inSat3D: 3D-Ready Satellite Operations

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We previously presented the concept of a 3D monitoring tool called inSat3D, which follows the trend of more visual displays to operate complex systems, by connecting the satellite 3D model to real-time telemetry. Now it has been used for different space missions, ranging from Earth Observation to Telecommunications, we can provide the space community with an objective return on experience about using 3D technology as: a simpler approach to monitoring, a support to the training of operators working on a project, as well as a communication tool about it.

First, relating telemetry parameters to a three-dimensional visualisation cuts the complexity by providing an intuitive assessment of the spacecraft's dynamics in its environment (position, attitude or pointing). Secondly, it also improves the overall understanding of a real or a simulated system, because it provides a synthetic picture of the system at a glance. For instance, physical values such as temperature can be mapped into the 3D model using pseudo-colour encoding to get a systemic vision of telemetry data. Another particularly useful feature is the ability to perform the diagnosis of geometry related problems, such as those induced by self-shadowing, orientation w.r.t. the Sun or equipment proximity. At last, the global state of a constellation of systems can be instantaneously assessed for beam coverage or inter-visibility with ground and celestial objects.

The paper briefly recalls the main concepts and capabilities of inSat3D. Then, it describes the architecture and the interfaces that have been setup in order to efficiently implement mission requirements. Particularly, how we have chosen to base our software largely on open standards in order to achieve such a generic solution (CCSDS, OGC and W3C). The paper also focuses on the performance issues related to the management of a constellation, as well as the assumptions and trade-offs that have been made. It details different real use cases to illustrate the added-value of such a tool for *monitoring*, *communicating*, and *training*. For instance, we demonstrate how it has been useful for on-board specific analysis on the Pléiades mission but also for the mission planning & control of the O3b constellation. Then, we explain how it has been used to produce images and videos material during the LEOP (Launch & Early Orbit Phase) of different satellites. At last, we highlight the cost reduction of the Spacebus 4000 satellites training courses and the user-friendly one-click documentation browsing on the Pléiades mission. In conclusion, we discuss the general benefits of the 3D tool over more traditional monitoring tools, such as alphanumeric displays or curve plots, and summarise future plans for further development.

I. Introduction

The primary concern of satellite operations is to ensure the health and safety of satellites. The worst case in this context is probably the loss of a mission but the more common interruption of a satellite functionality

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can result in compromised mission objectives. For instance, the temperatures inside the system should be kept within certain boundaries to make it behave properly and keep it safe. All the data returning from the spacecraft are known as Telemetry (TM), which contains information related to the health of all its subsystems (including the payload). Each single item of information (e.g. the ON/OFF status of a unit, a voltage or a temperature) is contained in a telemetry *parameter*, which represents a time-variant property (i.e. a status or a measurement) to be checked.

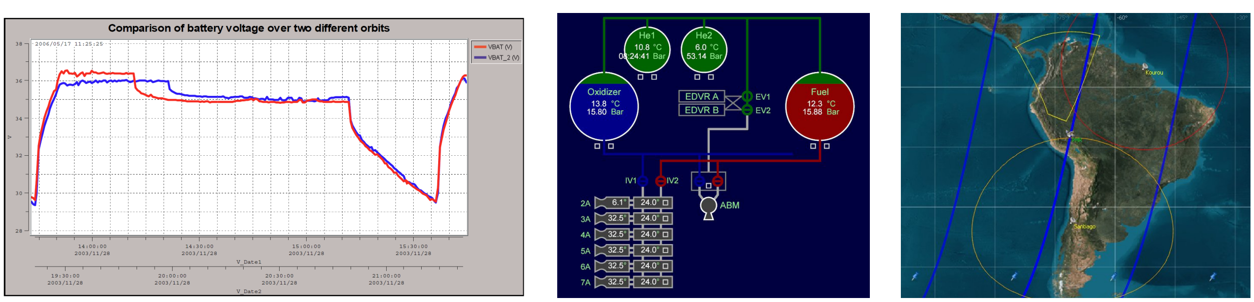
As a consequence, there is a continuous improvement of TM display applications in order to reduce the time required to respond to changes in a satellite's state of health. For example, the connection from the ground station to a LEO satellite can last only a few minutes, a fast conception of the current state of the satellite is thus very important in order to respond to occurring failures. In the context of the global satellite number expansion, there is also a need to increase the productivity of satellite controllers and the level of standardisation in satellite operations.

Classical monitoring is performed through several different kinds of display[1] including (Figure 1):

- alphanumerical pages where parameters values with alarm status are visualised as simple textual/colour information;
- 2D temporal curves to follow the dynamic evolution of parameters values against time;
- 2D functional diagrams with graphical elements representing parameters values with alarm status;
- 2D orbital displays to show the position of the system.

Although it is easy to monitor a subsystem having few parameters through these displays, engineers can hardly manage hundreds of them at the same time. The thermal subsystem is a symptomatic example of this challenge. Indeed, there are often so many thermal sensors that engineers can hardly figure out what is the global thermal status nor the correlation between different equipment thermal behaviours just looking at the values of telemetry parameters. Moreover, the large amount of textual information makes it difficult to create a synthetic and readable display. The ability to have a graphical snapshot of the system, in order to easily inspect how the temperature is distributed within the spacecraft by 3D navigation, is a great advantage in this case. Adding sun lighting conditions to this overall picture provides the immediate comprehension and the projection of their status in the future. Thus, it can also be used for training to explain thermal related matters to engineers not familiarised with the thermal subsystem. Other limitations of the usual telemetry displays are:

- the difficulty to know the real attitude of the satellite, when it is not in its canonical position (e.g. Earth pointed for geostationary satellites);
- the difficulty to know the relative position of the Earth, the Sun, the Moon or a ground station in relation to the satellite.



(a) 2D line plots showing any number of parameters against time

(b) 2D mimics showing a dynamic schematic form of parameters

(c) 2D map showing the geographical information relted to the system

Figure 1. Typical telemetry displays.

The paper is organised as follows. We present the background work in section II. The main features and the architecture of the product are detailed in section III. Then, main implementation issues for a mission as well as achieved performances are discussed in details in section IV. Real use cases are shown in section V. At last, we conclude and discuss about future in section VI.

II. Background

Three-dimensional displays have been widely used, either connected to telemetry data received from satellites in real-time[2] or ephemeris data,[3] to provide an intuitive perception of a spacecraft's dynamics in its environment. It also improves the understanding of the state of a simulation,[4] because the spacecraft is visualised as 3D object illustrating statuses like position, attitude, rotational rates, Sun direction and eclipse phases.[5] Using most out-of-the-box Mission Control Systems (such as SCOS-2000[6]) the only way to visualise the real-time telemetry or the output of a simulation is graphs and tables. For example, the satellite's attitude, its rotational rates, etc. are visualised via plots where three curves are plotted (one for each axis). They have to be combined mentally to determine the current rotational state of the satellite (which is an error-prone task), while a 3D display *shows* it immediately.

