Satellite AIS - an End-to-End Simulation Approach

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ABSTRACT

Space-based AIS Simulator Tool (SAST) was developed in order to analyse the end to end performance of a Satellite based AIS System. A recent study of a European consortium (Telespazio, Carlo Gavazzi Space, Edisoft, Elman, ITS) co-financed by ESA has investigated about the possibility of receiving from space AIS signals: a constellation of satellites could assure an AIS worldwide coverage using the same AIS transponders on vessels but with a dedicated satellite AIS receiver. The study will provide a detailed architecture and mission design for a Satellite based AIS System, with a business model and associated cost assessment.
The main goals of developing Space-based AIS Simulator Tool were:

- Emulate the space and ground segment elements;
- Emulate the traffic worldwide distribution;
- Emulate the SOTDMA AIS protocol;
- Evaluation of the system in a 20 years lifespan, this translates in an increasing number of emitters to satellite constellation;
- Include path losses in signal transmission, such as Doppler and Faraday Effect in addition to cable losses;
- Evaluation of performance with one or more satellites;
- Appraisal of more then one passage per satellite constellation;
- Assessment of the localisation and number of Ground Stations and respective elevation angle;

In view of the above mentioned, due to the reduce time to development, which lead to the use of COTS software tools, along with its proven capability in simulation tools, the development was essentially in Matlab® environment. However it was also used Basic STK® software, another COTS software tool with proven results in orbits emulations (one or more satellites) and accesses of satellites, targets and ground facilities results.
The SAST comprise three stage simulation: Models generation (namely Traffic Distribution, Satellite and Ground Stations), STK Engine (constellation emulator; generate analytical reports) and Simulator Engine. Thus each module has development and improvement flexibility. Seeking the most reliable and realistic simulation, the target distribution is generated based on real dataset allowing a velocity distribution along the main utilised courses, creating a density

distribution directly linked with sparse series. In what concerns Satellite Model, the user defines the desired constellation by introducing various parameters (altitude, eccentricity, Inclination, argument of perigee, RAAN, mean anomaly and propagator). The Simulator Engine is divided in two major layers:

- The physical layer simulates the system codification including hardware simulation and modelling.
- The logic layer emulates the software simulation, including the used communication protocol between target and satellite constellation. Using the several reports generated by the satellite constellation emulator, the targets-constellation communication scenario is generated, along with all instantaneous communications over time.

The SAST outputs present the results per each performance simulation in an end-to-end simulation systems perspective:

- Target message probability of detection
    - Per satellite
    - Per constellation
- Refresh time interval, which represents the time lag between two updates on the target.
- Timeliness, which is the time interval between the transmissions from the target and the time in which that information is available for the end user.

INTRODUCTION

The Automatic Identification System (AIS) is a maritime navigation safety communications system standardized by the International Telecommunication Union (ITU), adopted by the International Maritime Organization (IMO), that provides vessel information, including the vessel's identification, type, position, course, speed, navigational status and other safety related information. The AIS is used by ships and traffic services to identify and locate vessels: the AIS transfers packets of data over the VHF (Very High Frequency) data link and enables AIS equipped vessels and shorebased stations to send and receive identification information that can be displayed on an electronic chart, computer display or compatible radar. This information can help in situational awareness to assist in collision avoidance and also providing location and additional information on buoys and lights. The AIS works as a digital VHF-FM radio self-organizing local area network. The AIS messages are transmitted every 2, 4, 6 or 10 seconds dependent on the vessel's speed or course change; 3 minute intervals when at anchor or at speeds under 3 knots (Class B units transmit at every 30 seconds).

In the past years a number of studies and demonstration activities have taken place at ESA and National level, confirming that reception of AIS signals from space is feasible. Space-based AIS (SAT-AIS) technology can detect far reaching vessels equipped with AIS tracking devices that would be impossible to detect by conventional shore-based systems. Nevertheless SAT-AIS does face technical challenges (as per [1]) that were not considered in the original AIS standard (ITU-R M.1371-2):

Messages collisions - The typical radius of a SOTDMA cell (where no message collision takes place) is around 40 nm. The self-organized structure is however lost when the messages received by more than one SOTDMA cell are received. This is the case of a satellite-based receiver due to the fact that the satellite field of view covers a high number of SOTDMA regions.

