Simple attitude visualization tool for satellite operations

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The attitude data delivered by a satellite are three-dimensional. This characteristic makes it difficult for the operation engineers to immediately interpret them. As a matter of fact, operations of low-Earth orbiting satellite usually impose to plot these attitude data in order to analyze different situations such as a sun-pointing phase, a slew maneuver during a data-take or a dump over a ground station. Finally one tries to get a three-dimensional image of the situation from many one-dimensional plots, which is time-consuming and susceptible to errors. As a consequence, an attitude visualization tool has been developed to quickly analyze and represent attitude data, as a complement of flight dynamics analysis. Such a tool has been implemented for the BIRD mission and had to comply with some constraints: a simple and low-cost design coupled with an easy-to-use, operation-oriented philosophy.

I. Introduction

ATTITUDE data are per nature three-dimensional. As a consequence, the best way to get the whole picture about the orientation of a satellite is not plotting each orientation angle versus time, or even projecting the data on a plane but implies a true three-dimensional display. Nowadays, the power of computers is such that a real-time display of fast changing data in three dimensions is not a problem anymore. Consequently, a natural evolution in operations of attitude control system shall involve the development of attitude visualization software, which can be coupled with the telemetry stream of the satellite.

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II. The BIRD mission and the birth of the idea

A. Background about the BIRD mission

The BIRD Micro-satellite (Bi-spectral Infra-Red Detector) was launched on October 22nd, 2001 on a PSLV rocket from Shriharikota (India) into a sun synchronous orbit with a height of 570 km and an inclination of 97,8 degrees.

The primary objective of the BIRD Mission was to test a new generation of infra-red sensors for the detection and scientific investigation of hot spots (forest fires, volcanic activities or coal seams) as well as the demonstration of new micro-satellite technologies in space. The nominal lifetime was designed to last a year and a half.

The BIRD attitude control and navigation system is equipped with four pairs of sun sensors, a magnetometer, a gyroscope assembly (Inertial Measurement Unit: IMU), two newly developed star sensors and a GPS receiver. Four reaction wheels allow a three-axis stabilized attitude and three magnetic coils are used to autonomously desature these reaction wheels.

Nominally the solar panels of the satellite were sun-pointed in order to charge the batteries. These batteries were then used to provide the required power during the data-takes, which required turning the satellite to the target scene.

The performance of the onboard system was good over 2 years until the gyroscope assembly began delivering permanently misleading data to the onboard attitude control system. As a consequence the orders sent to the reaction wheels were based on erroneous attitude estimation and were not related to the actual situation. The reaction wheels ran then to their limit rotation rate and stayed in this state. This happened during a non coverage period, leading to the complete depletion of the batteries… The board software entered a self-sustained cycle: the empty batteries triggered the board to boot itself, which consumed the remaining power available. A spin motion prevented a long exposure of the solar panels to the sun, rendering communication with the satellite very difficult. Finally, when the gyroscope assembly could be switched off, there was only one operational wheel left. Fortunately a complete check of the BIRD onboard systems and the payload showed good performances.

B. The need for a simple visualization tool

The situation was all the sudden completely new: three out of the four reaction wheels and the IMU were out of order! Since the payload and batteries were still operational, it was decided to upload a new software to prevent the board computer to use the failed equipments. New attitude control laws relying only on sun sensors and magnetic coils have been implemented to ensure battery charging. The satellite was safe again from that point on and the payload was still in good shape.

It was then decided to implement further attitude control laws in order to go on using the payload. Due to the coarse measurements of the sun sensors and the very low torque of the magnetic coils, a precise orientation of the satellite was not possible. Moreover difficulties occurred when trying to use star camera data in the control loop. As a matter of fact, the star cameras mounted on BIRD are very sensitive to accelerations and blending either from Earth or Sun so that they were able to lock themselves only under special circumstances and for a very short time. Consequently, star cameras could not be used to stabilize satellite during the data-takes. Last but not least, the BIRD payload has to be orientated with respect to the flight direction so that it functions properly. Ideas to use the remaining valid reaction wheel in conjunction with magnetic coils have been investigated as well.

Designing and testing a software, based primarily on sun sensors and magnetic coils, for attitude control and taking into account the previous constraints has been challenging. However operating such experimental software also turned out to be challenging in understanding what the satellite was actually doing!

