** should be considered when more observations are available. Regarding the former, the benefits of fitting techniques are three: mitigate measurement noise effect, reduce the number of measurements and estimate measurement rates. On the other hand, observation selection is closely related to **orbit observability**, which depends on the relative geometry and dynamics between the object and the sensor station at the observation epochs.

In the circular case, depicted in Figure 2 (left), the orbit observability key parameter is the difference between true anomalies at the observation epochs, directly to the observations spacing. To reconstruct the orbital plane from the line of sight (or position vectors if range is available), the best IOD results come from combinations of observations with a difference between true anomalies close to 90 degrees, i.e. perpendicular position vectors. On the contrary, if the spacing is too low, small errors on the line of sight will lead to large errors on the orbital plane estimation.

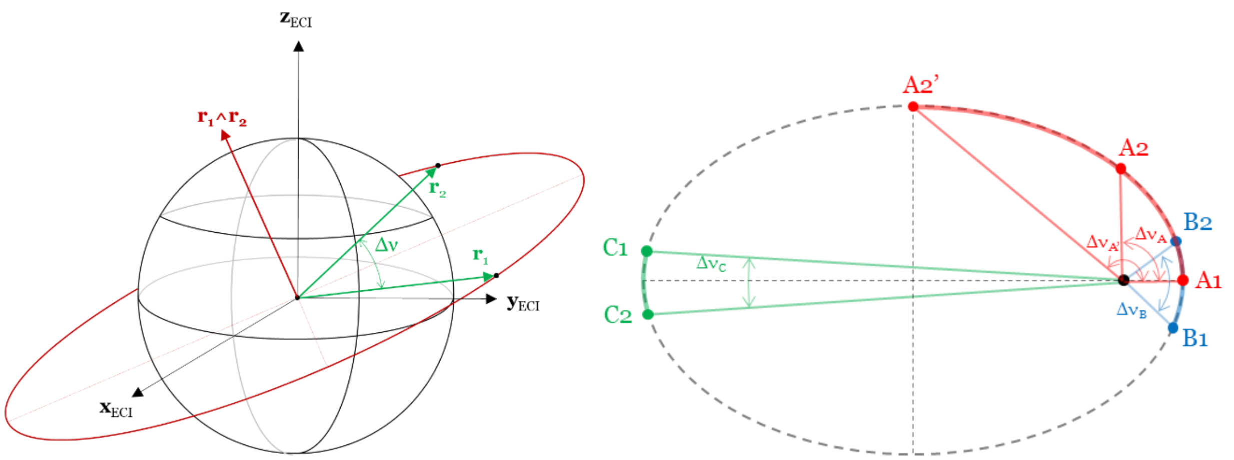

Figure 2: Observation geometry under circular orbit assumption (left) and general case (right)

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In the most general case, i.e. eccentric orbit, the analysis is far more complex. A trade-off between orbital plane reconstruction and orbital radii observability must be performed. In this case, the orbital plane reconstruction does not guarantee to properly capture the orbital eccentricity, since it might not lead to great differences on the orbital radii. These two sides of the trade-off drift apart as the eccentricity increases, and as if this were not enough, the available information at the trade-off time is reduced: just measurement data.

Figure 2 (right) shows four observation geometry cases, *{A,A',B,C}*, for a set of two observations, *{1,2}*. The grey dashed line represents the true orbit, while the points correspond to the object orbit position at the observation epochs. Case *B* and *C* are not expected to provide reliable IOD results due to both criteria, while *A* and *A′* suitability is to be determined by studying the trade-off. On the one hand, *A* provides the best geometry configuration for orbital plane determination, but instead the orbital radii difference is small compared to the maximum orbital radius variation. On the other hand, *A'* provides a worse geometry configuration for orbital plane determination but higher orbital radii difference.

2.2 Batch and sequential estimators

IOD methods are limited in the sense that they require a certain number of observations with a fixed number and type of measurements (e.g.: right ascension, declination and range at each observation epoch) and provide certain orbit data (e.g.: state vector at the first observation epoch). Their structure is not flexible and their use limited. Furthermore, they are suitable for a relatively low number of observations and thus they are susceptible to geometry singularities and measurement errors.

