PASSIVE RANGING SOLUTION DESIGN TO MAINTAIN A CATALOGUE OF ACTIVE OBJECTS IN GEO

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ABSTRACT

The number of man-made objects sent to space has risen in the last decades, leading to an overcrowded environment of resident space objects and orbital debris. Consequently, the space cataloguing activities are becoming increasingly challenging year after year.

Currently, there are over 500 operational satellites only in Geostationary Earth Orbit (GEO), with typical manoeuvre frequency of a couple of weeks for chemical and hours for electrical satellites. Space Surveillance and Tracking (SST) systems predominantly observe them using optical or radar sensors. The cost of these sensors, as they continue to depend on active and complex systems, is quite notorious in terms of development, operation, and maintenance.

Passive Ranging (PR) is proposed as a lower-cost alternative to the existing techniques, capable of providing improved latency, timeliness (24/7 access to data without climate conditions or sunlight dependency) and accuracy. It allows for a rapid detection and estimation of manoeuvres in the order of few hours, and it can be integrated into SST-dedicated operation centres.

Thanks to this supply of rapid high-accuracy orbital information, the provision of collision-avoidance (CA) service takes a leap forward by reducing the object's uncertainties, hence improving the classification of conjunction events, and by increasing the catalogue update frequency, making it possible to assess the conjunctions in the new orbit within few hours after a manoeuvre has taken place.

1 INTRODUCTION TO A PASSIVE RANGING SYSTEM

The concept of PR is rather straightforward. It is based on the acquisition of the relative Time Difference of Arrival (TDoA) of the payload carrier signal, emitted by active satellites and received by several distant stations on the ground. The use of these systems is usually limited to satellites in geostationary orbits since their emission patterns in Ku-band are extensive as opposed to the narrow Ka-band satellites. Pointing to GEO satellites is manageable from the ground (being satellites virtually fixed in space) and their visibility, if available, is constant over time. Nonetheless, this technique can also be applied to other orbital regimes (LEO, MEO and HEO) even though the visibility is not continuous, passes are short, and pointing is more complex.

In contrast to dual-ranging systems, the minimum number of passive tracking stations required to determine the orbit is 4 to obtain 3 linearly independent TDoA observables, typically, all with respect to a given reference station. All these stations must be radiated (within the satellite antenna radiation pattern) and observing (pointing to the satellite and connected to a certain frequency) simultaneously to satellite to be tracked. If several satellites are to be tracked, a coordinated tracking plan should be defined for all stations so that all of them observe the same satellite simultaneously.

At each station, the payload carrier signal or telemetry in the same frequency band from each satellite in view and illuminating the station location is collected, processed, sampled and time stamped using an accurate local clock, usually based on GNSS, and coordinated with the other clocks in the stations network. These samples of the signal collected by each of the stations (time-stamped) are then transmitted to a central operations centre that correlates them and calculates the linearly independent TDoA measurements. This concept is graphically described in Fig. 1.

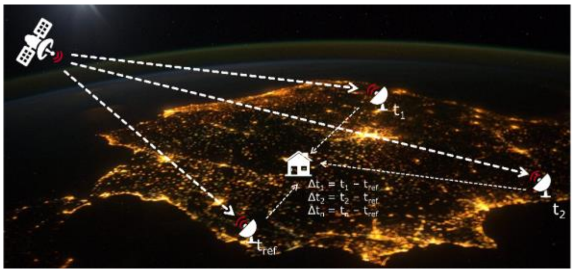


Figure 1 Process of obtaining TDoA data

The main reasons for proposing the concept of PR to support the CA service via an improvement of orbit determination (OD) are, among others, the fact that it constitutes an independent and accurate source of low latency and high frequency data, while being completely autonomous and automated, and keeping a significantly lower cost for deployment, operations (it is completely passive), and maintenance than the other typical SST systems. It allows for a rapid detection and estimation of

Proc. 2nd NEO and Debris Detection Conference, Darmstadt, Germany, 24-26 January 2023, published by the ESA Space Safety Programme Office
Ed. T. Flohrer, R. Moissl, F. Schmitz (http://conference.sdo.esoc.esa.int, February 2023)

manoeuvres in the order of few hours while maintaining high orbital accuracies, and it can be integrated into SST dedicated operation centres, providing them with 24/7 stream of information of the satellites being tracked.

2 FEASIBILITY AND PERFORMANCE STUDY OF A PASSIVE RANGING SYSTEM

A PR system is conceived and analysed to verify its feasibility. The system is to be deployed in Spain, with the 4 reception points of the regional network are proposed to be located in separated locations within the Iberian Peninsula.

The main expected performances are that all satellites in view by a regional network and operating in Ku band will be suitable to be tracked. They will be tracked sequentially from East to West to minimize the repositioning time of the antennae. As a reference, one track every 1-2 h for each satellite will be provided per satellite, each track having a length of 30-60 seconds with a frequency of the TDoA measurements in a track of 0.5-1 Hz (one measurement every 1-2 s).

Prior to studying the expected performance of the system, an analysis of the system's error budget must be carried out. This will provide an order of magnitude of the accuracy of the TDoA data that can be obtained with the system. This data (together with the geometrical questions on Dilution of Precision marked by the topology of the network) is the main reason for the performance that can be obtained with the system.

The main sources of error in a PR system are the time synchronization error between stations, errors in the signal correlation process and errors due to the signal traversing the troposphere and ionosphere. The overall accuracy (1 sigma) of the TDoA data provided by the PR system is expected to be of the order of 4.2 ns (equivalent to 1.25 m in distance), computed as the RMS of the individual errors. Detailed link budget is provided in Tab. 1:

Table 1 Error budget for a passive ranging system

Source of error	Error (1 sigma)
Time synchronization	3.0 ns
Signal correlation	2.8 ns
Troposphere	0.2 ns
Ionosphere	0.3 ns
TOTAL	**4.2 ns**

Note that the expected error is one order of magnitude better than the one achieved by means of telescopes data. It has been estimated that the orbital precision performance obtained for a hypothetical 4-station network in Spain is such that the 1-sigma position errors after 10 days of propagation are in the order of 150m in along-track and 75m in radial (with a linear secular growth over time), and 50m in cross-track (constant over time). In comparison, it is noted that the typical accuracies achievable in GEO with the use of telescopes are at least an order of magnitude worse, considering an observation accuracy of 0.5-1 arcsecs for telescope measurements.

