Attitude Control of the Spacecraft TARANIS: Sun Acquisition Robustness

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Abstract

This paper deals with the study of the robustness concerning the attitude control of the spacecraft TARANIS regarding disturbances on its sun acquisition sensors. Two kinds of disturbances have been studied: the masking of the sunlight by the different spacecraft devices as well as the sunlight reflection on their surface. This study has been performed by doing first the sensor and observer modeling on a simulator specially designed for the study from the whole spacecraft simulator. Then the modeling of the disturbances has been achieved depending on the characteristics of the sources in terms of size, positioning, roughness and light reflection. Finally a set of simulations of the acquisition and survival mode has been executed in order to evaluate the impact of the disturbances on its convergence time. The study shows that the algorithm designed to calculate the spacecraft attitude from the solar sensors data set is robust concerning these disturbances with the actual design of the satellite, but also shows limits concerning the size and positioning of its devices.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>TLE</td>
<td>Transient Luminous Event</td>
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<tr>
<td>TGF</td>
<td>Terrestrial Gamma Flashes</td>
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<tr>
<td>MAS</td>
<td>Acquisition &amp; Survival Mode</td>
</tr>
<tr>
<td>SAS</td>
<td>Sun Acquisition Sensor</td>
</tr>
<tr>
<td>MAG</td>
<td>Magnetometer (Sensor)</td>
</tr>
<tr>
<td>RWS</td>
<td>Reaction Wheel (Actuator)</td>
</tr>
<tr>
<td>MTB</td>
<td>Magnetic Torquer Bar (Actuator)</td>
</tr>
<tr>
<td>RAAN</td>
<td>Right Ascension of the Ascending Node</td>
</tr>
<tr>
<td>FDIR</td>
<td>Failure Detection, Isolation and Recovery</td>
</tr>
<tr>
<td>α</td>
<td>Azimuth angle [deg]</td>
</tr>
<tr>
<td>δ</td>
<td>Elevation angle [deg]</td>
</tr>
<tr>
<td>θ</td>
<td>Co-elevation angle [deg]</td>
</tr>
<tr>
<td>Φ₀</td>
<td>Mean solar energy flux [W/m²]</td>
</tr>
<tr>
<td>S</td>
<td>Sun direction unit vector [-]</td>
</tr>
<tr>
<td>X⁻</td>
<td>Side on negative X wise [-]</td>
</tr>
<tr>
<td>X⁻</td>
<td>X⁻ side normal vector [-]</td>
</tr>
<tr>
<td>rCe</td>
<td>Lightning matrix [-]</td>
</tr>
<tr>
<td>β</td>
<td>SAS cone of visibility angle [deg]</td>
</tr>
<tr>
<td>ε</td>
<td>Absolute angular error [rad]</td>
</tr>
<tr>
<td>σ</td>
<td>Standard deviation of a quantity [-]</td>
</tr>
</tbody>
</table>
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Introduction

As a part of my studies at the Royal Institute of Technology (KTH - Stockholm, Sweden) in the Master of science in Aerospace Engineering, my Master Thesis took place in the French national space agency CNES\(^1\) (Toulouse - France), in the AOCS\(^2\) department.

The spacecraft design requires a great attention on each domain due to their strong interaction: embedded software, mechanical structure, telecommunication, mission devices functioning, etc. For instance, electronic devices could perturb a magnetometer through their induced magnetic field. The slightest change in the design in one of these areas can have major consequences on the good functioning of others. The Taranis project (Section 1.1), currently in a development phase, encounters actually many slight adjustments in the design. One particularity of this satellite lies in the design which shows sizable devices or structure panels. Thus their bulk raised a question:

**Could the devices or the structure panels disturb the spacecraft when it tries to acquire the Sun direction in any way?**

On Taranis the Sun direction is only used during the "Acquisition and Survival Mode", when the spacecraft is in a critical situation, after the rocket drops it or after any incident that triggers an alarm by the FDIR. Thus the satellite has a complete unknown initial attitude and angular velocity when the Acquisition and Survival Mode\(^3\) turns on, and the question above becomes really crucial, since the spacecraft can be lost if it is not able to come back in a stable and known attitude with respect to the inertial frame. The Acquisition and Survival Mode is described in detail in this paper allowing a better understanding of the expected performances (Section 1.2), as well as the model of the Sun sensors and the Sun observer algorithm (respectively in Section 1.3 and 1.4).

A complete simulator environment, called MACSIM\(^4\), has been developed earlier in CNES and encoded in FORTRAN-90, but the AOCS department has decided to make a porting of this simulator within ESCAPE\(^5\), an over-layer of MATLAB/SIMULINK\(^\circledast\) developed by THALES ALENIA SPACE and easier to use in projects preliminary phases. Thus a part of the work done for the Master Thesis was to create a working model in ESCAPE inspired by MACSIM before modeling the disturbances. MACSIM can also create a geometrical definition of the solar sensors with its baffle (Section 1.3).

Two kinds of disturbances on sensors have been studied: masking and unwanted reflection. The masking occurs when a device interferes with the sunlight and shades the solar sensors. It has been modeled with a MACSIM routine. The unwanted reflection occurs on more or less bright devices when the sunlight is reflected and lights the sensor backwards. A general model was created taking into account all the possible geometry as well as the brightness and the roughness of the surfaces (Section 2.3).