Path delay - the length of AIS messages was designed to face with differential propagation delays between messages from different ships up to 2 ms. Path delays among vessels and spacecraft varies, depending on the vessels location and on the maximum satellite antenna footprint. A consequence of exceeding the buffer delay is the burst overlap even between bursts transmitted in different slots of the TDMA frames

***Low Signal* to Noise ratios** - due to higher path losses and depending on the particular satellite antenna gains, C/N values between 20 to 0 dB are expected.

Multipath and atmospheric attenuation - negligible at VHF frequencies. The multipath component may have some (limited) impact at very low elevation angle due to reflections on the sea surface.

Interference from terrestrial VHF - terrestrial fixed and mobile systems: in certain geographical areas on the Earth the interference from VHF Public Correspondence stations (VPC) in the maritime mobile services and Land Mobile Radio (LMR) systems may not be negligible.

Faraday rotation - a linearly polarized wave entering the ionosphere, may have a different polarization angle when it leaves, caused by the Faraday Rotation. This polarization rotation is primarily dependent on frequency, elevation angle, geomagnetic flux density and electron density in the ionosphere.

Doppler Effect - the Doppler frequency shift is a function of relative velocity between transmitter and receiver. In the case of the satellite-based AIS system, the ship's velocity is small compared to the satellite.

Due to the increasing interest of maritime organizations to detect and track ships at distances from coastlines that can not be covered by terrestrial VHF communications, a European satellite based AIS would certainly be beneficial to many European entities particularly in assisting them in law enforcement, fisheries control campaigns, maritime border control operations, maritime safety and security issues including marine pollution response, search and rescue, anti-piracy and military intelligence.

Under this scope, a recent study of a European consortium (Telespazio, Carlo Gavazzi Space, Edisoft, Elman, ITS) co-financed by ESA, has investigated about the possibility of receiving from space AIS signals: a constellation of satellites could assure an AIS worldwide coverage using the same AIS transponders on vessels but with a dedicated satellite AIS receiver. The study will provide not only a detailed architecture and mission design for a Satellite based AIS System, but also a business model and associated cost assessment.

As satellites become a commodity and End-Users become involved on the early mission definition, the mission paradigm shifts from satellite features to an overall system performance view centred on performance indicators as perceived by the end user. The Satellite AIS is one of those examples were the end user community has been involved since a very early phase and where the satellite data is complementary to other sources of data in a cost/benefit approach.

This has imposed a set of stronger requirements into the simulation infrastructure that shall support all system level decisions.

As part of this study, two main performance indicators have been identified:

- Time Update Interval - The time update interval between 2 consecutives vessel AIS messages at AIS processing Centre.
- Timeliness - The timeliness of each detected AIS message (wait period since a message is received and when it is delivered to the AIS processing centre).

And an important scalability factor has been considered:

- Vessels Growth -The system capability to accommodate Class A vessels growth during the constellation life time (around 15 years).