Three-dimensional displays are also widely used for mission planning and design. Donati et al.[7] presented a forecasting tool to predict the spacecraft thermal sensor values for a certain sun distance and attitude. This tool allowed the users to better plan the trajectory and attitude of Rosetta by providing a colour-coded synthesised representation of key telemetry parameter values mapped to the 3D physical model of the satellite. VTS[8,9] is a software visualization suite for space data developed for CNES concurrent engineering sessions. Its purpose is to enable experts with various points of view to describe mission scenarios, and to analyse and exchange their simulation results (solar and albedo fluxes, battery depth of discharge, current of the solar array, RF links, ...) in the reference context. It displays and animates satellites in 2D and 3D environments, and is used to support all activities related to data production during satellite mission design. The Image Generation Software (IGS) initially intended to provide realistic 3D visualization for the European Robotic Arm (ERA) Mission Planning and Training Equipment (MPTE), which used EuroSim[10] as its simulation platform. Similarly to VTS, a new activity ran as an ESA contract in the GSTP-4 programme transformed IGS into an open middleware framework to encourage the independent development of reusable functionality while isolating and minimizing the amount of application specific elements.[11]

Collision risk monitoring activities grow with the ever-increasing number of orbital debris or satellites,[12] becoming another application of 3D displays. For instance, the contingency procedure for collision management at CNES includes a dangerous conjunctions fine assessment stage involving 3D visualization.[13] Indeed, the 3D visualization helps to fully understand the geometry of the problem and validate the computation results in order to determine dangerous conjunctions that need to be mitigated.

However, three-dimensional displays have not been widely used for satellite operations. We previously presented the concept of such a tool[14] and our aim in this paper is to demonstrate how an accurate 3D representation of the spacecraft and its internal subsystems, connected to real-time telemetry data, can be used to improve system monitoring for operations. Indeed, this 3D visualization, animated in real time, allows a much simpler (thus faster) approach by providing:

- an understanding of the satellite in its environment including its subsystems/equipment;
- a synthetic, systemic and immediate vision of telemetry data (colour code or visual effect);
- an intuitive navigation system between subsystems/equipment to access the documentation.

Moreover, we want to prove that a tool like inSat3D, relying on operations standards, simplify the integration of 3D technologies into control centres compared to previous approaches. Indeed, the difficulty usually comes when integrating these tools into an existing environment. This is especially true in the space industry where specialised or one-off applications are not uncommon.

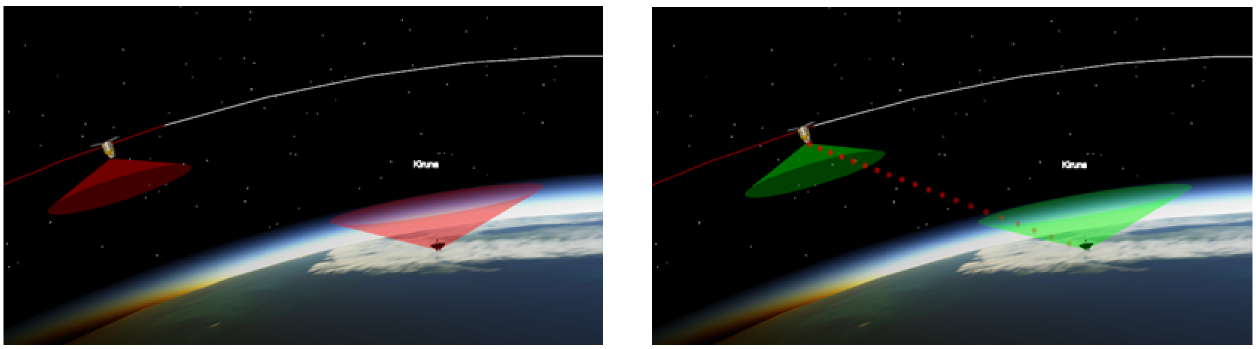
III. Product description

III.A. Main features

As a monitoring tool, inSat3D allows displaying the values and the status (validity states, alarm states) of telemetry parameters to the user. However, it uses a dynamic 3D visualization in order to provide new ways of presentation, analysis and interaction. The 3D animations describing the state of the system are created by relating (or *linking*) telemetry parameters to the visual attributes of 3D objects such as the colour, the transparency, the visibility, the position or the orientation (rotation angles or attitude quaternion). This intuitive mapping of telemetry data is a valuable tool to support satellite operations, operations training solutions as well as communication (through live demonstration or by using the image/video capture capability).

By relating telemetry parameters to 3D object's orientation, geometry related issues such as panel deployment, Sun facing or Earth pointing manoeuvers can be easily analysed. Furthermore, the implementation of an advanced lighting model for enhanced scene realism, including sun lighting as well as self-shadowing, has proven to be a useful analysis tool for complex thermal problems. Furthermore, it is able to evaluate Sun's eclipse and simulate the field-of-view of embedded sensors (star trackers or Sun/Earth sensors) including Earth, Moon, Sun and Star modelling for enhanced realism.

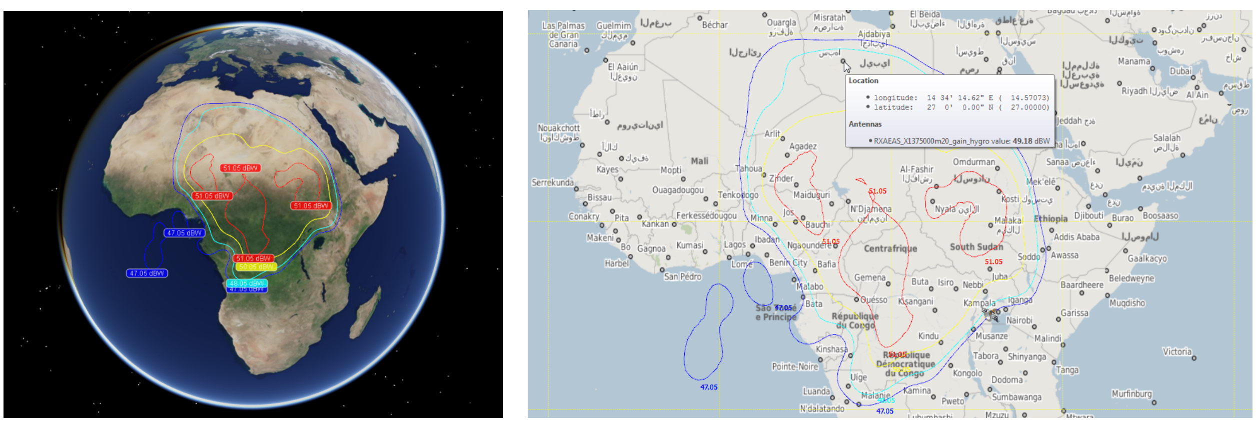
inSat3D provides orbit propagation with 2D/3D orbital related displays, and computes geometrical visibility between satellites (e.g. for GPS positioning) or satellites and ground stations (Figure 2). The internal orbit propagators used to predict satellite positions are based on Elliptical Keplerian trajectories or on the Simplified General Perturbations-4 (SGP4) and the Simplified Deep-space Perturbations-4 (SDP4) models.[15] Algorithms to compute the positions for the Sun, the Moon and the major planets provide a fairly good accuracy of at least a fraction of an arc minute for the Sun and the inner planets, about one arc minute for the outer planets, and 1-2 arc minutes for the Moon.[16,17,18] The IAU 2006 precession model[19] and the IAU 2000B nutation model[20] are implemented to compute Earth orientation with a sufficient accuracy. Based on the restitution of the system's attitude, inSat3D is also able to compute the geographic projection of the radiation pattern of telecommunication antennas and displays the result in a 3D or 2D (i.e. map) view to support mapping operations (Figure 4).



(a) The antenna and the ground station are not geometrically visible to each other

(b) The antenna and the ground station are geometrically visible to each other

Figure 2. The ground station and the acquisition representations.



