GSTS

SR v2.0
Project Executive Summary Report

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1 INTRODUCTION

1.1 Purpose of the Document

This document is the GSTS Executive Summary Report. It summarizes the findings of the GSTS project concisely and informatively.

1.2 Applicable Documents

[AD.1] Statement of Work, "Interference Detection/Protection for Telemetry/Telecommands and Mission Links", Appendix 1 to ESA AO/1-8117/14/NL/HK
[AD.2] ESA-AO8117-QASC-GSTS-v01_DP, "GSTS Ground to Space Threat Simulator" Proposal, 18/11/2014
[AD.3] ESA-AO8117-QASC_GSTS-ClarificationAnswer_v05, "Clarification Answer Document", 11/02/15
[AD.4] ESA-QAS-GSTS-SSD1-1.1 "SSD1 Software Requirements and Design Document"
[AD.5] ESA-QAS-GSTS-TN1-1.3 "TN1 Interference Location Processing Techniques and Architectures"
[AD.6] ESA-QAS-GSTS-TN1A-1.1 "TN1A Functional and Performance Verification Plan"
[AD.7] ESA-QAS-GSTS-TN1B-1.1 "Scenario Definition and Experimentation Plan"
[AD.8] ESA-QAS-GSTS-TN2-3.1 "Localization Performance Experimentation and Analysis for Static Emitters Using Batch Techniques"
[AD.9] ESA-QAS-GSTS-TN5-2.0 "Sensitivity Analysis and Experimentation Results for LEO Satellites and On Ground Target"
[AD.10] ESA-QAS-GSTS-TN3-2.1 "Localization Performance Experimentation and Analysis Using Sequential Localization Algorithms"
[AD.11] ESA-QAS-GSTS-TN4-1.1 "Localization Performance Experimentation and Analysis using state of the art localization algorithms"

1.3 Reference Documents

[RD.1] Richard A. Poisel, "Electronic Warfare Target Location Methods", Artech House, 2012.
[RD.2] R. Schmidt, "Multiple Emitter Location and Signal Parameter Estimation", IEEE Transaction on Antennas and Propagation, vol. AP-34, no. 3, March 1986, pp. 276-280.
[RD.3] A. De Martino, "Introduction to Modern EW Systems", Artech House, 2012.
[RD.4] Wade H. Foy, "Position-Location Solutions by Taylor-Series Estimation", IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-12, No. 2, pp. 187-194, 1976.
[RD.5] G. A. Einicke, "Smoothing, Filtering and Prediction: Estimating the Past, Present and Future", Intech, 2012.
[RD.6] Stone L. D., Streit R. L., Corwin T. L., and Bell K. L., "Bayesian Multiple Target Tracking," 2nd Edition. Artech House, 2014.

1.4 Acronyms and Definitions

ACM	Amplitude Comparison Monopulse
AoA	Angle of Arrival
BER	Bit Error Rate
CAF	Cross Ambiguity Function
CW	Continuous Wave
EKF	Extended Kalman Filter
FDoA	Frequency Difference of Arrival

FoA	Frequency of Arrival
GC	Geolocation Core
GSTS	Ground-to-Space Threat Simulator
GUI	Graphical User Interface
JPDA	Joint Probabilistic Data Association
LPAT	Location Performance Analysis Tool
MHT	Multiple Hypothesis Tracking
MUSIC	MUltiple SIgnal Classification
PLL	Phase-Locked loop
RDGE	Raw Data Generation Emulator
RSSD	Received Signal Strength Difference
SGT	Scenario Generation Tool
TDoA	Time Difference of Arrival
TS	Taylor-Series

2 GSTS SOFTWARE DESCRIPTION AND LOCATION TECHNIQUES

2.1 High-Level Software Description

Ground-to-Space Threat Simulator (GSTS) has the goal to 1) study and evaluate the performance of detection, characterization, and location techniques of interfering signals in realistic scenarios, and 2) develop a simulator capable to generate user defined scenarios, process and analyze the performance of different architectures and techniques to support the location of signal sources from space.

