Improvement and Validation of a Space Debris Orbit Determination Tool

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Abstract

The European Space Agency estimates that more than 670.000 objects larger than 1 cm orbit the Earth. These objects pose a threat to active satellites, as an impact at orbital velocities can have catastrophic consequences. To avoid collisions, their orbit must be known with sufficient accuracy. Airbus Defence and Space has been developing SPOOK, an Orbit Determination tool able to simulate different observation strategies and perform Orbit Determination of a single space object. The target of this project is to enhance this tool. New radar sensor types were introduced to produce the measurements of the tracked objects. Also, the measurement generation process as well as the Orbit Determination algorithms were improved by taking into account the delay introduced by the finite velocity of light. Real world data can now be used to predict the orbit of real space objects. Data from a experimental radar was tested with the tool and the state vector of the tracked object could be predicted. Multiple objects can now be tracked in a singular run of the program. Thanks to parallel processing, these objects can be simulated simultaneously, with the subsequent savings in computational times if computational resources are available. Lastly, a newly introduced postprocessing mode facilitates the analysis of the data produced by SPOOK, by creating relevant statistics about the simulation in addition to the raw data of the prediction. All the recently implemented features enhance the capabilities of the tool to analyse different space debris surveillance scenarios and make possible the tracking of space objects with real data supplied by space and ground based observers.

I. Introduction

The Inter-Agency Space Debris Coordination Committee (IADC) defines the term *space debris* as: "Space debris are all man made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non functional" [1]. Since the early days of space flights with the launch of Sputnik 1 in 1957 space has become more and more crowded with active satellites and space debris. The U.S Space Surveillance Network currently catalogues more than 17.000 objects [2]. However, the real number of objects can only be estimated via scientific models. By 2013, European Space Agency (ESA) estimated that 29.000 objects larger than 10 cm and 670.000 objects larger than 1 cm were orbiting the Earth. If we go down to objects larger than 1 mm, the number of objects is estimated to be greater than 170 million [3].

Two main events led to a major increase in the number of space debris. In 2007, China destroyed its own satellite Fengyun 1C in an anti-satellite weapon test, leading to an increment of over 2000 objects [4]. The second one, in 2009 was the collision of two satellites: the US Iridium 33 and Cosmos 2251, a non-operational Russian satellite. Over 1500 new fragments were catalogued only from that collision [5].

All this objects pose a threat to the operational satellites that are currently orbiting the Earth. Due to the orbital velocities, even the impact of the smallest object can have catastrophic consequences. In order to be able to predict and avoid collisions, the orbits of objects in space must be known with sufficient accuracy.

Operational satellites can determine their own orbit, e.g using GPS data. However, passive debris such as rocket bodies do not have the means to estimate their own orbit and they must be determined through other means, using external measurements. Different approaches can be used, e.g. radar measurements, telescope observations or laser tracking from ground and from space. By gathering a number of measurements of a target along its orbit one can predict and refine the object's orbital elements over time. This is known as the orbit determination problem and will be the main topic of this paper.

Airbus Defence & Space has been developing Space Object Observations and Kalman filtering (SPOOK), an Orbit Determination (OD) Tool (based in Fortran) in order to test different observation strategies for space debris. This tool can simulate measurements of different sensors (optical and radar sensors) and observers (space-

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based and ground-based observers) and it performs the orbit determination by using techniques such as the Extended Kalman filter or Weighted Least Squares. The objective of the project is to further develop and improve this tool. New radar sensor types were implemented. The delay introduced by the finite velocity of light can now be taken into account for the measurement generation process and the orbit determination algorithms. These two new features allowed the analysis of experimental real world data coming from the Poker Flat Incoherent Scatter Radar (PFISR) and its feasibility to be used for future collision avoidance applications using this tool. Lastly, multiple objects can now be simultaneously tracked by SPOOK thanks to the software parallelization carried out using OpenMP libraries.