Orbit Determination (OD) algorithms allow to improve IOD solutions by considering larger sets of data and taking into account related statistics, as well as additional information, if available.

There are two families of estimation methods:

- **Batch or least-squares estimator**: improves an IOD solution by processing all available measurements. All measurements are simultaneously processed and the solution is obtained via an iterative method over the whole dataset.
- **Sequential estimator**: instead of processing all available measurements at a certain time, it processes only one and improves the previous solution. The advantage of this estimator is that it is not required to re-process all the measurements when new measurements are available. That is why it is suitable for on-board real-time applications. Square Root Information Filter (SRIF) is used for updating the orbit information of already catalogued objects when a new track is correlated against them.

Sequential estimators have been broadly used in the Apollo program and for interplanetary navigation, while batch estimators have been applied to operational and scientific orbit determination [6]. Furthermore, they are very suited for SST with scattered data collection during catalogue maintenance operation. Their main disadvantage is the sensitivity to locally bad conditioned data, which may cause the estimator diverge and thus require a certain stabilization period to recover a stable solution.

Batch estimators are preferred to sequential ones in SST for their simplicity and control over the set of considered measurements: it is direct to select the number and type of measurements to consider for the estimation. On the contrary, sequential estimators make use of information matrices and the contribution of each measurement cannot be directly inferred.

One of the typical challenges found when dealing with **non-linear least-squares estimation** is the condition of the normal equations matrix, which is related to the number of measurements and orbit observability (in terms of true anomaly difference between observations), as shown in Figure 3 (right) and Figure 3 (left), respectively. This means that the cost of solving the linear system increases, as well as the sensitivity of the solution with respect to the estimation.

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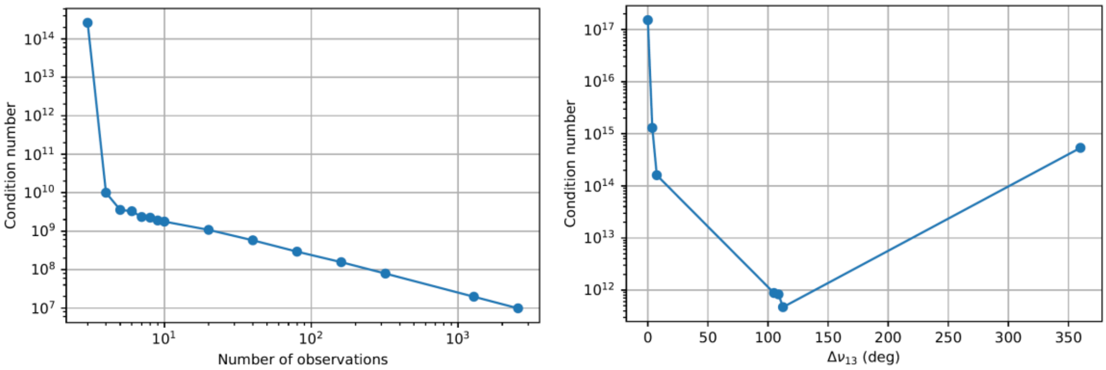

Figure 3: Condition number as a function of the number of observations (left) and true anomaly difference (right)3. Measurement and orbit correlation

The IOD and OD techniques presented above require that all the observations belong to the same object. This is not a problem for tracking sensors, since they are normally aware of the object they are observing, but not a trivial problem when dealing with survey measurements. That is why correlation plays an important role during both the build-up and maintenance of a catalogue of RSOs. An excessive rate of false positive correlation, i.e. number of wrongly correlated pairs or associations, may lead to a pollution of the catalogue, making it completely useless.

3.1 Orbit-to-orbit correlation

Orbit-to-orbit correlation consists in correlating orbits from two catalogues, e.g. it can be used to compare objects detected by the sensor network with an external catalogue, such as the TLE catalogue from the 18th SPCS, in order to match objects information between them. A common application of this correlation technique is to assign the COSPAR designator (also known as International Designator) and the NORAD catalogue number.