To reach the above goals, the GSTS software suite is composed of the following four main modules:

1. **Scenario Generation Tool** (**SGT**): it is responsible for the overall scenario configuration and generation, it includes a GUI from where the simulation settings can be configured;
2. **Raw Data Generation Emulator** (**RDGE**): it is responsible for the signal generation, propagation, reception, and processing. The most important outputs of this modules are the location measurements, that are used to localize the interference source; the RDGE includes interference detection and characterization modules;
3. **Geolocation Core** (**GC**): it processes the location measurements generated by the RDGE in order to localize the interference source. It can implements multiple localization techniques;
4. **Location Performance Analysis Tool** (**LPAT**): it compares the estimates generated by the GC with the actual value of the parameters (e.g., real interferer position and velocity, etc.), and based on this comparison it generates the required figures of merit.

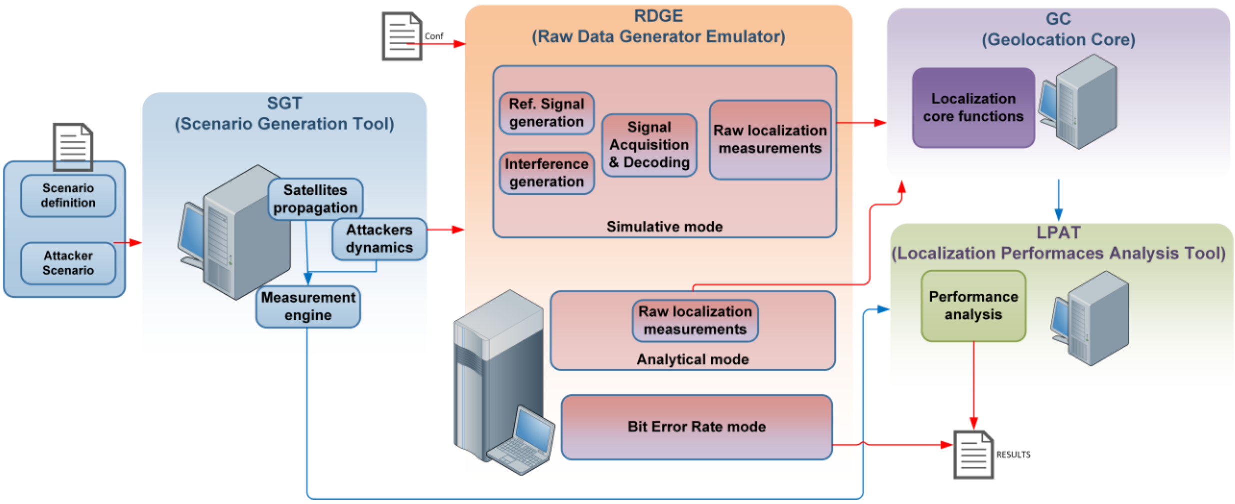

Figure 2-1: Representation of the GSTS simulator.

For geolocation purposes, the GSTS tool can operate in two distinct modes:

1. **Simulative mode**: location measurements are generated from the simulation of the overall system. That is, signals are generated by the transmitters (interferers and uplink stations), propagated through the channels, received by the front ends, and processed with the desired signal processing techniques. The proposed satellite frontend is a dual-path frontend. This allows to tailor the design and the parameters of each branch to achieve the specific goal of that branch;
2. **Analytic mode**: location measurements are generated by computing the real measurements and adding to such measurements random zero-mean Gaussian errors. The standard deviations associated to such Gaussian distributions can either be set by the operator, or they can be pre-computed with the simulative mode, which saves the standard deviations in files that are accessible by the analytic mode.

GSTS can also operate in **Bit Error Rate mode**, which allows to evaluate the impact of an interference signal on an uplink signal, in terms of Bit Error Rate (BER) degradation.

2.2 Location Measurements Generation

This chapter lists the most important location measurements that have been considered during the GSTS project: the TDoA generated through CAF, the AoA generated by MUSIC, and the AoA generated by ASM. Other location measurements, such as the FDoA through CAF, the FDoA generated by multiple single antenna FoA estimations, and the RSSD have been implemented and evaluated, but the localization accuracy achievable with these measurements is significantly lower than the one achievable with TDoA or AoA measurements.

