SSA Sensor Simulator (SSIM): Space object environment simulator and measurements generator

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ABSTRACT

The overall aim of the Space Situational Awareness (SSA) Preparatory Programme is to support the European independent utilisation of and access to space for research or services, providing timely and quality data and expertise regarding the environment, the threats and the sustainable exploitation of outer space.

Space Situational Awareness (SSA) is defined as a comprehensive knowledge, understanding and maintained awareness of:

- The population of space objects
- The space environment
- The existing threats/risks

The objective of the SSA Sensor Simulator, hereafter referred to simply as the SSIM, is to provide an environment for end-to-end validation of the future SSA system before its actual deployment.

In order to achieve this objective, the SSIM interfaces with SSA's Planning System and Data Processing Chains generating radar and optical raw measurements for both SST and NEO populations.

The SSIM reproduces physical models for all system elements involved in the data generation process: sensor planning constraints, orbit propagation of SST and NEO, radar measurement generation, ground based optical measurement generation and space based optical measurement generation.

Within the SSA Preparatory Programme, the SSIM supports early testing and validation of:

- Algorithm prototypes
- Pre-operational elements
- Overall SSA performance and evolution
- Interface alignment and compatibility across multiple SSA systems

Moreover, one of the main objectives of the SSA Preparatory Programme is the provision of a number of so-called SSA precursor services. Several of these precursor services are expected to be deployed on a Common SSA Integration Framework (COSIF) based on the principles of the Service Oriented Architecture (SOA). The COSIF is intended to enable the integration of existing assets as well as deployment of new heterogeneous SSA applications.

The SSIM is implemented on top of ESA's simulation infrastructure, SIMULUS, and is to be deployed on COSIF. Hence for SSA, the SSIM serves as an architectural proof-of-concept exposing its high level functionalities via COSIF in the form of SOA services (SOA mode). In addition to this SOA mode, the SSIM is able to run as a standalone application (non-SOA mode).

The SSIM takes advantage of the wide palette of tools and components offered by SIMULUS in order to provide, among other things, a dedicated HMI that allows operators to configure runtime simulation scenarios, visualize simulation data and monitor and operate the facility itself.

In this paper we will describe how the SIMULUS infrastructure is reused and the algorithm challenges addressed in the implementation of the SSIM. We also include numerical results from preliminary test scenarios.

INTRODUCTION

The SSIM provides a simulator for the population environment and models sensors observing that population. This simulator accounts for a realistic modelling of the population of objects observed by the sensors, the sensors themselves and the interaction with other elements of the future SSA system. These elements are the Sensor Planning system (SP), devoted to the centralized scheduling of tracking observations of objects when needed, and the Data Processing Chain (DPC), intended to process the observations generated by the sensors (initially those simulated in the SSIM) to create and maintain a catalogue of space objects. Prototypes of both these systems are also being developed in the frame of the SSA Preparatory Programme.

SSIM is developed as a SMP2 compliant simulator on top of ESA's simulation infrastructure, SIMULUS. Moreover, SSIM will expose its high level functionalities in the form of SOA services via COSIF. The COSIF is intended to enable the integration of existing assets as well as deployment of new heterogeneous SSA applications.

The models implemented within SSIM are two-fold:

- Objects population: Earth orbiting man-made objects and Near Earth Objects, hereafter also referred as SST and NEO objects respectively.
- Sensors: Optical sensors located on-ground or mounted on satellites and radar sensors. Even though optical sensors can be used for SST and NEO observations, radars are usually required for objects at low altitudes.

In addition to the type of sensor, two different observation modes are required for simulating SSA activities: Surveillance and Tracking. Surveillance mode is dedicated to the (normally) continuous observation of part of the sky to generate observations of the large number of objects that cross the observed field. In contrast, tracking mode is devoted to the observation of a particular object; with the aim of improving the knowledge of its orbit or physical properties.

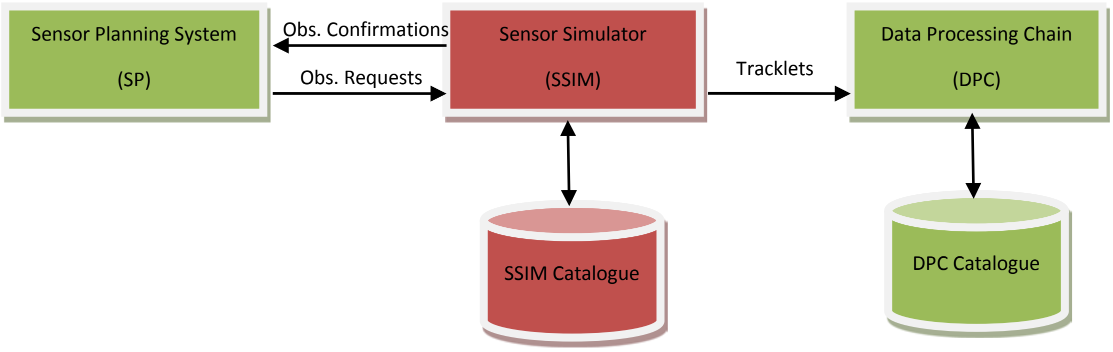


Figure 1: SSIM System Context

The figure above shows the main flow of events and interfaces characterizing SSIM's place in the simplified SSA system context of the Preparatory Programme.