II. METHODS

New sensor types

New radar sensor types producing different combinations of slant range ρ and slant range-rate $\dot{\rho}$ measurements were introduced in SPOOK. The orbit determination algorithms perform the estimation of the tracked object position and velocity $\vec{X}$ by comparing the predicted state against the measurements $\vec{Y}$ coming from the observers. This comparison is made using the observation matrix H defined as:

$$H = \frac{\partial \vec{Y}}{\partial \vec{X}} \tag{1}$$

This observability matrix will be derived for the slant range and slant range-rate measurements. The slant range is defined as the distance between the observer and the tracked object while .

$$\rho = \sqrt{\vec{r} - \vec{r}_{obs}} \tag{2}$$

$$\dot{\rho} = \frac{d\rho}{dt} = \frac{1}{\rho}\left(\vec{r} - \vec{r}_{obs}\right)\left(\vec{v} - \vec{v}_{obs}\right) \tag{3}$$

The observation matrix for the case where both measurements are available would be

$$H = \frac{\partial Obs}{\partial \vec{X}} = \begin{bmatrix} \frac{\partial \rho}{\partial \vec{r}} & \frac{\partial \rho}{\partial \vec{v}} \\ \frac{\partial \dot{\rho}}{\partial \vec{r}} & \frac{\partial \dot{\rho}}{\partial \vec{v}} \end{bmatrix} \tag{4}$$

It is seen in 2 that ρ does not depend on the velocity. Differentiating 2 and 3 against position and velocity we obtain the following observation matrix

$$H = \begin{bmatrix} L_x & L_y & L_z & 0 & 0 & 0 \\ L'_x - \frac{\dot{\rho}}{\rho}L_x & L'_y - \frac{\dot{\rho}}{\rho}L_y & L'_z - \frac{\dot{\rho}}{\rho}L_z & L_x & L_y & L_z \end{bmatrix} \tag{5}$$

where the vectors $\vec{L}$ and $\vec{L}'$ are, respectively,

$$\vec{L}' \equiv \left[\vec{L}_x, \vec{L}_y, \vec{L}_z\right] = \left[\frac{r_x - r_{x_{obs}}}{\rho}, \frac{r_y - r_{y_{obs}}}{\rho}, \frac{r_z - r_{z_{obs}}}{\rho}\right] \tag{6}$$

$$\vec{L}' \equiv \left[\vec{L}'_x, \vec{L}'_y, \vec{L}'_z\right] = \left[\frac{v_x - v_{x_{obs}}}{\rho}, \frac{v_y - v_{y_{obs}}}{\rho}, \frac{v_z - v_{z_{obs}}}{\rho}\right] \tag{7}$$

Light Time Delay

The sensors implemented in SPOOK rely on the visible light (optical sensors) or radio waves (radar-based sensors) reflected by the tracked object and detected by the observer. Both visible light and radio waves are assumed to travel at the speed of light in the vacuum (c = 299792458 m·s^{-1}). If we assume that the light speed is infinite, the apparent position of the object from the observer coincides with its true position at the time of measurement. However, in a more realistic implementation, during the time that the light needs to reach the observer, the tracked object will have continued its trajectory making the apparent measured position different from the true position at measurement time. The typical Light Time Delay (LTD) for Earth orbiting objects ranges from 1 μs to 0.2 ms [6].

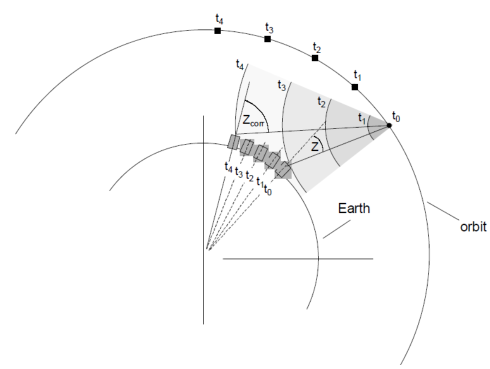

Figure 1: *Light Time Delay effects [6]*

Taking as reference figure 1, we assume that the object reflects the wave (visible or radio) at time t_0. Due to the finite velocity of light, the wave does not reach the observer until time t_4. As a consequence, at detection time t_4 the apparent position of the object is not the object's real position (at time t_4) but its position at time t_0. The difference between times t_4 and t_0 is the Light Time Delay Δt_{ltd}.