2.2.1 Time Difference of Arrival (TDoA)

Time Difference of Arrival (TDoA) is defined as the time shift between the receptions of a signal at two receiving antennas. TDoA provides information about the position of the interferer source, indeed an individual TDoA measurement, associated to the interferer signal, defines a loci of points within which the interferer source could be located. Such locus of point is a hyperbola in a 2D space or a hyperboloid in a 3D space, whose foci are the two receiving antennas.
A single TDoA measurement between a pair of antennas can be obtained by computing the Cross Ambiguity Function (CAF) $\chi_{s,g}(\Delta t, \Delta f)$ between the signals $s(t)$ and $g(t)$ received by the two antennas during a common acquisition time interval. The CAF is a two-dimensional function: one variable corresponds to the applied relative time shift, the other variable corresponds to the applied relative frequency shift. For a certain frequency shift Δf, the CAF is equivalent to a correlation between the signal $s(t)$ shifted in frequency by an amount Δf and the signal $g(t)$. The values Δt and Δf at which the CAF is maximized correspond to the estimated TDoA and FDoA. A more formal discussion about the use of the CAF is provided in [AD.10].
It is important to remark that such an approach to estimate the TDoA can be affected by an error bias due to differential filter delay associated to the two processing chains. Calibration approaches can be employed to compensate for such a bias, as described in [AD.5].

2.2.2 Angle of Arrival (AoA)

An angle of arrival (AoA) measurement represents the angle of the vector connecting a receiver to the transmitter with respect to a reference direction (in a 2D or 3D space) or a reference system (3D space). If the AoA is computed with respect to a reference direction, the AoA locus of points is two half lines in a 2D space or a cone in a 3D space. If the AoA is computed with respect to a reference Cartesian system in a 3D space, then the AoA is actually a pair of angles, representing the azimuth and elevation with respect to the Cartesian system. In this case, the locus of points is a half-line departing from the reference position, or two half-lines if the sign of the elevation angle is ambiguous.
The **MUltiple SIgnal Classification** (**MUSIC**) algorithm is a super-resolution direction finding technique for processing the signals received by an antenna array to obtain estimates of the AoA of multiple signal components [RD.1], [RD.2]. By comparing the differential phases of the signal received at different antenna elements, MUSIC is able to estimate the number of incident signals (as long as they are lower than the number of antennas) and the AoA for each of them.
Another important technique to estimate the AoA of a signal is the **Amplitude Comparison Monopulse** (**ACM**), which compares amplitude measurements taken at different angles [RD.3]. This can be done by a set of fixed antennas (or a single antenna with multiple feeders) that are oriented toward different angles. At least 4 antennas are considered in the literature to obtain an AoA in a 3D space.
More details about the MUSIC and ACM techniques are given in [AD.10].

2.3 Location Techniques

This chapter lists all the location techniques that have been considered during the GSTS project. More details about these techniques can be found in [AD.5], [AD.10], and [AD.11].

2.3.1 Single Interferer Batch Location Techniques

Batch location techniques require the collection and processing of a set of measurements, taken at different time instants, to localize an interference source. The batch technique considered in the GSTS project is the **Taylor-Series** (**TS**) estimation technique [RD.4], which is an iterative scheme for the solution of a simultaneous set of algebraic position equations (generally nonlinear), starting with a rough initial guess and improving the guess at each step by determining the local corrections.