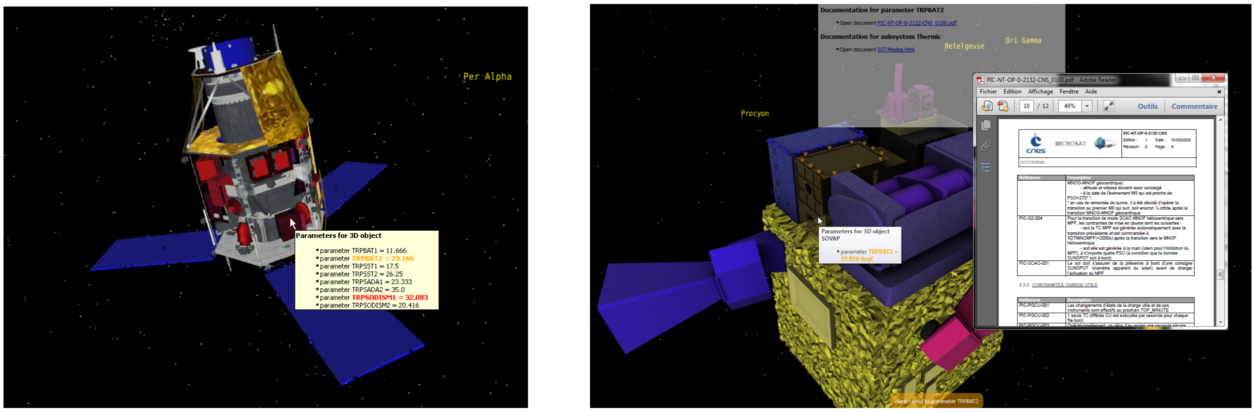
(a) A 3D representation of the radiation pattern of a payload communication antenna

(b) A 2D representation of the radiation pattern of a payload communication antenna

Figure 3. The antenna radiation pattern representation.

inSat3D comes with a set of user-friendly graphics editors to configure animations, e.g. the colour gradient that will be related to the parameter variation range, and advanced GUI operations (such as drag & drop) are used whenever possible. It is easy to select the target documents associated with an element (parameter/subsystem) and open it whenever required by 3D object picking, or through a hyperlink overlay appearing when an alarm is raised. Similarly, a link can be created between an element and a system command in order to execute it easily by 3D object picking. This has been used to open the mimics associated with a given equipment directly from the 3D model for instance.

inSat3D allows the observation of the satellite, including its subsystems/equipment, from all angles. It can manage pre-defined viewpoints as well as simplified views of the system (e.g. subsystem filtering) to focus on relevant status parameters and respond faster and more effectively to alarms. These pre-defined views can be defined according to a large set of standard reference frames such as Earth mean equator and equinox of J2000 (EME2000) or Earth true equator of date (ETOD). inSat3D displays the parameter values related to an equipment as a 2D text overlay or in a dedicated window where a selected set of parameters can be dropped on the fly. Depending on the current alarm status of the parameter, its text colour will be chosen accordingly. Similarly, attached 3D objects will blink accordingly until the alarm has been closed on the related parameter.



(a) A 3D colour-coded representation for the thermal control of equipment (blue indicates a low temperature and red indicates a high temperature)

(b) Contextual information can be automatically shown when an alarm is raised

Figure 4. Illustration of colour coded telemetry and fast contextual information access.

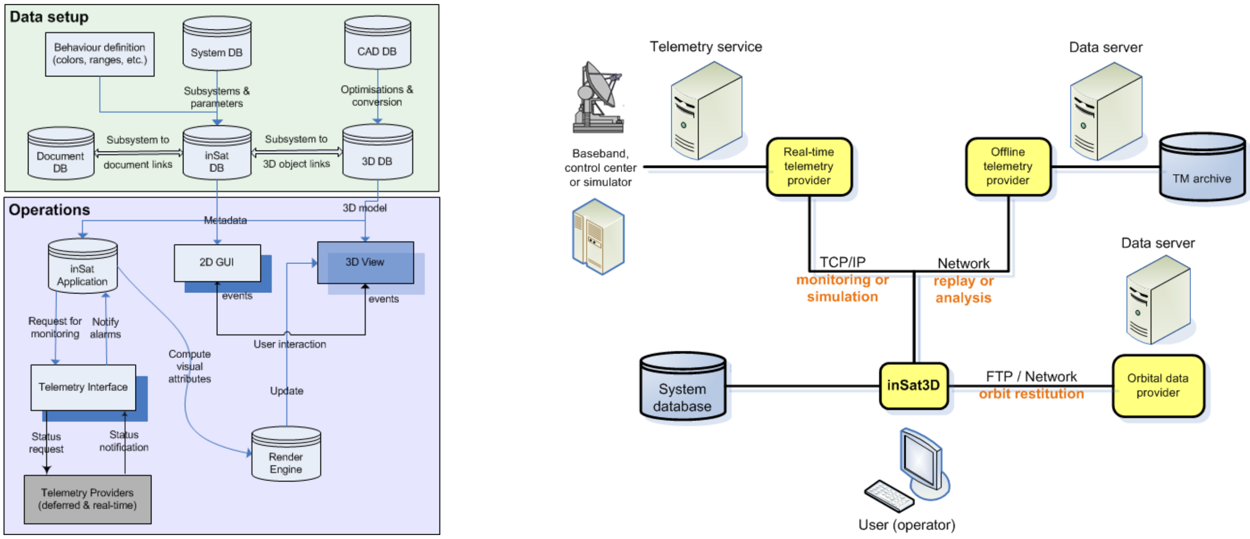
III.B. Architecture

The internal inSat3D architecture is based on the separation between the data setup phase and the operations phase. The data setup phase consists in:

1. importing/updating input data, i.e. the CAD (Computer-Aided Design) model and the System Database (SDB);
2. creating/checking the links between the different databases (3D, SDB and documents) in order to build a working environment.

The operations phase then consists in connecting this environment to telemetry providers in order to monitor the system. Once done, the render engine is in charge of updating the visual attributes of the system whenever a parameter status evolves. The value of a visual attribute is computed according to the user-defined behaviour (i.e. the set of active links or built-in animation algorithms) based on the current parameter value provided by the telemetry data source. The application reacts to user interaction through the 3D view (navigation, picking) as well as the 2D GUI (selection, edition). The general architecture diagram is shown Figure 5a.

In order to achieve a durable and cost effective solution, we have chosen to base the software largely on open source components for GUI management and 3D rendering. The choice of these components was based on extensive research to understand their strengths, weaknesses, popularity, and community support. Moreover, these components have been intensively used across industrial projects, assuring scalability and stability as well as continuous improvement. The 3D viewer combines Open Scene Graph (OSG) (www.openscenegraph.org) and the Visualization Toolkit (VTK) (www.vtk.org) to provide 3D high-level functionalities. OSG is an open source high performance 3D toolkit allowing a level of quality/realism comparable to what is available on the market with top level serious games. VTK is used for post-processing of multi-dimensional meshes to perform data extraction (cutting planes, iso-lines, iso-surfaces, etc.) or data



(a) The internal architecture of inSat3D

(b) The typical integration architecture for inSat3D in a control centre

Figure 5. The general architecture of inSat3D.

interpolation (colour mapping on a 3D mesh for instance). At last, Qt is the cross-platform application and UI framework supported by Digia (qt-project.org/) that has been used to develop the GUI and operating system level features.

IV. Product integration

IV.A. Interfaces

As most agencies are on the way to integrate even more space community standards in its product line with the ultimate goal of spacecraft operations systems unification, different file formats proposed by the Consultative Committee for Space Data Systems (CCSDS) can be directly imported by inSat3D. This includes the Orbit Parameter/Ephemeris Message (OPM/OEM) file format for orbital elements,[21] Attitude Ephemeris Message (AEM) file format for attitude[22] and the XML Telemetric and Command Exchange (XTCE)[23] for system databases. Indeed, it allows retrieving the hierarchical decomposition of the system in terms of subsystems/equipment, as well as the description of the attached set of TM parameters (including ground alarms).

