SST ANALYSIS TOOL (SSTAN) SUPPORTING SPACE SURVEILLANCE AND TRACKING (SST) SERVICES ASSESSMENT

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ABSTRACT

Space Surveillance and Tracking (SST) constitutes the ability to study and supervise the objects orbiting the Earth. It involves the detection, tracking, cataloguing and identification of artificial objects, i.e. active/inactive satellites and space debris. A SST system can be considered as a service provision system based on the data retrieved from sensors, as telescopes and radars.

SST Analysis tool (SSTAN) was developed in the frame of P2SSTI project (Development of Supporting Analysis Software and International Standard Validation) for ESA and it is composed of several independent inter-related modules intended for the evaluation of the performance of an SST system. These modules can be categorised into SST environment and sensing modules, a cataloguing tool and SST service analysis modules. The first category includes the Population Generation module, the Fragmentation Generation module, the Measurement Generation and Post-Processing modules, all of them simulating environment and sensing architectural aspects. The Cataloguing module allows obtaining the estimated population of objects as derived from the simulated observations. On the other hand, the so-called service analysis modules group includes the Re-entry Analysis module, Collision Risk module, Fragmentation Detection and Identification module, Manoeuvre identification module and the Attitude identification module. These modules allow identifying the performances of services provided by an SST system, in the basis of the sensing architecture and derived cataloguing capability.

This paper presents a brief description of the functionalities of the SST service analysis modules implemented in SSTAN with emphasis on the Re-entry Analysis module. Furthermore, a detailed re-entry prediction analysis is included in order to assess catalogue performance for different SST architectures.

The re-entry module allows the user to analyse the uncertainties added to re-entering objects during the cataloguing process in comparison with the real orbit of the objects. The re-entry prediction for the real orbit is compared with the one made for the estimated orbit (obtained from simulation modules) in order to check the accuracy of the second one. The re-entry predictions are obtained by means of numerical propagations of both real and estimated orbits.

Some simulation cases for the other service modules are also presented, showing the possible analysis to evaluate compliance of SST architectures in regards to the requirements imposed for such kind of systems.

1 OVERVIEW OF SSTAN TOOL

SST systems are complex systems with a large inter-relationship between the different service performances. All services derive from the catalogue generated through processing object observations from sensors. These observations and the underlying population of space objects shall be simulated to properly evaluate the capacity of the system from a cataloguing point of view and with regard to the services extracted from the information in the catalogue. Thus, two main elements of SSTAN tool are the Population Generation and the Measurement Generation Tools. Being the origin of all simulations and analysis, these two tools provide large flexibility, with regards to the objects in space (covering cases to be analysed through the modules devoted for service evaluation) and in relation to the sensor configuration (number, types and performance).

The generation of observations shall be executed prior to the evaluation of performance of all services. Services rely on the catalogue and thus, the cataloguing module shall be used to create the catalogue according to the configured sensors. Once this catalogue is generated, the capability to provide the services up to the required performance level can be evaluated.

It may be the case that the underlying population includes relevant events to be further analysed (for example, re-entering objects), but it is also needed to allow the user to enter some particular events (i.e.

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fragmentations). This can be done independently or in a general approach. Individual population files can be created only with the objects associated to a particular event, so very detailed analysis of those events can be done. On the contrary, the baseline population file, (which is based on MASTER population) can be enlarged with those user-defined objects to evaluate the impact of those events on the cataloguing performance (i.e. a large fragmentation event). Additionally, the baseline population file is configured to scale the number of objects in the population, both in general and per orbital regimes.

Once observations and a catalogue are generated, the following aspects can be analysed by a set of modules:

- Statistics on population features and observations profile shall be provided to allow the user evaluate the suitability of the analysis and some requirements
- Catalogue performance (general information): information from the cataloguing process will be provided
- Catalogue performance with regard to Collision Risk minimisation
- Capability to address Re-entry Service requirements
- Evaluation of observation gaps will also be provided to evaluate compliancy with requirements on orbital update frequency. This can be provided by the execution of the measurement post-processing tool.
- Capability to address Fragmentation Service requirements
- Capability to address Manoeuvre Identification requirements
- Attitude Identification can be done by processing the signal of the attitude over the sensor provide information (Radar Cross Section (RCS) and Visual Magnitude (VM)).

Other SST services can also be checked with the formerly listed modules, such as:

- Specific cases of observational campaigns can be simulated and analysed through the definition of proper population file (if needed) by the Population Generation tool, configuration of the proper sensors in the Measurement Generation tool and the analysis of the simulated observations through the Measurement Statistics module. Population file suitable for the analysis shall be configured.
- Analysis on discrimination of graveyard orbits (support mitigation guidelines) can be done relying on the simulation of the complete cataloguing process chain over a population of objects in the orbits of interest. Through the statistical information on the observation capacity and the accuracy of the estimated orbits, it is possible to assess the capability of the system to identify objects fulfilling the mitigation guidelines. This analysis is also linked to the capability to identify manoeuvres.
- Special mission support, including anomaly analysis, controlled re-entry and object search can be completed. The performance requirements are mainly related to those of the cataloguing service, with some modifications as those for the object search, which may require analysing the observation capability in tracking mode.

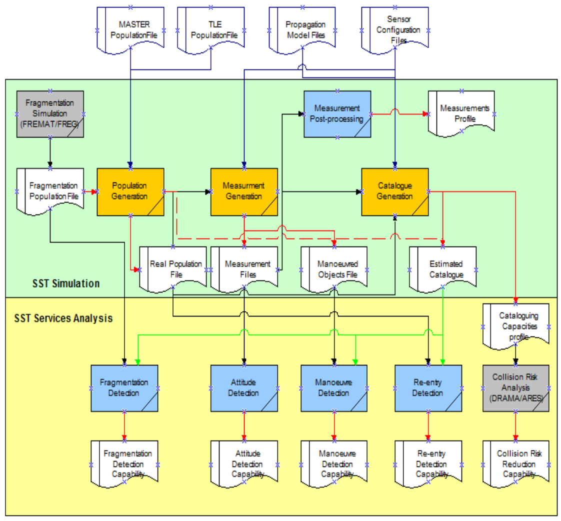

Figure 1: Overview of SSTAN Modules interaction

Although the execution of independent modules is possible, the suite provides the means to cover the complete SST chain analysis and using it as a whole avoids interface problems with other tools. As shown in Fig.1, a population of objects must be generated by means of the Population Generation Module. Once the real population of objects is generated, objects coming from a fragmentation simulation can be inserted into the population.

After that, the measurements shall be generated accordingly to the user-defined parameters and can be processed to obtain information and statistics by using Post-processing Module and shall be used as input in the Attitude Identification Module to recognize the rotation state of the objects. The Cataloguing Module can be executed using the measurements obtained by Measurements Generation Module to provide an Estimated Catalogue which serves to run Fragmentation Detection Module (together with the population of fragments), Re-entry Risk (together with Real Population) and Manoeuvre Identification Module.

As we are working on a simulated environment, the first step requires the creation of a simulated population for the analysis. This simulated population shall include the main aspects to be covered by the analysis (i.e., if fragmentation detection capability is to be studied, fragmentation event shall be included in the simulated population).