$$\Delta t_{ltd} = t_4 - t_0 \tag{8}$$

In order to compute this time delay, the true light path (ρ_{tlp}) must be evaluated. This light path is defined as:

$$\rho_{tlp} = \left|\mathbf{r}_{\text{object}}(t_0) - \mathbf{r}_{\text{observer}}(t_4)\right| \tag{9}$$

Taking as a reference the detection time t_4 and combining expressions 8 and 9 the equation to evaluate the Light Time Delay is:

$$\Delta t_{ltd} = \frac{\left|\mathbf{r}_{\text{object}}(t_4 - \Delta t_{ltd}) - \mathbf{r}_{\text{observer}}(t_4)\right|}{c} \tag{10}$$

Equation 10 is a non-linear implicit equation that must be solved iteratively. Taking as initial point a 0 time delay, at each solving step k the object's position is propagated backwards from t_4 by Δt_{ltd}^{k} and equation 11 is evaluated. The iterative process finishes if the difference between the previous value of the LTD and the next one is below a certain threshold.

$$\Delta t_{ltd}^{k+1} = \frac{\left|\mathbf{r}_{\text{object}}(t_4 - \Delta t_{ltd}^{k}) - \mathbf{r}_{\text{observer}}(t_4)\right|}{c} \tag{11}$$

This Light Time Delay must be taken into account both when measurements are simulated as well as in the orbit determination algorithms.

III. Orbit Determination Using Real Data

The use of data coming from the PFISR observations to perform orbit determination of space Debris and to be used for future collision avoidance applications was assessed using SPOOK. The experimental data has been supplied by LeoLabs Inc. and it is still in development phase, meaning that calibration of the data is still needed and it is not perfectly characterized. No successful orbit determination had been performed using this data previously to this project. The PFISR radar is able to produce angle measurements (azimuth β and elevation el) as well as slant range ρ and slant range-rate $\dot{\rho}$. The observation technique used for this surveillance scenario is of the type step and stare, where the radar does not point directly towards the object but towards a region of the space and waits for the object to cross its beamwidth. For this reason, the resolution of the angle measurements is very low, using the whole beamdwith as the standard deviation of the angular measurements. The slant range-rate information have not being processed as much as the slant range information and its noise parameters are not as clear. For these reasons, the first efforts will be focused on using only the slant range information to perform the orbit determination taking into account the new sensors type implemented in SPOOK. The characteristic parameters of the data are shown in table 1.

	Azimuth	Elevation	Slant range	Slant range-rate
σ	1.1 deg	1.1 deg	20 m	75 cm s^{-1}
Bias	N/A	N/A	10 m	N/A

Table 1: *Characteristic parameters of the PFISR data*

The analysis of the PFISR data will be focused on the data coming from the SPOT 6, as both Two Line Element (TLE) files and ephemerides for this object are available, making it possible the validation of the Orbit Determination process. This data is distributed in several tracklets spanning over a time of 9 days. Approximately, two passes of the object (or tracklets) per day are available. In figure 2 the data available is shown.

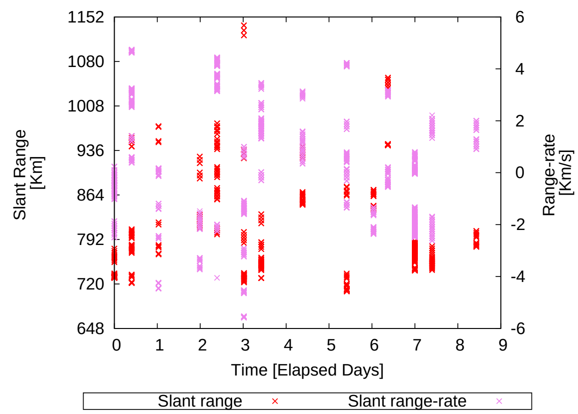

Figure 2: *Measurements of SPOT 6 coming from PFISR radar*

As stated before, the first attempts at performing an OD will be made using only range information. Having only range information, an initial orbit determination can not be made with the Initial Orbit Determination (IOD) methods currently availble in SPOOK. To initialize the process, an initial covariance propagation will be made using as an initial state data from the TLE files.