During eclipse the attitude is not controlled, yielding a random attitude. As soon as the sun reference is available again, the attitude correction starts but performances depend on the local magnetic field orientation and the start attitude. Consequently it sometimes happens that the sun pointing is not reached prior to the next eclipse, causing a shortage in power leading to safe mode triggering. Analyzing the reactions of the satellite requires taking into account many parameters (start attitude, local magnetic field as already said but also sun direction, flight direction…).

The analysis of a slew maneuver is even more demanding with the reference to the nadir orientation. Such an analysis is of course done offline by flight dynamics experts, who can very accurately describe what happened and the reasons of the observed behavior. Here are some examples of such analysis:

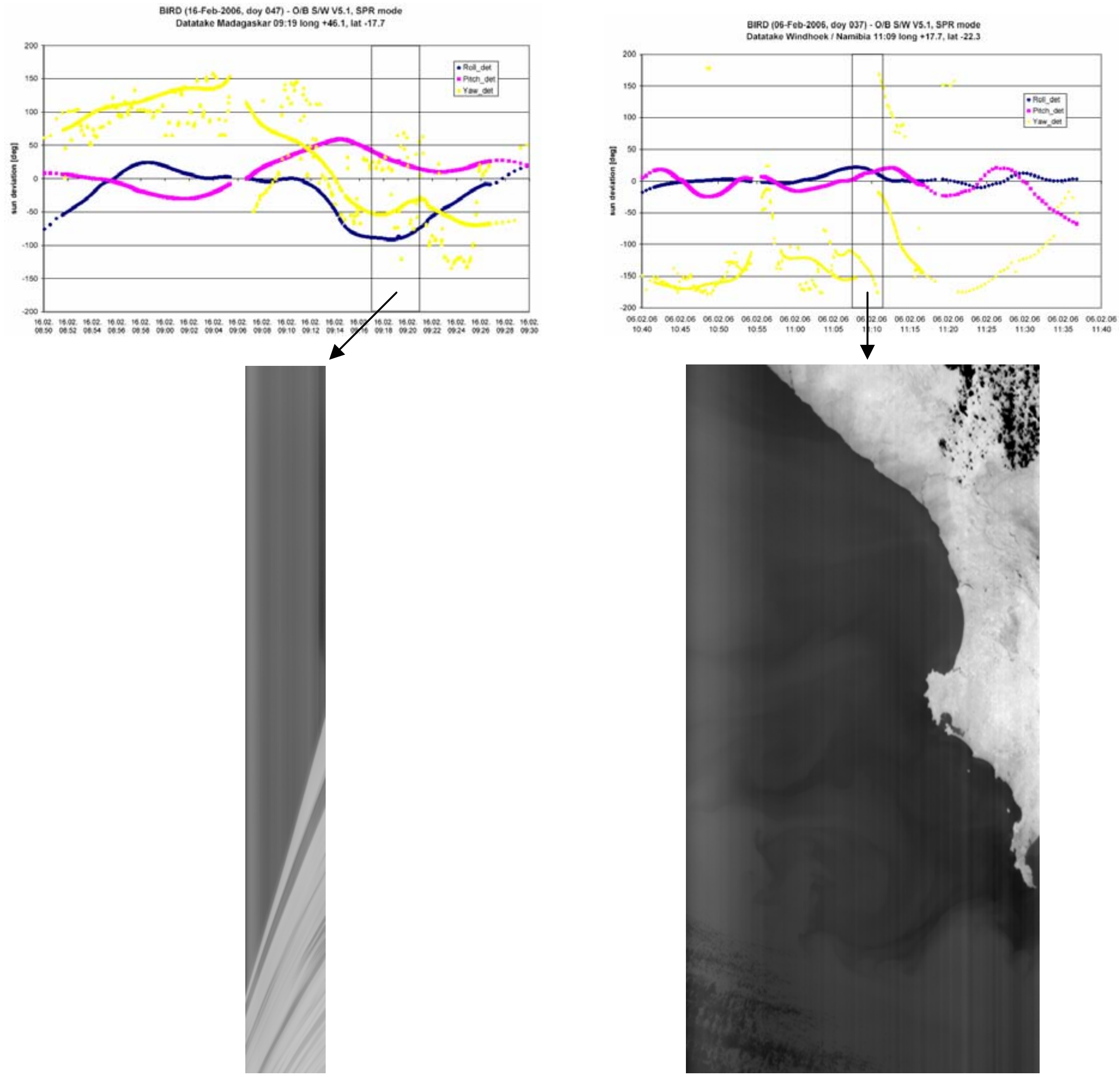

Figure 1 : Two attitude plots and the corresponding picture

Although perfectly correct, it is often difficult to get an overview of the situation with such plots, which focus themselves on a small number of parameters. To fully understand what happened, such plots have to be combined with other plots and one shall remember the conventions attached to these data: right-handed reference frames to orientate the axis, rotation rates usually in body-fixed reference frame, quaternion definition (which reference frames are used? is the scalar part given by the first or that last component?), around which axis is the pitch rotation? What is the sequence for the Euler angles?... There is a long list of conventions, which are often different from a satellite to another! Of course, this is the job of the ACS expert to examine such data and report about the situation to the operation manager. However such analysis could be time consuming and, as Napoleon said, a picture is worth a thousand words: so the idea came up to use a simple offline tool to quickly investigate and visualize the attitude history.