As the main aim of an SST system is to create and maintain a catalogue of objects to support the provision of services, the catalogue generation execution should be seen as the second step first step for most of the analyses. An artificial catalogue can also be generated with the Population Generation Module by means of adding uncertainties to the orbits of the observed objects.

2 ENVIRONMENT SIMULATION TOOLS: POPULATION GENERATION MODULE

The population module generates catalogues that contain the full orbital information corresponding to the population of objects that may be observed or detected by the sensors simulated afterwards.

This module encompasses different activities:

- The generation of the baseline population in the basis of a user entered MASTER population file or a TLE (two line elements) data set (plus information on estimated mass and area for every object)
- Conversion between catalogue formats used within SSTAN tool
- The insertion into the population file of objects with specific features for the evaluation of the SST system performance in regards to some of the services to be provided. In particular, this tool allows to:
    - Insert objects from an on-orbit fragmentation (explosion/collision) generated with Fragmentation Event Generator FREG. The fragmentation event is generated by independent module FREG (Deimos tool developed for FREMAT project). More details are presented in [2].
    - Option to insert an object with specific features (size/a/e/i) that derive a population as defined by a scaling factor selected by the user. The idea is to be able to analyse cases where the population can increase globally or at certain regimes, or particular sub-populations.
- Application of filters (optional and user-configurable filters) to the objects in the catalogue.
- In order to simplify as much as possible the analysis of service requirements, it is recommended to consider that analysis of special events (fragmentation identifications, re-entry analysis, manoeuvre identification, etc.) will be done in the basis of an established catalogue. For that, the population generation allows creating also estimated catalogues in the basis of assumed orbital accuracy and observation capability (mainly basic size-altitude function) which can be served as initial catalogue for some analysis use cases. This rough estimated catalogue avoids large cataloguing generation analysis for some particular use cases.
- Classification of objects per orbit types (classic classification: LEO, GEO, MEO, GTO, OTHER).
- Generation of sub-catalogues filtering objects from the total population. This option allows the user to obtain specific subsets of objects in order to use them for analyses of special events (e.g. re-entry analysis).
- Processing of the estimated catalogues (binary files, generated after processed the measurements) obtained from the Cataloguing Module. The tool can convert the binary files to ASCII in order to apply filters, generate statistics and use any of the options the module offers to the converted catalogue.
- Computation statistics for all baselines catalogues types and generation of gnuplot plots. Generation of catalogues from AS4 format catalogues created in former executions or from estimated catalogues that are needed to be reprocessed by the user.

The population generation tool can be used incrementally, i.e., once a population file is generated in the basis of MASTER or TLE data, it can be re-used for re-processing (introducing additional objects derived from the user-defined events, filtering, computation of statistics, etc.)

The Population Generation module generates the simulated real catalogues (population from MASTER or TLE plus inserted special objects if needed, considered as real catalogued objects) that will be used as input for the Measurements module, Measurements post-processing module, Cataloguing module, Fragmentation detection and identification module and Re-entry module.

An example of application of this module is presented below. The example consists in the insertion of released objects of a fragmentation in a baseline catalogue. First, FREG is executed independently for the simulation of a fragmentation in Leo. Once the execution is finished, the output files containing the fragments generated from both colliding objects are ready to be processed by the Population Generation Module.

For this example the collision between Cosmos 2251 and Iridium 33 is reproduced.

Figure 2: Histograms of all objects from MASTER baseline + fragments from collision LEO inserted in the baseline population, from top to bottom and from left to right: number of objects versus semimajor axis, eccentricity, RAAN and inclination

Fig.2 represents histograms built from the discretization of orbital elements and size of the objects. The green colour corresponds to the fragments obtained from the collision and the red one symbolizes the objects from the MASTER population. The reader can observe that for inclination and RAAN, the fragments from the collision are distributed in two different groups, each of them corresponding to the value of inclination and RAAN of the colliding object that generated it. Fig. 3 presents the distribution of the main orbital elements of all objects contained in the output catalogue. The plots show eccentricity versus semimajor axis and inclination versus semimajor axis. The different orbital regimes are represented by different colours in the graphs.

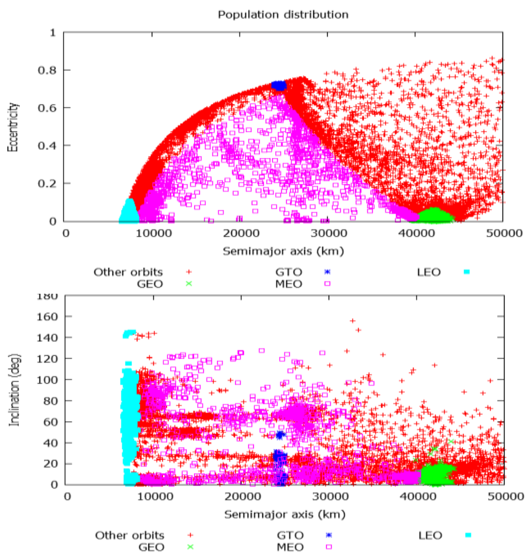

Figure 3: Distribution of all objects for baseline+fragments from collision LEO

Fig.4 contains results obtained from processing the catalogue containing only the fragments from the collision. It is noticeable the lack of fragments in some orbital regimes (i.e. MEO, GEO, GTO) since the collision occurred in a LEO region, and the orbit of the fragments keep close to the parent orbits. If the delta-v obtained in the collision is large, the orbits of the fragments can present greater differences if compared with the parent orbit. For this reason, fragments are visible in OTHER type of orbit (i.e. an orbit that is not classified as LEO, GEO, MEO, GTO or LEO).

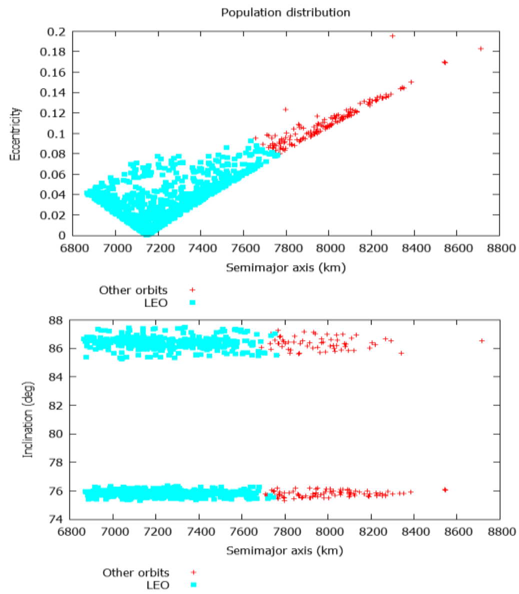

Figure 4: Distribution of all fragments from collision LEO

3 SENSING SIMULATION TOOLS: MEASUREMENTS GENERATION AND POST-PROCESSING MODULES

3.1 Measurement Generation Module

This module is one of the core elements of the SSTAN tool and it provides large flexibility regarding sensor types, sensor configuration and constraints. It generates the observational information associated to the sensing network of all observed objects and auxiliary information in regards to manoeuvres, attitude estimation and orbital evolution of some particular cases.