The flow can be viewed as starting with the generation of Observation Requests by the Sensor Planning (SP). According to these requests, the SSIM applies the aforementioned population and sensor models to generate observation tracklets [RD-10] that are passed in turn to the Data Processing Chain (DPC). The tracklets delivered to the DPC are used by the DPC to update and maintain its catalogue of objects.

It is important to make the distinction between the catalogues of the DPC and the SSIM:

- DPC Catalogue: contains object orbits estimated as part of DPC's tracklet processing
- SSIM Catalogue: contains the real population to be used in the simulation environment for the generation of measurements. This population is slightly different to the one used by the DPC as the SSIM accounts for differences derived from the lack of knowledge in real world catalogues.

From a deployment point of view the SSIM shall support two scenarios:

- 'Standalone mode' (or non-SOA mode): where the SSIM does not rely on external systems and can run autonomously based on data exchanged via input/output directories.
- 'COSIF mode' (or SOA mode): where the SSIM is deployed as part of a Service Oriented Architecture (SOA) solution exchanging information with the two formerly mentioned components (SP and DPC) using open standards such as SOAP XML messages.

SSIM ARCHITECTURE AND SIMULUS

SIMSAT (Software Infrastructure for the Modelling of SATellites) [RD-7] is the core of the SIMULUS suite and provides the common elements of a simulation. SIMSAT comprises a soft real-time Kernel for the execution of satellite models, a graphical user interface to control and monitor a simulation and the Model Integration Environment (MIE) to assist the development of Simulation Model Portability 2 (SMP2) compliant simulators. SMP2 [RD-8,9] enables reuse and portability of simulation models between simulator applications within and across space projects. The purpose of SIMSAT is to provide the common elements of a satellite simulation, thereby reducing the overall simulation development effort. SIMSAT has been specifically designed to support the design and implementation of SMP2 compliant models and is fully backward compatible to SMI.

There are three main architectural components in a SIMSAT simulation, namely:

- Models: Via the SMP Adapter, SIMSAT supports both the SMP1 (SMP 1.0, also known as SMI) and the SMP2 v1.2 standard. Models are not dependent on SIMSAT at all.
- Kernel: As the 'engine' of the simulation, the Kernel takes care of low level tasks such as creating and running models, storing and reading data and providing standard simulation services.
- HMI: This is the interface between the user and the simulation. The HMI is used to control and study the running system during configuration and use. The HMI in SIMSAT communicates only with the Kernel.

The figure below shows how the SSIM architecture extends SIMSAT's infrastructure.