Finally a set of simulations on ESCAPE\(^\circledast\) (Section 3) has allowed us to validate the effect of those disturbances and to draw a conclusion for all the satellites sharing a part of the Taranis design. In particular this study has shown that the Sun observer algorithm is intrinsically robust to those disturbances if a sufficient coverage is guaranteed to the Sun acquisition sensors.

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\(^1\)Centre National d’Etudes Spatiales: "National space agency"
\(^2\)Attitude and Orbit Control System
\(^3\)It is called MAS in French ("Mode Acquisition-Survie")
\(^4\)Moyen d’Accueil pour la Conception de SIMulations: "Simulators design environment"
\(^5\)Enhanced Simulink Control and Analysis PackagE
1 Spacecraft design

1.1 Scientific mission characteristics

TARANIS (Tool for Analysis of RAdiations from lightNings and Sprites) is a scientific satellite (Figure 1a) which aims to study the magnetosphere-ionosphere-atmosphere coupling via transient processes. These phenomena are blue jets, red sprites, halos, elves, etc, covered by the term TLEs (Transient Luminous Events - Figure 1b), which occur above storm clouds. TARANIS also aims to study the Terrestrial Gamma Flashes (TGFs) which are probably associated to TLEs. The TARANIS mission has four main objectives:

- Estimate the rate of occurrences of TLEs,
- Characterize TGFs and runaway electrons accelerated upward from atmosphere to magnetosphere,
- Identify the effects of both TLEs and TGFs on the coupling ionosphere/magnetosphere,
- Specify the role of precipitated electrons on the coupling magnetosphere/atmosphere.

![Taranis Spacecraft](image1.png) ![Transient Luminous Events](image2.png)

**Figure 1:** The TARANIS mission [1] - CNES©

The spacecraft is developed by the French space agency (CNES), and its launch is scheduled in October 2015. TARANIS is currently in the C-phase and it belongs to a micro-satellite family called MYRIADE which defines the general platform design of such a spacecraft\(^1\). Thus TARANIS is developed from the MYRIADE design, and we have endeavored to make maximum use of the available models and methods of MYRIADE standards to perform the study presented here. The main mission characteristics of TARANIS are gathered in Table 1 below (information in October 2012).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>Drifting Circular Sun-synchronous at ([650 - 720] \text{ km})</td>
</tr>
<tr>
<td>RAAN</td>
<td>([22:30 - 23:30] \text{ or } [0:30 - 2:00] \text{ or } [10:30 - 11:30] \text{ or } [12:30 - 14:00])</td>
</tr>
<tr>
<td>Life duration</td>
<td>2 years expected</td>
</tr>
<tr>
<td>Mass</td>
<td>164 kg</td>
</tr>
<tr>
<td>Power</td>
<td>60 W (orbit with eclipse)</td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>0.5 deg \text{ during scientific measurements}</td>
</tr>
<tr>
<td>Pointing stability</td>
<td>0.03 deg \text{ between two measurements at } 4 \text{ Hz}</td>
</tr>
</tbody>
</table>

**Table 1:** Specifications of the mission

The circular sun-synchronous orbit implies that the spacecraft is eclipsed by the Earth on a sizable part of the orbit, which has an effect on the acquisition and survival mode described in the next section.

\(^1\)MYRIADE counts many satellites such as: DEMETER, PARASOL, PICARD, MICROSCOPE, ESSAIM, SPIRAL, ELISA, etc.
1.2 Acquisition and Survival Mode of Taranis

The study presented here takes close interest in a particular mode of the flight software. A Myriade spacecraft turns into the MAS\(^1\) when the battery level is low or after any alarm detected by the FDIR (over-angular velocity, high misalignment, etc.), as well as during the first acquisition after the rocket drops the spacecraft. The MAS allows the satellite to turn one particular body axis toward the Sun with few robust actuators and sensors which do not use a lot of energy to preserve the current battery level, and guarantees an angular stability. Thus the solar panel points toward the Sun, the battery can be charged, and the spacecraft is in a simple and better configuration (in terms of attitude and angular momentum) to switch to the next software mode. The MAS uses only one reaction wheel (RWS) and three magnetic torquers (MTB) as actuators, as well as one magnetometer (MAG) and three sun acquisition sensors (SAS) to acquire its attitude and angular velocity. Figure 2 below shows Taranis above the south pole after the MAS converged, with the sun direction unit vector \( \mathbf{S} \) in yellow as well as Taranis body axes (\( X \) in red, \( Y \) in green and \( Z \) in blue). On Taranis the MAS must orientate the side \( X^- \) toward the sun. The side \( X^- \) is the side which has \( X^- = -X \) as a normal vector and whose coordinates are negative along \( X \) direction.