This tool was to present the attitude motion of the satellite as well as important reference directions such as the one of the Sun or the nadir. It shall be based mostly on telemetry data dumped from the satellite but would of course require the computation of external data (sun direction for example). This tool was to be used as a *complement* to flight dynamics investigations, and is not meant to replace them. It is only a support to better summarize and display the relevant data.

III. Realisation: the SatelliteSim tool

The idea of a visualization tool is not new but such a tool was not available at GSOC when the need described at the previous chapter aroused. The actual realization resulted from a night shift discussion: G. Mihail had already developed a three-dimensional animation concept in order to build a satellite simulator whereas F. Chatel was concerned about the reactions of BIRD. G. Mihail succeeded into customizing his tools to fit the need of the mission.

At this point, it must be said that his entire work has been done as a part-time activity and cannot pretend to have reach the status of a fully grown and implemented tool. However this work proved itself to be valuable for the analysis purposes already exposed. This tool has been developed quickly (around six months), for a specific use and has been kept as simple as possible without neglecting the rigor where it was required.

From the beginning, it was decided to use this tool offline (when no real time telemetry data is available, between the contacts) in order to reduce the complexity of the data interface. The BIRD history data are indeed processed separately and saved as ASCII files, which can be easily processed. Since the main goal was to analyze the data-take sequence, during which the satellite is pointed to its earth target, the Earth surface is the only reference displayed.

The following drawing gives an overview of the architecture, which will be developed in the following chapters.

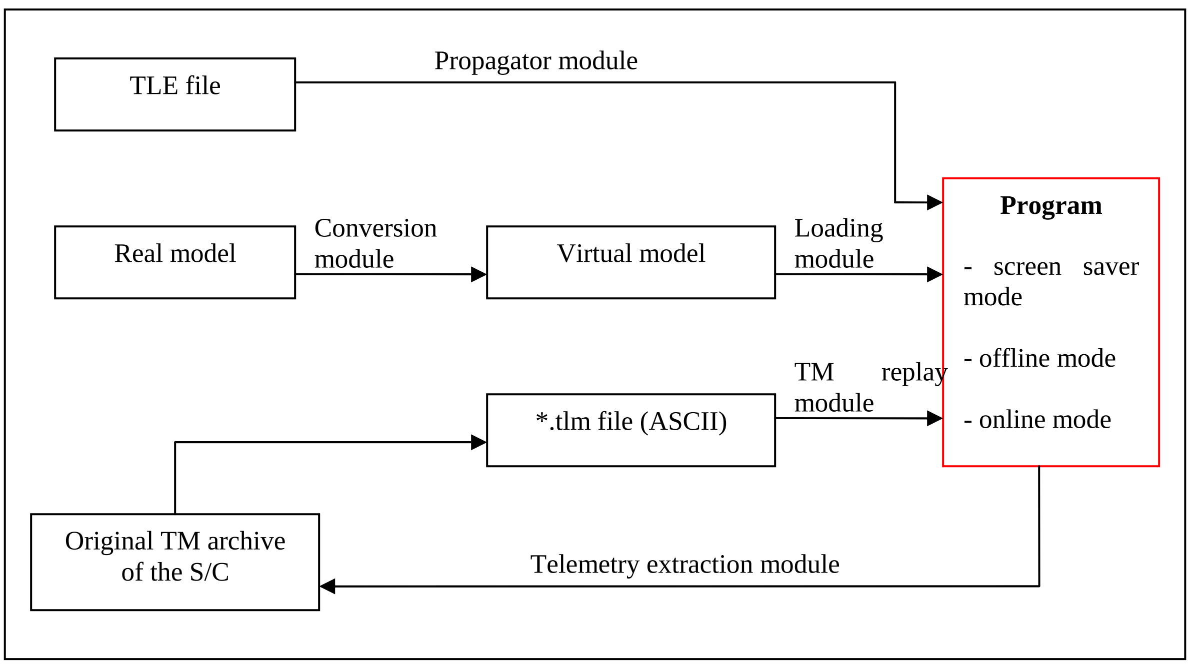

Figure 2 : General architecture of SatelliteSim tool

A. The real and virtual models

The real model has been developed under AutoCAD from the drawings provided by the satellite manufacturer. It respects the dimensions of the real spacecraft. The accommodation of the main equipments has been included in order to facilitate the further analysis. As a matter of fact, not only the external surface will be displayed in the 3D animation, but also all the equipments, thus allowing simple assessments about the pointing of the payload, possible blinding of the star cameras by the Earth and so on.