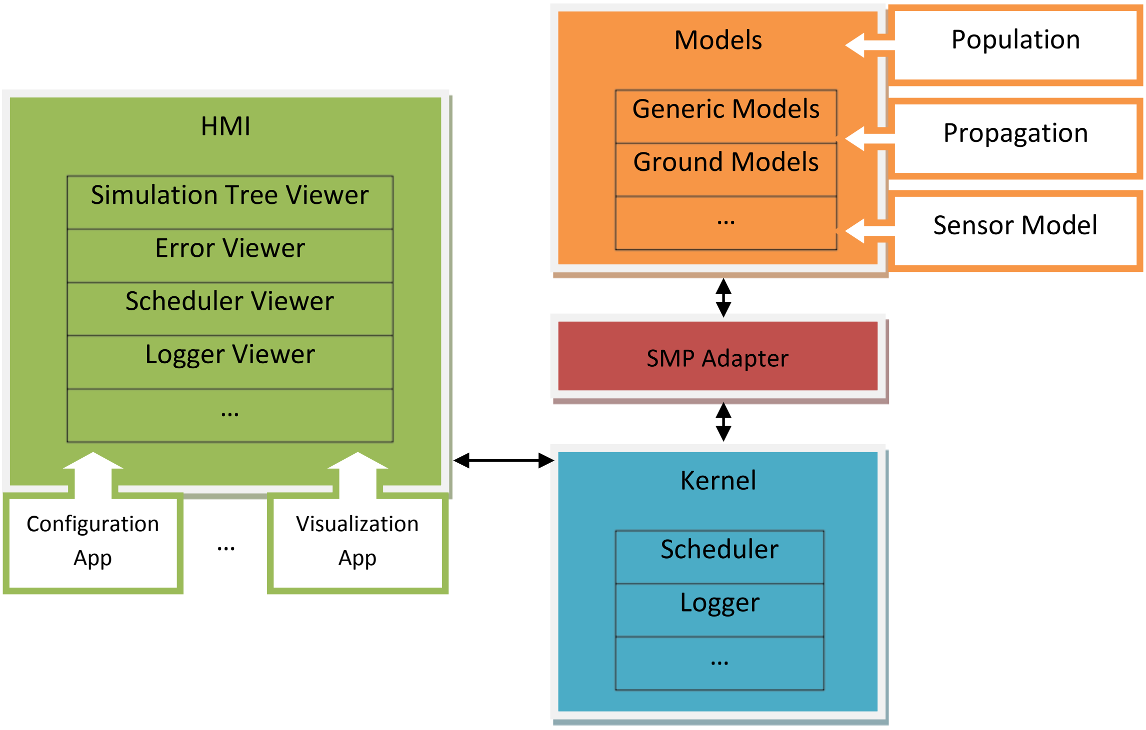


Figure 2: SSIM's conceptual extension of SIMSAT

As part of the SSIM development, a large number of FORTRAN routines used in previous developments (eg. ESA mission analysis libraries and the DEIMOS AS4 simulator, [RD-4]) have been embedded into SMP2 C++ wrappers. The following extensions can be identified in terms of models:

- Population model: This includes all functionalities related to the catalogues: creation of a catalogue, providing an object of the catalogue, and applying an event or a filter on the catalogue.
- Propagation orbit model: This is composed of the functionalities necessary to provide an orbit at requested time.

- Sensor model: This includes all functionalities required to both determine whether or not an object is observed/detected by a sensor, and to generate the corresponding tracklet for the observation.

SIMSAT's HMI infrastructure, based on Eclipse RCP technology, enables the implementation of HMIs in the form of collaborative plug-ins. The default SIMSAT perspective is the Runtime. This perspective contains the following views:

- Simulation Tree view, where the SSIM simulation components can be explored and accessed.
- Error Log view, where the system and simulation errors are shown.
- Log Viewer view, where the SSIM logs for any operation are shown.
- Commander view, where commands to interact with the simulation can be introduced.
- Schedule viewer, where the scheduled events are shown.

Additionally, SSIM development has extended SIMSAT implementing the following plug-ins/perspectives.

- Login application, which manages authentication and security.
- Configuration, which manages the parameters controlling the configuration of the sensors, the SSIM system and the SSIM simulation scenarios.
- Visualization Data, which presents data. This perspective contains a Status Viewer with the information regarding the simulation, a view with the list of tracklets, the Log Viewer and a Configuration view displaying tabs with information regarding the Observation request processes.
- Space Object's Catalogue, which manages the SSIM's Object Catalogue.
- Administration, which consists on the administrative tasks provided through the HMI.
- Monitoring and control, which covers common start/stop simulation operations as well as visualization of the status of key SSIM entities such as observation requests, confirmations, and notifications.

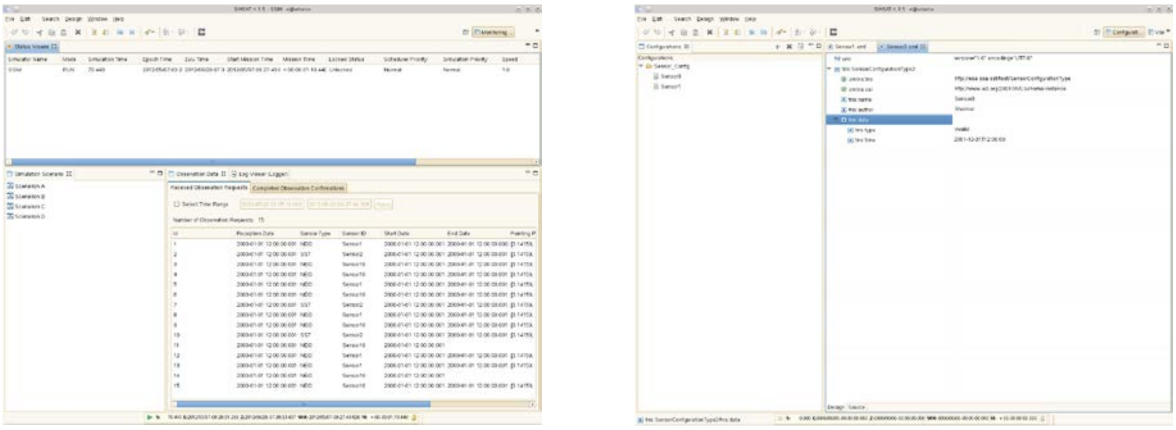


Figure 3: Screenshots of SSIM's 'Monitoring and Control' and 'Configuration Design View' Perspectives

