SENSOR SIMULATOR SUPPORTING THE PILOT DATA CENTRES FOR THE SPACE SITUATIONAL AWARENESS (SSA) PREPARATORY PROGRAMME

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ABSTRACT

This paper focuses on SSA's Sensor Simulator (SSIM), and how it is defined to support the testing and evaluation of Sensor Planning System and Data Processing Chain prior to the deployment of real sensors, in the frame of SSA programme.

The Sensor Simulator for the Pilot Data Centres reproduces physical models for all system elements involved in the data generation process: observation constraints and strategies (tracking and survey), debris orbit propagation, Near Earth Objects (NEO) orbit propagation, generation of radar, ground based optical and space based optical measurements. A review of the capabilities, main models and associated algorithms is presented in this paper. Examples of the use of SSIM for the simulation of observations of both Space Surveillance and Tracking (SST) and NEO objects are provided, highlighting the differences between these two operational cases.

SSIM is designed and implemented to make use of the ESA SIMULUS infrastructure and it will be deployed on top of the Common SSA Integration Framework. A brief description of the architecture of the system is provided.

1 INTRODUCTION TO SSIM

The eventual Data Centre of the SST segment can be expected to be composed of several functionalities coordinated in order to fulfil an overall objective: Generation and maintenance of a catalogue of Earth orbiting objects, and the utilization of such a catalogue to diminish the risk posed by space debris to both ground infrastructure and operational satellites. The current DC-II activity, in the frame of SSA Preparatory Program, aims to develop some elements of a Pilot Data Centre for SSA. Among these elements are the design, development and deployment of the SST Data Processing Centre (DPC), the Sensor Planning System (SPS) and the SSIM. The DPC is limited to the SST processing chain whereas the SPS and the SSIM address both NEO and SST segments.

When SSA sensors are present, the SPS would command them to execute observational tasks. Those sensors would in turn provide observations to the NEO and SST data processing chains which would maintain catalogues of NEO and SST objects. In the event that the cataloguing system required additional observations of an object in order to improve its orbit knowledge, the SPS would be requested to schedule new observations. In this way, the three elements, when integrated, form a systems that has been defined on the basis of common approach.

Since SSA sensors are not yet available, the goal of the SSIM is to reproduce the main features of real devices.

SSIM has been 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 the Common SSA Integration Framework (COSIF). The COSIF is intended to enable the integration of existing assets, as well as ease the deployment of new heterogeneous SSA applications.

From an operational point of view the SSIM will support two deployment scenarios:

- 'Standalone mode' (a.k.a. non-SOA mode): here SSIM does not rely on external systems and can run autonomously based on data exchanged via input/output directories.
- 'COSIF mode' (a.k.a. SOA mode): here SSIM is deployed as part of a Service Oriented Architecture (SOA) solution exchanging information with the SPS and DPC, among others, using open standards such as SOAP XML messaging.

2 SSIM Model description

The models implemented within SSIM are twofold:

- Population of objects, addressing the two type of objects: 1) Earth orbiting operational satellites and

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debris, which can be observed by SST sensors and catalogued within the SSA SST Segment, and 2) NEO objects which will be observed by NEO sensors and catalogued within the SSA NEO segment.

- Sensors addressing the two type of sensors: 1) Optical sensors located on-ground or mounted on-board satellites that can be used for the observation of both SST and NEO objects, and 2) Radars located on ground that can observe and/or track objects orbiting at low altitudes that are difficult, or even impossible, to observe with optical sensors.

Apart from the type of sensors, two different observation modes are needed for simulating SSA activities. These modes are Surveillance and Tracking. The first one is dedicated to the (normally) continuous observation of a part of the sky to generate a large number of observations of objects crossing the observed field. The second one is devoted to the observation of a particular object, with the objective being to improve the knowledge of its orbit and/or physical properties.

2.1 Population Model

In order to simulate man-made (SST) and NEO populations, we need to consider a set of objects and a dynamic model allowing the propagation of those objects with time.