Application-specific data are the links created between the different databases. These links are grouped together into different monitoring plans, which can be activated on user's request. The eXtensible Markup Language (XML)[24] is internally used by the application to store user environments, i.e. the monitoring views and plans created by the user. This format has the advantage to be easily read by both computers and human beings. Configuration utilities can thus be written easily to generate inSat3D environments from configurations defined in other formats or through an automated process. The map view can integrate data coming from raster geospatial data formats (such as GeoTiff, ECW and JPEG2000) or Web (or Tile) Mapping Service[25] providers such as OpenStreetMap to cross-reference ground projected information and geographical entities (country borders, cities locations, etc.).

inSat3D also uses a service-oriented consumer-provider API, inspired from the Spacecraft Monitor and Control (SM&C) CCSDS standard,[26] which simplifies the interface with data providers and the integration into a Service Oriented Architectures (SOA). This C++ API is tailored to the Core Parameter Service[27] and is summarised hereafter:

```
/* Structure defining parameter status */
struct status
{
        /* parameter identifier */
        String                  entityKey;
        /* date/time of the status */
        DateTime                timeStamp;
        /* might be DISABLED, UNCHECKED, UNEXPECTED, OK, LOW, HIGH, ... */
```

```
        CheckStatus          checkStatus;
        /* might be INVALID, UNVERIFIED, EXPIRED, VALID, ... */
        Validity             validityState;
        /* raw parameter value */
        Value                rawValue;
        /* engineering parameter value */
        Value                convertedValue;
}

/* Interface to be implemented by all data providers (TM, orbit, etc.) */
class ProviderInterface
{
        /* register a consumer to the provider for the given list of parameters
          (only status updates for this parameter set will be notified to the consumer) */
        void registerForMonitorStatus(const ConsumerInterface&, const list<parameter>&) = 0;

        /* deregister a consumer from the provider for the given list of parameters
          (status updates for this parameter set will not be notified anymore to the consumer) */
        void deregisterForMonitorStatus(const ConsumerInterface&, const list<parameter>&) = 0;

        /* retrieve the current status (value, alarm checking)
           of the given parameter (synchronous) */
        status requestStatus(const parameter&) const = 0;
}

/* Interface to be implemented to receive parameter status update notifications */
class ConsumerInterface
{
        /* notification sent by the given provider when the given parameter
           status has changed (asynchronous) */
        virtual void notifyMonitorStatus(const ProviderInterface&, const status&) = 0;
}
```

The Figure 5b summarises the standard integration of inSat3D in a control centre. The main data providers to interface with are the real-time telemetry provider, the archived telemetry provider (for replay) and the orbit/attitude data provider. Depending on the control centre architecture all providers might be accessible from the same interface (either message or file based) or independently.

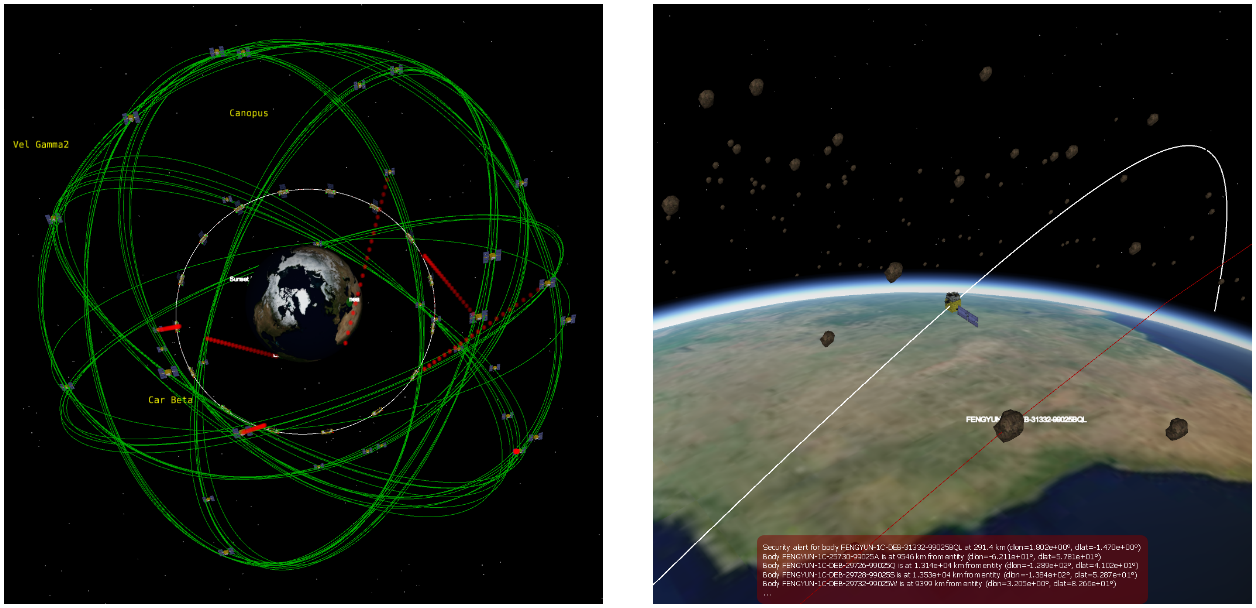
IV.B. Performances

inSat3D is able to display 3D models directly coming from design thanks to its high performance 3D engine managing both frustum and contribution culling. The goal of frustum culling is therefore to be able to identify what is inside the frustum (totally or partially), and cull everything that is not. Only the 3D objects that are inside the frustum are sent to the graphics hardware. Thus, the graphics hardware solely renders what is potentially visible, saving on the processing of all those objects that are not visible anyway. Furthermore, this can potentially improve the performance of the application since only the objects that are part of the visible part of the 3D model are kept on the graphics card memory, and these are more likely to fit than the whole 3D model. The goal of contribution culling is to discard objects if their screen projection is too small (in practice, the projection of their bounding volume and a user-defined threshold is used). This form of culling isn't conservative, but is still very interesting (Table 1) because CAD models often include many small parts such as screws, wires, etc. that do not contribute significantly to the final image. Moreover, for wide views some satellites of a constellation might become very small and project only on a couple of pixels. However, contribution culling has almost no effect on close-up views, where everything is "large enough". At last, culling and drawing can be performed on a separated application thread (these are read-only operations) on multi-core architectures to increase performances (Table 2). The performance results presented in Table 1, 2 and 3 have been achieved on an Intel Core 2 Duo P8600 CPU and a Quadro FX 2700M GPU. The reference constellation contains 8 or 16 satellites for a maximum number of one million of triangles (Figure 6).

The different data providers (TM, orbit), as well as the different animation algorithms, usually generates value updates at 1Hz, whenever a new set of values is available though. To avoid jerky movements for animations and for performances reasons, inSat3D can interpolate the target position or orientation/angle between two consecutive updates depending on the user's choice, i.e. the environment configuration. In this case, the representation actually displayed will be one "step" or a frame late from the real source value.

In order to tackle the complexity of a constellation of systems, the following assumptions have been made:

- the same 3D model is instancied for each entity of the constellation;



(a) Rendering of a constellation of 16 satellites (white orbit line) with ground stations and GPS satellites (green orbit lines) visibility

(b) Rendering of a huge set of debris (Fengyun-1C) scaled up to make them visible, the ones nearer than a user-defined distance are highlighted (red orbit line)

Figure 6. High performance capabilities (rendering and visibility/proximity computations).

- the same system database is shared by all entities of the constellation.

This allows memory saving and the use of geometry instancing, which is the practice of rendering sequentially multiple copies of the same 3D object differentiating parameters to improve the runtime performance. However, performance can still be an issue because each instance needs to have its own behaviour, which is not generic (i.e. it will be independently managed by the tool). This means that each entity has an independent dataflow and update sequence fed by the different providers (telemetry, orbit/attitude data, etc.). If the 3D model and the system database are generic, so are the monitoring links or the animation algorithms. For instance, if a link is used to manage the angular rotation of a solar panel or the temperature of an equipment on a satellite it does exist on other satellites. The user selects a *current* entity on demand in the software (by 3D picking or through mission chooser) and if a link is applied on a single entity (the current one) or on all entities at once for simplification. Whenever the current entity changes, the active single-entity links follow (i.e. ”jump” from the previous entity to the new one).