SSIM AND SERVICE ORIENTED ARCHITECTURE

A future European SSA system can be expected to be a complex system of systems aiming at promoting interoperability and reuse of existing assets. To this end it was decided to apply a service oriented architecture (SOA) to the development of some of the precursor services to be implemented within the SSA Preparatory Programme.

Service Oriented Architecture (SOA) is a set of design principles used during the phases of system development and integration in computing. SOA-based systems are characterised by the composition of loosely coupled services that are made available as part of a Service Inventory [RD6].

Following the decision to incorporate SOA, the development of a Common SSA Integration Framework (COSIF) was initiated by SSA. COSIF is intended to ensure a homogeneous SOA approach for SSA introducing a software platform and a set of design and development guidelines.

Therefore, despite being based on a non-SOA framework (SIMULUS/SIMSAT), SSIM supports a deployment approach identified as ‘COSIF mode’. In this mode, SSIM contributes to the overall SOA solution adopted by SSA by exposing three key services to be deployed on COSIF:

- Sensor Simulator Service: this service enables COSIF based applications to submit new observation requests and retrieve the simulated results of the observations.
- Sensor Simulator Monitoring Service: this service enables COSIF based applications to monitor SSIM.
- Sensor Service: this service enables COSIF based applications to access the sensor configuration parameters managed by SSIM.

In addition to these services, SSIM deployment in ‘COSIF mode’ allows the reuse of SSA Generic Services as well as Space Weather Services made available via COSIF.

SOA systems adopt business centric design principles. In this respect, from the SOA point of view, SSIM’s solution is composed of a single high-level business process as illustrated in Figure 3.

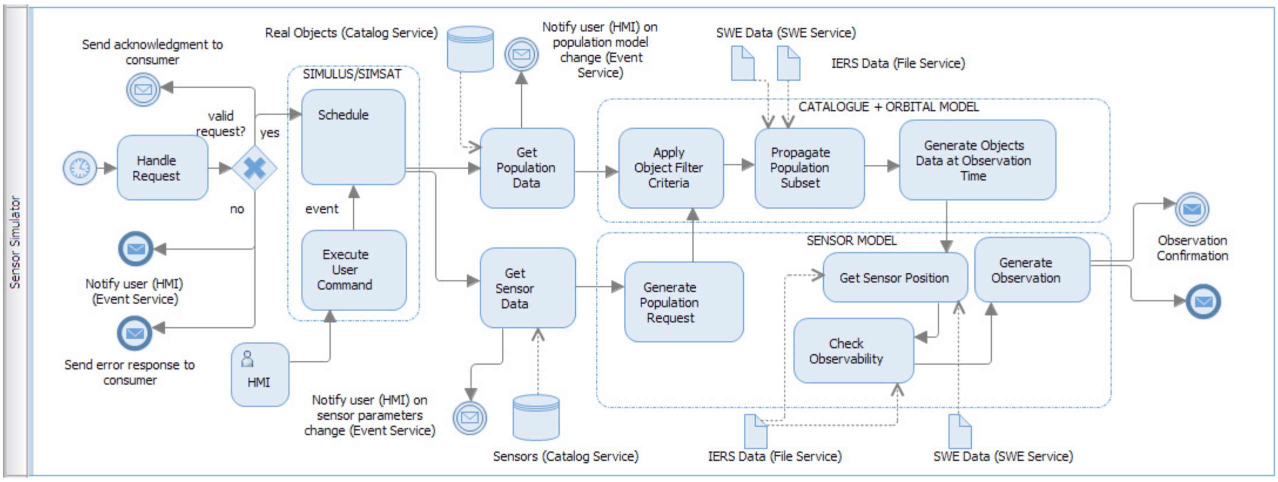


Figure 4. Sensor Simulator High-Level Business Process, from [RD-1]

POPULATION AND PROPAGATION MODELLING

In order to simulate man-made Space Surveillance and Tracking (SST) and NEO populations, a set of objects and a dynamic model allowing the propagation of those objects in time must be considered.

The population model contains the full orbital information for all the objects that can be observed or detected by the sensors. Different databases are used in the SSIM to contain information for these two different populations – NEO and SST objects. Once the SSIM is executed, the initial object databases are propagated but the user is allowed to also insert some events during the course of the execution. Therefore, the SSIM must distinguish between the initial catalogue, a database that is not modified during the execution of the program, and the run-time catalogue, a database that is modified at each time step during the execution. A complete description of the models used in the SSIM is provided in [RD-3].