![Figure 2: Taranis body axes and Sun direction - Converged MAS case](image)

The MAS is divided into three phases (Figure 3). At the beginning, the MAS aims to reduce the satellite global angular momentum under 0.2 \( N.m.s \) (phase 1) using the magnetic torquers (MTB). Then the reaction wheel (RWS) along the \( X \) axis is turned on in order to give an angular momentum stiffness to the satellite. Finally when the angular momentum along \( X^- \) reaches 0.12 \( N.m.s \) (end of phase 2), the spacecraft attitude is controlled thanks to the MTB to point the side \( X^- \) toward the sun (phase 3). The whole MAS must provide a convergence in less than 25000 \( s \) with a maximal misalignment of 40 \( deg \) between \( X^- \) (red thin arrow in Figure 2) and \( S \) after the convergence occurs in phase 3. During the first phase, the angular velocity of Taranis is determined with both the magnetometer (MAG) and the solar sensors (SAS) by performing a measurement hybridization. The reason is that a SAS does not provide any information when the spacecraft is in eclipse, and the MAG does not provide any information on the angular velocity component along the Earth magnetic field lines. During the phase 3, only the three SAS are used to determine the relative attitude of the spacecraft with respect to the Sun.

![Figure 3: MAS phases](image)

Considering the scientific mission of Taranis, the spacecraft includes heavy measuring devices on \( X^+ \) as well as antennas (see Figure 2 and Figure 5 below). These instruments (and more generally the whole design) could interfere with solar rays used in MAS. The particular design of Taranis combined with the critical aspect of the MAS has motivated the study presented here.

\(^1\)Mode Acquisition Survie: “Acquisition and survival Mode”
1.3 Sun Acquisition Sensors

The SAS used for Taranis are built-up with four solar cells placed in a pyramid-shaped structure\(^1\) as shown in Figure 4a. They are surrounded by black-painted baffles in order to stop the reflected light beams from the multi-layer insulation (MLI) which covers the spacecraft, and their field of view is basically the half space above them (180 deg). The Sun azimuth “\(\alpha\)” and co-elevation “\(\theta\)” angles relative to one SAS are described in Figure 4b.

\[\text{Figure 4: Geometry of a SAS}\]

The SAS are placed on the sides \(X^+, Z^+\) and \(X^-\) (see Figure 5 where the SAS on \(X^+\) is hidden). This configuration gives a half ring gap of about 10 deg height faced to the side \(Z^-.\) But this is not really impeding because after the second phase of the MAS the spacecraft has a spin on the \(X\) axis and the Sun will be in the \(Z^-\) SAS field of view at one time or another.

\[\text{Figure 5: SAS location on Taranis}\]

\(^1\)The half-angle of the pyramid is about 17 deg. The Sensors (Bass 17) are made by EADS Astrium.
For each solar cell on a SAS, the electric current is given by:

\[ I_k = K_{cell,k}C_{sun} + B_0 + N_G \quad [A] \]  

where \( K_{cell,k} \) is the gain, \( B_0 \) the sensor bias and \( N_G \) a random Gaussian noise \([4]\). The Sun lightning coefficient \( C_{sun} \) of a cell depends on the sun direction \( \textbf{S} \):

\[ C_{sun} = \Phi_0 \cdot \lambda \cdot (1 - \epsilon^{9.6}) \cdot \textbf{S} \cdot \textbf{n} \quad [W/m^2] \]  

where \( \Phi_0 \) is the mean solar energy flux at one astronomical unit, \( \lambda \) the ratio between the cell surface lighted and the whole cell surface, \( \textbf{S} \) the sun direction unit vector, \( \textbf{n} \) the normal unit vector to the cell, and \( (1 - \epsilon^{9.6}) \) the solar cell efficiency depending on the absolute angular gap \( \epsilon = \arccos(\textbf{S} \cdot \textbf{n}) \) \([4]\). The second part of Equation (2) on the right is determined before any simulation for all Sun directions (azimuth and co-elevation) and each cell of each SAS. This information is contained in a four dimensions\(^1\) hyper-matrix \( \text{rCe} \) called “lightning matrix”. In order to depict this hyper-matrix and to compare two of them in case of change, a specific figure was created. Figure 6 below shows the \( \text{rCe} \) values for one SAS with its baffles as in Figure 4b above, for all Sun azimuth and co-elevation in the SAS frame. The values of \( \text{rCe} \) are non-dimensional in the range \([0, 1]\).

\[ \text{Figure 6: Sun lightning coefficient - SAS with normal geometry} \]

This figure shows that the SAS can not see the Sun when the co-elevation is greater than 90 deg (i.e. under the SAS plane), and the coefficient is also zero if the Sun is behind the cell. However the coefficient given by a cell is maximal when \( \textbf{S} = \textbf{n} \) in Equation (2), which corresponds to a co-elevation of 73 deg since the angle of the SAS pyramid-shaped structure is 17 deg.

This matrix is computed by a routine from the simulator MACSIM and describes the whole SAS behavior with respect to the Sun. Thus the \( \text{rCe} \) matrix is the most important point of this study and will be later modified to take into account the disturbances.

\(^1\)The four dimensions come from the SAS number, the cell number, the azimuth angle and the co-elevation angle.
1.4 Sun direction observer

During MAS phase 3, the Sun direction is computed from data of only one sensor at a time. The Sun direction observer algorithm [3] aims first to determine which one of the three SAS is best placed (or lighted). The algorithm which determines the best SAS is described in details below and in Figure 7.