The population model contains the full orbital information corresponding to the objects that can be observed by the sensors. As already noted, sensors simulated within SSIM can be used for detecting space debris objects, but also NEO objects. Different databases are used to contain information for these two different populations. On the other hand, once SSIM is running, the initial databases can be modified, typically they are propagated but also the user may insert events (eg. new launch objects, manoeuvred satellites or re-entered objects) creating a so-called run-time catalogue different than the initial one. Therefore, SSIM distinguishes between its initial catalogue, which is a database that is not modified during execution, and its run-time catalogue which is a database that is modified at each time step during the execution. The complete description of models in use is provided in [3].

The initial catalogue for SST objects is based on a TLE data set (upon agreement with JSpOc) whereas the NEO catalogue is based on the population at NEODyS.

In order to make the population of objects evolve with time, SSIM includes a propagation model which takes into account two different issues: the dynamic model and the numerical integrator.

The Dynamical Motion Model computes the set of accelerations that affect the simulated object state vector. The main contributions to the SST model of motion, in addition to spherical gravitational field are:

- Atmospheric drag based on the MSIS-00 model. This model requires solar and magnetic indexes that will be provided by SSA's Space Weather services [4]
- Solar radiation pressure
- Gravitational perturbation by third bodies (eg. the Sun, the Moon, other planets)
- Gravity from the Earth as per EGM96
- Solid tides

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

- Solar radiation pressure
- Gravitational perturbation by third bodies (from all the planets in the solar system), which are computed using planetary ephemerides from JPL files

The Dynamical Model of Motion can generate nominal values as well as simulated errors (namely, the solar radiation pressure and atmospheric drag perturbations) to be added on top of the nominal effects.

SSIM makes use of a mixed schema of propagation and interpolation using so-called 'rolling windows'. The first time the function receives a request for an orbit, SSIM propagates the state vector, not just up to the requested time but a little bit more, and the corresponding orbit is stored internally. The next time the function is called, the software checks if the requested time is within the limits of the pre-propagated and internally stored orbital information. In this case, SSIM uses interpolation for calculating the orbital position (no additional propagation is performed). Otherwise, the older orbit arc is removed, and a new one is stored by propagating the newest position as an additional step. In this way, the simulator stores pre-propagated time windows for each object. The rolling window and interpolation implementations are done similarly for all objects, but the parameters driving each orbital regime are different.

For example, for the GEO case, the execution time for the simulation using propagation and interpolation is around 50 seconds (for a single object, with a ground-based telescope, for a two day long simulation using a complex model of propagation) while, if we use only propagation, this time increases to 75 seconds. For the LEO case, the execution time for the simulation using propagation and interpolation is 120 seconds (1 object, radar survey, 2 days and complex model of propagation) while, if we use only propagation this time increases to 230 seconds.

In order to verify the implementation of the orbit propagation, some comparisons are executed for both SST and NEO objects. Test cases for SST objects are based on the comparison of orbits generated by SSIM with those generated with DEIMOS operational software used in DEIMOS-1 satellite's Flight Dynamics centre. NEO propagation is compared with the orbits generated by the ESA LOTNAV tool. All tests have shown good agreement.

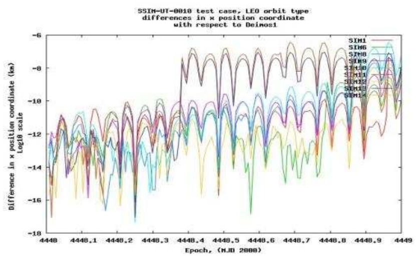

Figure 1: Position differences between SSIM propagated orbits and those obtained with the DEIMOS-1 operational tools

2.2 Sensor Model

As already mentioned, SSIM supports modelling of different types of sensors that would be expected to be used in the frame of SST and NEO segments. In this section, we present some key details about these sensor models, together with a brief description of the tracking and surveillance modes of observation. The complete description of the models is provided in [3].

The **Radar Sensor Model** supports the simulation of objects having orbits close to the Earth. Orbits that come closer than 1500km to 2000km (depending on the radar configuration parameters) are expected to be detected by radar sensors. Therefore, in particular, the NEO population cannot be detected by radar.

SSIM provides the capability to simulate two different types of radar sensors: tracking radars and surveillance radars. Whereas tracking radars intend to observe a given object in the sky based on its ephemerides, surveillance ones can observe any objects passing through an area of the sky during a given timeframe.