This module allows the simulation of the following measurements types:

- **Radar measurements**, both on tracking and surveillance configuration. A radar sensor can provide the following observables: Azimuth (deg), Elevation (deg), Doppler (m/s), Range (km) and Radar Cross Section (dB). Tracking radars are simulated by assuming steerable capability and thus, allowing to reach large Azimuth-Elevation intervals.

- **Ground-based Optical measurements**, using telescopes, which provide the following observables: Right Ascension (hours)/Azimuth (deg), Declination/Elevation (deg) and Visual Magnitude (VM). The tool allows a flexible definition of the architecture and observation strategies to be analysed. Architecture definition includes the number and location of observation sites, the number of telescopes per site, the independent features of each telescope. The observation strategy can be defined independently for every simulated telescope in a very flexible way.

  The user may define outages due to maintenance or bad weather conditions (which may last complete or partial nights). These outages can be entered in a deterministic or random way depending on the typical weather conditions of the simulated sites. Tracking activities can be considered by allowing the sensors to have steerable condition as for the radar case.

- **Space-based Optical measurements**, for user-defined constellation of satellites with a large variety of observation strategies. Similarly to the case of ground-based telescopes, the case of space-based measurements is defined in a very flexible way. The number of satellites of the constellation observing the space objects, the orbit where those satellites are located and the observation strategies can be defined by the user.

  Among the observation strategies, it is possible to define strategies with the telescope fixed to the platform, and strategies with free motion of the telescope with respect to the platform. Complex pointing strategies are also allowed for the proper observation of some type of objects.

The measurements can be generated assuming manoeuvred objects in the space population and bad weather conditions (affecting optical measurements from ground-based telescopes).

Spherical objects are considered for the nominal case but object shapes and attitude modes can be selected for particular attitude determination analysis.

The problem of simulated measurement generation consists of, on one side, determining if a body within the catalogue is visible from a telescope (ground based or space based) or radar and, on the other side, if so, evaluating the observables (azimuth, elevation, Doppler and range).

For each body, visibility determination is accomplished in several steps, with different filters and discarding criteria. Instead of the evaluation of the azimuth, elevation and signal received by the telescope or radar from each debris body at each time step, different filters are used to discard candidates in an optimum way.

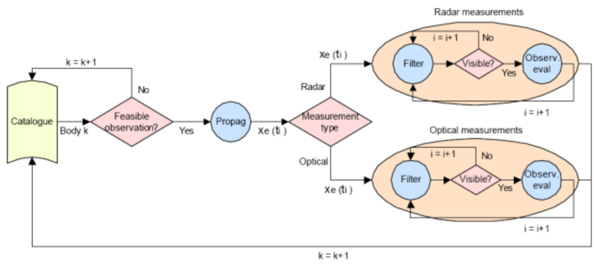

Figure 5: Overview of Measurements Module algorithm

Each object within the catalogue follows the next sequence:

- Feasibility criteria are applied, in order to discard bodies that will not be visible from the corresponding radar or telescope at any time. In case of space telescopes, all objects are considered as visible. These criteria impose bounding values to feasible bodies on several orbital parameters, which can be checked directly on the catalogue. These feasibility criteria work as pre-filters that allow discarding bodies without necessity of propagation of body trajectory or any other further computation, reducing drastically the computation time.
- Trajectory propagation for those bodies identified as feasible.
- Visibility criteria are applied at different observation time values using trajectory propagation data for feasible bodies. These criteria are applied at lower level than the feasibility criteria, which discard bodies from catalogue but only during a characteristic time period, i.e. 1 hour for radar and 1 day for optical telescopes. So, after that characteristic period, the body will be checked again.

With this approach, using different filters, the time consumption to determine the visibility conditions for the complete set of objects within the debris catalogue is optimised.

Pre-filters used for observation feasibility analysis to be applied to each body are based on geometrical and physical considerations. They are able to discard a large number of bodies from the catalogue using the orbital parameters from catalogue. These pre-filters work as preliminary filter to skip debris bodies out of the scope of the observation site.

Depending on the measurement type, different algorithms have been derived.

At each time step that a particular body within the catalogue has been identified as visible from either an optical or a radar station, the evaluation of the observables (azimuth, elevation, range and Doppler) values is performed.

3.2 Measurement Post-Processing Module

The Measurements Post-Processing Module provides statistical information from the data generated by the Measurements Generation Module. It makes use of the inputs selected by the user to provide the best information display according to the user demands. The input is composed by the measurements files and the key parameters used to provide data classification.

This module makes use of several user-selected flag options that make use of computational algorithms and procedures to structure and classify the data. The algorithms of the Post-Processing Module are based on data treatment and analysis, which provides statistics of objects and measurements. It allows analysing the observational data in regards to frequency of observations, observational gaps, duration of tracks, timeliness to detect and other aspects. The main use options are the following:

- Computation of statistics, GRIDS, histograms and distribution functions that allow analysing the observational data
- Option to provide observed object information with any sensor
- Option to provide information about not observed objects
- Possibility to check the re-entry objects during Measurements Generation simulation
- Option to categorise radar measurements and to classify the catalogue objects depending on their orbital regime

The most important option is the one that allows the computation of statistics and grids as a function of Fast Indicators (main performance figures of merit for a sensing network).

Having indicators that estimate cataloguing performance without running the cataloguing module is useful in evaluating the performance of observation strategies. These fast indicators are mainly based on the duration and frequency of the measurements. They allow comparing different observations strategies in a relatively fast computation: the generation of the measurements and later post processing. There are four main different fast indicators:

- Duration of the first gap is the time for new object detection (from when the simulation starts until a first observation track is completed). This time represents the time required for constructing a catalogue (with one observation (track) an initial orbit determination (IOD) can be computed and the construction of the catalogue can be started). In case of a survey strategy, this value is the same as the timeliness. Therefore, a shorter first gap correlates with faster catalogue construction and better correlation performance.
- **Duration of the gaps of measurement or re-observation period** is a good indicator of the capability of the set of measurements to maintain a catalogue: the lower the re-observation period, the more often the objects are observed, the larger the chances for correlation of incoming observations, and the better the orbital determination will be. Consequently, the better the conditions for maintaining a catalogue will be. In practical computations, during the simulated time, the orbit has several gaps of measurements. The mean, the maximum and the minimum of all these gaps (without taking into account the first gap) are computed.
- **Duration of the track** plays relevant role in the computation of the first estimation of the orbit. The longer the duration of the track is, the more accurate the first estimation is.
- **Number of images per track** plays a similar role to the duration of the track -the larger number of measurements per track, the better the corresponding accuracy.

In order to quantify these indicators we compute distribution functions within the percentage of population that has the considered values of them.

The results corresponding to a simulation of observations made with a radar in survey mode for a real catalogue generated by the Population Module is shown below in order to present some of the functionalities of this module. The population derives from MASTER catalogue containing objects greater than 5cm. Only 10% of those objects (randomly selected) are included in the real catalogue. The configuration of the sensor is provided in Tab. 1.