Synthetic Measurements

As a first step to assess the use of PFISR data to perform an OD, synthetic measurements will be generated with the same characteristics as the PFISR data and the same orbit as the SPOT 6. The Weighted Least Squares (WLS) algorithm will be used to perform the OD, considering the following perturbations in the force model: atmospheric drag, Solar Radiation Pressure, Solar Gravity, Lunar Gravity, Thermospheric Winds and a non-spherical gravity field with a degree and order up to 30. The WLS process converges towards a solution.

In figure 3 a 3D representation of the orbit estimated by SPOOK is plotted in Earth-Centered, Earth-Fixed (ECEF) coordinates.

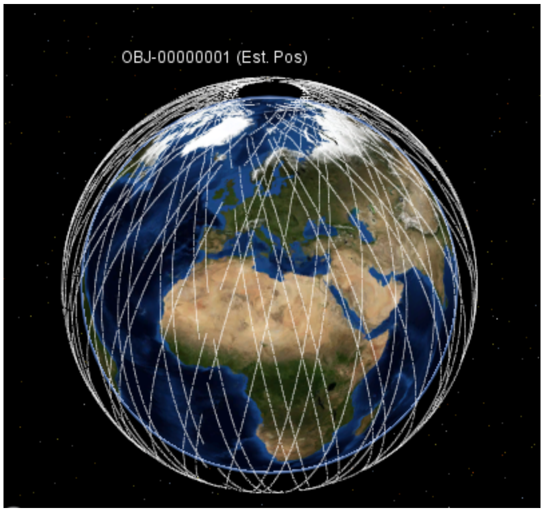

Figure 3: *3D representation of the SPOT 6 orbit estimated by SPOOK*

The results obtained by SPOOK for position are compared with the available ephemerides data of SPOT 6 in figure 4 to 6. The reference frame used is the Radial, Tangential and Normal (RTN) frame. Also the 3σ predicted uncertainties from the covariance matrix are plotted.

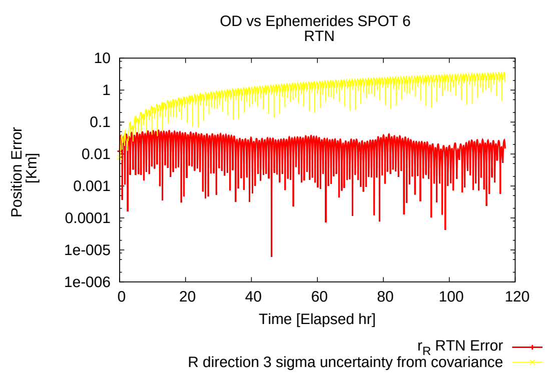

Figure 4: *Position errors in R direction for OD using WLS and synthetic measurements*

Errors below 100 meters are achieved for the radial and normal position while for the tangential position the errors are in the order of Km. This is an expected result, as the tangential direction contains most of the orbital velocity, yielding the biggest errors when it is not perfectly estimated. However, is proved that an Orbit Determination can be made using an observer with similar characteristics as PFISR, as the obtained errors are in line with the predicted errors from the covariance matrix.