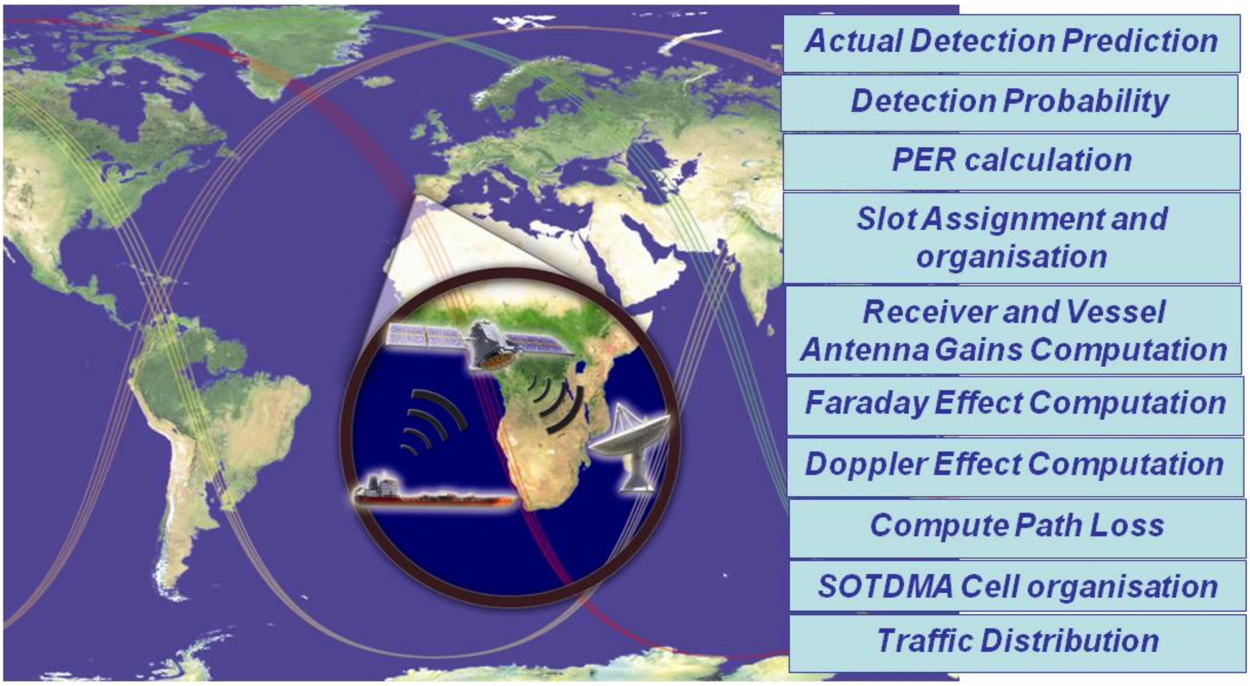

Fig. 1. Overall Sat-AIS Simulator Environment

These requirements lead to the development of end-to-end performance simulator capable of modelling the vessel density per area, since the vessels distribution across the globe are mainly distributed along well-established shipping lanes. The correct modelling of the vessel traffic densities is of paramount importance, since the performance of Satellite AIS is mainly impacted by messages collision due to high number of SOTDMA cells, as per [1].

Also in order to support the satellite antenna design evolution and new concepts validation, the vessel-satellite physical communication link had to be modelled taking into consideration the identified SAT-AIS challenges, namely modelling the physical antenna characteristics of both vessels, satellites and effects like: path loss, Doppler and Faraday Effect. On top of the physical communication link it has been implemented a detailed SOTDMA protocol in particular special care has been taken on the SOTDMA cells organization and slots allocation which enables the accurate evaluation of vessels detection probability.

ARCHITECTURE

The SAST architecture had to cope with a very demanding implementation time frame, which lead to the use of COTS software tools. With a proven track record in simulation tools, the development was essentially in Matlab® environment which allows an increased flexibility to include new features. Together with Matlab® it was used also Basic STK®

software, another COTS software tool with proven results in orbits emulations (one or more satellites) and access of satellites, targets and ground facilities results.

The SAST architecture was driven by the capability to validate several antennas models and also to be able to implement complex scenarios (24H run, 9 satellites. 4 GS, >69.000 Vessels). SAST was divided as 3 main blocks (with well defined interfaces):

Scenario Generation (including the Traffic Model, Satellite Model and Ground Stations Model) - responsible for generating and configuring the subsequent simulation blocks,

STK engine - responsible for emulating the constellation, vessels and ground station behaviour in order to retrieve all the visibility reports that will enable then the communication link performance analysis

Simulator Engine –responsible for emulating the complete physical and logical communication link (based on the antennas physical behaviour along with the SOTDMA protocol under the influence of the above mentioned path losses effects) and performing the scenarios performance analysis

The following figure presents the overall structure of the developed simulation tool:

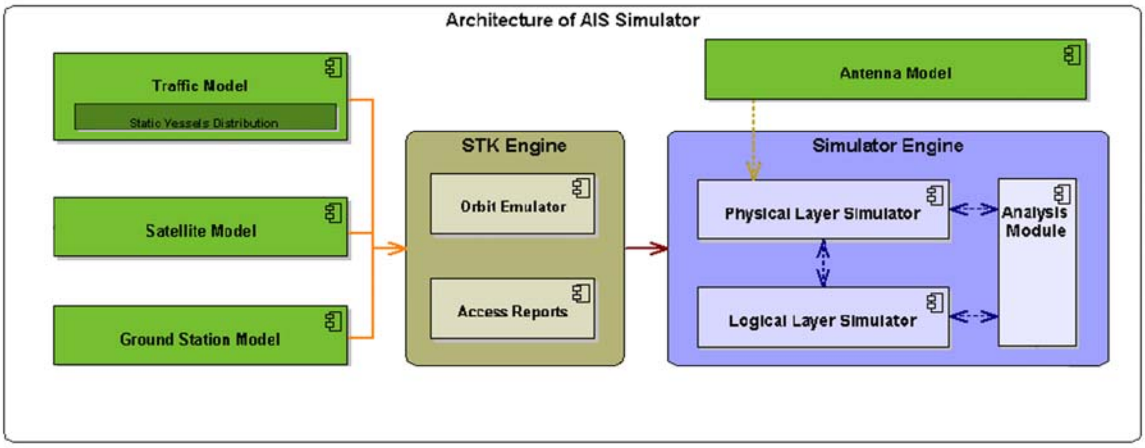

Fig. 2. Overall SAST Simulator Architecture

Traffic Model

The selected dataset to traffic characterization was the ICOADS data set, since it is the most comprehensive and robust data source and covers worldwide scenarios. The goal was to generate a vessel database to be used in the following simulation blocks. Although it would be relatively easy to implement a dynamic traffic model, it was decided to have a static traffic distribution instead of a dynamic one since it would require having at each simulation step a SOTDMA cell reorganization and this would substantially increase the simulation run duration. Nevertheless for the simulations timeframe and considering the difference between the satellite and vessels velocity this approximation does not have a relevant impact on the simulation results.
So as result of the traffic model a static traffic map is generated, i.e. vessels are in a unique position and have an instant velocity.

The following definitions are essential to generate a traffic scenario.

- Chain is defined as a group of vessels in a specific region (i.e. Atlantic Chain, Pacific Chain etc…)
- Trajectory is defined as a group of vessels, following the same shipping lane
- A set of path forms a trajectory
- Paths are formed by at least two waypoints
- Waypoints define a vessel specific path included in one trajectory
- Each vessel only has a path

The traffic scenario generation is done first by parsing the ICOADS data set, filtering all not vessel related data (such as Buoys, etc), then a robust regression is applied to the data set in order to stabilize the trajectories. The paths are then filtered to fit the simulations time frame. As result of this process a set of around one thousand unique trajectories is achieved. Which is a very small number, compared with the real number of vessels crossing oceans worldwide.
Therefore the generation of more paths, distributed in a realistic and uniform manner (following a pattern), is crucial. As such a prediction process is made using a Least Square Support Vector Machine (LSSVM).
After reaching a rich enough set of trajectories the vessels are distributed within the trajectories through a statistical process and the same process applies to the vessels instantaneous velocity (as an example see fig. 3. The colour code was used to represent different velocities).