The selection algorithm first normalizes the cell currents $I_k$ by dividing it by its maximal values $I_{k}^{\text{max}}$. Thus all currents are comparable. The value of $I_{k}^{\text{max}}$ is calculated when $S = n$ and considering the solar flux $\Phi_0$ estimated at $1371 \, W.m^{-2}$.

$$i_k = \frac{I_k}{I_{k}^{\text{max}}} \quad [-1]^1$$

(3)

Then the algorithm sums all the normalized currents from a SAS and compares the result to the threshold $t_s$. All the SAS satisfying the condition (4) below are considered as sufficiently lighted and readable.

$$\sum_{k=1}^{4} i_k > t_s$$

(4)

If no SAS satisfies Equation (4), the spacecraft is considered in an eclipse state, and the algorithm waits for new data from the SAS. If only one SAS satisfies Equation (4), the algorithm pursues with its data. If two SAS satisfy the condition (4), three cases could happen. If the $X^-$ and the $X^+$ SAS

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$^[1]$ non-dimensional
are selected, the one who has the lowest sum is eliminated and the algorithm pursues with the other. This case only appears when the spacecraft is between the Sun and the Earth, one SAS detecting the Sun and the other detecting the Earth albedo effect, and the SAS faced to the Sun is necessary the one with the higher current sum. If two adjacent SAS are selected ($X^-$ and $Z^+$, or $X^+$ and $Z^+$, the problem is completely symmetric), the algorithm determines the half-space including the Sun ($Y^+$ or $Y^-$) by cross-comparison of each cell current from the two SAS. Then the flight software chooses two cells of a unique SAS which give the best sum of currents and determines the Sun direction using these two cells.

Once the SAS to be used is selected, the flight software compares the current from each cell to a second threshold $t_c$. All the cells satisfying the condition (5) below are considered as sufficiently lighted and readable.

$$i_k > t_c$$

(5)

The algorithm computes the Sun direction from the data of one, two or four cells satisfying the condition (5) by considering an intersection of cones. Actually, the normalized current is a function of the angle between $S$ and $n$ defining a cone of solution around $n$ for each cell. In many cases, the intersection of cones is not singular, or sometimes non-existing (solution with only one cell), but this paper does not aim to explain the strategy of computing the best solution. See [3] for more details. If three cells satisfy the condition (5), the algorithm eliminates the cell with the lowest current, in order to use the “two cells” solution.

Figure 8 shows the performance of the Sun direction observer, i.e. the absolute angular error between the real Sun direction and the estimated one. An estimation error less than 30 deg is considered as reasonable (green-colored area). The uncolored part means that the Sun observer declares the satellite in eclipse (Sun out of the SAS field of view) and corresponds to the half ring gap faced to the side $Z^-$ described in section 1.3 (eclipse state), more visible in Figure 8c and 8d.

Figure 8: Map of performance - Sun direction observer in satellite body fixed frame
2 Means and Methods

2.1 Simulator details

Two simulators have been used for this study. MACSIM has been used to create all the \( \text{rCe} \) matrices with different in-data, since the algorithms are very complex and unusable on ESCAPE\(^\circ\). The latter has however been used to simulate the MAS and to make the results analysis, as well as MATLAB\(^\circ\) to create the disturbance models. ESCAPE\(^\circ\) allows to manage model libraries and configuration files for the models (such as scattering parameters), making easier the design and analysis of a simulations set. Appendix C shows the whole MATLAB/SIMULINK\(^\circ\) scheme for the MAS.

As the simulator was designed for all the MYRIADE spacecrafts, the first task has been to configure each block (and sub-blocks) with the correct parameters value to really match Taranis. This includes for instance inertia, controllers settings, filters settings, orbit, set points, actuator and sensors characteristics, etc. This has shown some errors in the first MAS simulator version (for instance one filter was not correctly modeled and has led to instabilities).

The second task has been to create two MATLAB/SIMULINK\(^\circ\) models: one for all the SAS and one for the Sun observer, as described in Section 1.3 and Section 1.4 respectively. Indeed, in the previous version of the MAS simulator, the SAS model only added noises to the Sun direction information before delivering it directly to the flight software model ("DirSolSas" entry of the "Estimateur" labeled orange block in Appendix C). Figure 9 shows these two new models extracted from the MAS scheme.

The cell has been modeled by considering Equation (1) page 6. Figure 10 shows the content of the cell block. The entry ”CoeffAbdo” corresponds to the lightning coefficient from the Albedo effect. It has been added in anticipation, but is set to zeros in this study. "FluxSol" entry corresponds to \( \Phi_0 \), "CoeffEclt" entry corresponds to \( C_{sun} \) from the \( \text{rCe} \) matrix, and \( K \) is the cell gain \( K_{cell,k} \) in Equation (1). A saturation block has also been implemented since any real sensor gives a finite output (the saturation is set to 15 mA).

![Figure 9: SAS model with Observer - SIMULINK\(^\circ\) blocks](image)

![Figure 10: Cell model - SIMULINK\(^\circ\) blocks](image)
The complete behavior of a SAS is described by both the cell and the lightning coefficient. As the latter is an entry of the cell model, the $\mathbf{rCe}$ values are used in the upper block. Figure 11 shows the SAS model which includes four cell models described above. The Sun direction is first converted from the satellite body fixed frame to the current sensor frame, then normalized before determining the Sun Azimuth and Elevation angles. The MATLAB® function in Figure 11 is an algorithm which picks up the right $\mathbf{rCe}$ values according to the Sun direction before applying them to the cells on the right ("CoeffEclt" inputs).