2.3.2 Single Interferer Sequential Location Techniques

Sequential location techniques maintain in memory a status that is updated as soon a new measurement is observed. After that the measurement can be immediately removed from the memory. The sequential technique considered in the GSTS project is the **Extended Kalman Filter** (**EKF**) estimation technique [RD.5], which is the nonlinear version of the Kalman filter, in which non-linearities are approximated by a linearized version around the current state estimate. It produces estimates of unknown variables by using Bayesian inference. This means that it keeps in memory a state estimate $\hat{\boldsymbol{x}}_k$ and the uncertainty associated to such state estimate, quantified by a covariance matrix $\boldsymbol{P}_k$ (the subscript *k* is used to denote a specific time instant), and whenever new measurements (with the associated accuracies) are available the state estimate and the associated uncertainty are updated, exploiting the additional information carried by the new measurements. Another sequential techniques that has been considered within the GSTS project is the **Particle Filter** [RD.6]. However, it is important to remark that Particle Filter has not been evaluated as a stand-alone technique, it has been developed because it is exploited by the multiple hypothesis tracking technique, described in chapter 2.3.3, to track each detected interferer. Particle filter is a general Bayesian inference estimation technique that empirically estimates the probability distribution on a target state.

2.3.3 Multiple Hypothesis Tracking Techniques

Multiple Hypothesis Tracking (MHT) techniques [RD.6] allow for the possibility that there is more than one target for which the state must be estimated. The main challenge when there are multiple interferers is to estimate the number of interferers and to associate measurements to different interferers. Multiple hypothesis tracking techniques perform jointly the association step (this includes the interferer number estimate, in case it is unknown) and the localization step, keeping in memory multiple assignation possibilities (named “hypotheses”), resulting in multiple possibilities for the estimated number of interferers and the estimated location for each of them. The multiple hypothesis tracking technique considered in the GSTS project is the **Joint Probabilistic Data Association** (**JPDA**) technique [RD.4]. The main characteristic of this technique is that it allows for soft associations: measurement are associated to a given track with a certain probability. This account for the fact in some occasions one is not 100% confident to which track to assign a measurement. Another characteristic of the JPDA is that it assumed that the number of targets is known. However, in addition to the standard JPDA, in GSTS an extended JPDA version has been implemented as well, allowing to automatically add new tracks (up to a maximum number of tracks that must be set by the user), and to automatically remove old tracks.

3 RESULTS

This section summarizes the most important experimentation results obtained within the GSTS project. Additional results with more detailed discussions can be found in [AD.8], [AD.9], [AD.10], and [AD.11].

3.1 Geolocation Performance with a Static Interferer

Figure 3-1 shows the average geolocation distance achieved by different geolocation schemes for a single static interferer transmitting a CW signal, for different measurement combinations and for different time instants. The average are computed based on the results of 10 simulation. In addition, Figure 3-1 shows also the error bars associated to a ± 1-sigma deviation from the average values.
In general, for all the techniques and the measurement combinations, the average geolocation distance always improves in time, but there is a big difference between the performances associated to different measurement combination:

- TDoA allows to achieve an average accuracy of few hundreds of km even after a long collection time;
- AoA (MUSIC) allows to achieve average accuracies of few km, or even of hundreds of meters, after a short collection time interval. This is due to the high precision at which MUSIC estimates the AoA;
- AoA (ACM) is not as accurate as AoA (MUSIC) in the short time, but its performance improves quickly. This happens because, in the considered scenario, the AoA estimated by ACM is not as precise as the one estimated by MUSIC at the beginning of the simulation, but it improves in time as the satellite become closer to the interferer zenith.

Comparing the results achieved by the TS technique with those obtained by the EKF technique and the MHT technique, it is possible to see that TS performs very poorly with respect to both EKF and MHT when few measurements are available, in particular for TDoA and AoA (ACM) measurements that are less accurate than AoA (MUSIC) measurements. When many measurements are available the performances of the TS become comparable, or even better, than those achievable by the EKF and the MHT, in particular for very accurate measurements such as the AoA generated by MUSIC or ACM. Looking at the performance in the short and long time and for different measurement types, the best geolocation technique seems to be the MHT, which is also the most complex technique.