It consists in correlating N_A orbits from *Catalogue A* with N_B orbits from *Catalogue B*, generating a correlation matrix of N_A x N_B dimension. This generic methodology can be applied to self-correlation, i.e. detection of duplicated objects, generating a symmetric matrix, as well as for manoeuvre detection.

The correlation methodology consists in generating pairs of objects (pairs clustering), analysing them (pairs evaluation) and solving the correlation matrix, depicted in Figure 4.

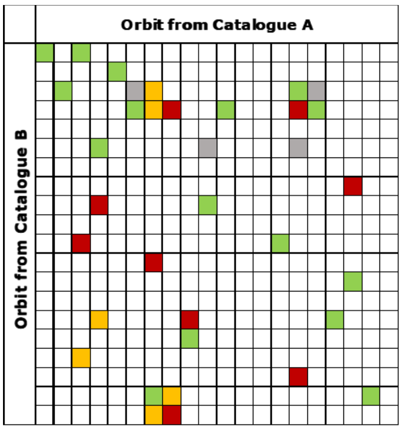

Figure 4: Sketch of an orbit-to-orbit correlation matrix. Red squares represent pairs with higher likelihood

One of the main challenges in the orbit-to-orbit correlation problem is the proper detection of outliers. They may appear if a manoeuvre is only detected in one of the catalogues, or just as a consequence of observation offsets between the two SST networks involved. This challenging problem can be effectively tackled by analysing the evolution of the correlations along time, i.e. storing the **history of the correlation process** and making use of statistical filtering methods to prune spurious correlations between objects. As shown in Figure 5, the stability of the correlation is improved and it is possible to keep correlating orbits of manoeuvring object even when it has not been considered in one of the two catalogues.

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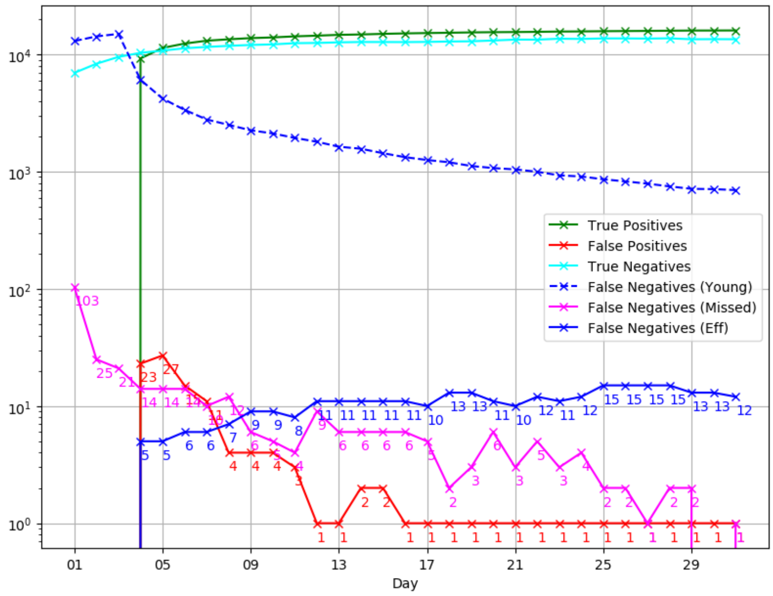

Figure 5: Evolution of the correlation metrics trough daily analyses

3.2 Track-to-orbit correlation

When a new track, set of observations assumed to belong to the same object, is received by the SST network, it is first correlated against the existing catalogued orbits, i.e. track-orbit-correlation. Only this way it is possible to update the orbit estimation with the new available information. Therefore, this family of correlation methodologies is mostly focused on cataloguing maintenance.

Some methodologies (e.g. [7], [8] and [9]) relies on the **orbit domain** to perform the correlation, by directly computing the difference between two state vectors, the first estimated from the incoming track and the second propagated or interpolated from the catalogued orbits. This orbital difference can be weighted with the associated uncertainty of each of the estimations, e.g. Mahalanobis distance [10], although it may cause tracks with larger uncertainty to have lower distance values. Furthermore, it requires the uncertainty to be properly modelled and characterised, which is not an easy topic and lies into **uncertainty realism**.