In order to make the population of objects evolve over time, it is needed to include a propagation model, which takes into account two different issues: the dynamic model and the numerical integrator.

The Dynamical Model of Motion computes the set of perturbation accelerations that affect the object's state vector. Depending on the altitude of the orbit to integrate, modelled forces acting on objects can be classified as SST or NEO.

The main contributions to the motion of SST objects, in addition to Earth spherical gravitational, include:

- Atmospheric drag based on the MSIS-00 model [RD-3]. This model requires solar and magnetic indices that should be provided by SSA's Space Weather SOA services [RD-1, 2].
- Solar radiation pressure
- Third bodies gravitational perturbation (eg. Sun and Moon)
- Harmonics to the spherical Earth gravity model. Here the SSIM uses EGM96 [RD-3].
- Solid tides

The main contributions to the motion of NEO objects, apart from the Sun's gravitational attraction, include:

- Solar radiation pressure
- Third bodies gravitational perturbation (eg. Jupiter and Saturn). Here the SSIM uses planetary ephemerides from JPL.

The SSIM's Dynamical Model of Motion generates nominal values but also simulates perturbations such as the Solar Radiation Pressure and atmospheric drag that are added on top of the nominal effects.

SENSOR MODELLING

As already stated, the SSIM supports modelling of three different types of sensors that can be used to carry out SST and NEO segment observations. In this section, some key details about these models are presented, together with a brief description of the associated tracking and surveillance modes. The complete description of these models is provided in [RD-3].

The **Radar Sensor Model** supports the simulation of objects with orbits close to the Earth. Orbits that come within 1500-2500km (distance will vary depending on the radar configuration parameters) are expected to be detected by radar sensors. Therefore, in particular, the NEO population will generally not be detected by radar.

The SSIM provides two different types of radar sensors: tracking radars and surveillance radars. Whereas tracking radars are expected to observe a single object in the sky at any time based on its ephemerides, surveillance radars potentially can observe many objects simultaneously in an area of the sky during a given time frame.

The following are considered as the key aspects of the SSIM's Radar Sensor Modelling which determine whether or not an object is observed:

- The relative distance between the radar and the orbit is expected to be between the minimum and maximum detectable range (a configurable parameter of the radar that depends also on the size of the object).
- The Signal to Noise Ratio (SNR) of the radar is expected to be above a minimum configurable value associated to the object. If this threshold is exceeded, an appropriate probability function is applied to determine if the detection of the object is successful.

The **Ground-based (GB) Optical Sensor Model** supports the simulation of both the SST and the NEO populations. It is important to note that SSIM uses the same telescope model to simulate NEO and SST observations.

The SSIM telescope sensors can be used to simulate both tracking and survey activities. In the case of tracking activities the approach described above for tracking radars applies. On the other hand, survey activities are characterised by a sequence of telescope observations performed according to a surveillance strategy. Available surveillance strategies in the SSIM are:

- Vertical strip pointing to a close-to-anti-sun direction, a typical strategy used for ground based observation of SST GEO objects.
- Horizontal strip, a typical strategy used for ground based observation of SST MEO objects.
- Free mosaic, a typical strategy used for NEO observations and also suitable for more flexible SST observations, if needed, from GB telescopes.

The **Space-based (SB) Optical Sensor Model** supports the simulation of SST and NEO populations. This model is very similar to the ground based telescope model. The main differences with respect to the GB telescope model are the presence of some additional visibility criteria. These criteria include the relative velocity between the observer and the object as well as the propagation of the orbit to where the telescope is located. SB telescope sensors support simulation of tracking and survey activities in the same way as GB telescopes. Surveillance strategies available for this type of sensor are based on the pointing direction fixed in a local or inertial reference frame.

PRELIMINARY RESULTS

In order to validate the SSIM preliminary tests have already been performed. This section presents the results for an SST population obtained in simulations using the surveillance radar and the surveillance optical (ground-based) models.