The following aspects are considered by the SSIM's Radar Sensor Model in order to determine whether or not a given object is detected:

- The relative distance between the radar and the orbit must be within the minimum and maximum detectable range (configurable values).
- The Signal to Noise Ratio (SNR) value must be greater than the SNR minimum (configurable value). When the SNR is greater than the minimum SNR value, an appropriate probability function is applied in order to decide whether the object is detected.

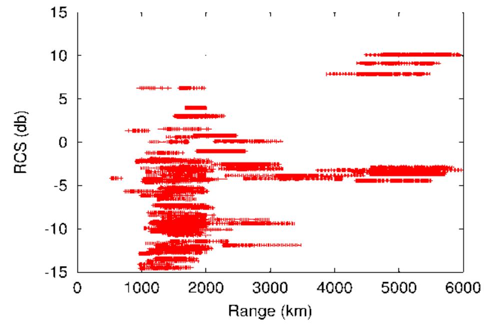

Figure 2: Radar Cross Section as a function of Range for observations generated with a simulated radar and 100 observed objects (253 tracklets are generated)

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

The SSIM ground-based telescope sensor model can be used to simulate both tracking and survey activities. In the case of tracking activities, the approach previously described for radars is applicable (i.e. ephemerides based follow-up of the object). On the other hand, survey activities are characterised by a sequence of telescope pointing instructions to be produced according to a defined surveillance strategy. In the SSIM. The available surveillance strategies are:

- Vertical strip with the telescope pointing to a close-to-Anti Sun direction (typical strategy for ground based SST observations of GEO objects)
- Horizontal strip covering different right ascension values for a fixed declination band (typical for ground based SST observations of MEO objects)
- Free Mosaic (typical for NEO observation and also suitable for more flexible SST observations if needed) allowing the definition of a right ascension/declination pattern as a function of time

The Space-based (SB) Optical Sensor Model supports the simulation of observations of the SST and NEO populations. This model is very similar to the ground based telescope model. For SB sensors some additional visibility criteria (like relative velocity between the observer and the object) appear versus GB telescopes and there is the need to propagate also the orbit where the telescope is located. SB telescope sensors support the simulation of tracking and survey activities in the same way as per GB telescopes. Surveillance strategies available for this type of sensors are based on usage of a pointing direction fixed in a local or inertial reference frame.

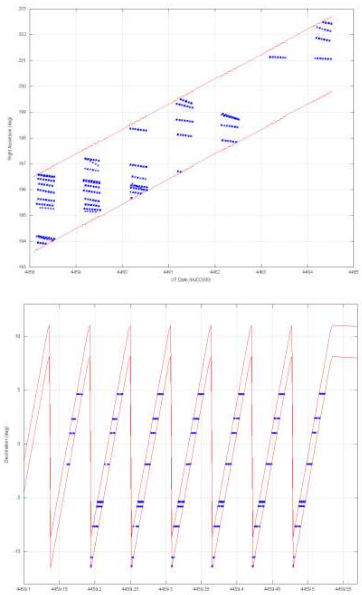

Figure 3: Simulation of Free Mosaic strategy from a ground-based telescope and the reported observations for a long-term NEO survey

The results of the observations with simulated sensors has been compared with real data for some particular cases, where such data is available, mainly for ground-based optical sensors. The first set of test consists compared the SSIM results against the simulated results by CHISTES (DEIMOS software developed for supporting the design of observation strategies for ground based telescopes, and used in the frame of operational observation campaigns with OAM). For this, we considered a set of objects that have been observed with CHISTES, and introduced as input parameters the pointing of the telescope where the objects have been actually observed. In this test the SSIM produces simulated observations of the same objects, in the same situation, at the same simulated time. On the other hand, we also consider objects that are not observed with CHISTES, and we check that the SSIM does not observe them either.

The second type of tests consists compare SSIM results against real observations performed by the La Sagra Observatory (see table 1). For this, we consider a set of objects that have been observed from La Sagra, where observations have been generated by OAM. We introduce the time and the pointing of those observations into the SSIM and compare the resulting simulated measurements with the real ones from the La Sagra telescopes. Please note that the real object position and the simulated position may differ due to the inaccuracies of the SSIM catalogue, as it is based on a TLE dataset from a date distant to the observation time.