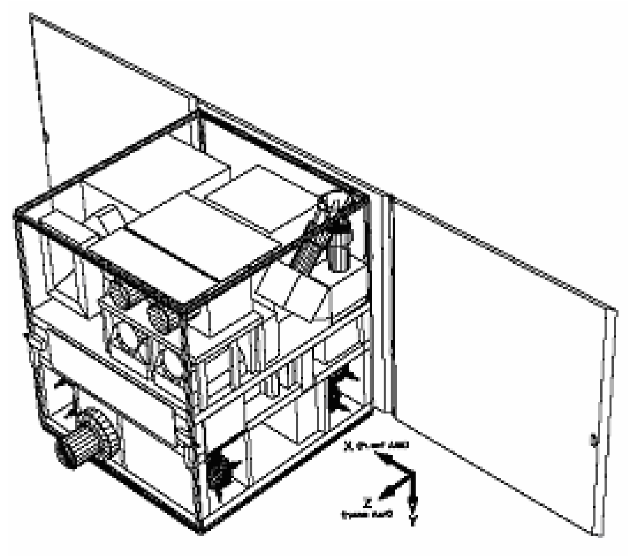

Figure 3 : Simple representation of BIRD satellite – industry drawing

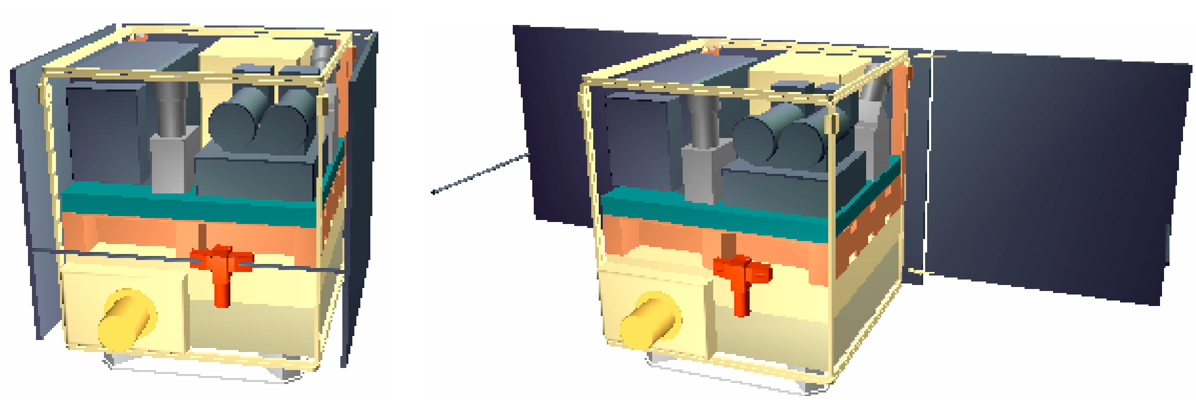

Figure 4 : BIRD launch and flight configuration – industry drawing

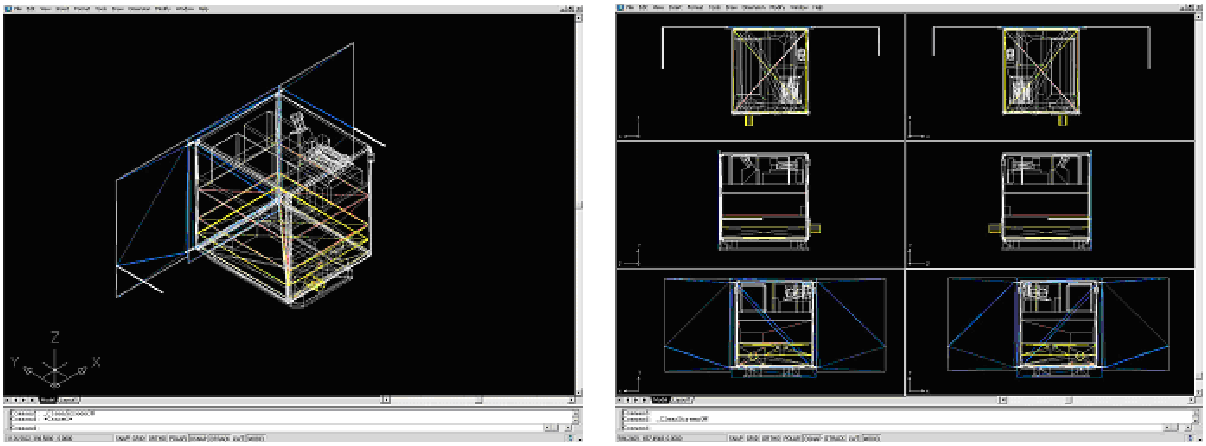

Figure 5 : BIRD model in AutoCAD – Isometric and 6 viewports (top/bottom/left/right/front/back)

Since it would be very difficult and resource-consuming to animate the real model in a real-time application, a “simplified” model (called virtual model) has been generated from the real model. It consists in a collection of points, lines and surfaces corresponding to the real model and stored as matrices. The simplification of the virtual model comes from the reduced number of information stored in this model, thus allowing real-time animations.