In any case, the drawback of this strategy is that the orbit that can be estimated from a single track is not reliable enough to ingest the correlation figure of merit. Hence, it is preferred to perform the correlation in the **measurements domain**, i.e. by associating synthetic measurements against real ones provided by the sensor network. By comparing the real and synthetic tracks, as shown in Figure 6, it is possible to compute various correlation metrics, and based on different thresholds and weighted correlation quality factors and indexes it is possible to correlate tracks with a high success rate while minimizing miscorrelation events. Although it may seem simple at a first sight, there are a number of events that may increase the complexity of the correlation, such as new objects, manoeuvres or fragmentations.

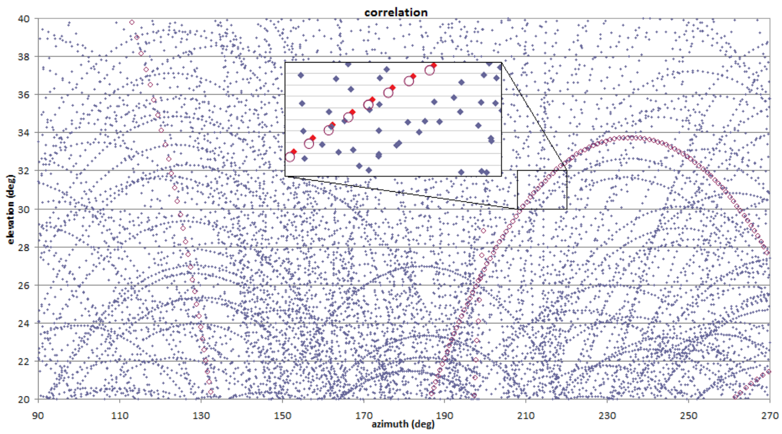

Figure 6: Measurements matching for correlation. Blue squares represent real measurements, purple circles synthetic measurements and red squares real measurements that have been correlated with synthetic ones

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Several techniques can be applied to the track-to-orbit correlation problem, such as quality thresholds (to evaluate the likelihood of the best correlation with respect to the second-best one), intermediate thresholds, filters and corrections aimed at minimising miscorrelations (tracks correlated to the wrong objects). At the end, the trade-off is similar to the typical in correlation: an acceptable level of false positives (miscorrelations) and false negatives.

Apart from the definition of the figure of merit and its related statistical considerations, the computation performance of the synthetic tracking generation is also important. It takes most of the computation time during the correlation procedure due to the visibility and measurement reconstructions models involved. Therefore, preliminary pruning, synchronisation and task parallelisation is required to compute the synthetic tracks of all feasible correlations for the entire sensor network.

3.3 Track-to-track correlation

If a new track received by the SST network cannot be correlated with any existing catalogued orbit, manoeuvred or not, then a completely different strategy is required since now the objective is to initialise a new object in the catalogue. It is essential for the catalogue build-up that the estimated orbits are accurate enough to allow subsequent track-to-orbit correlation when new tracks are received after the object is detected.

Unlike the track-to-orbit correlation problem solution presented above, the track-to-track correlator is based on observations residuals data. It consists in a multi-step sequential filter that makes use of IOD and OD methods to evaluate associations of a certain number of tracks. Given the large number of possible combinations, simple and fast methods are applied first, leaving the more accurate and computationally expensive methods for the last steps, when most of the false combinations have been filtered out.

A challenging decision to ensure good correlation performance is a selection of the minimum number of tracks required to initialise an object. In the case of radar tracks, as Figure 7 suggest, **four associated tracks are enough** to reliably isolate false associations from true associations. This conclusion matches the requirement stated in [11]: three or four tracks are required by the Air Force Space Surveillance Network before adding a new object to the catalogue.