Table 1: Comparison of simulated observations generated by SSIM and real measurements

	TIME	*DE (deg)*	*RA (deg)*
SSIM	4346.043287	56.713544	-1.688329
OAM, real	4346.043285	57.189375	-1.601222
DIFFERENCE	0.000002	0.4758321	0.087107
SSIM	4346.043426	56.762591	-1.676967
OAM, real	4346.043428	57.2400834	-1.5892778
DIFFERENCE	0.000002	0.4774924	0.087689
SSIM	4346.043576	56.8116403	-1.6656079
OAM, real	4346.043570	57.2901668	-1.5778335
DIFFERENCE	0.000006	0.4785265	0.087774

3 SIMULATION RESULTS AND EXAMPLE CASES

In order to validate SSIM correctness, we have performed a number of preliminary tests. This section presents the results for the SST population, obtained with simulations of the surveillance radar and optical (ground-based) models.

For the **SSIM surveillance radar model**, the motions of one Low Earth Orbit (LEO) object and one GEO Transfer Orbit (GTO) object have 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 [8].

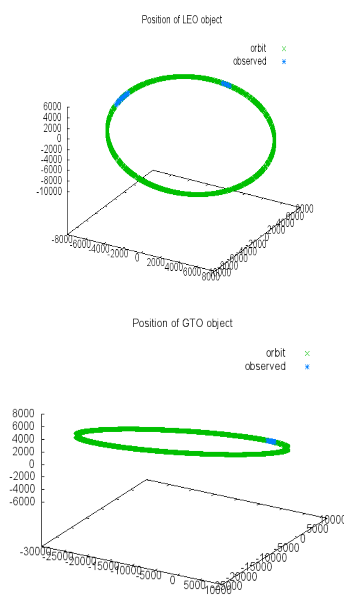

Figure 4: Representation of LEO and GTO orbits and the observation arc with a radar

Figure 4 shows the detection of both objects (blue) versus their orbits (green). 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 that correspond to the parts of the orbit that are correctly oriented with respect to the radar and that pass in between the proper elevation. In the GTO case, the orbit is highly eccentric. The only part of the orbit that is detected is close to the perigee.

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 [8]. 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
- Seeing 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 of –17 deg, Maximum declination of 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

Figure 5 shows the detection of the object (blue) versus its orbit (green) for both strategies.

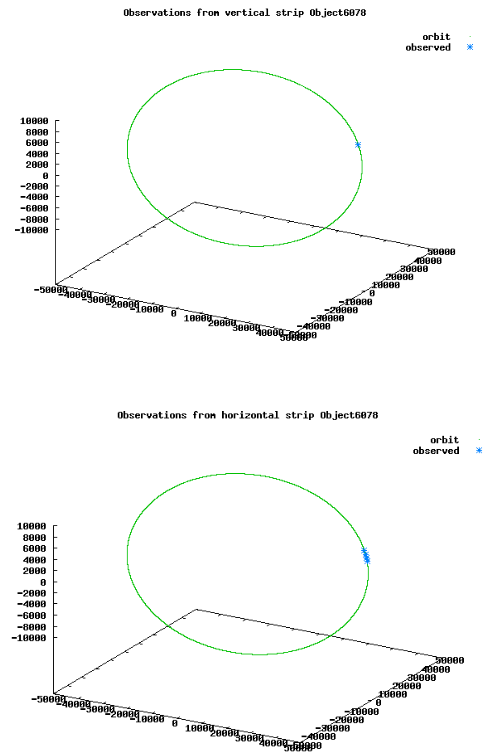

Figure 5: Observation of the same object in the case of a vertical and horizontal strip strategy

The first observation strategy 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 object observation periods provided by this strategy are formed by a very short number of (even one) single tracks (about seconds).

The second observation strategy covers a longitude band located around the equator. The motion of the telescope in this case is (more or less) parallel to the motion of the objects. Therefore the tracklets generated with this strategy are longer than the tracklets generated with the previous strategy, lasting up to several minutes.

In addition to the execution in the nominal case, SSIM allows the introduction of different kinds of events during execution time. Figures 6, 7, and 8 illustrate the impact on the observations generated with both radar or optical sensors for some of these different types of events.