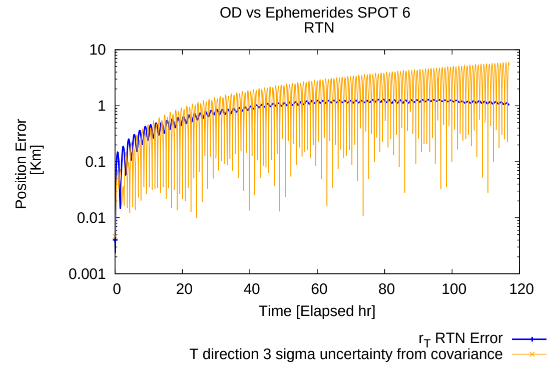

Figure 5: *Position errors in T direction for OD using WLS and synthetic measurements*

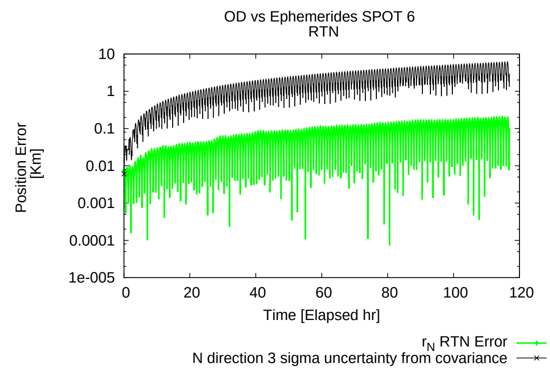

Figure 6: *Position errors in N direction for OD using WLS and synthetic measurements*

Real Data

The same algorithm has been used to perform the OD using the real measurements. The results of the predicted position have been again compared against the available ephemerides in figures 7 to 9. It can be seen again how the errors follow a similar distribution and order of magnitude as with the use of synthetic data, with the bigger errors concentrated in the tangential direction. However, now these errors are bigger than the predicted uncertainties from the covariance estimation.

The results from the synthetic generated measurements and the real data are very similar in terms of the prediction error. However, the results of the orbit determination using the real data could not be used for collision avoidance applications, as the predicted error is not in line with the real error. This can be explained as the experimental data is still in the development phase, and has not been used before to produce a successful

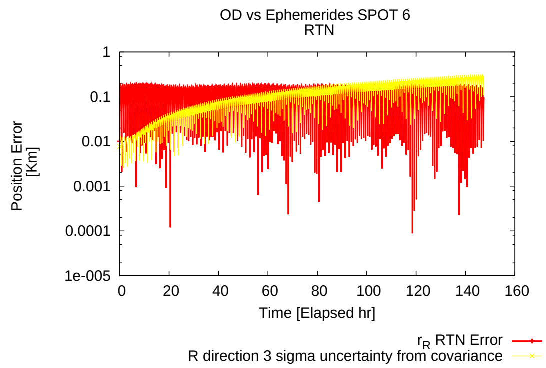

Figure 7: *Position errors in R direction for OD using WLS and real measurements*

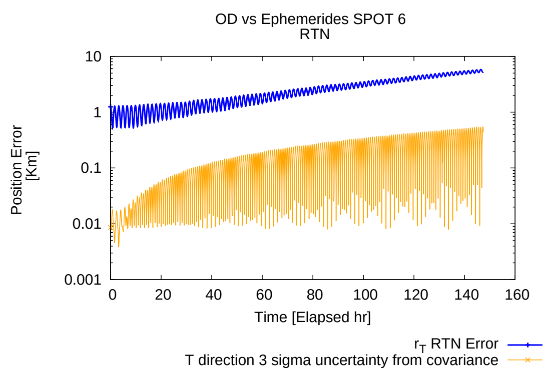

Figure 8: *Position errors in T direction for OD using WLS and real measurements*

Orbit Determination. The characteristics parameters of the data still have to be adjusted. Also, this data has not been yet been filtered and lacks some basic calibration such as atmospheric corrections. The lack of atmospheric corrections introduces a source of non Gaussian error, being one of the explanations behind the uncorrelation between the predicted error and the real error. Also, the distribution of the data concentrated in small periods of time (tracklets duration of around 2 minutes) and very sparse through time (around two tracklets per day) for SPOT 6 does not help the determination of the object's state.