Table 1: Radar Survey Configuration

Parameter	Value
Localization (LON, LAT, ALT)	3.114305 deg,40.6115 deg, 1000 m
RCS of reference	-20.0
SNR (Signal to noise ratio) of reference	18.76 dB
Distance of reference	1550 m
TNR	18.76
Wavelength	0.24 m

Minimum SNR	16.0 dB
Minimum Elevation	50.0 deg
Maximum Elevation	70.0 deg
Minimum Azimuth	120.0 deg
Maximum Azimuth	240.0 deg
Integration Time	7.27 sec
Sigma Range	3.0 m
Sigma Elevation & Azimuth	0.0645 deg
Sigma Doppler	0.17 m/s

Some examples of distribution function of fast indicators are depicted in Fig.6 in order to estimate the cataloguing performance for the set of objects used in this simulation. Additionally, examples of GRIDS associated to observability of the senor used in the simulation are also shown in Fig. 7. This last figure contains plots representing: coverage versus inclination, coverage versus perigee height, re-observability per object versus inclination, re-observability per object versus perigee height, duration of track versus inclination and duration of track versus perigee height.

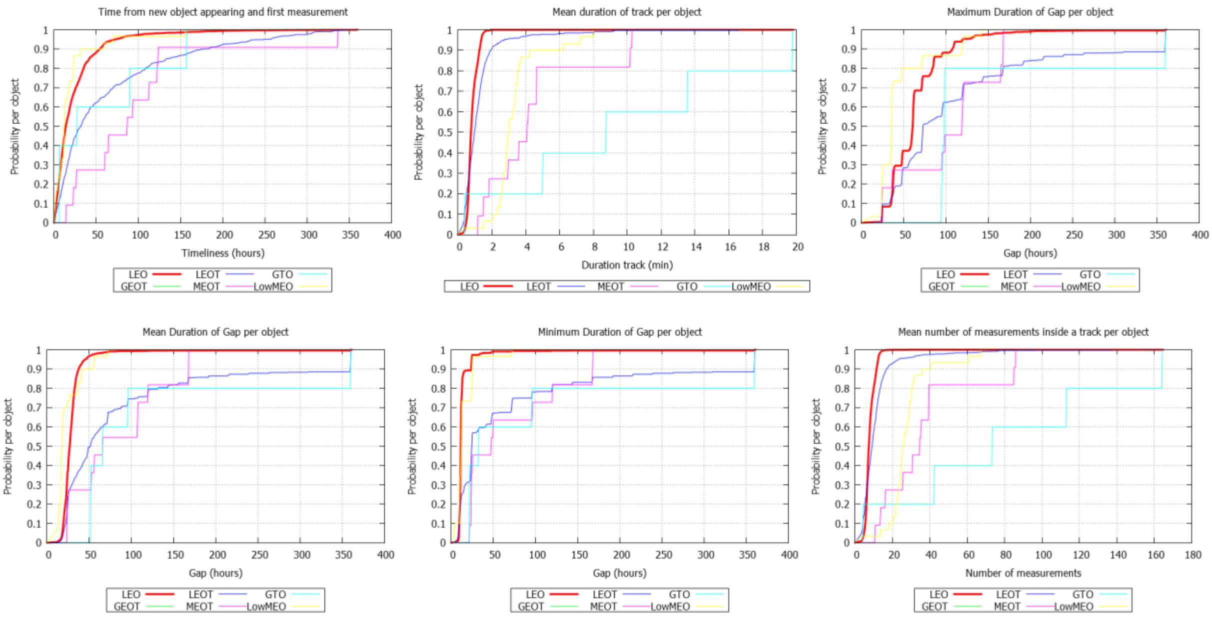

Figure 6: Fast Indicators (timeliness, maximum duration of track, maximum, minimum and mean gap duration and number of images inside a track) for radar in survey mode

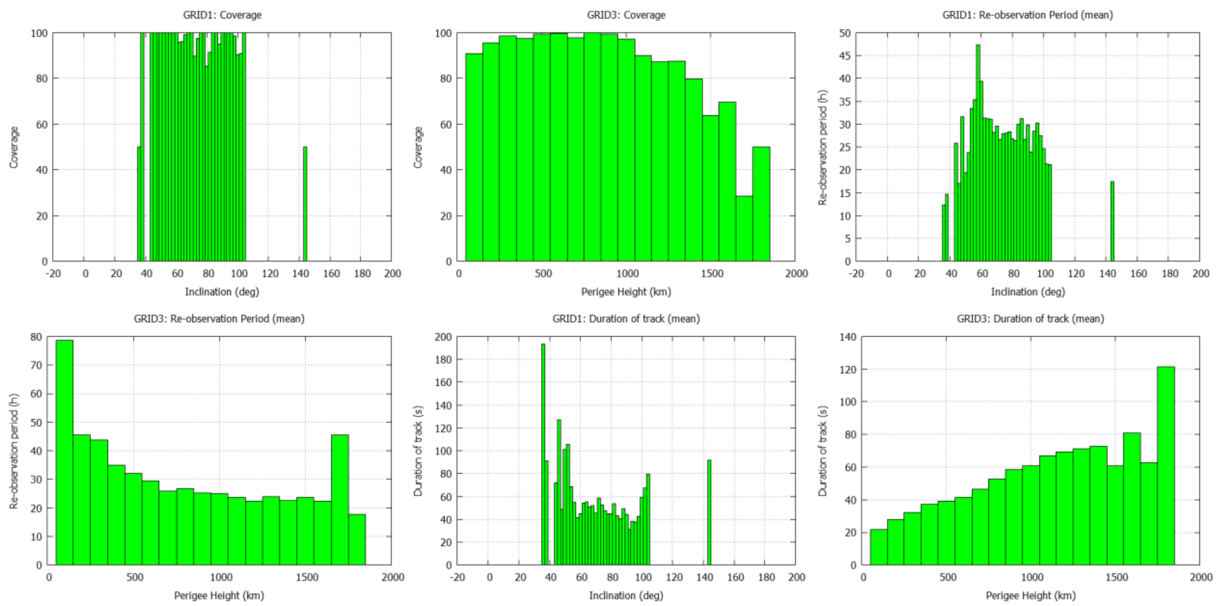

Figure 7: GRIDS associated to observability of radar in survey mode

It is worth showing the number of observed objects (for different orbital regimes) in order to check the coverage fulfilled in the simulation. Fig. 9 and Fig. 10 represent a comparison between main features of observed and not observed objects during the simulation.