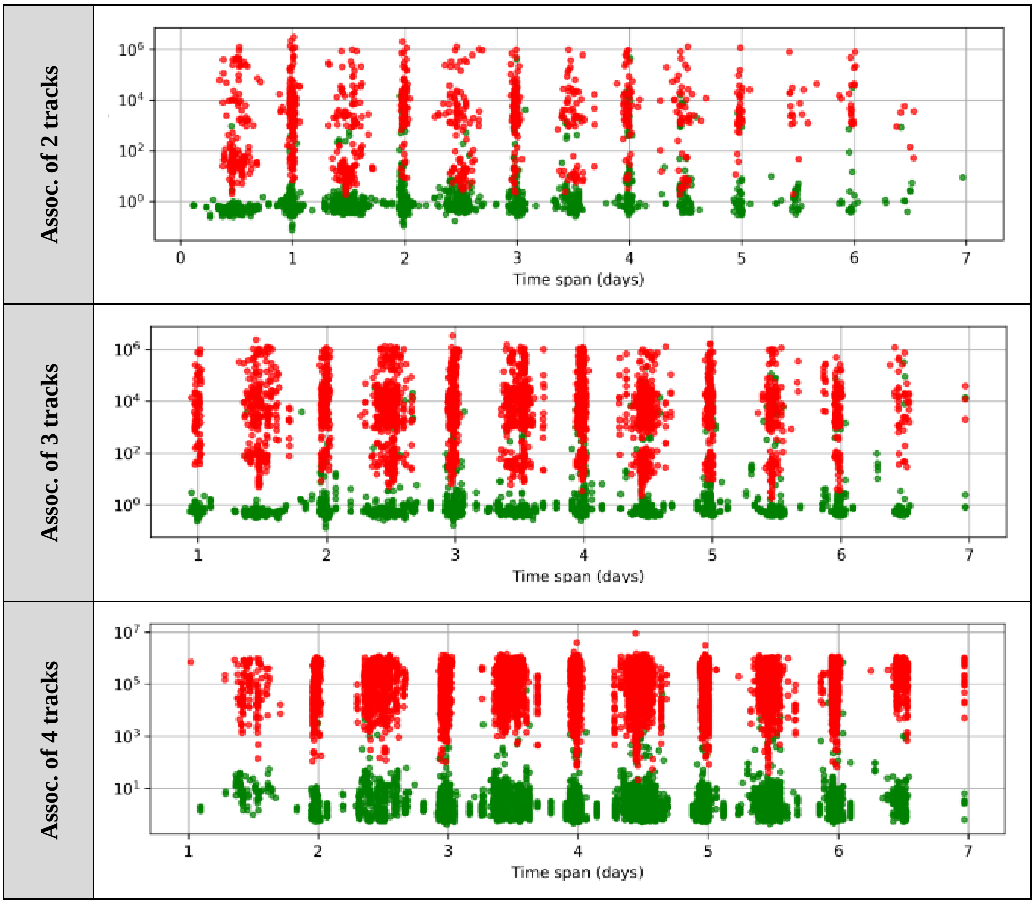

Figure 7: Distribution of the figure of merit for correct associations (green) and incorrect associations (red) for different number of associated tracks in a simulated radar scenario

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One of the most challenging aspects of the track-to-track association is the **coupling between correlation and estimation**, since it is not possible to solve the two problems independently. Approaches based on Multi Hypothesis Tracking (MHT) [12] are very suitable since brute-force is not an option due to the high computational cost involved.

4. Manoeuvre detection and estimation

Manoeuvre detection can be understood as an extended correlation problem between measurements of the state of the object before and after a manoeuvre. Performing this correlation in the measurement domain, as done in track-to-track correlation, is too ambitious considering current technology level [13]. This topic is still on a preliminary research level.

In recent years, the interest in the automatic detection of manoeuvres has increased due to the growth in the size of the catalogues of objects in orbit to maintain. The approaches to the problem can be categorized in two broad categories:

- Use of historical data to establish the possible correlation
- Use of stochastic filters

Regarding the former, several works in the recent years are devoted to exploring and analysing the possibility of using historical data to associate new observations of an object with the catalogue entry after a manoeuvre [14]. Criticisms to this approach lay in the fact that the use of historical data is based on the commonality of the manoeuvres [15], which is not always guaranteed.