IV.C. Platform and mission customisation

inSat3D customization is usually performed by designing:

1. a specific 3D model relying on the CAD data or created from scratch;
2. specific interfaces to access orbit/attitude data and/or telemetry servers;
3. specific animation algorithms such as orbit position & attitude, deployment, thrusters, etc.;
4. specific configuration features such as SDB converters, automated configuration, etc.;
5. configuration of the tool with respect to the system.

Depending on the genericity of the platform and the control centre interfaces, some of these steps may be conducted at these levels to create a version of inSat3D able to handle the recurring missions more easily. For instance, it does exist a version of inSat3D for the Spacebus 4000 platform as well as the Eurostar 3000 platform, adapted to the OPEN SCC[28] or I4S control centers. In these cases, the single step to perform for a new mission is the configuration of the tool (step 5).

Table 1. Contribution culling performances.

Threshold*	Draw time†	Draw speed‡
0	35	45
2	31	50
10	19	75

* in number of pixels.
† in milliseconds, including update/cull/dispatch/draw.
‡ in number of frames per second.

Table 2. Multi-threading performances.

systems	# objects	threading	Draw speed*
GPS + O3b	47	single	47
GPS + O3b	47	multi	62
GPS + Globalstar	109	single	60
GPS + Globalstar	109	multi	65
Fengyun-1C debris	2751	single	30
Fengyun-1C debris	2751	multi	36

* in number of frames per second.

Table 3. Visibility computation performances.

# satellites	# antennas	# stations	# GPS satellites	time*
16	2	8	0	2.8
16	2	4	0	1.8
8	2	8	0	2.7
16	2	8	31	17.7
8	2	8	31	8.9

* in milliseconds.

Step 1 usually consists in processing the digital satellite model coming from design in order to produce an optimised 3D model well-suited for real-time rendering, and this task is performed through the use of external COTS. First, the different CAD surfaces related to a specific part (e.g. stellar sensor) are merged into a single output 3D mesh (i.e. object) for optimal performances. The accuracy for the approximation of input surfaces into polygons is the visual quality/rendering performance trade-off. Second, unnecessary parts are removed from the CAD model (such as screws for operations) and the assembly structure is simplified, while conforming to the generic structural elements (antennas, thrusters, etc.) used for animations. Third, textures and materials are fine-tuned in order to match real samples at best. At last, the 3D model is converted to the native input format of inSat3D (OSG).

Step 2 usually consists in developing the real-time connection to the control centre in order to retrieve decommuted TM data and associated monitoring information through the available interfaces. In addition, it is also common to be able to read decommuted TM data and associated monitoring data from archive files in order to simulate real-time data flow (i.e. deferred time) through the playback (play/pause/stop/jump) interface. This data flow can be used for testing purpose or offline diagnosis. At last, predicted orbit/attitude data coming from Flight Dynamics Subsystem (FDS) are often integrated to manage the LEOP because before reaching its nominal position the on-board orbit control is often disabled and one require predicted ephemeris updated regularly to follow the operations.

Step 3 can be tackled by configuration only through the generic links available in the software if relevant TM parameters are designed by the satellite experts in order to provide inSat3D with all the required information in a ready-to-use format (rotation angles, attitude quaternion, etc.). However, built-in animation algorithms can also be integrated to compute system-specific data on the fly based on specific telemetries: position, attitude, solar array deployment/positioning, thruster activation, payload antenna activation/orientation/target, etc.

Although links between the different databases can be created manually, an automated process is often setup to ensure that most of the generic platform parameters are handled automatically. The starting point of the step 4 is a SDB extraction, which includes at least the TM CODE (parameter identifier or mnemonic), converted to the input native SDB file format (XTCE). Then, the box codes (functional identifiers on the CAD model) are linked to the SDB through a correspondence table or naming rules (e.g. regular expressions). For each TM parameter/box code pair, a link is automatically created between the source parameter and the target 3D object in the CAD database, i.e. the instance having the same box code. During this phase, a layer and a 3D view corresponding to each subsystem (i.e. the subset of 3D objects corresponding to subsystem's equipment) is also created by the software. To automatically generate the colour animation links based on temperatures for thermal control, the absolute variation range and the corresponding colour gradient are first configured through a GUI. A link is only created when a single temperature parameter drives the 3D object. Indeed, otherwise, this means that the measurement point or the thermistor is not represented in the CAD database, which stops at a coarser level of detail. In this case, multiple measurement points should be "virtually" inserted onto the 3D object. However, we do not generally know the position of the sensors in the 3D model to do it automatically. Thus, the virtual sensor links have to be created manually using the inSat3D built-in capability. An option also allows to create a dedicated layer for thermal control, i.e. a layer containing all target 3D objects of generated temperature links.

The final step consists in creating the relevant configuration files defining the active elements used for the mission in the software (through the GUI or by editing XML environment files): the field of views of the sensors, the radiation patterns of the antennas, the ground stations to be used, etc.

V. Use Cases

V.A. inSat3D for Satellite Operations

V.A.1. Specific analysis for Pléiades

The Pléiades constellation is composed of two very-high-resolution optical Earth-imaging satellites operating in the same phased orbit and are offset at 180 to offer a daily revisit capability over any point on the globe. inSat3D is currently used as a plugin of VTS[9] to support specific analysis on this LEO mission at CNES, and focus on locating the telemetry in the satellite equipment. In this context, inSat3D is able to read offline telemetry data and to be synchronised through the VTS broker with other telemetry displays, such as plots, during a replay sequence.

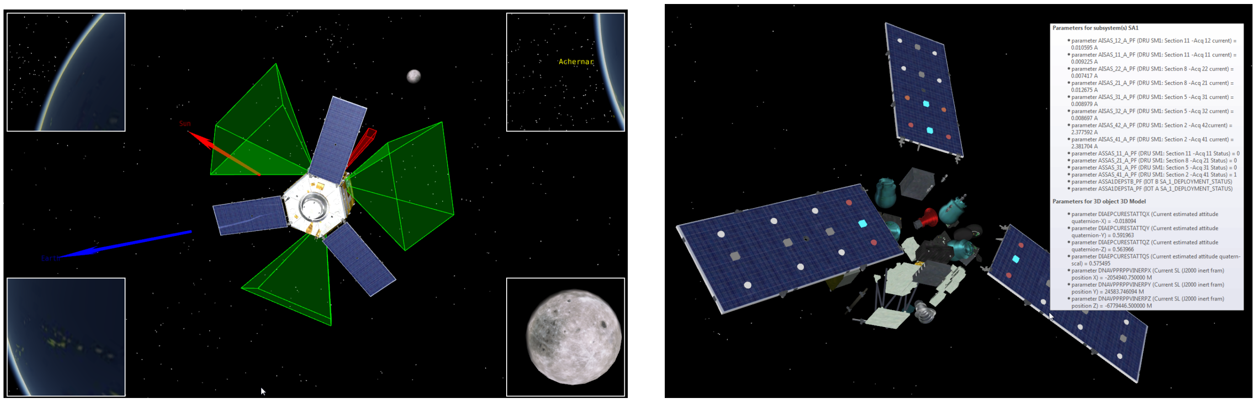
A use case has been the explanation of a blindness of the three star trackers simultaneously during about half an hour. This behaviour has been noticed at the monthly operations assessment, where about one thousand parameters selected by system experts are analysed (minimum value, maximum value, mean value, etc.). Although the spacecraft's blindness was only temporary and without any operational consequences (because the duration was lower than the alert threshold of one orbit period), inSat3D helped the operators to understand the reason of this behaviour by providing a synthetic picture of the field of views (Figure 7a) and the status (Figure 7a) of the different sensors involved. It appeared that the satellite was pointing toward the Moon because the image quality team was generating a unique data set of the Moon at very high spatial resolution (380 m) to improve the ROLO (Robotic Lunar Observatory) lunar model,[29] developed by USGS (United States Geological Survey), which is internationally accepted and used by every space agency for the calibration of satellite which are able to aim at the Moon. Indeed, thanks to its total lack of atmosphere and the perfect stability of its surface and thus optical properties, the Moon constitutes an ideal calibration site for Earth observation missions.