Manoeuvres are expected to be detected and estimated 6-8 hours after they take place, being 1-2 h (the time between consecutive observations) the latency of the system. It is noted that the latency of a tracking system based on telescopes data only is of the order of 1 day (as only operating during night-time). As a result, a very accurate and low latency catalogue for active satellites can be maintained with this PR data. This is critical for the population of manoeuvring space objects.

3 PASSIVE RANGING SOFTWARE PROTOTYPE

The Passive Ranging Simulation tool, ***parasim*** hereafter, is a software comprised of a group of tools that has been intended to simulate the time difference of arrival (TDoA) measurements for a network of stations as well as to process real TDoA data. These measurements are referred to a group of geostationary satellites defined by the user or given by an external dataset. The PR stations network consists of a set of slave stations and at least one master station to which the TDoA measures are referred to.

Parasim allows to generate an observation plan and simulate a DVB-S2 compliant signal to obtain signal samples for a set of GEO satellites and PR stations within a configurable network. These samples are correlated to generate the TDoA data among these stations. The orbital information for the tracked satellites is maintained based on the processing of the TDoA data generated. ***Parasim*** is also able to run based on real TDoA data from an external source.

The ***parasim*** tool consists of the following main blocks:

- Configuration of the analysis scenario: a PR sensor network, composed of a master station and a configurable number of secondary stations. It is also possible to define the list of satellites to be observed by the system and the type of propulsion (chemical or electric) of the satellites.
- Generation of a reference catalogue for the requested satellites, including a simulated station-keeping

maneuver plan for each of them as well as the initial orbits for the maintenance of the objects catalogue.

- Observation plan generation: with the possibility of defining different re-observation frequencies for each group of satellites and providing azimuth and elevation information of the satellites to be observed at each instant of time from each of the stations that make up the network.
- Simulation of the received packages signal by each of the network stations and signal correlation process for the TDoA computation.
- Finally, the generated measurements go through data processing where possible maneuvers are detected and estimated. The orbital determination including the effect of the estimated maneuvers is performed as well as a catalogue update with the latest computed information.

As it was explained before, ***parasim*** is also able to work with real TDoA measurements (and external reference orbits) generated by third parties, making the configuration of the scenario and observation plan dependent on the available TDoA data. The manoeuvres detection, estimation and catalogue maintenance steps are common for both operating methods.

3.1 Catalogue maintenance

The purpose of the ***parasim*** prototype, when simulating PR data and when processing real data is to maintain an ephemeris catalogue for the satellites considered in the execution. In this catalogue-maintenance process, the manoeuvre detection plays a significant role, and it will be depicted in following sections. Also, it should be noted that in an operational implementation of the system for CA products provision, the quality of this ephemeris catalogue would directly affect the quality and accuracy of these products.

In previous sections, it has been mentioned the benefits of using TDoA data in comparison with typical data sources such as telescopes or radars. These benefits are related to the high frequency of data provision and low latency of the data.

A set of satellites of the EMEA network have been considered for a ***parasim*** execution during a period of 10 days. These satellites are shown in the table below together with their current longitude and type of propulsion. Their names are concealed for confidentiality reasons. The real TDoA data has been provided by Safran Data Systems as well as the satellites ephemeris for this period which have been considered as reference for the catalogue quality check.

Table 2 EMEA satellites under study

Satellite name	Longitude	Propulsion
Sat 1	-30.0	Chemical
Sat 2	-30.0	Chemical/Electric
Sat 3	31.6	Chemical/Electric

Fig. 2 shows the catalogue comparison. During the first 24 hours, the catalogue has not converged, and the RMS obtained are considerably large. After this time, the catalogue comparison tends to the convergence and the RMS are within the expected thresholds. It should be mentioned that the dataset under analysis has two gaps, the second one being of around 12 hours. This has a non-negligible impact in the catalogue quality degradation giving as a result an increase in the RMS at the end of the simulation.

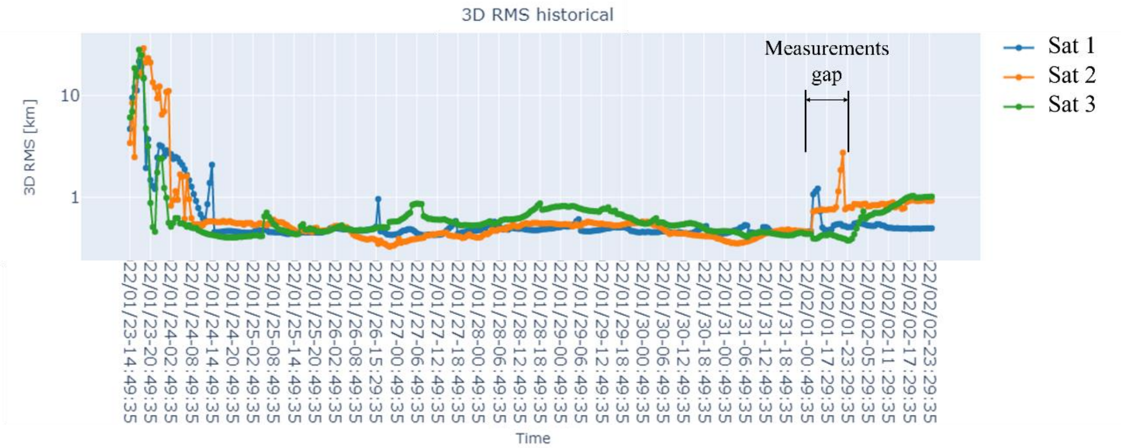


Figure 2 Catalogue quality comparison

A specific calibration process of the TDoA measurements is required to obtain the possible time bias introduced per each PR station. For this calibration, consecutive SP Catalogue ephemeris have been considered as reference ephemeris for the TDoA measurements calibration process during a period of one week.

In this case, the orbital comparison for the satellite Sat 4, tracked from the EMEA network and the Sat 5, from the CONUS network are shown in the Fig. 3 (a) and (b). This comparison shows that the orbital differences are within the expected range for all the components.

(a)

(b)

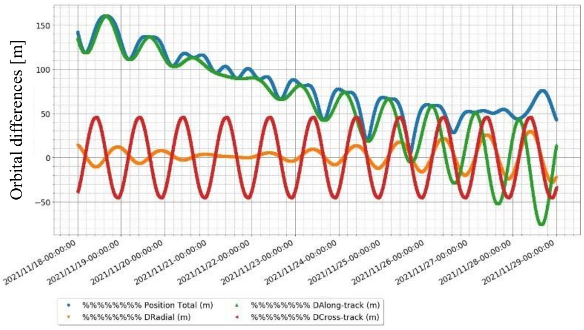


Figure 3 Orbital comparison: (a) Sat 4 (EMEA), (b) Sat 5 (CONUS)

3.1.1 Passive ranging data conversion

One small limitation of TDoA data is that operation centres need to update their processing capabilities to be able to ingest it. Nevertheless, PR tracking information can be easily converted to more frequently used data formats such as range, right ascension, and declination without any loss in accuracy.