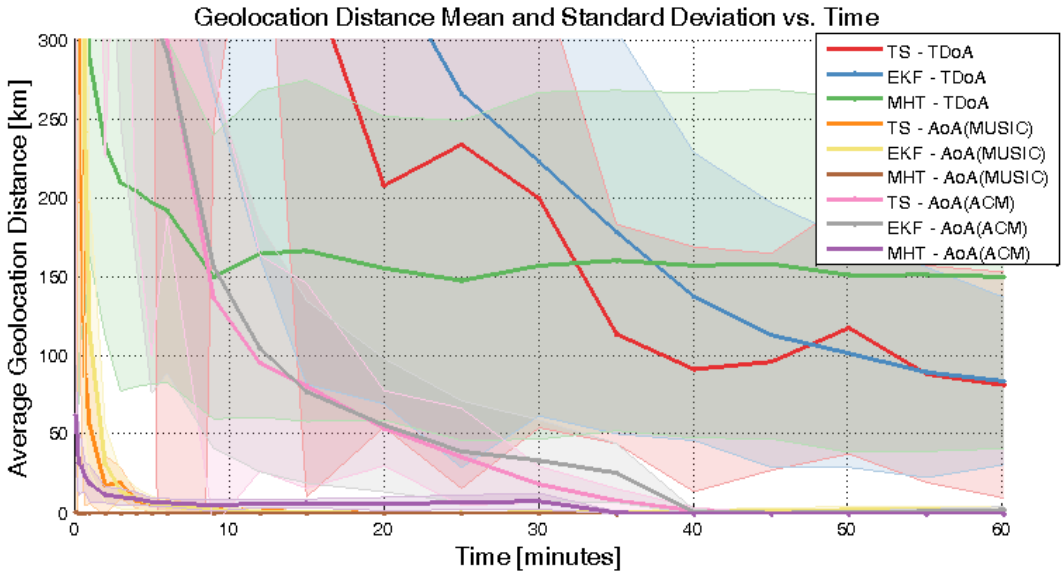

Figure 3-1: Average geolocation distance of different techniques for the static interferer scenario, the colored strips represent the associated standard deviations.

3.2 Geolocation Performance with a Dynamic Interferer

Figure 3-2 shows the average geolocation distance achieved by different geolocation schemes for a single dynamic interferer transmitting a CW signal, for different measurement combinations and for different time instants. The interferer moves at about 100 km/h and the average results are computed based on the results of 10 simulations. Figure 3-2 shows also the error bars associated to a ± 1-sigma deviation.

Differently from the results achieved in the static case, it is possible to observe that for a dynamic interferer the geolocation distance not always improve in time. This is particularly evident for the TS and MHT techniques and for the measurements allowing to achieve high accuracy, i.e., AoA (MUSIC) and AoA (ACM). Indeed, such schemes converge to a very accurate interferer position estimate after a short collection time interval. However, because it is dynamic, the interferer moves away such a position estimate, hence the geolocation performance gets worse in time. The current version of the MHT implicitly assumes that interferers are static. Hence, similarly to the TS, it is not able to update a track to follow a dynamic interferer. However, after the dynamic interferer achieves a location that is far enough from all the currently available tracks, the MHT initializes a new track, whose geolocation accuracy is initially very accurate (before the interferer moves away from this new track as well). As a consequence the geolocation distance trend for MHT is fluctuating: as soon as a new track is initialized it improves considerably, but then it slowly degrades until a new track is initialized.

Concerning the EKF, it is possible to see that in the short term the results are very similar to those obtained for a static interferer, but in the long term they are worse, in fact when the interferer is dynamic it takes a longer time to track its trajectory.