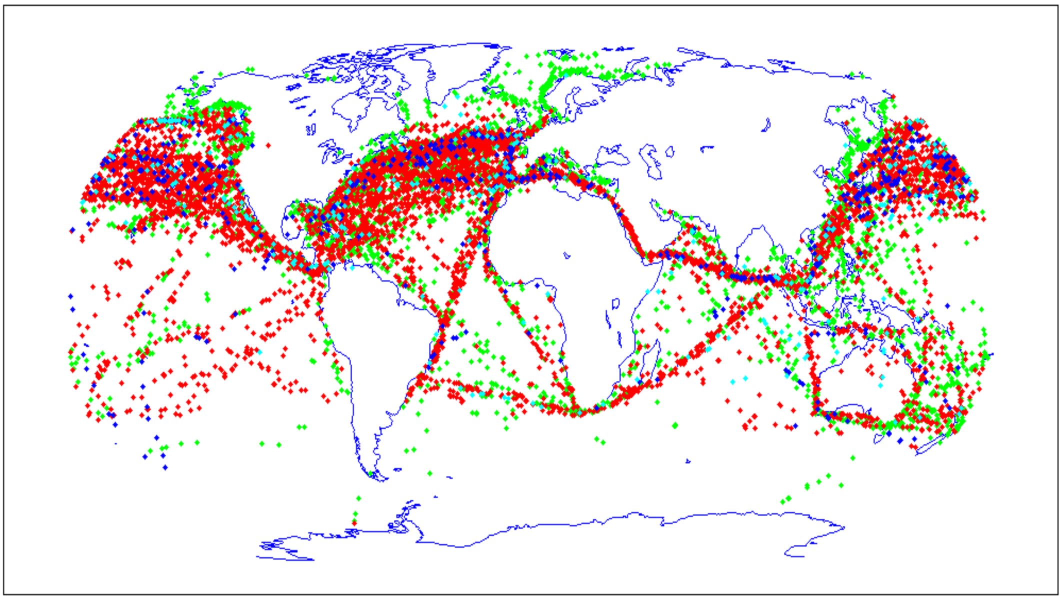

Fig. 3. Sample Vessels Traffic distribution output (with statistical velocity assignment)

Satellite Model

The satellite model is generated taking advantage of the Basic AGI STK® features. The constellation is loaded into the STK® through the definition of typical constellation parameters, namely:

- Number of Satellites
- Altitude [Km]
- Eccentricity
- Inclination [deg]
- Argument of perigee [deg]
- RAAN [deg]
- Mean Anomaly [deg]
- Propagator

This module performs all the necessary steps to load these configuration parameters into STK® engine block.

Ground Station Model

The Ground Stations model enables the ground stations network configuration selection from a preset list of ground stations. A station database is provided as part of the SAST, including: Estrack stations, ESA cooperative network and preliminary Galileo ULS stations. It is also possible to insert a custom station through the provision of standard station parameters: Station Name, Country, Longitude, Latitude, Altitude and minimum elevation angle.
This module performs all the necessary steps to load the stations configuration parameters into the STK® engine block.

STK Engine

The SAST uses Basic STK® software to predict the satellite constellation orbits (one or more satellites). This process output is presented as access reports per each satellite passage.
The STK engine combines the various accesses of satellites, vessels and ground stations. Reporting what objects (in this case vessels and Ground stations) are seen by the satellite (FOV), how many times and for how long the satellites are seen (by the ground stations).
STK® output files are generated in a specific format and are then converted and stored in a .mat file. These files contain the information regarding each satellite passage, including the following variables:

- vessels_data
- satellites_data
- facilities_gap
- facilities_revisit
- facilities_duration

Due to memory constraints, for STK® to support a scenario with a large number of vessels (>60.000 vessels) the computation is done by dividing the procedure in blocks and the processing is done by blocks of vessels

Simulator Engine

The Simulator Engine is split in two main parts, the Physical and Logical Layer.
The physical layer includes communication link modelling (i.e. receivers and transmitter's antennas gain modelling, path loss effects prediction and signal processing). The communication link is simulated using real antenna models, which is done through the generation and use of elevation, azimuth Vs gain lookup tables (the use of lookup tables was implemented as part of the performance improvement process).

The logic layer is responsible for all protocols logical part implementation, which in this case means that it is responsible for the implementation of all relevant SOTDMA protocol features, i.e. cell organization, AIS messages sampling rates, etc.