The system of equations to be solved for the measures conversion is the following (for *i = 1, …, N-1* stations):

$$\boldsymbol{R}_i + (\rho_0 + c\tau_{i0})\boldsymbol{L}_i = \boldsymbol{R}_0 + \rho_0\boldsymbol{L}_0 \qquad (1)$$

Where $\boldsymbol{R_i}$ represents the position vector of sensor i, ρ_0 is the distance from the reference sensor (subindex 0) to the object, c is the speed of light, τ_{i0} is the difference between the signal reception times at station i and at the reference station (the TDoA between these two stations), $\boldsymbol{L}_i$ is a unit vector characterizing the pointing of sensor i and it is determined by the right ascension and declination as:

$$\boldsymbol{L}_i(\alpha_i, \delta_i) = \begin{pmatrix} \cos\alpha_i \cos\delta_i \\ \sin\alpha_i \cos\delta_i \\ \sin\delta_i \end{pmatrix} \qquad (2)$$

The number of unknowns is *1+2N* $\{\rho_0, \alpha_i, \delta_i\}$ and the number of equations is *3(N+1)*. This means the system of equations is determined only when N=4. This gives three different scenarios depending on the number of equations:

- N=4. The system of equations is determined, and the solver used finds a unique solution.
- N<4. The system of equations is underdetermined, and it is required to use a dynamic model to connect consecutive time steps to have enough information to solve it.
- N>4. The system of equations is overdetermined, and a least-squares solver is required.

Additionally, it is possible to transform the TDoA uncertainty into range, right ascension, and declination uncertainties. This can be obtained using the perturbative expansion in the Eq. 1 ($\tau_{i0} \rightarrow \tau_{i0} + \Delta\tau_{i0}$, $\boldsymbol{L}_i \rightarrow \boldsymbol{L}_i + \boldsymbol{\Delta L}_i$ and $\rho_0 \rightarrow \rho_0 + \Delta\rho_0$) giving as a result the Eq. 3.

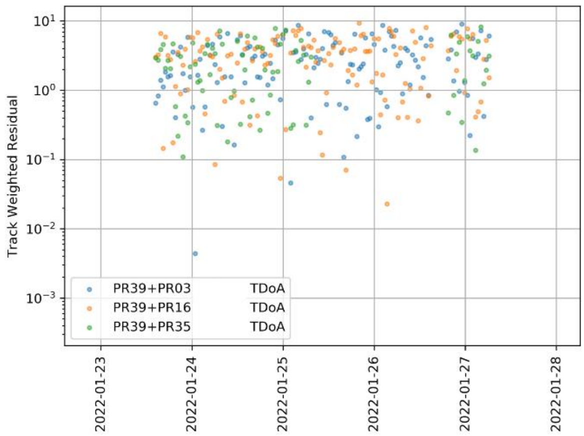
$$(\rho_0 + c\tau_{i0})\boldsymbol{\Delta L}_i + (\Delta\rho_0 + c\Delta\tau_{i0})\boldsymbol{L}_i = \Delta\rho_0\boldsymbol{L}_0 + \rho_0\boldsymbol{\Delta L}_0 \qquad (3)$$

The analysis of the TDoA conversion results show that when four PR stations are considered, the quality of the catalogue is as good as when TDoA data is processed directly. On the contrary, the conversion when the system of equations is underdetermined yields a degradation in the orbital quality and the conversion is not recommended. This is because to compensate for the missing data, an intermediate Keplerian orbital model needs to be added to the process which introduces significant differences.

Under these degraded conditions, TDoA data could still be collected from the remaining stations, maintaining the possibility for orbit determination and manoeuvre detection if the operations centre is able to process the TDoA format. On the other hand, this “degraded” TDoA data would not be converted, and it would appear as a complete measurement gap if only Ran-RaDec information could be processed.

An example of this can be seen in Fig. 4, which shows the weighted residual tracks at each observation of a given satellite. Fig. 4a represents the TDoA data directly (each point corresponds to a measurement and each colour represents one pair of ground stations), while Fig. 4b displays the converted data to Ran-RaDec. Note how there is a two-day period, from the 25th to the 27th, where data from PR35 station is unavailable. This results in less available measurements for the TDoA processing but in a complete data gap for the Range-RaDec case.

(a)



(b)

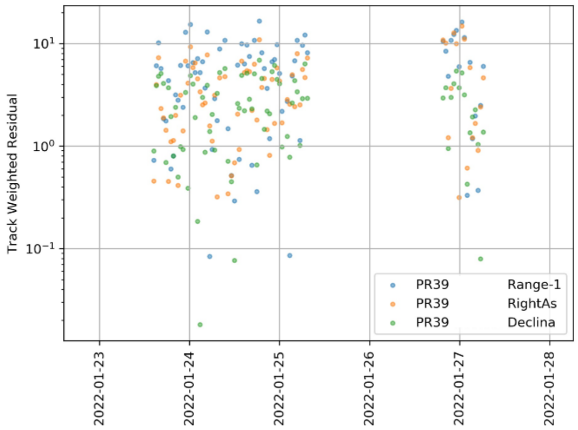


Figure 4 Track weighted residuals for TDoA measurements (a) and Ran-RaDec measurements (b) in a period with an unavailable station.

3.2 Manoeuvre detection and estimation

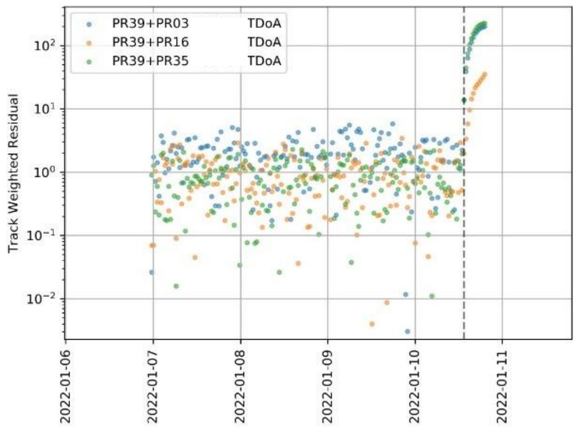
The manoeuvre detection and estimation methodology follows the logic presented in [1] for the detection and estimation of single burn manoeuvres via track-to-orbit. It relies on the difference between the residuals of the estimated orbit before the manoeuvre (reference orbit from the catalogue) and the tracks afterwards (obtained from the TDoA measurements). It is based on the footprint of the manoeuvre on the weighted residuals between the pre-manoeuvre orbit and the post-manoeuvre tracks.