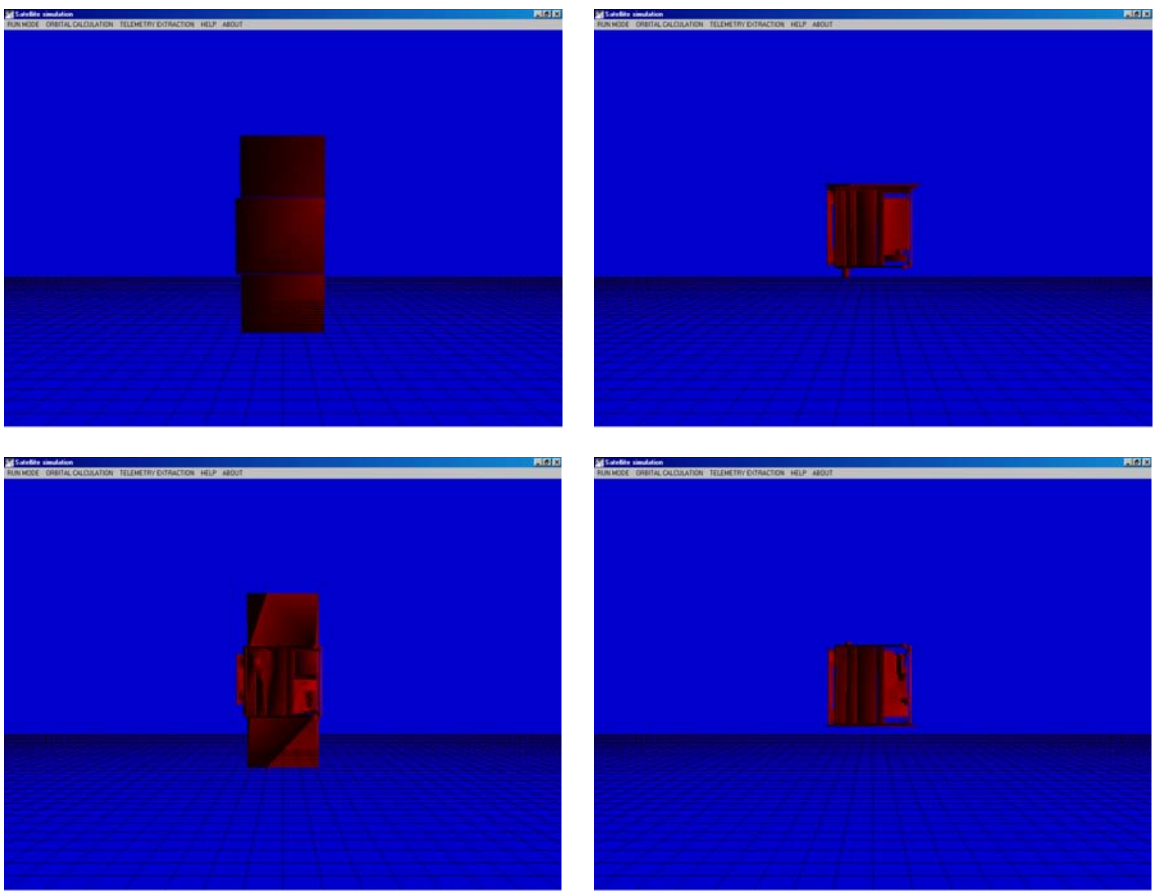

Figure 6 : Several views of BIRD virtual model in SatelliteSim tool

B. The telemetry extraction module

The extraction module aims at retrieving the parameters of interest from the satellite raw telemetry files. These parameters are interpreted and formatted into a specific file format (ASCII) that will be later used by the core program. All calculations for the other derived parameters are performed at this stage. The highlighted part on figure 6 corresponds to a single TM stamp that will be played by the satellite simulation tool.

```
2004/01/05 00:00:34   5.000394   IN_USE   IN_USE NOT_USED   IN_USE NOT_USED
IN_USE NOT_USED   IN_USE NOT_USED   IN_USE  AAM  0.00055  0.00031 -0.99994
0.36609 -0.70599 -0.60614
-0.0053838 -0.3532708  0.6490566  0.6737182   IN_USE   IN_USE   IN_USE   IN_USE
IN_USE   IN_USE   IN_USE -3533682.0    1316294.0     -5819687.0    0.6294629
0.1613369      -0.2331447     -0.7234573    4  OD      27.970776  95.988995  -
148.166452  !
2004/01/05 00:01:04   5.000741   IN_USE   IN_USE NOT_USED   IN_USE NOT_USED
IN_USE NOT_USED   IN_USE NOT_USED   IN_USE  AAM  0.00104 -0.00006 -0.99994
0.36047 -0.73389 -0.57562
 0.0003689 -0.3481723  0.6509087  0.6746064   IN_USE   IN_USE   IN_USE   IN_USE
IN_USE   IN_USE   IN_USE -3336442.0    1310974.0     -5936220.0    0.6331905
0.1494738      -0.2228124     -0.7260041    4  OD      28.049796  95.840853  -
149.134895  !
2004/01/05 00:01:34   5.001088   IN_USE   IN_USE NOT_USED   IN_USE NOT_USED
IN_USE NOT_USED   IN_USE NOT_USED   IN_USE  AAM  0.00055  0.00018 -0.99994
0.35681 -0.76642 -0.53406
 0.0033133 -0.3452297  0.6510930  0.6759315   IN_USE   IN_USE   IN_USE   IN_USE
IN_USE   IN_USE   IN_USE -3135672.0    1303386.0     -6046373.0    0.6367483
0.1375714      -0.2124210     -0.7283564    4  OD      28.100384  95.608555  -
149.698619  !
```

Figure 7 : Output of the telemetry extraction module