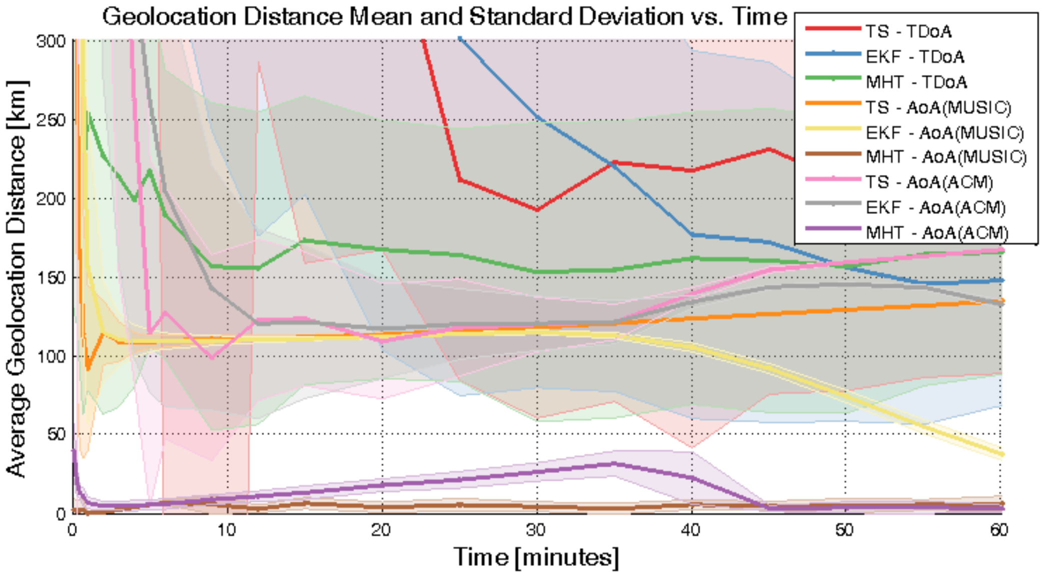

Figure 3-2: Average geolocation distance of different techniques for the dynamic interferer scenario, the colored strips represent the associated standard deviations.

3.3 Geolocation Performance with Multiple Interferers

Figure 3-3, Figure 3-4, and Figure 3-5 show the average geolocation distance achieved by different geolocation techniques for two static interferers separated by about 100 km. In Figure 3-3 the two interferers are jointly transmitting CW signals, in Figure 3-4 they are jointly transmitting a NOISE-BB and an Agile signal, and in Figure 3-5 they are transmitting CW signals in switching burst mode. An Agile interferer is defined as an interferer that is changing the type and the power of the transmitted signal in time, whereas in switching burst mode the two interferers coordinate such that one and only one of them transmits a signal at a given time instants.

When the two interferers are jointly transmitting with the same transmission power (Figure 3-3), the processing techniques (CAF, MUSIC or ACM) are actually estimating location measurements (TDoA or AoA) that are in between the measurements associated to the first interferer and the measurements associated to the second interferer. As a consequence, the location techniques tend to converge halfway between the real interferer locations. For this reason the average geolocation distances of the techniques exploiting AoA measurements converge quickly to 50 km, which is half the interferer separation.

The situation improves, at least for MHT techniques, when one of the two interferers is an agile interferer (Figure 3-4). This is due to the fact that an agile interferer is changing its transmission power. Because at the beginning the two interferers transmit with the same power, both AoA (MUSIC) and AoA (ACM) converge to a position that is in between the two interferers, associated to an average geolocation distance of about 50 km. However, with the simulation that proceeds and the agile interferer that changes its transmission power, the achievable geolocation distance improves, because MUSIC and ACM become capable of estimating the AoA of either of the two interferers.

Finally, Figure 3-5 shows that in the switching burst mode the results for the MHT-AoA (MUSIC) and MHT-AoA (ACM) are much better than those achieved when the two interferers are jointly transmitting. Indeed, in this case only one interferer is active at any given time, and both MHT-AoA (MUSIC) and MHT-AoA (ACM) are able to accurately track the active interferer.