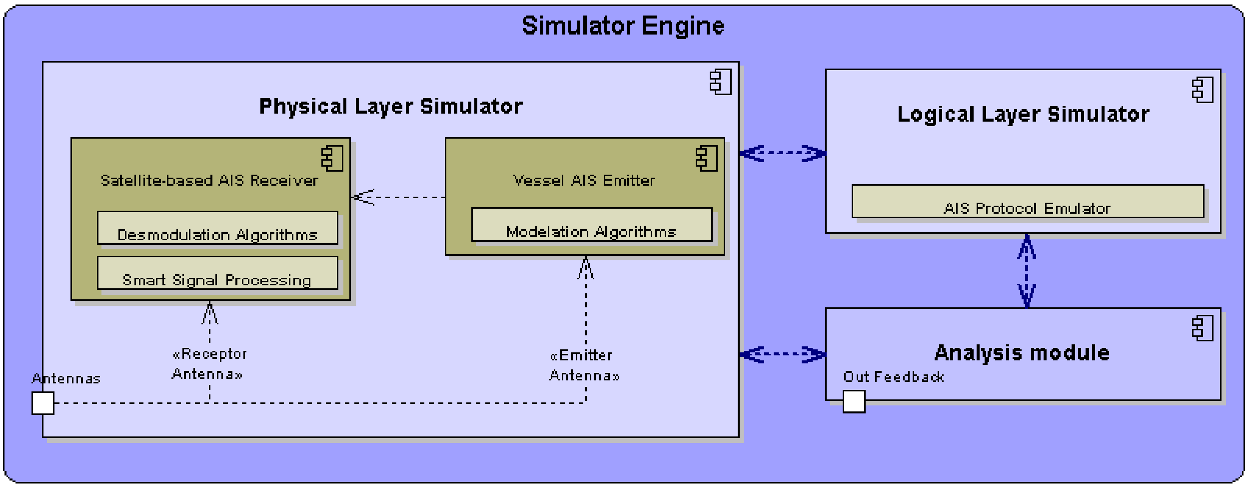

Fig. 4. Simulator Engine Decomposition

Fig. 4 presents the main functional block decomposition of the Simulator engine.

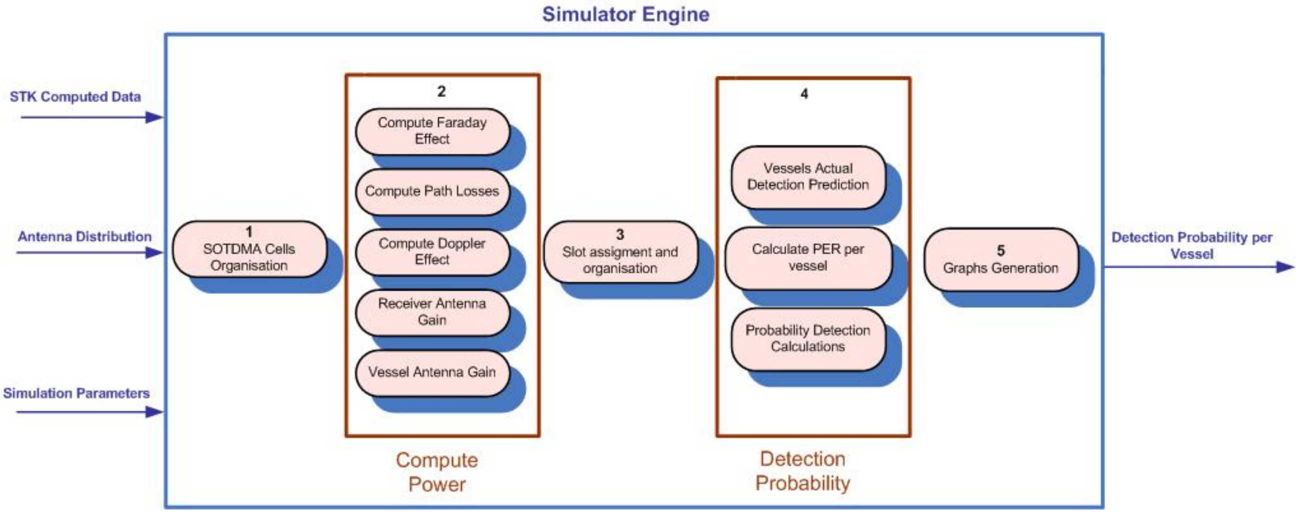

Fig. 5. Simulator Engine decomposition

Analysis Module

The analysis module is responsible for the post processing of the simulation results and for the preparation of the relevant graphical presentation of them (also available are the numerical tables with the relevant date, allowing further processing). The following outputs are currently provided:

- Probability of detection of the whole constellation (and per satellite) during the simulation period
- Revisit time per Ground Station and per satellite
- Access duration between Ground Station and satellite
- Number of contacts between each Satellite and Ground Station during the simulation period
- Maximum refresh time interval

- Antenna Gain (without Polarization Losses), Faraday Rotation Plots and Antenna Total Gains including Polarization Losses
- Global refresh time statistics for the whole constellation, ground station network and vessel distribution

The following figures (fig 6, 7 and 8) present a sample subset of the SAST outputs.