![Figure 11: Sensor model - Simulink® blocks](image)

This model has been validated through a comparison with experimental results [5]. The test has consisted in a light source simulating the Sun and passing above the sensor, in the plane including the SAS normal vector and the considered cell normal vector (see Figure 4b page 5). Figure 12 shows the comparison on one cell, where the blue line is the model results and the red points the experimental measurements. The experimental measurements gives a non-zero intensity when the light source is

![Figure 12: Validation of the model](image)
behind the cell. This is due to the reflection on the baffle (which were not black-painted at this time). The model implemented in the MAS simulator gathers all the three SAS (Figure 9). Its inputs are the solar energy flux "FluxSol" (Φ₀), the Sun direction in the satellite body fixed frame "DirSolSat" (S), and the natural eclipse state of the satellite "FlagEclipse" (typically when Φ₀ = 0). Its outputs "Courants" is a 1x12 vector containing all the electric currents from the cells (4 cells on each SAS, and 3 SAS).

Concerning the Sun direction observer of the flight software (Figure 13 below), its inputs are the electric currents from the cells, and its outputs are the computed Sun direction in the satellite body fixed frame "DirSolSatEst", and the eclipse state "EclipseEst". There is no link between "FlagEclipse" and "EclipseEst", since the latter is determined by the observer and based only on the values of the electric currents from the 12 cells. The observer block contains basically only the Sun direction algorithm described in Section 1.4 encapsulated in a MATLAB® function. One can see the switched connexions between the cells and the Sun observer. This is due to the complete reuse of the Myriade algorithm in which the SAS on Z⁺ had an other orientation with respect to the satellite.

2.2 Simulation strategy

When TARANIS switches into the MAS, its attitude, angular velocities and initial position on the orbit could have any values, since it can happen at any time. This aspect should be taken into account when we try to verify the impact of a parameter or a disturbance by running simulations. That is why a set of simulations was created to ensure that the results are relevant, with a minimal number of simulations. But the number of simulations has to be also reasonable, since it increases the whole calculation time. An other study[6] in the TARANIS project has identified six "worst cases" about the initial angular velocities, according to the inertia of the spacecraft and the specifications of the launcher drop. The inertia of the spacecraft used in calculation corresponds to the first acquisition configuration (stacked scientific measuring devices, but deployed solar panel):

\[
I_{SAT} = \begin{bmatrix}
18.8 & 1.5 & -0.2 \\
1.5 & 20.8 & 0.1 \\
-0.2 & 0.1 & 29.2
\end{bmatrix} \text{[kg.m}^2\text{]} \tag{6}
\]

The initial position on the orbit is taken regularly around the Earth, and the initial attitude is chosen randomly in each simulation. Furthermore the residual magnetic momentum from electronic
devices of TARANIS is also scattered, since they create an important additional torque on the platform \( C = M_{\text{sat}} \times B_{\text{Earth}} \). Its nominal value in the satellite body frame is \( M_{\text{sat}} = [-0.04, 0.664, 0.05] \, \text{A.m}^2 \) with a standard deviation of \( [0.172, 0.153, 0.134] \, \text{A.m}^2 \). Table 2 gathers the values of all the initial parameters for the simulations set.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Values</th>
<th>Number of draws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital position</td>
<td>deg</td>
<td>0, 30, 60, ..., 330 (from RAAN)</td>
<td>12</td>
</tr>
<tr>
<td>Angular velocity ( [X_{\text{sat}}, Y_{\text{sat}}, Z_{\text{sat}}] )</td>
<td>deg/s</td>
<td>([5,5,0], [5,0,5], [-5,5,0], [-5,0,5] ) ([5,3,5,4,3,54], [5,3,5,4,3,54] )</td>
<td>6</td>
</tr>
<tr>
<td>Residual magnetic momentum</td>
<td>( \text{A.m}^2 )</td>
<td>( M_{\text{sat}} / M_{\text{sat}} + \sigma / M_{\text{sat}} + 3\sigma )</td>
<td>3</td>
</tr>
<tr>
<td>Attitude on each axis</td>
<td>deg</td>
<td>Random in [0,360]</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2: Scattered parameters - General simulation set

These parameter draws lead to a set of 217\(^1\) simulations with the nominal case (in which all parameters are set to zeros), for a time of calculation of about 14 hours\(^2\). This set of simulations is managed by ESCAPE\(\text{©} \) which saves the outputs and the values of the parameters, especially for the initial attitude drawn randomly, in order to run again a particular simulation if something interesting is identified. Later on, this set of simulations allows to study the influence of any parameters or disturbances, and will be the basis of the demonstrations.