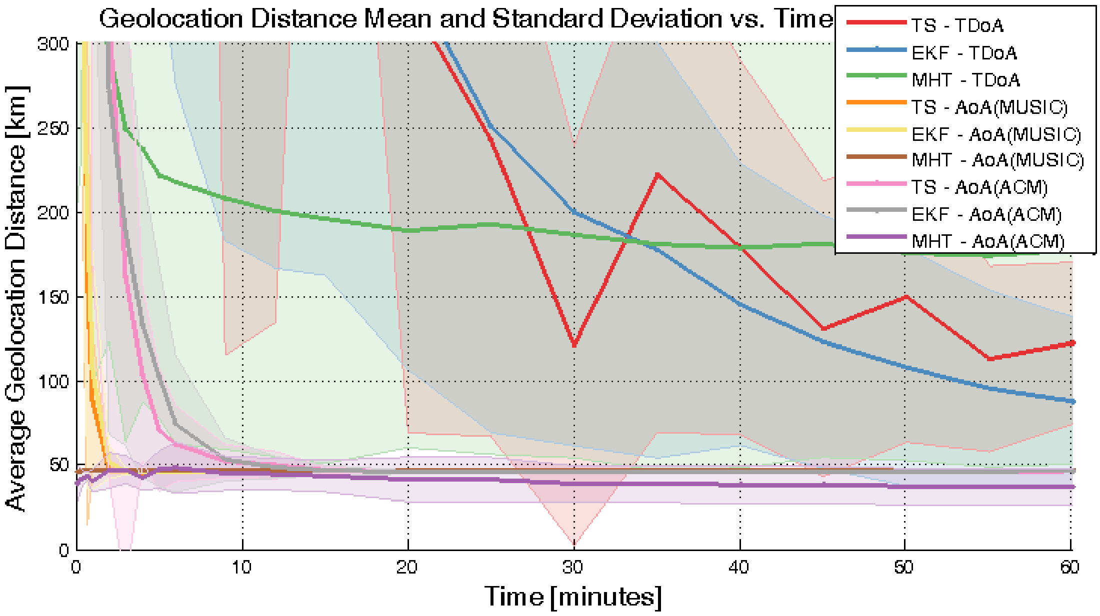

Figure 3-3: Average geolocation distance of different techniques for the multiple interferer scenario, for interferers transmitting the signals CW + CW and separated by 100 km, the colored strips represent the associated standard deviations.

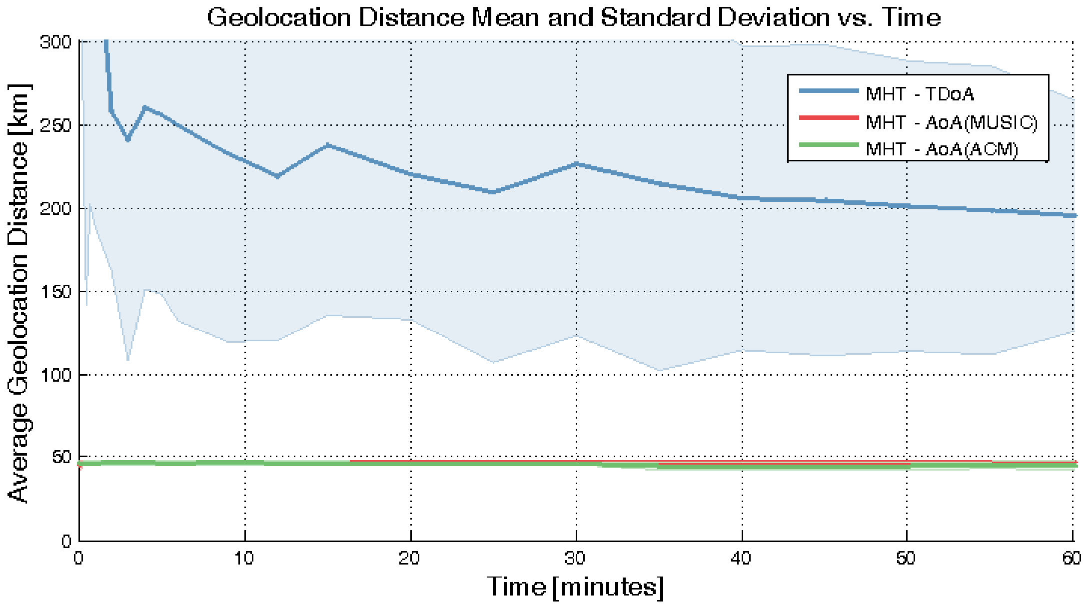

Figure 3-4: Average geolocation distance of different techniques for the multiple interferer scenario, for interferers transmitting the signals NOISE-BB + Agile and separated by 100 km, the colored strips represent the associated standard deviations.