For the **SSIM surveillance radar model**, the motion of one Low Earth Orbit (LEO) object and one Geo Transfer Orbit (GTO) object has been simulated. The orbits of both objects (NORAD numbers 13660 and 849) have been taken from the TLE catalogue published the 10th of February of 2009 in [RD-5]. The configuration of the sensor was defined by the following parameters/values:

- Location of the transmission antenna: Latitude = 45 deg, Longitude = 0 deg, Altitude = 2500m
- Location of the reception antenna: Latitude = 45 deg, Longitude = 0 deg, Altitude = 2500m
- Orientation of the radar: Maximum elevation = 40 deg, Minimum elevation = 20 deg, Maximum azimuth = 240 deg, Minimum azimuth = 120 deg
- Detection capabilities of the radar: RCS of reference = -20 dB, Distance of reference = 1300 km, SNR of reference = 18.45 dB, Minimum SNR = 4 dB, SNR offset = 12.5 dB, Wavelength = 0.24 m, Maximum detectable range = 15000 km
- Accuracy capabilities of the radar: Accuracy in Azimuth (the accuracy in azimuth depends on the SNR according to a probability function) = 1 sigma, Accuracy in Elevation (the accuracy in elevation depends on the SNR according to a probability function) = 1 sigma, Accuracy in range (this does not depend directly on the SNR but has an associated probability function) = 3 sigma, Doppler accuracy (this does not depend directly on the SNR but has an associated probability function) = 0.17 sigma

The following picture shows the detection of both objects (blue) versus their orbits (green).

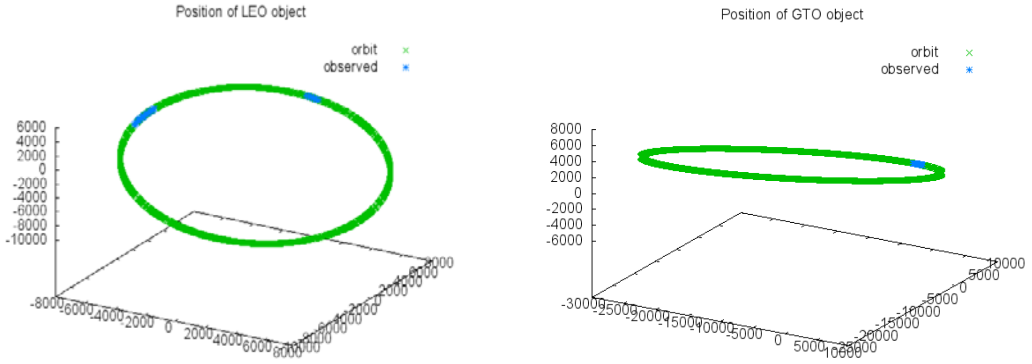
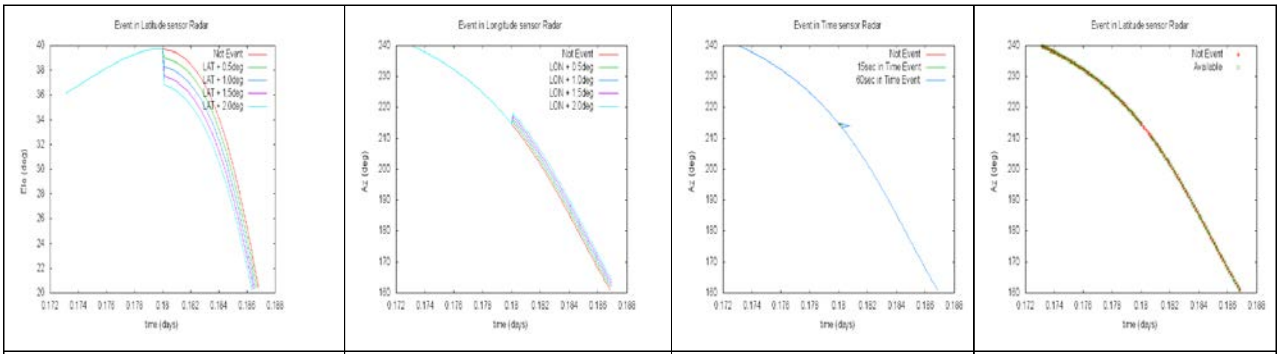


Figure 5. Detection of the two Orbits in the Simulation

In the LEO case, the orbit is circular but with a high inclination. Therefore there are two different parts of the orbit that are detected by the radar. These correspond to the parts of the orbit that are both correctly oriented with respect to the geometry of the radar and also pass within the detectable elevation of the radar.

In the GTO case, the orbit is highly eccentric. Here the only part of the orbit that is detected is close to the perigee.