The extracted parameters are not limited to the attitude quaternions from the satellite but also include useful other parameters such as the components of the magnetic field and sun vectors or the currently used sensors and actuators. The SatelliteSim tool provides a display capability and these parameters can be viewed on specific pages during the animation, thus enabling a more complete analysis.

C. The propagator module

An orbit propagator has been included in the SatelliteSim tool although it was not absolutely required to meet the primary goal of displaying the attitude motion of the satellite. This module is however interesting since BIRD is able to autonomously compute its position from GPS measurements. Indeed, it enables a cross checking of the performances of the on-board navigation software. Another reason for implementing such a module was to improve the display: the Earth is only figured as a grid and the Sun is not represented. This propagator builds the basis for these future improvements, as presented later in this document.

The propagator module uses the two lines element format as input. It is a classical propagator program including the NORAD SGP/SDP4 model for orbit perturbations.

D. The core program

The main application has been developed under Visual C++, making use of the OpenGL library for the graphical part. This library provides some specialized mathematical functions for animations. The rotations applied to the virtual model are coded as rotation matrices.

The core program loads the virtual model at start-up. Two modes are then available: offline or online. The offline mode is a kind of presentation mode for the satellite, in which the model can be zoomed in, zoomed out or rotated. The online mode on the other hand is used to replay telemetry data, which have been extracted by the telemetry extraction module. This mode displays the attitude motion of the satellite and offers the option to browse the other parameters on six specific display pages. The start frame as well as the replay speed (fast or slow) is settable.