The high-level steps that need to be followed to detect and estimate a manoeuvre are:

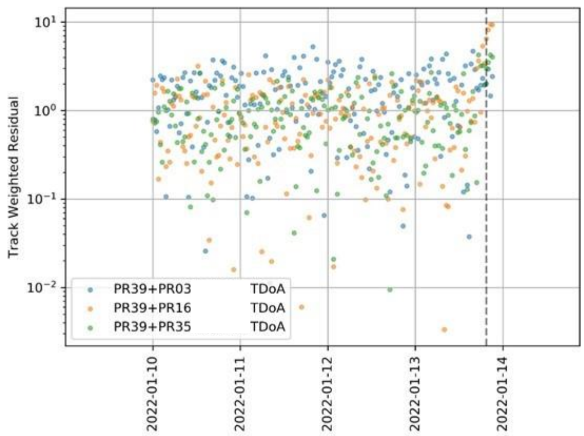
1. Select a reference orbit against which the TDoA measurements will be checked.
2. Verify if there is a divergence in the weighted residuals from the reference orbit (using a pre-defined threshold).
3. If so, a maneuver has occurred and the tracks that present the divergence are classified as information post-maneuver.
4. Once enough post-maneuver tracks are available the first estimation of the maneuver is computed.
5. Run an orbit determination that will calculate the final estimation of the maneuver and will update the orbit of the satellite.

Fig. 5a shows the divergence in the weighted residuals after a cross-track manoeuvre, Fig. 5b after an along-track manoeuvre, both coming from a satellite using chemical propulsion. Fig. 5c and Fig. 5d show the divergences when an electrical manoeuvre is detected (the satellite manoeuvres twice a day, with a period of 12h). All the points after the dotted line correspond to the information classified as post-manoeuvre that is used for the manoeuvre estimation.

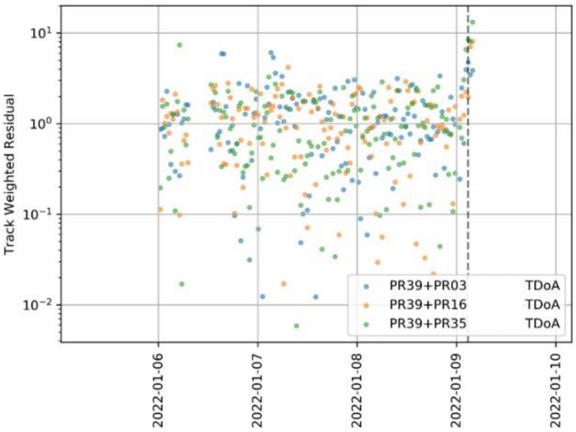
(a)



(b)



(c)



(d)

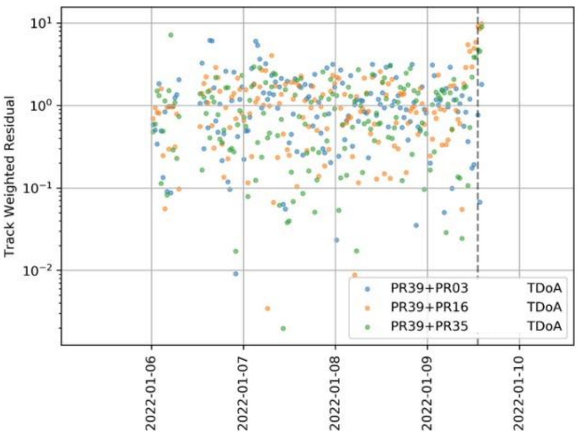


Figure 5 Divergence in the weighted residuals after a chemical cross-track (a), chemical along-track (b), and two electrical manoeuvres (c) and (d).

To verify the correct functioning of the ***parasim*** tool in the manoeuvre detection and estimation, real TDoA data was obtained from the Safran Data Services's PR networks (WeTrack) in Europe and America for a mix of satellites with different propulsion systems. The detected manoeuvres were then compared against the real manoeuvres provided by the satellite's operators. By aggregating the results obtained for all the satellites, the following metrics are obtained for the manoeuvre detection:

Table 3 Overall maneuver detections

# True mans	True Positives	False Positives	False Negatives
79	63	17	16

The causes of the false positives (manoeuvres that did not really exist but were detected) and false negatives (manoeuvres that did occur but were not detected) are mostly linked to the available TDoA data not being precise or complete enough:

- False positives: All of them appeared either during the first hours after the simulation had started or right after a maneuver had been computed, i.e., during convergence periods. False positives are detected because the current orbit diverges enough from the orbit used as reference such that it is thought that a maneuver has taken place. This is due to the small amount of data available per observation (only one measurement corresponding to a single instant every 40 minutes approximately) that leads to orbital determinations that change the orbit enough from one point of available data to the next one.
  However, having access to the real raw data (not compressed, i.e., several measurements at each satellite observation) would be better to accelerate the orbit-convergence at the start of the simulation or after a maneuver has been estimated (in fact, it would also enhance the maneuver estimation) so that the number of false positives is drastically reduced or eliminated.

- False negatives: Nearly all the false negatives are due to maneuvers occurring at or right after periods where no TDoA data was available (data gaps). Sometimes, the system can recover from this lack of data, for example in the case of chemical satellites where the orbit is stable enough to accommodate a period with no data, e.g., 12-24h. However, for the case of electrical satellites that maneuver very frequently, the same period without measurements would reflect in missing 2 to 3 maneuvers and extremely lowering the quality of the orbit determination.

For the manoeuvre estimation (only true positives considered), the results obtained are presented in Tab. 4. The absolute errors are given in the Radial, Tangential and Normal components in the local reference frame. Accurate manoeuvre estimations are obtained, making it possible to maintain an exact catalogue of satellites.

Table 4 Overall maneuver estimations

	Mean	σ
Man Epoch error [s]	-147	2585
Dv error [mm/s]	0.0039	0.0360
R error [mm/s]	0.0212	0.0440
T error [mm/s]	0.0048	0.0249
N error [mm/s]	0.0301	0.0345

Finally, the time it takes the system to detect and estimate a manoeuvre is analysed. The detection and estimation delays are highly dependent on:

- The size of the maneuver: a bigger maneuver will create a larger disruption in the weighted residuals making it easier to detect that a maneuver has occurred.
- The satellite observation plan: the more frequently a satellite is observed, the faster the maneuver will be detected, and the faster enough post-maneuver information will be available for the estimation.