In addition to the execution in the nominal case, the SSIM allows the user the possibility to introduce different kinds of events during execution time. The next picture illustrates the different type of events that could be introduced in the execution of a simulation:

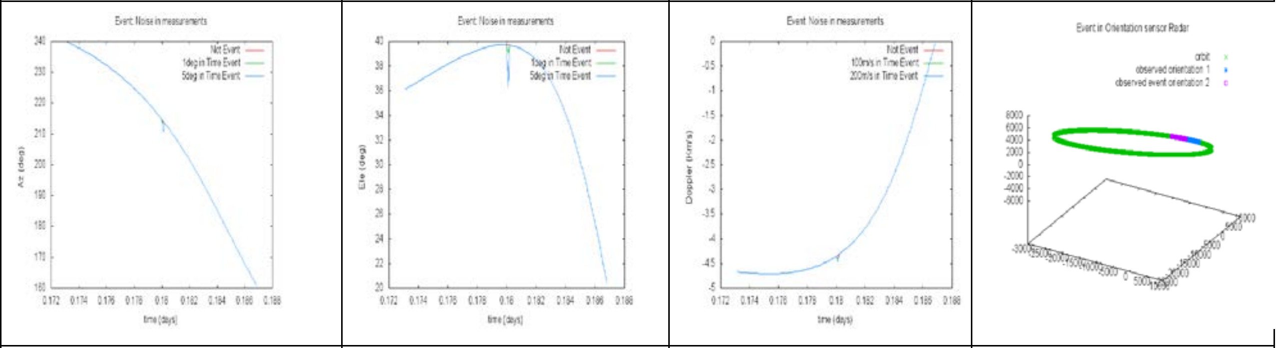


Change of the latitude of the radar.

Change of the longitude of the radar.

A delay in the time of the observation.

Non-availability of the sensor during a time interval.



Additional noise in the detected azimuth.

Additional noise in the detected elevation.

Additional noise in the detected Doppler.

Change in the surveillance radar orientation.

Figure 6. Event Types that can be Introduced during Execution - Radar

For the **SSIM surveillance optical ground-based model**, the motion of a geostationary object (GEO) has been simulated. The orbit of the object with NORAD number 6078 has been taken from the TLE catalogue published 10th of February of 2009 in [RD-5]. The configuration of the sensor was defined for two different observation strategies according to the following parameters/values:

- Location of the telescope: Latitude = 37.982630 deg, Longitude = -2.565670 deg, Altitude = 1530 m

- Detection capabilities of the telescope: Aperture diameter = 1 m, Pixel size = 0.6 arcs, Field of view (declination x right ascension) = 2x2 deg, Integration time = 1s, PSF size = 2 arcs, Mean optical transmission = 0.6, Mean quantum efficiency = 0.8, Camera read out noise = 8 e/pixel, Dark Current = 0.0005 e/pixel/s, Minimum SNR for detection = 4, Minimum detectable altitude = 10000km, Minimum solar zenith angle for detection = 100 deg
- Visibility conditions of the site: Mean atmospheric transmission = 0.88, Sky background magnitude = 21, Reference flux out of atmosphere = 8000 photons/s/m2, Reference distance for reflux = 36000 km, Reference magnitude corresponding to Reflux = 16
- Accuracy of the telescope: 1-sigma noise in the telescope pointing = 0.5 arcs
- Observation strategy 1 (declination strip): 3 images per tracklet, -30 images per declination strip, Minimum declination = –17 deg, Maximum declination = 17 deg, Time between consecutive tracklets = 5 sec, Time between consecutive images in a single tracklet = 2 sec, Angle of the survey = 15 degrees in the anti-sun direction, Mean distance of the observation = 42168 km
- Observation strategy 2 (longitude strip): 3 images per tracklet, 80 images per declination strip, Minimum longitude of the covered strip = –60 deg, Maximum longitude of the covered strip = 60 deg, Time between consecutive tracklets = 2 sec, Time between consecutive images in a single tracklet = 2 sec, Angle of declination = 0 deg, Mean distance of the observation = 42168 km

The following picture shows the detection of the object (blue) versus its orbit (green) for both strategies.