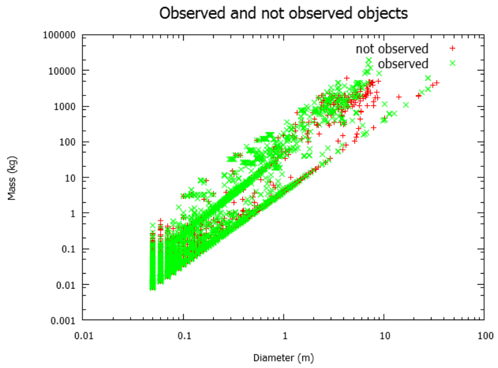

Figure 8: Diameter and mass (in logarithmic scale) of observed objects with radar survey

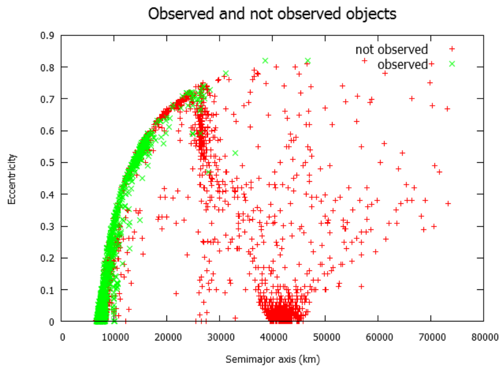

Figure 9: Semimajor axis versus Eccentricity for observed and not observed objects with radar survey

4 SST SERVICE ANALYSIS MODULES

4.1 Re-entry Analysis Module

The re-entry module allows the user to analyse the uncertainties added to re-entering objects during the cataloguing process in comparison with the real orbit of the objects (catalogues generated with the Population Generation Module containing real population from MASTER or TLE + inserted special objects if needed, considered as real catalogued objects). This real catalogue is compared with the propagated estimated orbit (from Cataloguing Module, or from Population Generation Module in the basis of assumed orbital accuracy and observation capability) in order to check the accuracy of the predicted re-entry time and location. Thus, the re-entry tool is focused on the generation of the report of decaying objects. The report provides the predicted entry epoch and location for every object that decays in the analysis period. Together with the estimated data, the real re-entry for every object is reported, and the error in the estimation (time and position) is provided.

Several estimated catalogues can be inserted and processed in a single execution for a specific real catalogue in order to obtain a different re-entry report for each estimated population data set. Additionally, user-configurable statistics and gnuplot scripts can be generated for each re-entry report or for a combination of different re-entry results.

An example of use of this module is provided below in order to show a re-entry analysis as a function of catalogue performance. This analysis relies on four different estimated catalogues containing LEO objects susceptible to re-enter. Habitually, this module should be executed with catalogues generated with the Cataloguing Module. Nevertheless, for this particular test case, focused in showing a parametric analysis in basis of uncertainties, the estimated catalogues were created with the Population Generation Module. Hence, the estimated catalogues were generated from a TLE population, selecting objects with low altitudes and introducing different uncertainties in their orbits in order to analyse the re-entry predictions as a function of the catalogue accuracy.

Table 2: Estimated Catalogues used for re-entry test

Estimated catalogue	Uncertainty in position (km)	Uncertainty in velocity (km/s)
1	0.0	0.0
2	0.1	0.001
3	0.01	0.001
4	0.01	0.01

Table 3: Characteristics of the analysed objects

SATNAME	DIAMETER	MASS
11849	4.10	723.043
26481	2.55	234.961
34157	8.03	5423.373
36835	5.15	1434.118
37874	4.16	754.781
39226	4.27	812.466
39395	2.4	195.547
40311	4.32	843.883
40421	4.71	1096.13
40736	4.39	884.155
40812	3.05	399.569

The levels of uncertainties used for each catalogue are listed in Tab.2. The characteristics of the objects analysed in this test are provided in Tab. 3 and Tab. 4.

Table 4: Orbital elements of the analysed objects (no uncertainties)

ORBITAL ELEMENTS

OBJ. ID	Sma (km)	Ecc	Inc (deg)	Raan (deg)	Aop (deg)
11849	6699.185	0.001045	97.638	320.19	346.61
26481	6644.686	0.003121	97.235	27.14	101.13
34157	6661.126	0.000753	86.423	108.65	350.79
36835	6670.968	0.001786	97.659	143.25	153.67
37874	6632.648	0.001174	97.368	135.65	163.23
39226	6693.787	0.001587	97.254	109.67	61.52
39395	6666.023	0.001633	40.466	180.54	35.92
40311	6685.55	0.002904	96.563	123.69	35.22
40421	6667.132	0.003154	97.683	10.79	331.16
40736	6692.704	0.000553	51.746	72.20	76.68
40812	6552.693	0.000668	51.696	63.38	77.88

Re-entry reports containing the predicted entry epoch and location for every object that decays in the analysis period are the main outputs of this module. Together with the estimated data, the real re-entry for every object is reported, and the error in the estimation (time and position) is provided. One report for each estimated catalogue is generated if several estimated catalogues are processed.

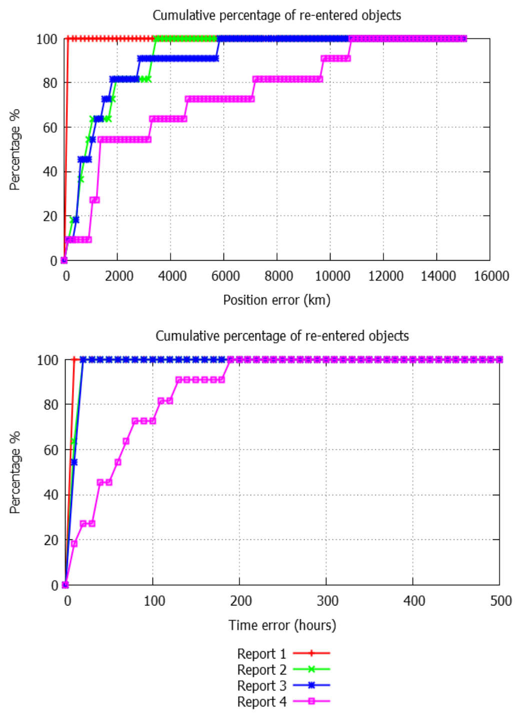

Figure 10: Cumulative percentage of re-entry objects as a function of position error (km) and time error (hours)

Fig. 10 exposes the cumulative percentage of re-entry objects as a function of the position error (km) and time error (hours) for each estimated catalogue (i.e. for each estimated catalogue, the cumulative percentage of objects that re-entered with an error lower than the one represented on the x-axis are shown). It is visible that for the estimated catalogue number 1, which corresponds to the case of null uncertainties, the errors in re-entry prediction are zero for all involved objects. The remaining catalogues, on the contrary, present none-zero errors in both re-entry position and epoch.

Furthermore, Fig.11 shows a comparison between the different accuracy levels by representing the prediction time and position errors versus the ID of the objects. In conclusion, the influence of uncertainties added to the velocity vector is remarkable after performing the analysis.