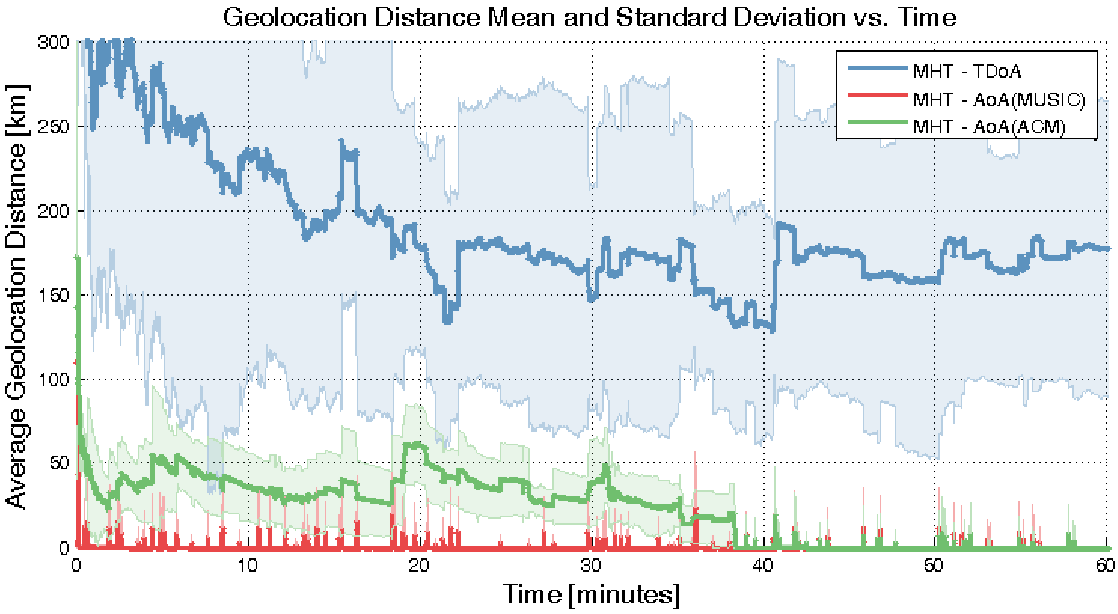

Figure 3-5: Average geolocation distance of different techniques for the multiple interferer scenario, for interferers in switching burst mode transmitting the signals CW + CW and separated by 100 km, the colored strips represent the associated standard deviations.

4 CONCLUSION

The GSTS simulator, which has been developed as part of the GSTS project, is a flexible and modular software tool that is capable of simulating the geometric and channel effects that have an impact on the signals sent by transmitters (interference sources and/or uplink stations) and received by satellite platforms. It also simulates the behavior of the front end receiver, of multiple signal processing techniques, and of multiple localization techniques. This enables different types of analysis, such as 1) the impact that an interference signal has on an uplink signals, in terms of BER degradation; 2) the capability to detect and characterize an interference signal; and most of all 3) the capability of locate a the interference sources. The flexibility of the GSTS simulator allows to simulate various scenarios and architectures (e.g., single or multiple interferers, static or dynamic interferers, different types of interferences including time-varying interference signal types and transmission powers, the use of uplink stations for calibration purposes, single or multiple satellite architectures, single or multiple antenna, etc.), and its modularity allows to incorporate additional features, such as new characterization and localization techniques.

GSTS paves the path towards the development of single satellite architecture approaches to locate a single or multiple interferer sources. The experimentations performed within the project prove the feasibility of such a solution. However, they also show that accurate localizations can be achieved only with very accurate location measurements (e.g., TDoA or AoA), this may require the adoption of calibration approaches to compensate the presence of undesired sources of errors (e.g., differential filter delays or satellite attitude biases). Some of these calibration methodologies (e.g., differential filter delay compensation through the use of an uplink signal) have been considered and successfully validate during the project.

END OF THE DOCUMENT