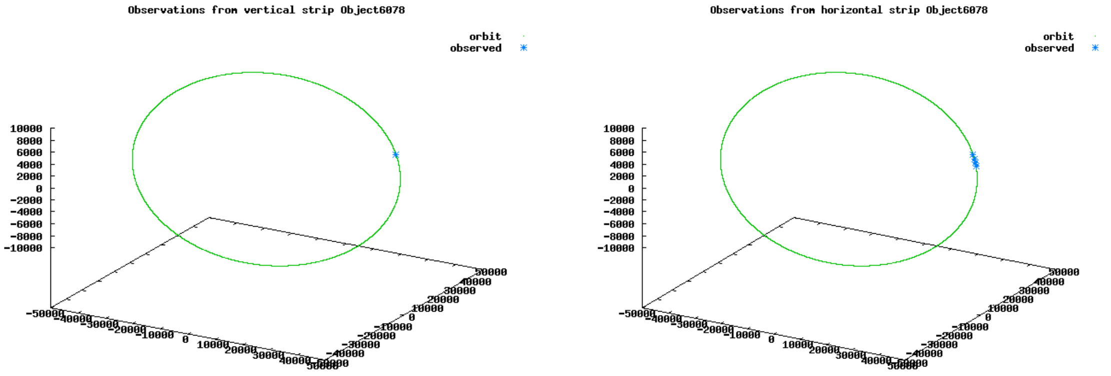
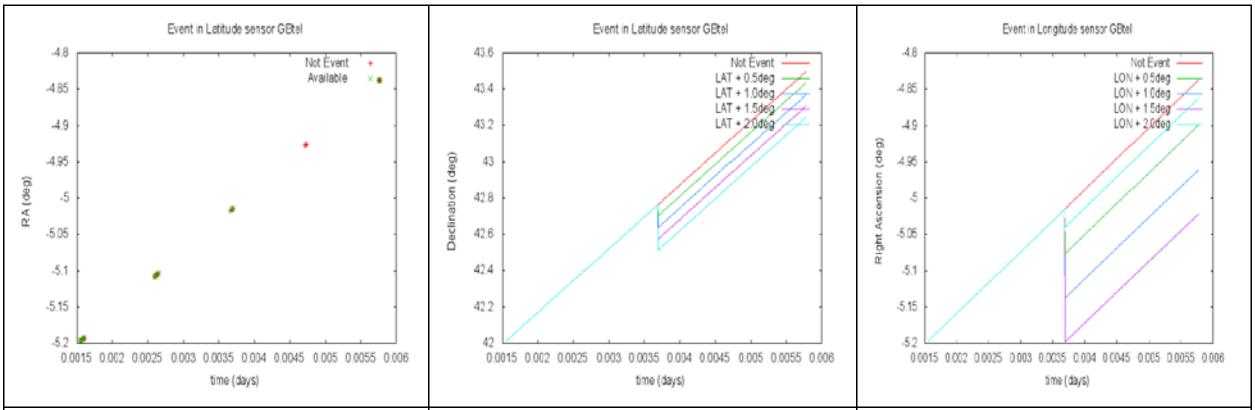


Figure 7. Detection of the Orbits in the two Observation strategies

Observation strategy 1 covers a declination strip that allows observing the objects in the GEO ring for a given longitude. The motion of the telescope in this case is perpendicular to the motion of a typical GEO object and therefore the tracklets provided by this strategy are “short”.

Observation strategy 2 covers a longitude band located at 0 degrees of declination. The motion of the telescope in this case is roughly parallel to the motion of the orbit. Therefore the tracklets generated with this strategy are longer than the tracklets generated with the previous strategy.

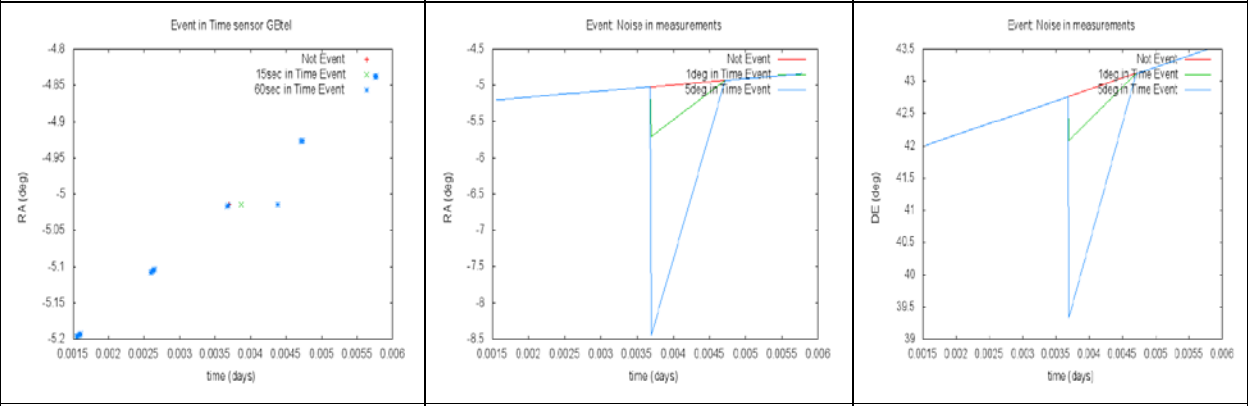
As in the radar case, the optical model can also admit events that the user can introduce during execution time. The following figure illustrates the different types of events that can be introduced in the simulation:



Non-availability of the sensor

Change in latitude of the sensor

Change in longitude of the sensor



Delay in tracklet generation

Noise in Right ascension

Noise in Declination

Figure 8. Event Types that can be Introduced during Execution - Optical

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