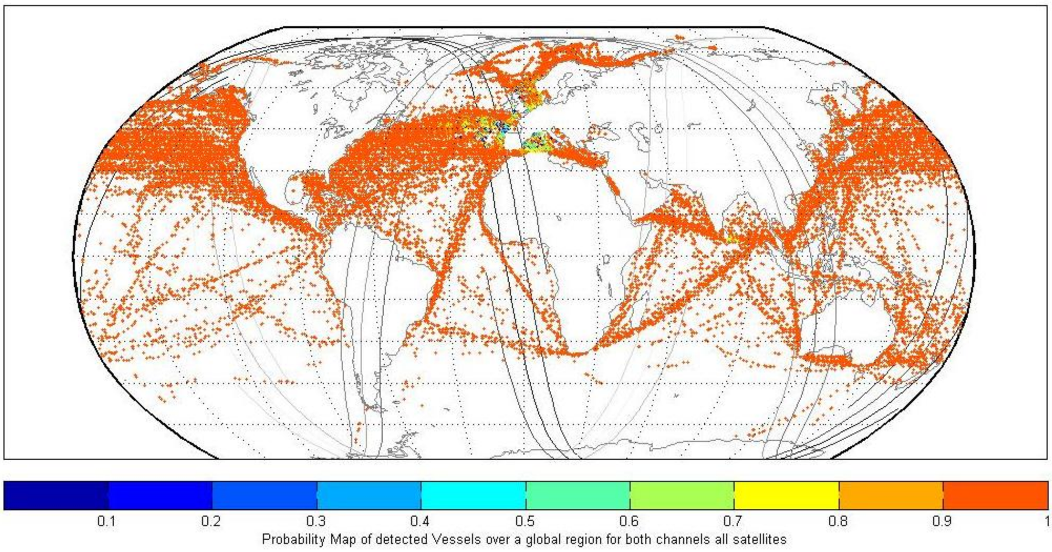

Fig. 6. Scenario detection probability map for the complete constellation

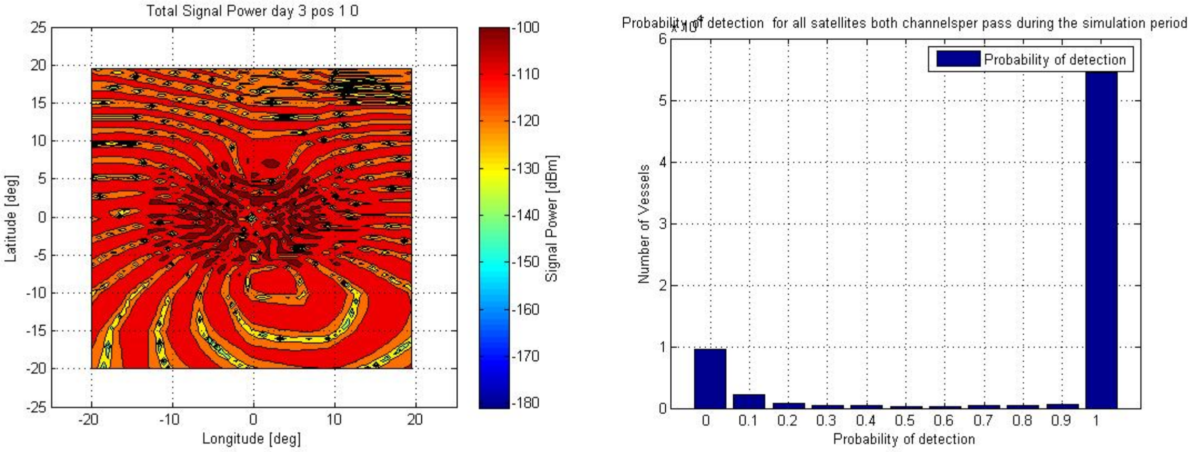

Fig. 7. Left – Total received Signal Power Right - Scenario Detection probability histogram