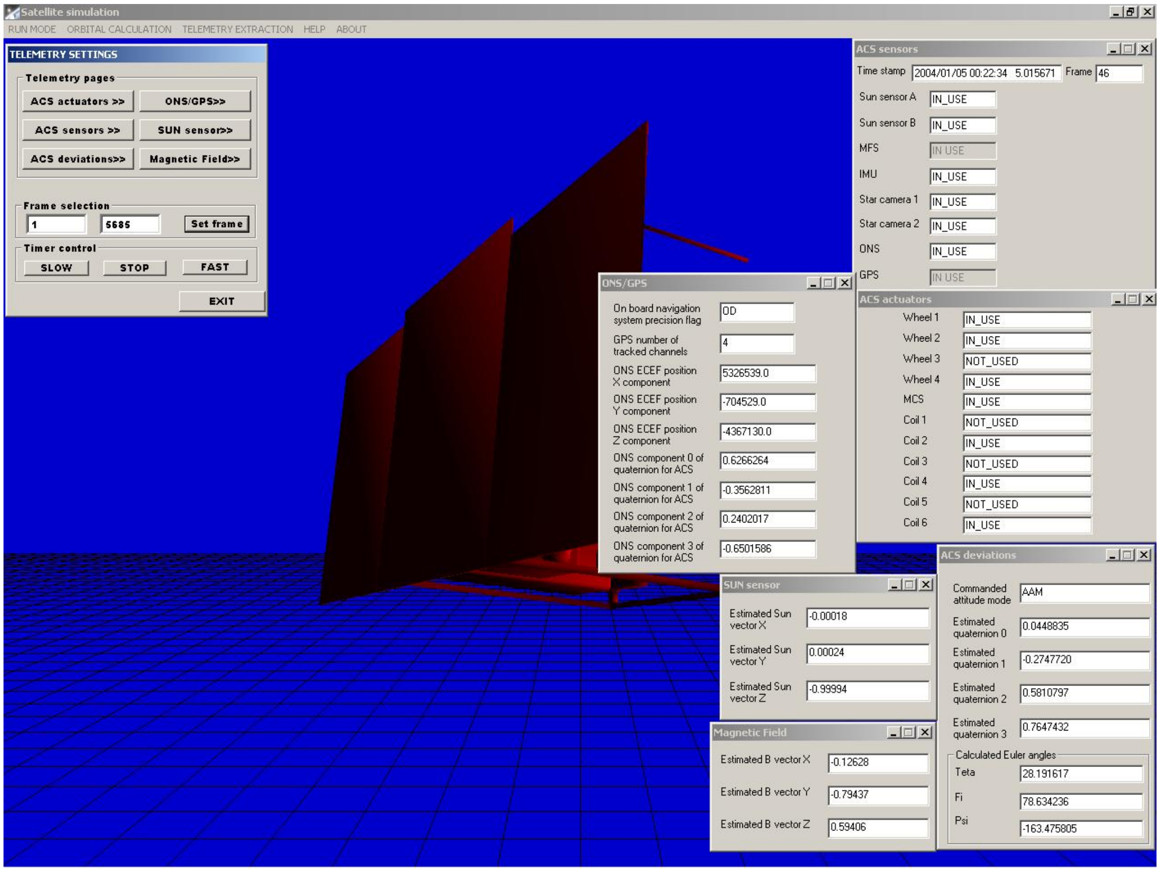

Figure 8 : Screenshot of SatelliteSim tool with display pages and control panel

From the performance point of view, the program has been tested on a Pentium 4 at 1.7 GHz, resulting in an average CPU load around 20% with a maximum around 40%.

IV. Use and results

The SatelliteSim tool has been successfully implemented and allowed quick analysis of all kind of attitude related behavior. It has been used to investigate the attitude maneuvers performed by the spacecraft during data-takes as well as dumps over the ground stations. The satellite pointing to a target on Earth could also be studied. This tool turns out to be valuable whenever an attitude problem occurs.

Not only pure attitude relevant problem could be investigated, but also those related to power and thermal aspects. As a matter of fact, it is possible to quickly assess whether a safe-mode was triggered by a bad sun-pointing resulting in a depletion of the batteries or by an overuse of the system resources (too many power consuming activities without recharging slots in between). Such interpretations are very useful to detect possible failures or to simply better plan scientific activities with the payload.

V. Future developments

A. Simulator

The SatelliteSim tool was originally thought as a simulator and this direction will be developed in the future. A real simulator with all the on board equipments simulated by mathematical models will be integrated, thus allowing the user to command different possible scenarios and see the results on the simulated spacecraft system. This is important in order to prevent future failures on the real system.

The propagator module already provides capabilities of predicting the satellite path and current sub-point, the Sun direction, and visibility of different ground stations. The next version will simulate the movement of the Moon and the Sun (which produce the main perturbations for the AOCS equipments) and display them together with the satellite in the same screen. Such information would enable computing and displaying the interferences of the star camera sensors for instance. A real map of the Earth can be also implemented for data-take analysis.