Even with this considerations, it has been proved the capabilities of SPOOK to use real data to perform Orbit Determination.

IV. Multiple Object Processing

The previous version of SPOOK only allowed to process one object at each run of the program. One of the main objectives of the project was to enable the analysis

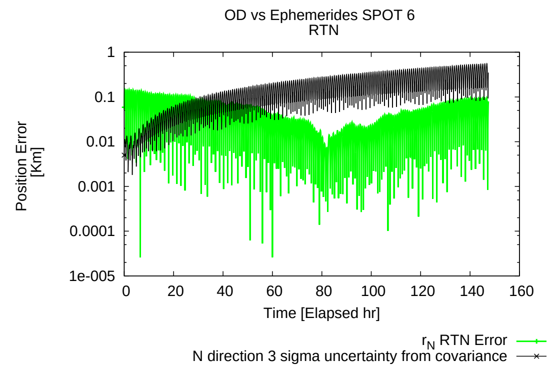

Figure 9: *Position errors in N direction for OD using WLS and real measurements*

of multiple Debris objects in the same run. To achieve this, no substantial changes had to be implemented in the way the algorithms that perform the different functionalities of SPOOK (observation simulation, Orbit Determination, propagation...) works. However, the way of how the different subroutines of the program interact between each other had to be modified.

Furthermore, to improve the efficiency of the code both in terms of computational effort and time the code has been parallelized using the OpenMP libraries [7] to take advantage of modern computer architectures. OpenMP is a specification for a set of compiler directives, library routines and environment variables that can be used to specify high-level parallelism in Fortran programs [8]. The parallelism has been achieved by assigning the computations related to each one of the processed object to a different thread of the machine. Figure 10 shows a graphic representation of how the program works in parallel mode.

Scaling test

To assess the performance of the code working in Parallel, a scaling test was carried out. A simulation scenario was defined (an observation strategy with multiple objects). This scenario was run multiple times, varying the number of threads used for each run. To assess the performance, the total simulation time of each run was compared.

The observation strategy chosen is the Geostationary Orbit Fence scenario, based on a study carried out by Airbus Defence & Space [9] to achieve maximum observation coverage for Geostationary Orbit (GEO) objects with only one optical observer. This scenario is based on the use of a space based observer flying in a dawn-dusk Low Earth Orbit (LEO). Extra information about this scenario can be found in [10, 11]. To assure

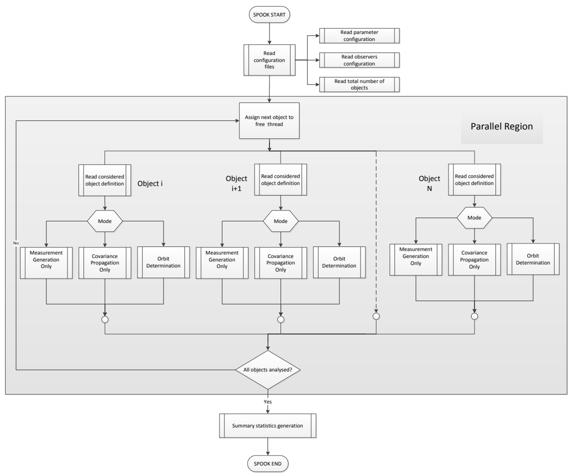

Figure 10: *Top-level structure of parallel SPOOK*

the maximum repeatability between the different runs all the objects had the same characteristics. Also, the random number generator (used to randomize the simulated measurements following a Gaussian distribution) was controlled to yield the same measurements for all the different objects. The object being selected follows a Geosynchronous orbit with the orbital parameters shown in table 2. The simulation start epoch is: 06/04/2014 at 06h 34' 35".

a [Km]	e [-]	i [deg]	Ω [deg]	ω [deg]	ν [deg]
42165	$2.5 \cdot 10^{-4}$	1	60	0	180