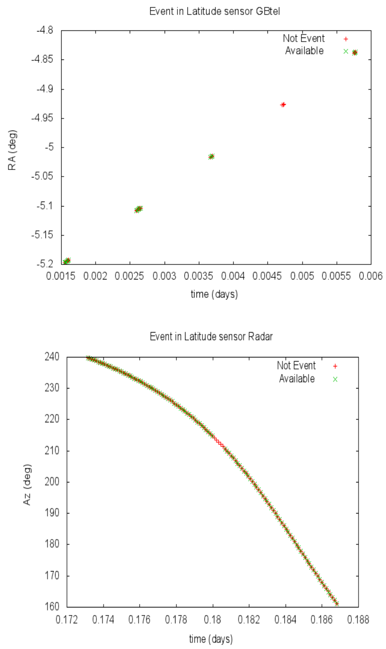

Figure 6: Impact of sensor unavailability for a ground-based optical sensor (top) and a radar sensor (bottom)

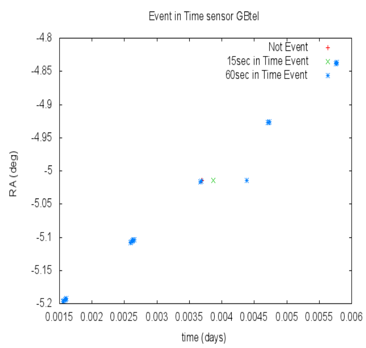

Figure 7: Impact of a large delay in the reported tracklet time for a ground-based optical sensor

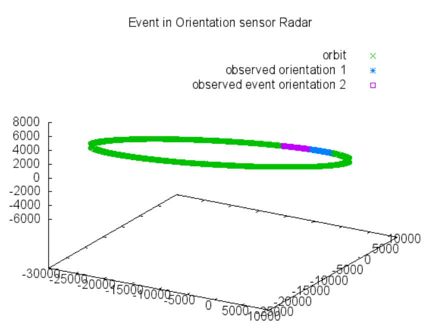

Figure 8: Impact of the change in the surveillance radar orientation

SSIM allows the simulation of sensors observing NEO objects. In the following discussion, we present an example of a test case used to determine whether the predicted position of NEO objects in the sky are predicted properly by the SSIM algorithms. In these tests, we compare the right ascension and declination reported by SSIM for certain objects with the right ascension and declination reported by the JPL HORIZONS tool for the same objects. Table 2provides the differences in right ascension and declination of the generated measurements during a survey campaign executed between 4660.0 and 4660.1 MJD2000.

Table 2: Comparison of simulated observations generated by SSIM and computed observations by JPL Horizons tool

Observed NEO Object	**Difference in RA (deg)**	**Difference in DE (deg)**
Syrinx	0.00292	0.00169
1993BW3	0.00249	0.00185
Baboquivari	0.00279	0.00073
Magellan	0.00323	0.00002

Similar tests for NEO tracking activities, where the comparison is made with JPL Horizon results, have also provided satisfactory results.

4 SSIM implementation within ESA SIMSAT infrastructure

SIMSAT (Software Infrastructure for the Modelling of SATellites) [5] is 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 [6,7] 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 and thereby reduce 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: This is the ‘engine’ of the simulation that takes care of the low level tasks such as creating and running models, storing and reading data and providing standard simulation services.
- MMI: This is the interface between the user and the simulation. The MMI is used to control and study the running system during development and use. The MMI communicates only with the Kernel.

As part of the SSIM development a large number of FORTRAN routines used in former developments (such as ESA mission analysis libraries and the DEIMOS AS4 simulator, [4]) have been embedded into SMP2 C++ wrappers. We can identify the following extensions in terms of models:

- Population model: This includes all functionalities related with the catalogues: creation of catalogue, providing an object of catalogue, applying an event or a filter in catalogue.
- Propagation orbit model: This is composed by the functionalities that provide orbit values at the requested time.
- Sensor model: This includes all functionalities that allow SSIM to determine if an object is observed/detected by a sensor and generate the corresponding tracklet.

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 called the Runtime. This perspective contains:

- 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.

In this way, the SSIM development has covered the implementation of Eclipse plug-ins/perspectives extending the SIMSAT installation to provide login, configuration, monitoring and visualization capabilities. The HMI allows the visualisation of the tracklets generated during the execution of a simulation. The logs viewed using the HMI give visibility to events entered into the object population as well as providing information on the observation request processes that occur during the simulation (see Fig. 10, from [9]).