From the multiple simulations run, it has been estimated that a manoeuvre can be accurately estimated within 6 to 8 hours after it has taken place, regardless of the type of manoeuvre. If there are no differences among the observation plans of all satellites, i.e., no satellite is observed more frequently than any other, the cross-track chemical manoeuvres are the fastest to estimate due to their big magnitude. Electric manoeuvres come next; even if electric satellites manoeuvre much more frequently than chemical satellites, their manoeuvres tend to include a cross-track component that is usually of relatively big magnitude. Finally, in-track chemical manoeuvres are the most difficult to estimate due to their very small magnitude (usually two orders of magnitude smaller than the cross-track ones).

4 USE OF PASSIVE RANGING IN OPERATION CONTROL CENTRES

PR technology is mainly used for cataloguing purposes to support the service provision, CA for example, as it makes usage of time synchronized ground stations to correlate the arrival of emitted signals from active satellites allowing the TDoA between stations which in turn can be used in orbit determination algorithms.

Optical telescopes mainly work under surveillance mode where the telescope observes a certain region of the sky or under tracking mode where the telescope follows a specific target satellite. Observation planning is required for a proper follow-up of sky objects from which derive tracking data. The usage of the PR technology to track specific active satellites could spare optical telescopes from performing observations on such objects.

4.1 Impact on CA services

The advantages of maintaining a catalogue using PR data are the higher accuracy in the measurements and the timeliness of the measurements compared to other techniques, such as telescopes, allowing for a quicker manoeuvre detection and estimation.

Each step of the conjunction assessment process can be potentially improved using this technology. Typically, the first step in conjunction assessment is to screen the objects to determine the possibility of any close encounter. This process involves the propagation of the objects, and it is very dependent on the type of propagation and the initial orbit provided.

Once a close approach is found, the probability of collision (PoC) is evaluated, provided the covariance is known. Several techniques have been developed to calculate this probability and the most common techniques depend on the covariance at the time of closest approach (TCA). The covariance needs to be propagated and the perturbing forces and the inability of analytical models to exactly describe these forces make the uncertainty to grow in time. Thus, a lower initial uncertainty would yield a more realistic close encounter and PoC computation. This could potentially lead to the reduction of false alarms.

In addition to this, a faster time of revisit for PR data could provide the CA service with newer and more precise orbits faster especially after manoeuvres by active satellites, thus turning the service more agile and flexible. Due to shorter propagation periods, the uncertainty would not grow as much in time and thus better results could be obtained.

4.1.1 Impact on the uncertainty in the probability of collision

The qualitative and quantitative effect that reducing the level of uncertainty in the position of objects have on the PoC have been analysed. To do so, a conjunction event is defined with growing levels of uncertainties and miss distances. Then, the probability of collision of each event is computed using the Alfriend & Akella method [2].

The test case used for the analysis, even though is based on synthetic data, it can be a realistic approximation to a close approach event between a geostationary satellite (primary) and a geosynchronous debris (secondary), such as a derelict rocket body. The state vectors at the TCA and a miss distance of zero meters, are given by:

Table 5 State vectors and span of primary and secondary objects in the tested conjunction

	X [Km]	Y [Km]	Z [Km]
Primary (10m)	39885.58	-13670.18	-203.73
Secondary (0.5m)	39885.58	-13670.18	-203.73

	Vx [Km/s]	Vy [Km/s]	Vz [Km/s]
Primary (10m)	0.997	2.908	0.067
Secondary (0.5m)	0.997	2.908	0.067

In the scenario presented here, the position of the secondary object accounts for the most part of the uncertainty of the problem. This statement assumes that the object has not been observed for long period of time, therefore its orbit uncertainty is large. Typical uncertainties for this case could be in the hundreds to few kilometres range.

On the other hand, the uncertainty of the primary object (GEO satellite) is assumed to be well known and it is typically obtained through an orbit determination process. For a common GEO catalogued object with optical measurements, these uncertainties could be around the hundreds of meters.

In addition to this, since the covariances are not known, there is no need to introduce additional complexity in this qualitative analysis by assuming non-diagonal covariance terms. Moreover, and for an easier visualization, the covariances through the analysis are expressed in the RTN frame. The x-axis of RTN frame is parallel to the position vector of the satellite with respect to the centre of the Earth, the z-axis is parallel to the angular momentum vector (thus, normal to the orbit plane) and the y-axis completes a right-handed frame.

Several test cases with different covariance combinations and miss distances (from 0 to 6000m) are created. The covariance ranges are shown in Tab. 6:

Table 6 Covariance ranges for the primary and secondary objects in the tested conjunctions

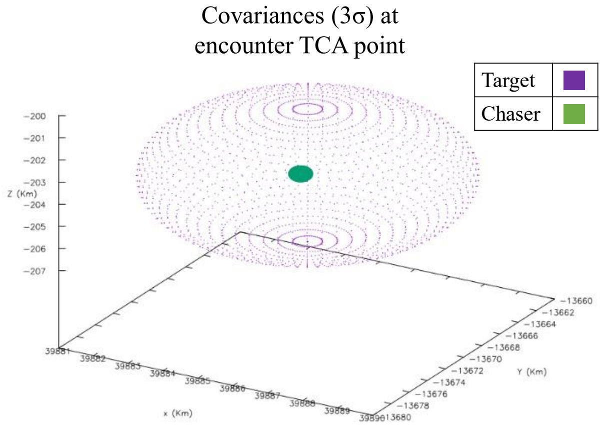
	Tracked by optical sensors		
	σ_R [Km^2]	σ_T [Km^2]	σ_N [Km^2]
Primary	0.01 – 2.0	0.05 - 10.0	0.01 - 1.0
Secondary	0.01 – 2.0	0.05 - 10.0	0.01 - 1.0

	Tracked by passive ranging		
	σ_R [Km^2]	σ_T [Km^2]	σ_N [Km^2]
Primary	0.0001	0.014	0.001
Secondary	---	---	---

The aim of these cases is to cover representative conjunction events with several uncertainty levels for both the primary and secondary, also varying the miss distance.

Results show the dependence of the PoC with the uncertainty. Particularly, they show that reducing the covariance matrix increases the PoC. It depends on the probability density, which at the same time is a function of the combined covariance matrix. If this matrix is smaller than the density is higher, hence the integration of this probability density results in a higher total probability. In Fig. 6, an example of this behaviour can be seen, where in (a) the covariance of the primary object is computed using optical measurements and in (b) passive ranging tracking is used and the uncertainty is drastically reduced (but due to the low miss distance, both covariances still intersect totally).