New estimators have been recently developed to specifically tackle the problem of the manoeuvre detection. Among them, it is worth citing the Optimal Control-Based Estimator, to detect and reconstruct manoeuvres with no a priori information [16]. This work is based on the definition of a control distance metric to address the feasibility of an alleged manoeuvre [17]. The metric is the necessary control effort and is used similarly to the Mahalanobis distance [18]. Estimating low-thrust manoeuvres is far from the current state of the art, not only from the operational point of view, but also considering ongoing research activities [13].

Apart from them, Bayesian inference is a different methodology for the tracking of manoeuvring objects that may switch among several operating regimes. Therefore, manoeuvre detection is tackled as a **hybrid estimation problem**, since both continuous and discrete based uncertainties are present. The former refers to the state estimation of RSO state and the latter to the motion mode that the object is undergoing. In this scheme, it is required to estimate both contributions. Motion mode uncertainty exhibits itself when the RSOs undergo a manoeuvre during an unknown time period. In general, a non-manoeuvring motion and different manoeuvres can be described only in different motion models and the selection of an incorrect model often leads to unacceptable results. The **Multiple Model Methods** approach [19] is aimed at solving this motion uncertainty challenge by using more than one model. The idea is to generate a set M of models as possible candidates, run a bank of elemental filters (each based on a unique model in the set) and provide the overall estimates based on the results of those filters [20]. As such, the Multiple Model Methods provide an integrated approach to the joint decision (choosing of the mode of operation) and estimation problem of manoeuvring RSOs [21].

A very appropriate initial approach before solving the classical batch least squares or even hybrid estimation problem is to assume Keplerian motion. Therefore, the problem could be stated as finding the epochs of two manoeuvres with which it is possible to go from an orbit A to an orbit B by the most optimal manoeuvre. The optimisation variables, unknowns, are the difference in the velocity vectors, Δv_A and Δv_B, and the manoeuvres epochs, t_1 and t_2. These two impulsive manoeuvres can be determined by solving the Lambert's problem given by the two position vectors before and after the manoeuvre and the time of flight. This transfer trajectory, depicted in Figure 8, allows to reduce the manoeuvre estimation problem to finding t_1 and t_2 such that the cost functions are minimised.

As a final clarification, the estimated manoeuvres may not necessarily represent the actual manoeuvres of the objects, as they are considered impulsive and multiple solutions can be found, but with the available observation information, this solution allows to link correctly the received tracks and to obtain a **continuous** solution on the orbit.

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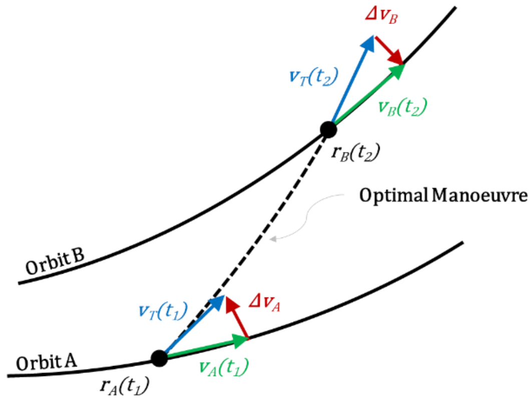

Figure 8: Sketch of the manoeuvre initial approach problem

5. Conclusions

This paper has presented some of the most relevant challenges present during the build-up and maintenance of a catalogue of RSOs, as well as proposed strategies and methodologies to tackle them. Most of the approaches have been assessed and investigated during the development and operation of both ***ssdsim*** and ***catsim*** and therefore not based only on theoretical studies but also on the know-how and experience acquired during more than ten years.

The development of the algorithms is on-going and still under research, but this paper has provide guidelines and insights on the key aspects of initial orbit determination, batch and sequential estimation, measurement and objects correlation and manoeuvre detection. All of them are fundamental components of the cataloguing chain [22]. Moreover, details and preliminary results in terms of correlation metrics and performance has been previously presented [23] [24].

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