5 SSIM within the Common SSA Integration Framework

The future European SSA system will be a complex system of systems aiming at promoting interoperability and reuse of existing assets. To this end, it was decided to experiment with a Service Oriented Architecture (SOA) approach in the DC-II activity of the SSA preparatory programme.

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 [2] .

As part of the SSA Preparatory Programme, a Common SSA Integration Framework (COSIF) is being developed. COSIF ensures a homogeneous SOA approach for SSA by 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 for DC-II 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 an SOA point of view SSIM’s solution is composed of a single high-level business process, see Figure 9.

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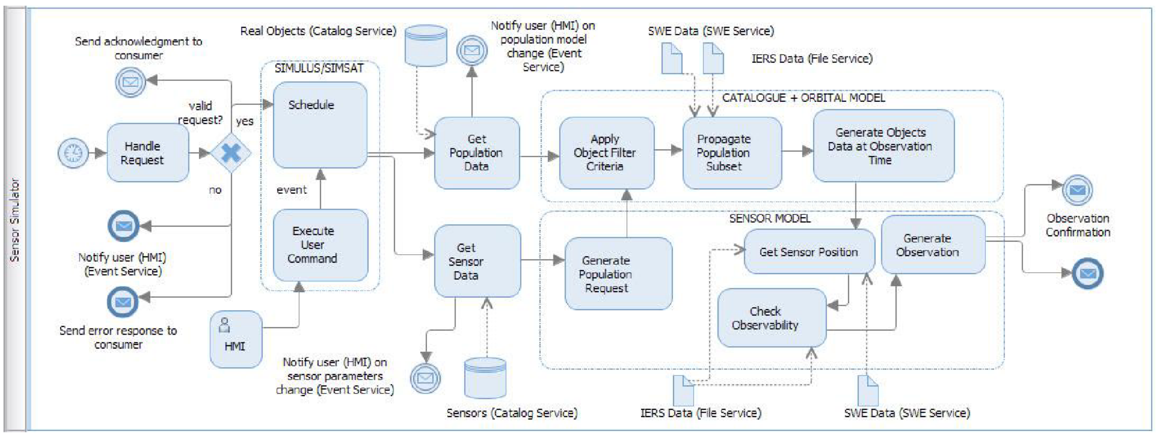

Figure 9. Sensor Simulator High-Level Business Process, from [1]

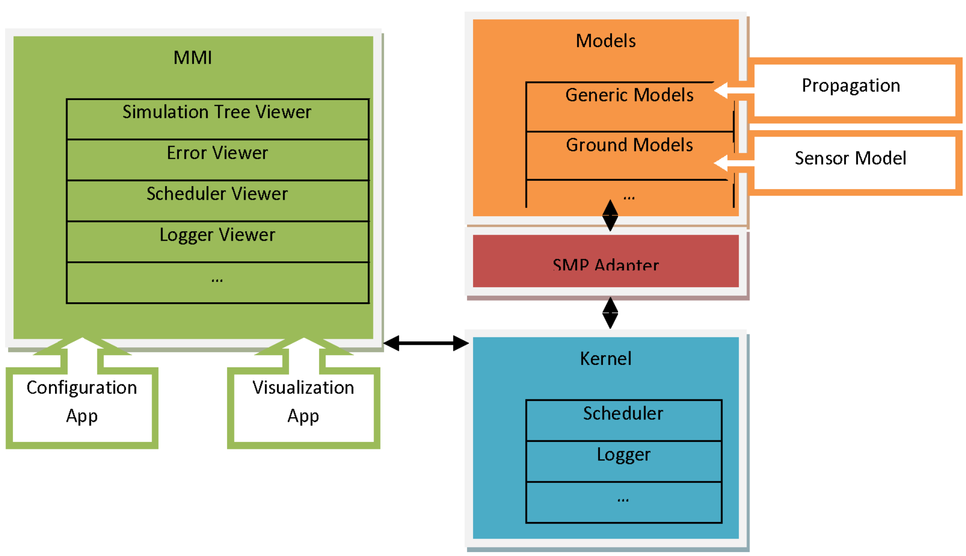

Figure 10. Conceptual extension of SSIM based on SIMSAT, from [9]