However, if another variable must be drawn, another strategy should be adopted. Since the set described in Table 2 is valid with only one \( rCe \) matrix, when different \( rCe \) matrices have to be tested, the set of simulations has to be defined in an other way. The six worst cases of angular velocities and the residual magnetic momentum are still the same, but the initial position on the orbit is now chosen randomly, as well as the attitude for each simulation in order to keep these unknowns. Two initial positions and attitudes are drawn for each combination in angular velocity and \( M_{\text{sat}} \). Table 3 below gathers the values of these parameters leading to a set of 36 simulations per \( rCe \) matrices (in total, \( 36 \times N + 1 \) simulations with the nominal case).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Values</th>
<th>Number of draws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular velocity ( [X_{\text{sat}}, Y_{\text{sat}}, Z_{\text{sat}}] )</td>
<td>deg/s</td>
<td>([5,5,0], [5,0,5], [-5,5,0], [-5,0,5] ) ([5,3,5,4,3,54], [5,3,5,4,3,54] )</td>
<td>6</td>
</tr>
<tr>
<td>Attitude on each axis</td>
<td>deg</td>
<td>Random in [0,360]</td>
<td>2</td>
</tr>
<tr>
<td>Orbital position</td>
<td>deg</td>
<td>Random in [0,360]</td>
<td>2</td>
</tr>
<tr>
<td>Residual magnetic momentum</td>
<td>( \text{A.m}^2 )</td>
<td>( M_{\text{sat}} / M_{\text{sat}} + \sigma / M_{\text{sat}} + 3\sigma )</td>
<td>3</td>
</tr>
<tr>
<td>( rCe ) number</td>
<td></td>
<td>1 to ( N )</td>
<td>( N )</td>
</tr>
</tbody>
</table>

Table 3: Scattered parameters - \( rCe \) simulation set

\(^1\)One nominal case and \( 12 \times 6 \times 3 \times 1 = 216 \) cases.

\(^2\)Depending on the computer capabilities.
2.3 Light reflection model

As mentioned earlier in this paper, one kind of disturbances (and not the least) is the unwanted reflection from devices on the spacecraft. On Taranis one bright antenna particularly close to the SAS on the side $X^-$, and a mat surface of the platform on the side $Z^+$ could create disturbances, as shown in Appendix B and Appendix A respectively. No simple model had been designed so far since CNES designs the spacecraft platform by considering this aspect differently, eliminating all possibilities to encounter such a disturbance. But the particularity of Taranis has required a deeper investigation.

Starting from scratch, the goal here is to determine the part of the light energy from such a reflective surface that comes to the sensors. The method was first to create a discretization of the reflective surface as well as the cells of the sensors, and then to compute the light energy radiating between them.

Figure 14 shows in red the light ray from the Sun that hits a slight part of the reflective surface ($dS_1$), and the light ray directly reflected toward a second surface $dS_2$ included in the cell of the sensor.

![Figure 14: Light reflection model](image)

At the Earth orbit (1 astronomical unit from the Sun), the mean solar energy flux is estimated to $\Phi_0 \approx 1371 \text{ W.m}^{-2}$. Considering Figure 14, the energy flux from the Sun that $dS_1$ finally receives is:

$$\Phi_{\text{Sun/1}} = \Phi_0 \cdot \cos \theta_1 \quad \text{[W.m}^{-2}]$$  \hspace{1cm} (7)

According to the nature of the reflective surface, $dS_1$ radiates a part of that light energy throughout the half-space above it. Assuming a reflective coefficient $\rho$, the whole energy reflected by $dS_1$ is:

$$\Phi_1 = \rho \cdot \Phi_{\text{Sun/1}} \quad \text{[W.m}^{-2}]$$  \hspace{1cm} (8)

But $dS_1$ does not necessarily radiate equally in all directions. Also depending on the nature of the surface, the spatial distribution of the energy flux can be uniform, purely specular (like mirrors for instance), or something in between. Figure 15 shows three different distributions of the light energy, where the incident ray is red-colored and the energy distribution is blue-colored depending on the direction.

![Figure 15: Light space distributions](image)
The uniform distribution (Figure 15a) is the simplest model, the energy radiates equally in all directions. This distribution is particularly close to the real reflection on black and mat surfaces [2]. Another model called "Lambert distribution" (Figure 15b) is a good approximation of very rough and mat surfaces [7] & [8]. But when the surface is bright and rough, the behavior is nearly specular with a scattering effect as in Figure 15c [9]. Thus in the direction of $dS_2$, the preliminary surface $dS_1$ sends an energy flux $\Phi_{1\rightarrow 2}$, and the second surface $dS_2$ receives an energy flux $\Phi_2$ such that:

$$\Phi_2 = \Phi_{1\rightarrow 2}. \cos \theta_2 \quad [W.m^{-2}]$$

(9)

The distribution of the energy sent by $dS_1$ depends on the direction of the observer ($dS_2$) and the direction of the incident ray. Assuming that we can attach a frame to $dS_1$, it allows us to define the azimuth and co-elevation of the incident ray ($\alpha_i$ and $\theta_i$) in the same way as in Figure 4b (page 5), and the same angles for the observer ($\alpha$ and $\theta$). The energy flux from $dS_1$ to $dS_2$ can be now described as:

$$\Phi_{1\rightarrow 2} = \xi(\alpha, \theta, \alpha_i, \theta_i) \cdot \Phi_1 \quad [W.m^{-2}]$$