Another example has been the analysis of long-term and periodic behaviours of the system with respect to the Sun. As a matter of fact, to ensure a balanced power budget over one day, the satellite was designed to point its arrays towards the Sun before and after every orbit imaging sequence, i.e. just before leaving and entering the eclipse. Then, the image transmission occurs in Earth pointing mode as illustrated in Figure 8a. The position of the ground station of Kiruna (the northernmost town in Sweden) according to the night zone is subject to a seasonal dependence, but the complete ground station visibility is always used to optimise image downlink. This means that the satellite may still point toward the Earth just after exiting the eclipse in this case. This has an expected consequence on the current and the temperature because all solar array panels do not "see" the Sun exactely at the same time, which can be easily verified through inSat3D as illustrated in Figure 8b, and correlated with plots of Figures 8c and 8d. inSat3D has also been useful to understand the additional masking phenomenon due to the shadow of the propulsion system on a section of a solar panel prior to launch, during simulation sessions. It helped the operators to tailor the alert thresholds setup to detect variations between the different sections during the life of the system.

V.A.2. Mission planning & control for O3b

The O3b [a] satellite constellation is designed to deliver satellite Internet services and mobile backhaul services, has begun its deployment in a circular orbit along the equator at an altitude of 8063 km (medium earth

[a]The name "O3b" stands for "[The] Other 3 Billion", referring to the population of the world where broadband Internet is not available without help.



(a) A synthetic picture of all the sensor field of views of Pléiades (star trackers are shown in green and the optical sensor in red). The inserts in the corners simulate the different views from the sensors, where one can see that the star trackers are blind by the Earth while the optical sensor acquire the Moon.

(b) The monitoring plan used to follow the current/temperature of the different sections of the solar array panels and the status of some equipment of Pléiades. The colours are used to immediately show the state of an equipment (e.g. grey means inactive, green means OK, red means not OK, etc.).

Figure 7. Monitoring use cases of Pléiades.

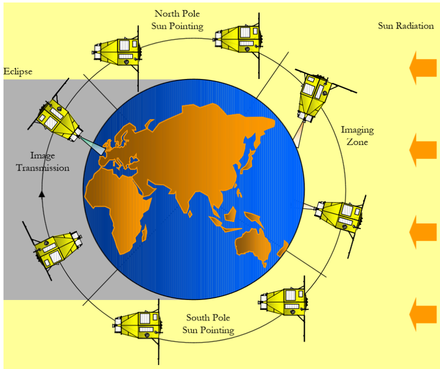
orbit). The first four satellites are currently in orbit, four more satellites are planned for launch next summer, and the constellation can reach up to sixteen satellites. Each satellite is equipped with 12 fully steerable Ka band antennas (2 beams for gateways, 10 beams for remotes), leading to possibly 192 ground targets to be monitored simultaneously. For this reason, inSat3D has been chosen by Thales Alenia Space (TAS) to ease the planning & control of the mission during the qualification and in-orbit tests.

The orientation of the payload antenna is based on a two degrees-of-freedom device providing rotations around two perpendicular axes which are both parallel to the satellite Earth deck panel. The rotations are performed such that the second axis rotation takes place about an axis whose orientation depends upon the preceding first axis rotation. For each antenna an angle describes the animation for each rotation axis, which value at a given time is computed by a dedicated algorithm according to the current number of steps sent to the motor of the antenna (Figure 9a). Once a mission table file defining the ground targets has been loaded, another algorithm automatically displays the current active target of each antenna on the Earth, with a label corresponding to the target ID of the mission targets file, as well as the associated desired line-of-sight for the antenna. A colour match is performed between the target elements and the antenna's beam to ease understanding (Figure 9b).

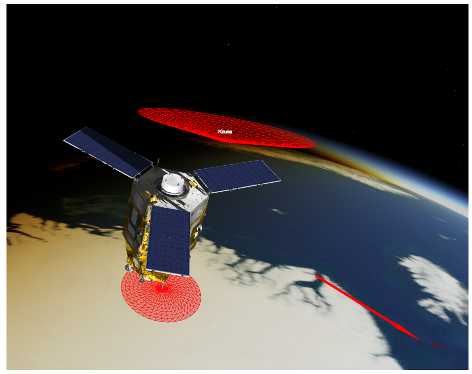
V.B. Communicate through inSat3D

For the last geostationary missions TAS has deployed inSat3D to follow in real-time LEOP and IOT (In-Orbit Test) operations. The 3D display capabilities of the product have a very positive impact on people who are not familiar with satellite operations. Employees, Managers, Customers are able to understand and follow LEOP and IOT activities through inSat3D, which makes the things more real by showing the complexity of some mechanisms (Figure 10). As an example, during antenna reflectors deployment, customer attendees did wonder about the close approach of the reflectors during their deployment. They did not imagine the cinematic implemented and were surprised by the precision required during this phase(Figure 11).

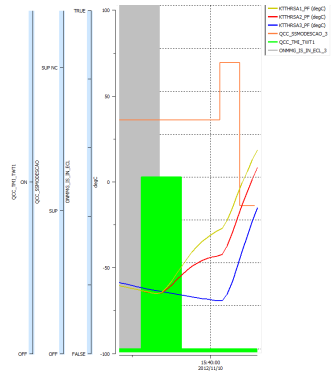
Another smart feature of the product is its ability to generate animated sequences. This function is used by TAS to build synthetic videos covering the LEOP phase, starting from the launch up to the final geostationary positioning. This "space movie", presented to the customer during the satellite final acceptance makes the link with the launch, the last visual phase of the project. Moreover, inSat3D is used internally for communication purpose. When customers, top level managers, students are visiting the TAS LEOP operations centre, a visual and dynamic projection summarises much better than words the work required to bring a satellite from the launcher separation up to its final position allowing to start its commercial life.



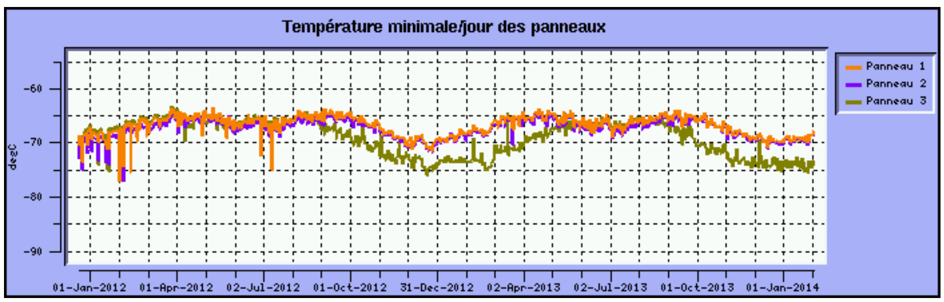
(a) Satellite pointing of Pléiades along the orbit. As the attitude changes often during the short orbit (Ĩh40) a 3D visualization is essential to understand the system behaviour.