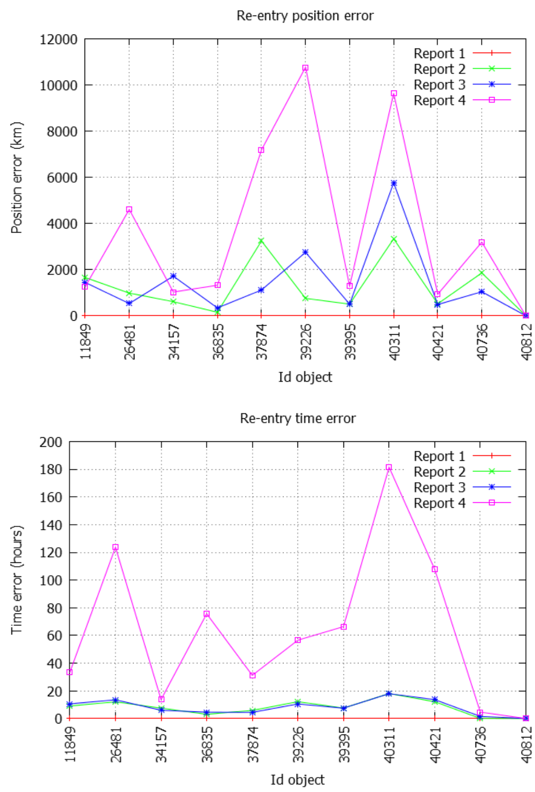

Figure 11: Re-entry errors (position on the left and time on the right) for each one of the estimated catalogues.

If we consider the different estimated catalogues used in this analysis as the results obtained from 4 different observation cases, each of them with a level of accuracy, the results presented in previous figures and table of this section would provide useful information about how reliable is a particular catalogue performance case.

Additionally, the module allows the user to compute statistics combining the individual results from each catalogue in order to evaluate the performance of a combination of observation strategies/cataloguing performances. For example, Fig. 12 shows the cumulative percentage of objects that re-entered with a minimum error lower than the one represented on the x-axis. That minimum error is obtained by selecting, for each particular object, the minimum error among the four error values obtained from each strategy. Analogically, Fig.13 represents the cumulative percentage of objects that re-entered with a maximum error lower than the one represented on x-axis.

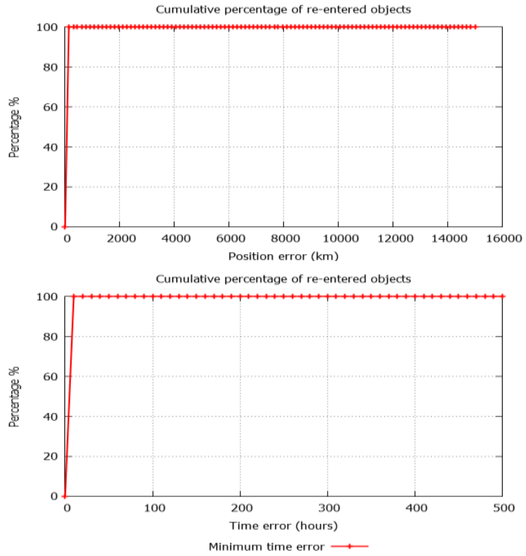

Figure 12: Cumulative percentage of re-entry objects as a function of position error (km) and time error (hours) for minimum errors

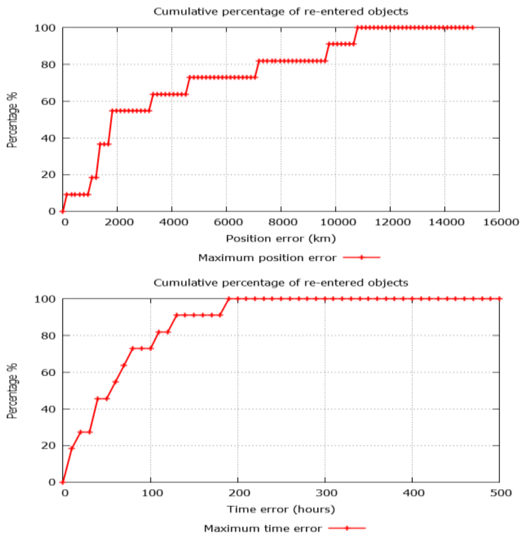

Figure 13: Cumulative percentage of re-entry objects as a function of position error (km) and time error (hours) for maximum errors

4.2 Manoeuvre Identification Module

The Manoeuvre Identification Module is intended to recognize the objects that have had a manoeuvre between two estimated catalogues at different dates, determining the instant of time when the manoeuvre has taken place and the applied delta-V.

All the newly detected catalogue objects are considered to be manoeuvrable. Similarly, all objects that have not been updated in the final catalogue are considered as possible manoeuvrable objects, lost objects.

The first part of the module is dedicated to the lost and new objects identification:

- An object is lost if the date of the final catalogue has not been updated compared to the initial catalogue.
- An object is new if a new object ID appears in the final catalogue without having measurements in the initial catalogue.

As a result of the object identification, two groups of objects are saved, one containing only the new objects and the other containing only the lost objects. Then, both sets of objects are be propagated in order to find the intersection point of their orbits.

The propagation is performed considering the following method:

- The lost objects are propagated and interpolated to the date of the new objects catalogue T_2, and the new objects are propagated backwards from T_2 to the date of the lost objects catalogue T_1.

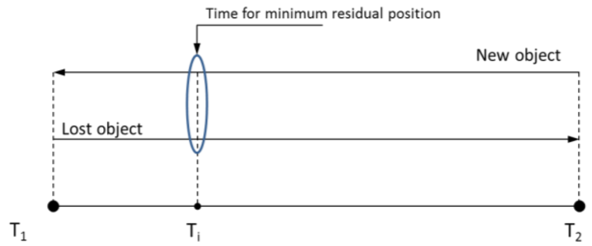

Figure 14: Forward propagation of a lost object and backwards propagation of a new object

- After interpolating the results, the position residuals are calculated (differences in position between new-lost pairs). The minimum residual position defines the manoeuvre time T_i and the residual of velocity provides the applied delta-V.
- The computation of the position residuals, epoch and delta-V, concerning the algorithm, are inside two loops: the first one corresponding to new objects and the second one corresponding to lost objects. Hence, for each object identified by the module as new its residuals are calculated with

respect to all the objects identified as lost. Once they are all calculated, a single lost object is assigned to each new one by choosing the minimum residual among all retrieved by pairs of candidates lost-new.

Finally, if the position residual is lower than a threshold configured by the user, the new object is assumed to be the result of the application of a manoeuvre on one of the lost objects. Fig. 15 shows a flowchart with the algorithm implemented in the Manoeuvre Identification module:

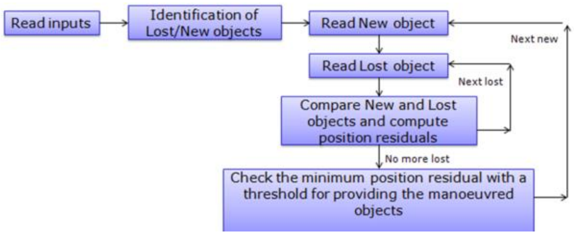

Figure 15: Manoeuvre Identification module flowchart

This algorithm is assumed to work in the cases where frequent re-observations of objects are available. It is expected then that the new object appear after a single manoeuvre. In the case of combined manoeuvres with more than one impulse, the algorithm will only work if the observations (and new object insertion) takes place after every single manoeuvre.

A test example is provided in order to show the use of this module. It is a brief analysis relying on two estimated catalogues generated with the Population Generation Module. One of the catalogues contains an object observed at an earlier date and the other one contains the same object, from a later observation, after a manoeuvre has been applied to it. Normally this module is executed making use of catalogues generated with the Cataloguing Module but, for this particular example, which is used to present the functionalities of the module, the cataloguing process can be avoided.