(10)

where $\xi$ describes geometrically how the energy is distributed in space. The energy flux $\Phi_{1\rightarrow 2}$ is also subject to the conservation principle in terms of energy:

$$\int\int_D \Phi_{1\rightarrow 2}.dS = \Phi_1.dS_1 \quad [W]$$

(11)

where $D$ is the half-sphere above $dS_1$, with a radius $\ell$ (typically $\ell$ is the distance between the source of the light $dS_1$ and the observer $dS_2$). Knowing that $dS = \ell. \sin \theta. d\alpha. \ell. d\theta$, Equation (10) and Equation (11) make the following equality:

$$\int\int \xi(\alpha, \theta, \alpha_i, \theta_i). \sin \theta. d\alpha d\theta = \frac{dS_1}{\ell^2} \quad [-]$$

(12)

For each pair of surfaces ($dS_1$ from the reflective surface and $dS_2$ from the cell of the sensor), the value to be added to the matrix $rCe$ for one Sun direction in the SAS frame, is the energy flux $\Phi_2$ compared with $\Phi_0$ and reduced by the coefficient $\eta$:

$$\Delta rCe = \Phi_2. \frac{\Phi_0}{\Phi_0}. \eta \quad [-]$$

(13)

The coefficient $\eta$ contains the information about the cell efficiency (see Equation (2) page 6), as well as the condition of interception of the ray by the baffle of the SAS (See Annexe M) and the condition of visibility between $dS_1$ and $dS_2$.

2.3.1 Example 1: Uniform distribution

In the uniform case, the energy is radiated equally in all directions, thus $\xi(\alpha, \theta, \alpha_i, \theta_i) = \Gamma$ is constant, and solving Equation (12) we get:

$$\Gamma = \frac{dS_1}{2\pi \ell^2}$$

Finally, using Equation (7) to Equation (13), for each pair of surfaces and for each Sun direction, the effect on $rCe$ is:

$$\Delta rCe = \eta. \frac{\rho \cos \theta_2 \cos \theta_1 dS_1}{2\pi \ell^2}$$
2.3.2 Example 2: Lambert distribution

The Lambert distribution is described as \( \xi(\alpha, \theta, \alpha_i, \theta_i) = \Gamma \cos \theta \), where \( \Gamma \) is a constant, and after solving Equation (12) we get:

\[
\Gamma = \frac{dS_1}{\pi \ell^2}
\]

Finally for each pair of surfaces and for each Sun direction:

\[
\bar{d}rC_e = \eta \cdot \rho \cos \theta_2 \cos \theta_1 \frac{dS_1}{\pi \ell^2} \cos \theta
\]

2.3.3 Example 3: Scattered specular distribution

The scattered specular distribution means that the light energy is concentrated around the specular direction, i.e. around the direction:

\[
\begin{align*}
\alpha_{\text{specular}} &= \alpha_i \pm \pi \\
\theta_{\text{specular}} &= \theta_i
\end{align*}
\]

The most intuitive law for such a natural phenomenon is the normal distribution (or Gaussian distribution), which scatter a parameter around a particular value. Assuming that the angular gap between the specular direction above and the observer direction \((\alpha, \theta)\) is \(\Delta \gamma\), the distribution can be described as a Gauss’ law with a standard deviation \(\sigma\):

\[
\xi(\alpha, \theta, \alpha_i, \theta_i) = \frac{\Gamma}{\sigma \sqrt{2\pi}} \exp \left[ \frac{\Delta \gamma^2}{2\sigma^2} \right]
\]

where \(\Gamma\) is a constant, and \(\Delta \gamma\) depends on \(\alpha, \theta, \alpha_i\) and \(\theta_i\). The larger \(\sigma\) is, the stronger the scattering effect. The solution of Equation (12) can not be found analytically. But since the right part of Equation (12) is constant, the double integral on the left is also constant, and can be calculated numerically:

\[
\begin{align*}
\frac{dS_1}{\ell^2} &= \int \int \xi(\alpha, \theta, \alpha_i, \theta_i) \sin \theta \, d\alpha d\theta \\
\frac{dS_1}{\ell^2} &= \frac{\Gamma}{\sigma \sqrt{2\pi}} \int \int \sin \theta \exp \left[ \frac{\Delta \gamma^2}{2\sigma^2} \right] \, d\alpha d\theta \\
\Rightarrow \quad \Gamma &= \frac{\sigma \sqrt{2\pi} dS_1}{I \ell^2}
\end{align*}
\]

Thus for each pair of surfaces and each Sun direction:

\[
\bar{d}rC_e = \eta \cdot \rho \cos \theta_2 \cos \theta_1 \frac{dS_1}{I \ell^2} \exp \left[ \frac{\Delta \gamma^2}{2\sigma^2} \right]
\]
3 Results

3.1 Reference case

One reference case has been computed with the set of simulations described in Section 2.2 with no disturbances. It has allowed to approve the porting of the model from MACSIM to ESCAPE©. It also gives orders of magnitude for the convergence times and the maximal misalignment to the Sun over the time (after the convergence occurred), as shown in Figure 16. The nominal case (no initial angular velocity) is the first simulation which appears on the extreme left in both Figure 16a and Figure 16b.