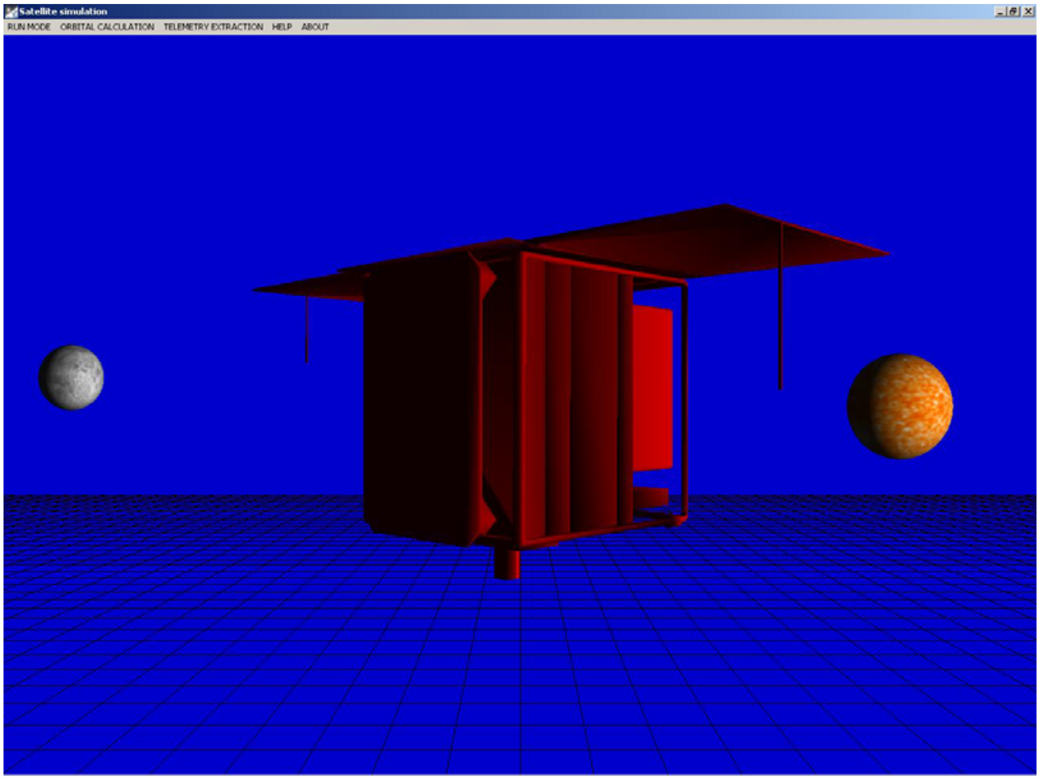

Figure 9 : Moon, Sun and spacecraft representation together in the virtual scene

B. Real-time animation in telemetry system

Another axis of development is to couple this visualization tool directly with the telemetry system. This allows displaying the attitude of the satellite in real-time, based on the telemetry data. Such a kind of display will be developed at GSOC in a close future to support upcoming missions.

The visualization of the satellite attitude in real-time is of great interest for the operations. It can be used in the interpretation of telemetry values. For example knowing which face is in the shadow of the sun or looks to deep space could help explaining the temperatures measured by the sensors. The blinding of equipments such as star sensors by the sun or the moon could also be easily understood.

Another aspect of the visualization is the forecast of potentially dangerous situations. For instance, displaying the antenna pattern with a model of the satellite could help foreseeing a loss of up/downlink signal, thus giving the chance to the operators to postpone some critical commanding (orbit maneuver, computer reboot, swap of sensors…).

Of course, the visualization is not limited to the satellite model and the Earth. One can get all the relevant information on the display. Depending on the mission and on the available telemetry, one could think on displaying the planets (for an observation satellite), the satellites of the GPS constellation (their availability often influences the on-board orbit computation) or the position of other satellites in the constellation in case of inter-satellite link is available.

VI. Conclusion

Attitude visualization tools are now within the computing power of normal machines. Such tools provide a very helpful support not only in the interpretation of three-dimensional attitude data but more generally of telemetry data from different subsystems. They allow displaying information from different sources, thus making possible to analyze complex situations involving ground stations or other satellites.

Apart from the use in operations, displaying the motion of the satellite has a tremendous didactical effect. Either in a simulator or on a screen in control room, an animation of the satellite makes it easier to discuss about various issues. It allows people getting a direct representation of a complex reality and this will certainly contribute to the vulgarization of the space business.