Fig.16 shows an example of type of plots than can be generated with manoeuvre module. This picture represents the propagation residuals (blue line) between two objects. The red point indicates the predicted time instant where the manoeuvre could occur. The x-axis represents the propagation time and y-axis represents the position error in logarithmic scale.

Table 5: Results from manoeuvre identification example

New object ID	2
Associated lost object ID / SATNAME	1
Time for minimum residual (MJD2000)	3409.001125
Time for minimum residual (YYYY/MM/DD HH:MM:SS)	2009/05/02 00:01:37.249619
Minimum residual position (km)	7.7822169
Minimum residual velocity (km/s):	0.0997260

The exact time when the manoeuvre was applied is 3409.0 (MJD2000). Therefore, the tool identifies the time when the manoeuvre was performed with reasonably low error as exposed in Tab. 5 and Fig. 16.

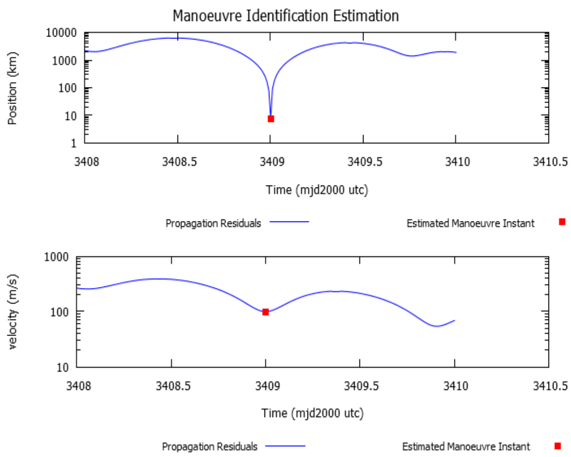

Figure 16: Estimated manoeuvre instant for the given test

4.3 Attitude Identification Module

The Attitude Identification Tool recognizes the rotation estate (attitude law) of an observed object, calculating its rotation period.

VM and RCS values will be obtained from the measurements files generated by the Measurements Generation module. The user selected objects will correspond to the objects whose RCS and VM has been previously calculated with a defined attitude law and geometry.

This tool has the next features:

- The user will select the ID of the objects whose attitude will be determined.
- The Attitude Identification Tool will read the Radar Cross Section (RCS) and Visual Magnitude (VM) measurements provided by the Measurements Generation Tool (configured for accounting with complex geometry satellites and attitude law simulation).
- The rotation period will be calculated considering the dominant frequency modes of the light curves, i.e. RCS and VM measured signals.
- Plots showing the light curves and RCS function (of time) will be provided as an output.

A test example is provided in order to show the use of this module. The simulation is based on radar measurements for an object with Galileo-like attitude model (generated with Measurement module, see Tab. 6). The aim of the test is to identify the satellite attitude using RCS measurements.

Table 6: Used Configuration in Measurements module in order to apply an attitude law to a selected object

azimuth angular speed (deg/s)	10.0
initial azimuth (deg)	0.0
elevation angular speed (deg/s)	10.0
initial azimuth of the (deg)	0.0

In this test, the Attitude Determination tool provides a maximum power at frequency 0.0550518 Hz or 0.34590098 rad/s. This value should be divided by 2 because the frequency of the variation of area is twice the frequency of rotation. Then, the frequency is 0,1730 rad/s, being approximately the same value than the angular speed applied by Measurements input as shown in Tab. 6 (10deg/sec = 0,1745 rad/s).

Remember that 1 rad/sec is approximately 0.159155 Hz.

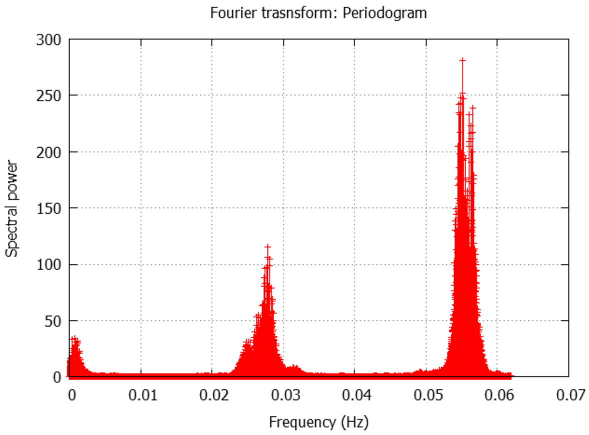

Figure 17: Associated periodogram to these radar measurements in order to find the maximum frequency to identify the attitude law

4.4 Collision Risk Module

Collision Risk Module can be used to analyse the collision risk of a satellite and the capability to reduce it, as determined by the performance of the SST object catalogue. This module allows the user to assess the statistical probability of collision between an operational spacecraft and the tracked objects orbiting around the Earth, the mean number of conjunction avoidance manoeuvres and the associated fuel consumption. The decision to manoeuvre a spacecraft to avoid a possible conjunction is related to the risk associated with that encounter and the allowed collision probability level. The risk related to the near-miss event is a function of the geometry of the encounter, the collision cross section and the uncertainty in the state vector of the two objects. In order to consider the uncertainty of the objects, the tool includes a look-up table of uncertainties based on TLE and CSM analysis, or it can use user-defined values.

The annual collision risk depends on the population, the type of orbit and spacecraft size, and it is computed in a completely statistical way. It allows considering not only the global risk, but also the risk due to events with associated Energy to Mass Ration (EMR) larger than that defining a catastrophic collision.

Avoidance schemes are based on the definition of the level of risk associated to an encounter that forces the spacecraft to perform a manoeuvre to diminish that risk. This level of risk is known as the Accepted Collision Probability Level (ACPL). The computation of the avoidance manoeuvres is based on semi-statistical formulations, which make use of deterministic formulae and the statistical population.

The analysis to be done with the tool makes use of the ESA DRAMA ARES module (see [1]).

The Collision Risk module aids the user to generate the required DRAMA ARES input files allowing assessing the capability of the system to support collision risk reduction, the execution of those ARES cases and the analysis of the obtained results. The Collision risk module creates a number of ARES input files according to the orbital parameters of the missions to be analysed, the coverage and accuracy of the catalogue orbital data.

In regards to the input files, the user may select a reduced number of orbits (specifying the orbital parameters and the area and mass of the object) or allow the tool to analyse objects in the catalogue generated by the SSTAN Cataloguing Module. In this case, assumptions on the objects that can be manoeuvrable are made.

In order to consider the uncertainty of the population, the tool uses the catalogue covariance generated as output by the Cataloguing Module, per the orbital groups defined in DRAMA/ARES. Missing covariance information in the aforementioned output is filled with typical TLE-like uncertainties used in DRAMA/ARES.

The module can be run with a collision event EMR threshold equal to 40 J/g, which will allow analysing the catastrophic collision risk requirements. It is also possible to set the EMR to a smaller value, so simplified lethality analysis can be executed. This simplification regards to the lack of modelling of satellite platforms and evaluation of the detailed EMR for lethal condition for each encounter geometry. An average value shall be set by the user as lethal condition, and the DRAMA tool will be run similarly than for the catastrophic collision case.