(a)



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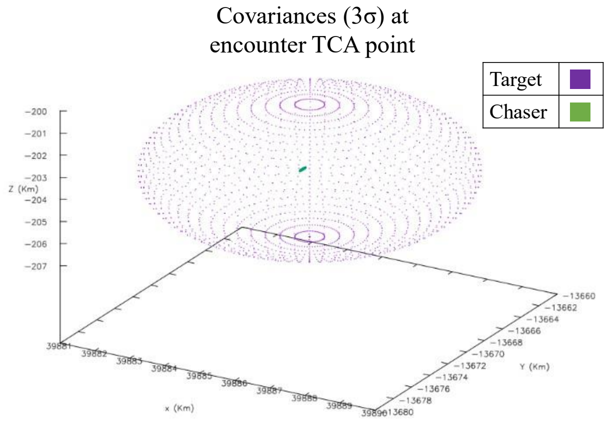
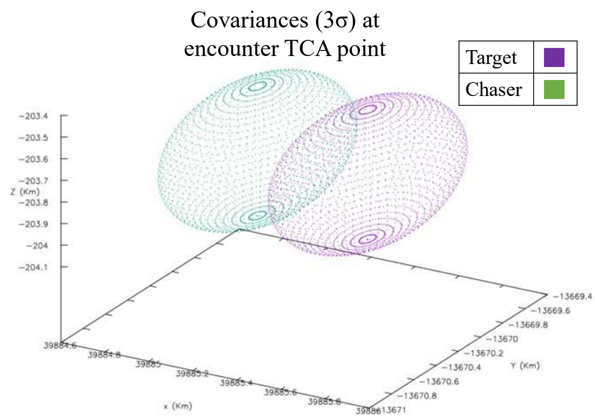


Figure 6 Example of uncertainty intersection in low relative distances between primary and secondary objects when the covariance of the primary is computed using optical tracking (a) vs passive ranging tracking (b)

This behaviour where the PoC is increased when the uncertainty is decreased only happens for low relative distances between the two objects. However, many other conjunction events might have larger relative distances where both covariances mildly intersect. This is the case where obtaining more precise measurements has a significant impact in the PoC. If the active satellite uncertainty is reduced, for instance by using PR data, it could be possible to achieve a case where the covariance does not intersect, lowering the PoC and thus reducing the false alarms. This is the case depicted in Fig. 7a and Fig. 7b, where the PoC decreases from 7.02E-06 to 3.88E-07 when passive ranging tracking data is used, that is one order of magnitude smaller.

(a)



(b)

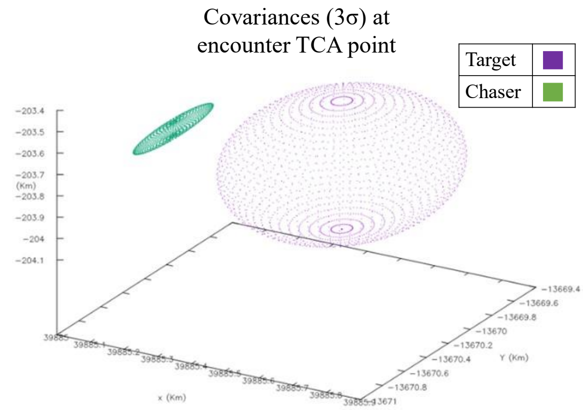


Figure 7 Example of uncertainty intersection in greater relative distances between primary and secondary objects when the covariance of the primary is computed using optical tracking (a) vs passive ranging tracking (b)

An in-depth analysis of the amount of Conjunction Data Messages (CDMs) received in the Spanish Space Surveillance and Tracking Operations Centre (S3TOC) is performed to further analyse the effect that the reduction of the uncertainty of the primary object would have on the CA operations.

Fig. 8 shows a histogram representing the number of CDMs (y-axis) per miss distance in meters (x-axis) raised by S3TOC for GEO events for the period 2018-2020. Fig. 9 represents the timely evolution of the % of CDMs at each event miss distance (MD).

The ALERT zone is highlighted in red (below 4 km) whereas WARNING zone is highlighted in yellow (above 4 km and less than 10 km). The examples tested in the previous test consider 100% of the miss distances for the ALERT events and more than 60% for the total of ALERT+WARNING events.

Over a miss distance of 6 km, the computed collision probability becomes very small. Thus, it is expected a reduction on the number of CDMs due to a better orbital knowledge allowed by the PR technology (less false .

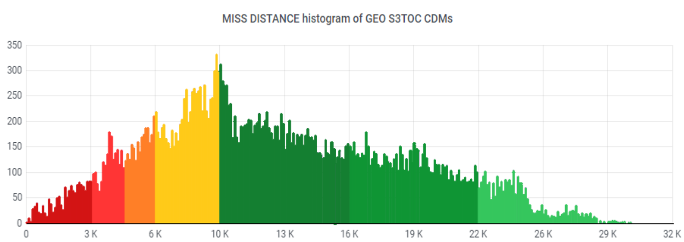


Figure 8 Miss distance histogram of GEO S3TOC CDMs

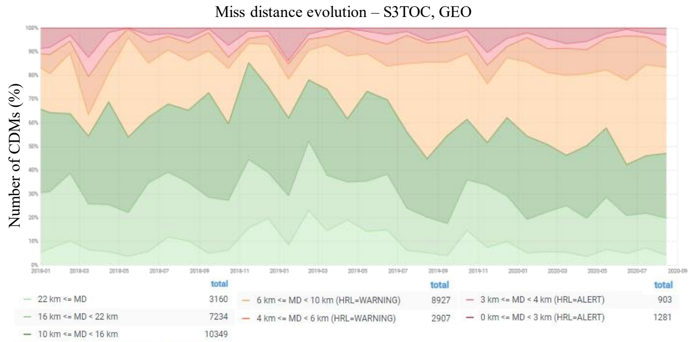


Figure 9 Evolution of the percentage of CDMs at different miss distances

Given the histogram above, the table below shows the results of the analysis about the usage of the PR technology:

- About 6% of the CDMs would increase its PoC for lower distances (less than 3 km). However, these are CDMs that were already being catalogued as ALERT even without the increase of PoC.
- About 94% of the CDMs would decrease the PoC for big distances (above 3km, even though a decrease could be observed starting from 1 km miss distance).