(b) Illustration of the shadow masking of a solar array panel by some part of the body and the propulsion system of Pléiades when exiting from the eclipse (the red arrow indicates the Sun).



(c) The masking induces a lower instantaneous current and temperature on the shadowed solar array panel (as plotted in blue).



(d) The masking also induces a seasonal variation of the minimum temperature on the shadowed solar array panel (as plotted in green).

Figure 8. The shadow masking use case of Pléiades (3D graphics and plots).

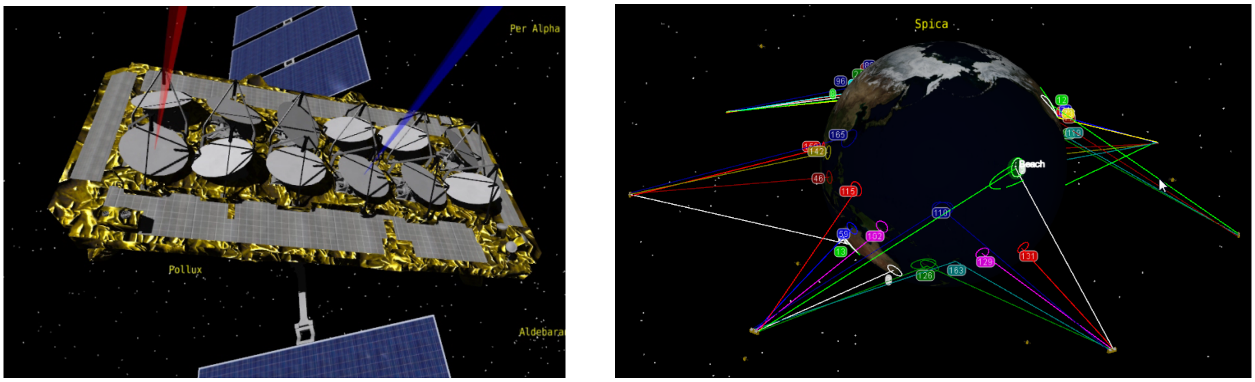
V.C. inSat3D as a Training Solution

V.C.1. Spacebus 4000 satellites training courses

For years, TAS provided to its customers satellites and associated operational services. Over the 90's, ours satellite engineers' teams were used to perform the critical operations like LEOP or IOT phase and then to transfer the spacecraft control to ours customers. These activities require to provide a dedicated training about the necessary spacecraft knowledge, nominal as well as contingencies operational procedures for satellite operations. The aim of this training is to build a new team with the necessary operational capability about spacecraft and ground systems through a complete training adapted to the "new comers" in the space activity field. In the frame of these operational training, inSat3D, connected to the Dynamics Satellite Simulator (DSS) telemetry flow, provides a powerful and a helpful support by displaying in real time the result of the exercises done by the trainees. More dynamic and visual than a PowerPoint slideshow, the inSat3D product, part of the training tools, reduce significantly the understanding time (Figure 12). It simplifies the teacher explanation and thus allow to achieve, in a shorter time than a classical training, the objective of the operational training: having a qualified team ready to control the satellite.

V.C.2. Pléiades training support

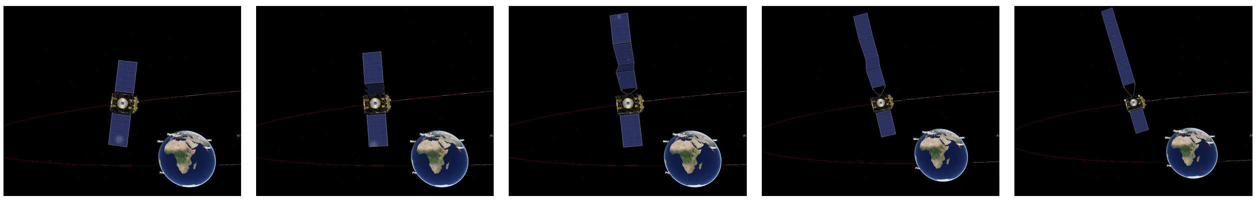
inSat3D is also used on the Pléiades mission to train operators by illustrating operational procedures such as the sequence to switch on/off a subsystem or interconnected equipment (Figure 13). Links to relevant and contextual documents have been included in the monitoring plans in order to shorter the learning curve of the system behaviour for the trainee.



(a) The 3D antenna positioning representation for a O3b satellite

(b) The 3D global coverage representation for the O3b constellation

Figure 9. The O3b use case.



(a) Partially deployed initial state

(b) 5 seconds after the total deployment beginning

(c) 20 seconds after the total deployment beginning

(d) 40 seconds after the total deployment beginning

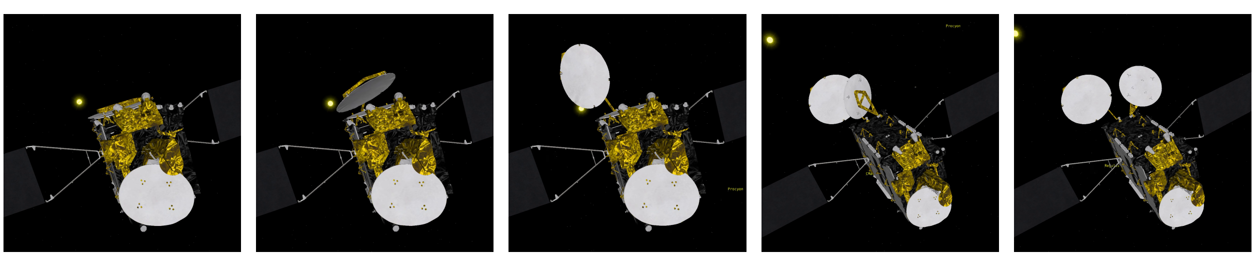
(e) Totally deployed state reached after 60 seconds

Figure 10. Different steps of a solar array deployment during a LEOP.

VI. Conclusion

So far, inSat3D has been used by CNES, TAS and Astrium across multiple missions, ranging from Earth Observation to Telecommunications. By mapping telemetry data into a realistic 3D model using animations, inSat3D provides an immediate overall, systemic and synthetic picture of the system. The ability to navigate through the spacecraft and all its internal subsystems simplifies access to contextual information for end-users. We hope to have demonstrated that it increases the efficiency of spacecraft operations and adds value to operations training and communication solutions. At last, inSat3D is a durable and cost effective solution, largely based on open source components and open standards.

In its next version, inSat3D will include a feature to compute the footprint of celestial bodies passing through a sensor field of view. It will also be able to graphically represent orbit events on the orbit line (such as entering/leaving eclipse, AOS/LOS, etc.). More ambitious future plans include the implementation of a fleet version to be able to simultaneously monitor a huge number of different missions. We have shown that the key point to handle the complexity of a constellation was to consider a generic system model duplicated N times. This is quite different from a fleet, which is composed of heterogeneous systems. In this case, each