The Collision Risk Module uses as input files the estimated catalogue generated by the Cataloguing

Module (that is the catalogue generated after processing the sensor measurements) or by the Population Generation Module (on the basis of assumed orbital accuracy and observation capability, for more details). Additionally, the user can define a list of individual user-defined objects to be used for the computation of collision probabilities against the MASTER population.

DRAMA ARES provides information on the expected number of encounters for a given mission and year. It also provides information on the capacity to reduce the risk of collision by means of avoidance manoeuvres as a function of the accepted collision probability level and the cataloguing performance of the surveillance system (determined by the limiting coverage size-altitude function and the orbital data accuracy).

A main issue related to risk reduction is the uncertainty in the orbital data. The orbit determination uncertainty of the population objects, together with the orbit determination of operating spacecraft play an important role in the risk associated to each near-miss event. Catalogue performance (in terms of accuracy of the propagated orbits and object coverage) can be imposed for different simulation cases in order to analyse their impact on collision avoidance capability. They must match the performance cataloguing obtained from the Cataloguing Process Module (or the mimicked estimated catalogue containing the orbits we want to analyse).

A very simple example of execution is show in this section in order to provide an overall idea about the inputs and the outputs of the module. For this example, some simple values are used for those uncertainties that are not related to any cataloguing performance. Hence, three different missions (two in LEO and one in MEO) were analysed. The target risk reduction and false alarms rate are both set to 50% in the example.

Fig. 18 represents the Manoeuvre Rate (annual collision avoidance manoeuvres) per ACPL defined by the user.

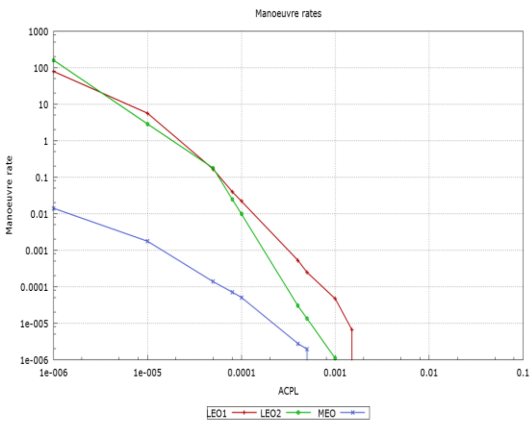

Figure 18: Manoeuvre Rate vs. ACPL

4.5 Fragmentation Detection and Identification module

The fragmentation detection and identification module analyses newly detected catalogue object to establish if they are the result of a fragmentation event. If several new objects are detected and they cannot be correlated with catalogue objects, assigned to a recent launch or correspond to a manoeuvre, it is possible they are the result of an in-orbit fragmentation.

The fragmentation analysis tool is the last step in the analysis and is preceded by:

- a fragmentation is simulated with the Population Generation Module
- observations are generated with the Measurement Generation Module
- the catalogue is generated with the Cataloguing Module
- the Manoeuvre Identification Module should be used to discard manoeuvred objects

The module performs two main activities:

1. Detection of a new fragmentation event

In order to evaluate the fragmentation event characteristics (time, location and source of the fragmentation event), it is assumed that a fragmentation analysis is raised whenever a number of new objects appear in the catalogue. The new objects are compared against old objects in the catalogue. For this purpose, two estimated catalogues (that are the catalogues generated after processed the measurements) obtained from two different observations separated in time are compared. The detection of a number of new objects raises a warning to the system allowing the initiation of the fragmentation analysis process (the second main activity)

2. Identification of the fragmentation event

Once a fragmentation has occurred, it is important to determine the time of the event, where it happened and the objects involved. The initial input to the tool shall contain all the fragments presumably resulting from the event, no matter whether it was an explosion or a collision (new objects with respect to a former catalogue). To identify the objects involved in the event (the "parent object(s)"), the type of event is determined (explosion or collision), the clouds (one for an explosion, two for a collision) are identified and the fragments are propagated backwards. When the average distance between the fragments and their centre of mass reaches a minimum, the location and epoch of the fragmentation event is identified (see Fig.19 for an example). The module will also yield real parent candidates from an input real catalogue considered as a background catalogue (generated using Population module and assumed to be containing real orbits).

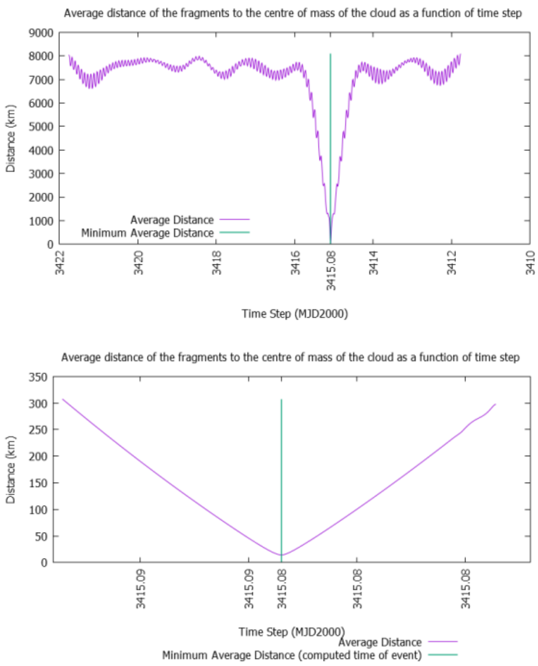

Figure 19: Average distance to the centre of mass vs. time for the first cloud. The bottom plot shows a final finer computation and the top plot a first rough approximation (identification of collision in LEO).

The first activity is optional. The user can choose to enable detection before identification or not. If the detection is not enabled, the user can insert an independent estimated catalogue containing objects that are assumed to be fragments in order to perform the identification of the fragmentation event

Fig.19 illustrates a simple diagram of the algorithm including the main steps.

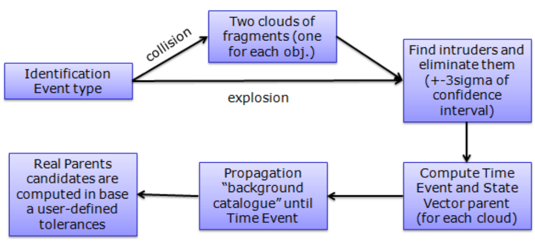

Figure 20: Fragmentation Detection Module diagram

5 REFERENCES

1. N. Sánchez-Ortiz, M. Belló-Mora, H. Klinkrad, *Collision Avoidance Manoeuvres During Spacecraft Mission Lifetime: Risk Reduction and Required ΔV*, Advance in Space Research 38 (2006) 2107-2116, Naval Postgraduate School, Monterey, CA 93943

2. Roxana Larisa Andrișan, Alina Georgia Ioniță, Raúl Domínguez González, Noelia Sánchez Ortiz , Fernando Pina Caballero, Holger Krag, *Fragmentation Event Model and Assessment Tool (FREMAT) supporting on-orbit fragmentation analysis*, 7th European Conference on Space Debris, 2017