Table 7 Share of GEO CDMs in low/high miss distances

	MD [km]	#GEO CDMs	CDMs over total [%]
Low miss distance	<3	2184	6%
High miss distance	>3	32577	94%

These results would allow a better discernment between actual risk situations and non-risk situations in operations based on PoC thanks to the PR technology.

4.1.2 Impact on the detection horizon

One of the best qualities of PR is the timeliness of the measurements and its ability to detect and estimate rapidly and accurately a manoeuvre, keeping the catalogue of the objects that can profit from PR tracking updated and hence improving CA services.

Fig. 10 presents a single-manoeuvre scenario. Particularly, an unplanned manoeuvre that is executed by the active satellite. In this new orbit after the manoeuvre, this satellite encounters a series of conjunction events with space debris or other satellites. In this scenario, the CA service timeline is presented when the satellite is being tracked using two different observation techniques:

- Optical instruments: products based on optical data would only be available with a latency 1 to 3 days after the event, depending on if near real-time processing capabilities are available or not.
- PR: it provides measurements continuously for the Ku-band satellite. The maneuvers can be perfectly characterized within 6-8h using a survey approach by the PR mechanism. A mitigation measure could be safely applied right-after.

It is assumed that the operational data is processed as it arrives in quantified batches or in near-real-time.

Using PR technology with near-real-time capabilities, all events but one, i.e., events 2, 3, 4, 5, are detected, and a collision avoidance manoeuvre could be designed to mitigate the problem.

Using optical telescopes configured with non-real-time capabilities, only the last event would be detected in due time to perform a CA manoeuvre, but probably would be too late as event 1, 2, 3 and 4 would have been missed and a collision could happen without a mitigation measure. On the other hand, if optical-based products used near-real-time processing, events 3, 4 and 5 could be avoided depending on the amount of data received. Nevertheless, without a-priori knowledge, specific tasking requests covering the unknown manoeuvre event would not be available and the amount of data would be insufficient even to detect events 3 and 4. So, realistically, even if real-time processing is added to the optical sensors, only the last event would be detected falling in the same case as before.

This same analysis could be done in the case where the primary trajectory of the active satellite intersects another object, and a collision event exists. However, the rapid detection of a manoeuvre allows the reanalysis of the future CDMs for the primary object, and, in the updated orbit, the event is no longer critical, and no mitigating action is needed. Again, for the case of the satellite being tracked using optical measurements, the time delay to detect, estimate and update the catalogue would be much greater making this fast-decision process impossible.

The previous analysis considered a low manoeuvring frequency of the satellite (typical of chemical satellites). If, on the other hand, an electric satellite is used, which manoeuvres about once or twice a day, the consequences seen in the previous scheme are strongly aggravated, making it not possible for optical sensors to provide CA services to electric satellites since the orbit update is way slower than the actual activity of the satellite.

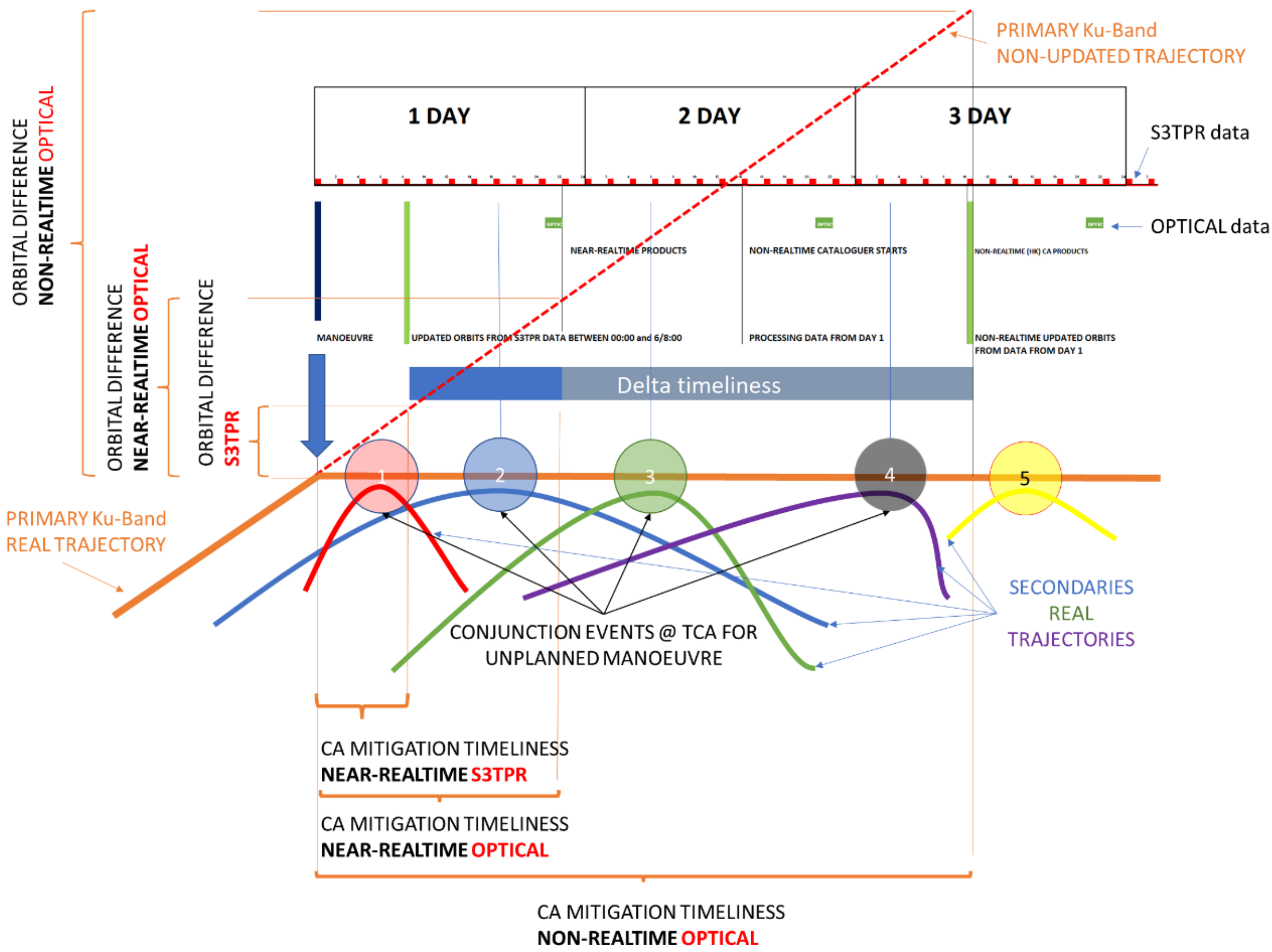


Figure 10 Manoeuvre detection improvement with passive ranging

Regarding manoeuvres for chemical geostationary satellites, Tab. 8 and Tab. 9

Table 9 describe the orbital errors between real orbit and estimated one (without being updated due to the lack of measurements) when a real manoeuvre occurs and there is no a-priori knowledge of its occurrence.