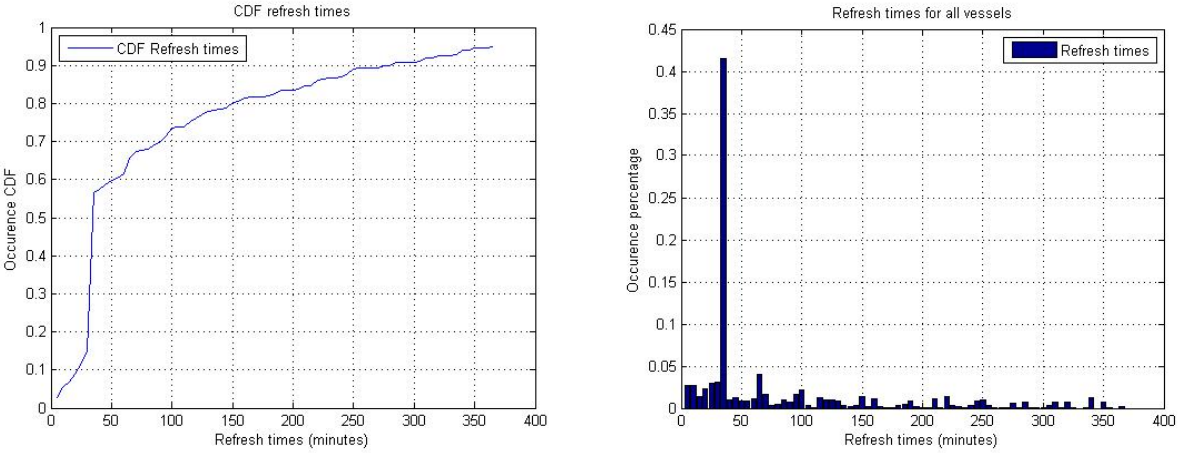

Fig. 8. Left Cumulative distribution function of the vessels msgs Refresh Times Right – Probability Distribution function histogram of the vessels msgs Refresh Times

PERFORMANCE

After the preliminary results of the SAST the simulator infrastructure had to be improved in order to cope with the main bottlenecks while considering worldwide scenarios (>69.000 vessels/targets) with 9 satellites and 4 Ground Stations: memory consumption and execution time constraints.

So the following techniques have been used for coping with the memory usage:

- Slicing the STK engine execution, per slots of vessels (per satellite)
- Slicing the Simulator Engine execution per longitude strips (for vessels cell organization)

As far as the execution time constraints, the following techniques were used:

- Convert specific parts of the Matlab® code into mex files, this was been performed for the following functions: SOTDMA Slots initiation and periodic vessels to slot reallocation
- Generate lookup tables for: faraday effect (using Geomag and Nequick mex support functions), Relative power vs Doppler Frequency, antenna patterns lookup tables (Gain Vs Elevation and Azimuth)
- Reduce the MMI capabilities
- Allowing the simulation run splitting per Satellite, in this way the execution can be parallelized across a set of machines.

Other performance improving measures have be analysed, such as converting the Matlab® code into executable code, nevertheless this solution has been discarded due time consumption necessary for the validation activities to assure the correct Executable code performance against the Interpreted code. Instead the simulation execution was split per satellite as already mentioned, since it allowed a more scalable solution (and at a later stage the conversion to executable code could be done also, since some successful porting tests have been done already).

Another option envisaged to improve the SAST performance would be moving to a 64bits architecture and in this way taking full advantage of multicore architectures and removing the 4GB memory limitation of the 32Bits architectures.

All the proposed performance enhancement solutions are in fact complementary and can be implemented together depending on the performance requirements established for the simulation Infrastructure.

CONCLUSIONS

This Simulation infrastructure has been developed to support de SAT AIS Mission performance analysis and is successfully supporting the antenna configuration selection, constellation characteristics and ground stations configuration. The SAST is capable of performing worldwide complex scenarios in a scalable time frame depending on the computational resources available. As such SAST can be easily extended to support other types of missions, in particular missions that present a large number of targets (such as vessels, aircrafts or terminals) are the ones that can benefit from the infrastructure already implemented and the process devised during its implementation.

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