(a) Stowed initial state

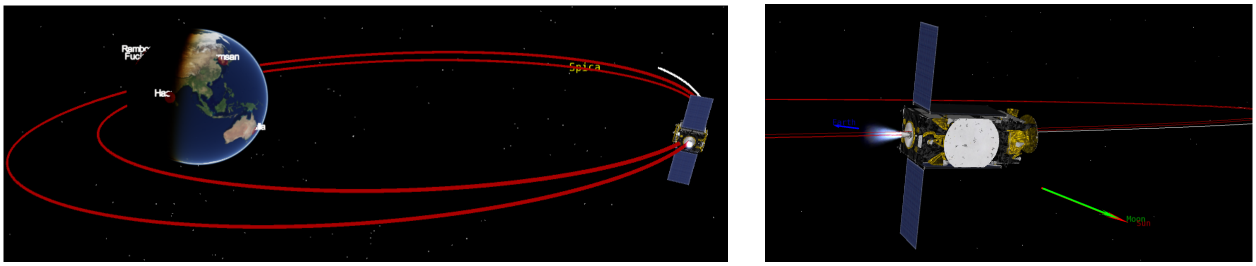
(b) Partially deployed first reflector

(c) Totally deployed first reflector

(d) Partially deployed second reflector

(e) Totally deployed second reflector

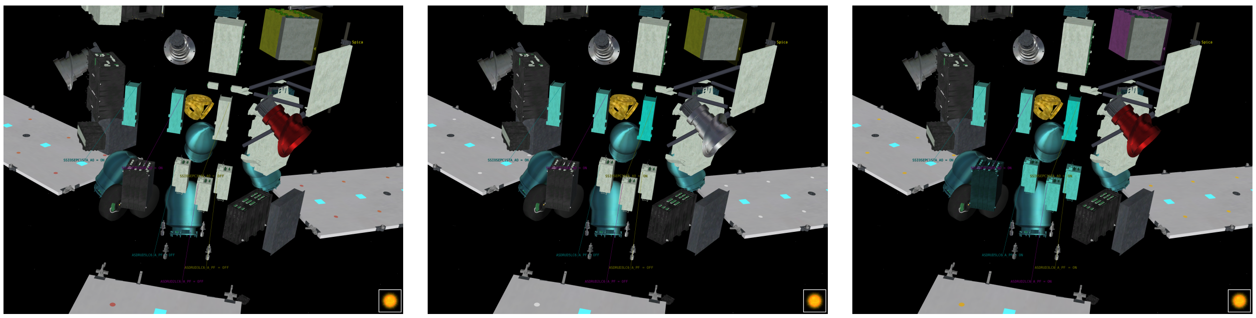
Figure 11. Different steps of the reflectors deployment during a LEOP.



(a) The past orbit position are shown in red while the new orbit position is shown in white

(b) A close-up view of the satellite showing the Apogee Boost Motor (ABM) firing during the maneuver

Figure 12. 3D Representation of an Apogee Motor Firing (AMF) during a LEOP.



(a) (b) (c)

Figure 13. A 3D representation of the different equipment states during an operational procedure.

system database and each 3D model can be a completely different entity and we cannot take benefit from the instancing. We will probably need to introduce a level-of-details strategy to load the relevant information on-demand. At last, we would like to create a web-based version of inSat3D in order to simplify access for the operators to this type of 3D tool.

References

[1] J.S. Noguero, S. Reid, J. C. G. A. P. H. and Ceballos, A., "SATMON - A Generic User Interface for Satellite Control," *Proceedings of SpaceOps 2004*, May 2004.

[2] Lee, S.-U., Cho, S.-K. C., and Kim, J.-H., "3D Display of Spacecraft Dynamics Using Real Telemetry," *Journal of Astronomy and Space Sciences*, Vol. 19, Dec. 2002, pp. 403–408.

[3] Crosnier, T., "3D Graphical Simulations for Spacecraft Missions," *Proceedings of the 4th International Conference on Astrodynamics Tools and Techniques (ICATT)*, May 2010.

[4] Pomerantz, M., Jain, A., and Myint, S., "Dspace: Real-Time 3D Visualization System for Spacecraft Dynamics Simulation," *Space Mission Challenges for Information Technology, 2009. SMC-IT 2009. Third IEEE International Conference on*, July 2009, pp. 237–245.

[5] Witt R., Fritz M., K. T. B. A. L. C. R. H.-P. E. J., "Real-time 3D Visualization in Satellite Development," *Proceedings of the 4th International Conference on Astrodynamics Tools and Techniques (ICATT)*, May 2010.

[6] Eickhoff, J., *Simulating Spacecraft Systems*, Springer Aerospace Technology, Springer, 2009.

[7] A. Donati, J.A. Martnez-Heras, P. N. and Torro, R., "Virtual Reality for Monitoring Spacecraft Thermal Subsystem.Concept & Prototype," *Proceedings of SpaceOps 2004*, May 2004.

[8] Jean-Luc Le Gal, Thierry Warrot, M. J. E. H., "Axes of Progress Engaged at CNES to Improve Capacity of Collaboration with Partners between Concurrent Design Facilities," *10th NASA-ESA Workshop on Product Data Exchange*, March 2008.

[9] Thomas CROSNIER, Jean-Luc LE GAL, Q. M. J. . M. J., "VTS: Visualization Tool for Space data," .

[10] de Vries, R., "EuroSim - New Developments," *Proceedings of SESP 2006*, November 2006.

[11] Skluzacek, C. and van der Plas, P., "OpenIGS 2:A Non-intrusive Middleware Framework for the Integration of Application and Simulation Components," October 2010.

[12] Laporte, F., "On the road to operational monitoring of collision risks in space," *Proceedings of SpaceOps 2000*, June 2000.

[13] Laporte, F. and Sasot, E., "Operational Management of Collision Risks for LEO Satellites at CNES," *Proceedings of SpaceOps 2006*, June 2006.

[14]Claustres, L. and Renaudie, E., "inSat3D: Real-time Spacecraft Monitoring in 3D," *Proceedings of the 61st International Astronautical Congress*, September.

[15]Vallado, D. A., Crawford, P., Hujsak, R., and Kelso, T. S., "Revisiting Spacetrack Report #3," *AIAA Astrodynamics Specialists Conference and Exhibit, August 2006*, 2006.

[16]van Flandern, T. and Pulkkinen, K., "Low-precision formulae for planetary positions," *apjs*, Vol. 41, Nov. 1979, pp. 391–411.

[17]Bretagnon, P. and Francou, G., "Planetary Solutions VSOP87 (Bretagnon+, 1988)," *VizieR Online Data Catalog*, Vol. 6081, May 1995, pp. 0.

[18]Chapront-Touze, M. and Chapront, J., "Lunar Solution ELP 2000-82B (Chapront-Touze+, 1988)," *VizieR Online Data Catalog*, Vol. 6079, May 1995, pp. 0.

[19]Vondrák, J., "Long-periodic Precession Parameters," *IAU Joint Discussion*, Vol. 16 of *IAU Joint Discussion*, Aug. 2006.

[20]McCarthy, D. and Petit, G., "IERS Conventions - IERS Technical Note No. 32," 2004.

[21]for Space Data Systems, C. C., "Orbit Data Messages - Blue Book - Issue 2," November 2009.

[22]for Space Data Systems, C. C., "Attitude Data Messages - Blue Book - Issue 1," May 2008.

[23]Russell, J. and Cohn, R., *Xml Telemetric and Command Exchange*, Book on Demand, 2012.

[24]Bray, T., Paoli, J., Sperberg-McQueen, C. M., Maler, E., and Yergeau, F., "Extensible Markup Language (XML) 1.0 (Fifth Edition)," World Wide Web Consortium, Recommendation REC-xml-20081126, November 2008.

[25]Open Geospatial Consortium, "OGC Web Map Service Interface," OGC 03-109r1, Version 1.3.0, January 2004.

[26]for Space Data Systems, C. C., "Mission Operations Services Concept - Green Book - Issue 3," December 2010.

[27]Poupart, E., Steere, S., Coccoluto, F., and Feliot, D., "Proof of Concept of the Core Parameter Service Using the CCSDS SM&C MAL Service," *ESA Special Publication*, Vol. 669 of *ESA Special Publication*, May 2009.

[28]Schmerber, P.-Y., "Ground Control Means for Satellite-Automated Operations: Thales Alenia Space Experience," *Proceedings of SpaceOps 2010*, 2010.

[29]S. Lachérade, S. Fourest, P. G. L. L., *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXII ISPRS Congress*, Vol. XXXIX-B1.