The numbers consider typical North/South (N/S) and East/West (E/W) manoeuvres for a 50-55 m/s yearly delta V budget to be dedicated to geostationary control. N/S manoeuvres are used to keep satellites within inclination dead-band whereas E/W manoeuvres are used to keep the satellite within the associated longitude box by controlling eccentricity and inclination vectors. Depending on the manoeuvre strategy and especially on the cross-coupling between N/S and E/W thrusters the delta V associated to each type of manoeuvres can vary. The tables below consider different N/S manoeuvre strategies that could be implemented on a weekly, by-weekly, and monthly basis. Respectively, ~50m/s / 56 weeks ~ 0.9m/s, 1.8m/s and 3.6m/s.

E/W manoeuvres here are considered using about 5% of the N/S manoeuvres budget (but this can vary as mentioned above). The following orbital errors would arise between the non-updated orbit and the actual orbit (after the undetected manoeuvre):

Table 8 Orbital error due to undetected N/S manoeuvres

N/S control cycle		**Normal error [km] (after 8h)**	**Normal error [km] (after 12h)**
Weekly	RMS	5.8	8.6
	MAX	8.3	12.2
Bi-weekly	RMS	12.2	18.1
	MAX	17.2	25.7
Monthly	RMS	23.1	34.5
	MAX	32.7	49.0

Table 9 Orbital error due to undetected E/W manoeuvres

E/W control cycle		Normal error [km] (after 8h)	Normal error [km] (after 12h)
Weekly	RMS	0.5	12.4
	MAX	1.6	21.0
Bi-weekly	RMS	1.2	27.8
	MAX	3.5	47.1
Monthly	RMS	2.3	55.7
	MAX	7.0	94.3

Note that EW manoeuvres could be the order of 1-2m/s for collocation. In such cases errors could be in the order of hundreds of Kms.

Tab. 10 summarizes the indicators that can be derived for chemical manoeuvres (performed every week: alternatively, E/W and N/S, i.e., corresponding to the bi-weekly strategy in the tables above):

Table 10 Indicators for chemical manoeuvres, optical vs PR tracking

	Optical tracking	Passive Ranging tracking
Latency	1 – 3 days	1 hour (6-8h for maneuver detection)
Erroneous orbital info	30%-50% of the time	3%-5% of the time
Normal error	~25 km, 12h after NS maneuver (24h periodic error, detected in 2nd-3rd period)	~17 km 8h after NS maneuver (24h periodic error, detected in 1st semi-period)
Along-track error	Up to ~47 km, 48h after EW maneuver (drifting detected very late)	Up to ~4 km 8h after EW maneuver (drifting detected almost immediately)

5 CONCLUSIONS

Passive Ranging is proposed as a lower-cost alternative to traditional SST tracking systems such as optical or radar sensors, capable of providing improved latency, timeliness (24/7 access to data without climate conditions or sunlight dependency) and accuracy.

The technical and economic feasibility of the system has been demonstrated, being able to maintain an up-to-date catalogue of satellites for both simulated and real TDoA data. Manoeuvres of the population have been accurately detected and estimated within 6-8 hours from the ignition date regardless of the propulsion type of satellites.

When analysing the manoeuvres detection and estimation using real TDoA data, it was seen that to mitigate the appearance of false positives or false negatives and to improve the orbit determination and estimation, it is imperative to provide the PR system with constant and abundant data. Data gaps are especially dangerous for electrical satellites which tend to manoeuvre more than once a day.

TDoA data can be easily converted to more frequently used data formats such as range, right ascension, and declination without any loss in accuracy. This facilitates sharing the tracking information with other operations centres, even if they do not have TDoA processing capabilities integrated in their system. However, in the case of a degraded scenario, that is, the data of one or more stations is unavailable, there is a loss in the available information leading to a loss in performance for centres without TDoA processing capabilities. It is then strongly advised to implement the ability to process TDoA measurements directly to avoid this limitation.

PR networks require to be calibrated before using TDoA data for cataloguing purposes similarly to telescopes or radar calibration processes. For that, the most precise orbit for a set of satellites is required in order to measure the time bias introduced by each PR station.

The continuous update of the satellite's orbital information and fast manoeuvre detection allows for more precise orbital products (lower uncertainties). Moreover, optical sensors could stop observing satellites that can be tracked using PR and devote the spare time to the observation of other objects, hence improving their accuracies.

Regarding CA services, if PR technology is used to generate products, the number of conjunction events is expected to decrease the higher the quality of the available products (tens of meters quality instead of hundreds of meters quality). Regarding true and false collision events:

- For cases with low miss distances, it is expected an increase of the PoC as the uncertainty of the primary will decrease and its covariance will fully intersect the secondary one. Thus, true positives will have the PoC increased. Note that these are actual true positives, meaning that this increase in PoC does not have negative effects (no false positives appear because of it).
- For cases with higher miss distances the probability will decrease as the uncertainty of

the primary will decrease and its covariance will not intersect the secondary one. Thus, true negatives will see their PoC decreased, even to the point where the conjunction might decrease the level of severity.

Finally, in relation to the benefits that arise thanks to the timeliness of PR data, it can be seen how the rapid and accurate manoeuvre detection of tracked satellites allows a fast update of the catalogue (6-8h post-manoeuvre against 1-3 days for the case of optical sensors). This results in the possibility to check for possible collision events in a shorter horizon. Approximately 60h of possible collision events are added after each detected manoeuvre when comparing PR to optical sensors. In the same way, it is possible to discard collision events that existed in the orbit prior to the manoeuvre much faster.

All these improvements give as a result a more agile and reliable CA service which is of vital importance considering the staggering increase in man-made objects and debris that populate the most demanded orbits such as the GEO regime.

6 ACKNOWLEDGEMENTS

The EU SST activities have received funding from the European Union programs, notably from the Horizon 2020 research and innovation program under grant agreements No 952852, No 785257, No 760459, No 713630 and No 713762, and the Copernicus and Galileo program under grant agreements No 299/G/GRO/COPE/19/11109, No 237/G/GRO/COPE/16/8935 and No 203/G/GRO/COPE/15/7987. The European Commission and the European Health and Digital Executive Agency are not responsible for any use that may be made of the information it contains.

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