Table 2: *Orbital parameters of the object used for the scaling test*

The machine selected to perform the scaling test had a maximum of 36 different cores. Each core can runs a single thread. For this reason, 36 objects were simulated in each run. The number of threads used in each run varied from 1 (sequential run) to 36 threads (each object will run in an independent thread). The results of this scaling test can be seen in figure 11

It can be seen how the total execution time drastically decreases from almost 755 s in the sequential mode to less than 55 seconds (a total reduction of 92.8% os simulation time). This is achieved for a modest case where only 36 objects where simulated. In a more realistic case, where a whole space debris catalogued could be used (around 17000 objects), time reduction is key factor for quick analysis of surveillance strategies.

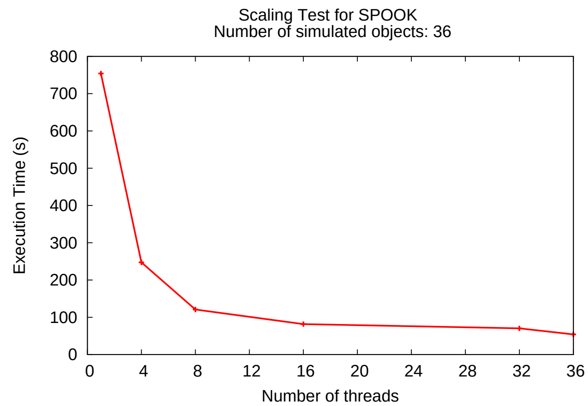

Figure 11: *Scaling test*

Coverage Analysis Mode

The newly multiple object processing feature enhances the capabilities of SPOOK to perform the analysis of different observation strategies. Instead of testing the observation strategy against a unique object, which would have to be representative of the kind of objects to be tracked, the entire known Debris population can be simulated. However, with no further changes to the code, the amount of data produced by such a large simulation (the U.S space Surveillance Network currently catalogues more than 17000) would make its analysis infeasible. For that reason, a postprocessing feature has also been added in the scope of this thesis. This postprocessing defines SPOOK's Coverage Analysis Mode, where simplified outputs are produced with relevant statistics about the performance of the observation strategy. The aim of this mode is, instead of obtaining a data file with the predicted state vector and covariance matrix at each instant of time per object, produce only one line per object with relevant statistics. If desired, a detailed output can still be produced.

The Coverage Analysis Mode was used to test the performance of the Geostationary Orbit Fence scenario introduced before to track objects in the GEO region. More than 15.000 objects coming from a real sapce debris catalogue are simulated. 1170 objects were found to be in this region. The results of this case are summarized in table 3. A coverage above 89% was achieved and 94 objects could be successfully catalogued with an average accuracy of 231 m.

V. Conclusions

Within the scope of this project, new kind of radar-based sensors were introduced, enriching SPOOK's capabilities to use different types of data. Also the Light Time

Detected	Catalogued	Undetected	Total
1045 (89.32%)	94 (8.03%)	125 (10.68%)	1170 (100%)

Average Accuracy [Km]	Average Revisit Frequency [1/day]	Average Observability [s]
0.231	29.0751	71.34

Table 3: *Results of the Covariance Analysis case*

Delay is now taken into account both in the synthetic measurement generation as well as in the orbit determination methods, producing more accurate simulations of real tracking data.

Real world data can now be used to predict the orbit of real space objects using the data coming from observers such as the Poker Flat Incoherent Scatter Radar. Being able to perform Orbit Determination of real space objects was one of the main goals when the development of SPOOK began.

At the beginning of the project only one object could be taken into account by SPOOK. Now, multiple objects can be processed in a single run of the program. This greatly enhances the capabilities of the tool to test different observation strategies, as different representative objects can be simulated, even the whole known space debris population, in the same run. Furthermore, all the objects are treated in parallel taking advantage of modern computer architectures, saving computational times as a result. To help the analysis of the data generated by such large simulations, a postprocessing mode was added to SPOOK, where relevant statistics are produced to allow a quick assessment of the results of the simulation.

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