![Figure 16: Reference case simulations results](image)

One can see the chaotic aspect of the MAS (since the values are very different from each other), and a slight increase of the maximal misalignment for the last 72 simulations (on the right of Figure 16b). This correspond to two of the six worst cases in terms of initial angular velocities mentioned in Section 2.2, and more precisely the cases [5, 3.54, 3.54] and [5, -3.54, -3.54]. Moreover, one can see that all cases lead to a MAS convergence under 40 deg in less than 25000 s as mentioned in Section 1.2 page 4. Table 4 below gathers the results of this reference case, where $\sigma$ is the standard deviation of the results. The value $\text{Mean} + 3\sigma$ is more or less significant here but in a case of Gaussian distribution of a parameter, nearly all values (99.73%) lie within 3 standard deviations of the mean [10]. But this value coupled with the maximal value allow to see the scattering of the results. The

<table>
<thead>
<tr>
<th></th>
<th>Convergence time</th>
<th>Maximal misalignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>13308 s</td>
<td>25 deg</td>
</tr>
<tr>
<td>Mean +3$\sigma$</td>
<td>19829 s</td>
<td>31 deg</td>
</tr>
<tr>
<td>Max value</td>
<td>18840 s</td>
<td>35 deg</td>
</tr>
</tbody>
</table>

Table 4: Reference case principal results - ESCAPE©

results are different from those given by MACSIM. This difference comes from the fact that MACSIM has many other sources of disturbances (such as the albedo effect, the inertia dispersion, etc.). These are not yet implemented on the MAS simulator using ESCAPE©. However, the results of ESCAPE© are still relevant since a set of simulations done on MACSIM with the same assumptions leads to the same orders of magnitude.
3.2 Sun observer settings

In Section 1.4 is described the Sun observer with any parameters. The two thresholds $t_c$ and $t_s$ in Equation (4) and Equation (5) are chosen to counteract the Earth albedo effect (reflection of the sunlight on the Earth). The parameter $I_{\text{max}}^k$ in Equation (3) is the on-board value to normalize the electric current from the cells. In the reference case as well as the other cases below this parameter is set to 15 mA, but we also consider in the SAS model the real gain of each cell (see Section 2.1). This leads to an inexact normalized electric current in Equation (3) since the real maximal value for each cell is not necessary 15 mA. A single simulation has been performed with the real maximal electric current (Table 5) for each cell in order to see the effect on the Sun observer performances. Actually the common value of 15 mA above comes from the settings of the Sun observer implemented on the spacecraft DEMETER, which has a design really close to the TARANIS one, and which has proved its worth. However the SAS of the latter are less efficient, and as mentioned earlier in this paper, the general MYRIADE design is first considered before improvements.

<table>
<thead>
<tr>
<th>$I_{\text{max}}^k$ [mA]</th>
<th>SAS $X^-$</th>
<th>SAS $Z^+$</th>
<th>SAS $X^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>13.2</td>
<td>13.0</td>
<td>13.1</td>
</tr>
<tr>
<td>Cell 2</td>
<td>12.9</td>
<td>12.2</td>
<td>12.1</td>
</tr>
<tr>
<td>Cell 3</td>
<td>13.2</td>
<td>12.8</td>
<td>13.0</td>
</tr>
<tr>
<td>Cell 4</td>
<td>13.4</td>
<td>12.6</td>
<td>12.6</td>
</tr>
</tbody>
</table>

Table 5: Real values of $I_{\text{max}}^k$ [5] - [6]

The map of performances (Figure 17) shows a marked improvement from this new setting compared to Figure 8a page 8. The green part is larger, and one can see the larger area corresponding to an absolute angular error under 10 deg. Actually, this Sun observer setting improves the pointing accuracy for the MAS (about 12% on the Mean value, and 20% on the Mean +3σ), but not the convergence time. This is not unexpected since the Sun direction is mainly used in the third phase of the MAS, after the first phase which takes actually the major part of the convergence time. Appendix D shows the detailed results of the set of simulations.
3.3 Safety field of view of the SAS

The motivation of this part comes from the Taranis design of the side $Z^+$. Appendix A shows in orange the surface which is likely to interfere with the sensor in red. The goal here is to study the effect of any object in the SAS field of view on any side. In order to determine the safety field of view for each SAS, it has been decided to act directly on the height of the baffles (see the SAS geometry in Figure 4 page 4), which is linked directly with the field of view as shown in Figure 19b. Different single simulations have run with a variable baffle height of each SAS, and with any blind SAS ($\text{rCCe}$ with only zeros). Figure 18 below is an example of the $\text{rCCe}$ with a baffle height of 29 mm (see Figure 6 page 6 for the reference geometry).

![Figure 18: Sun lightning coefficient - SAS with $\beta = 40$ deg](image)

This has shown that the SAS on the $X^-$ side is the most critical and the one on the $X^+$ side is less sensible to this kind of disturbances. However several sets of simulations have been done to find what is called above ”the SAS safety field of view” in order to create a specification on all the Myriade spacecrafts. More precisely this specification should guarantee the MAS convergence (under 40 deg in less than 25000 s) if no device is in the cones of visibility as defined in Figure 19a below.

![Figure 19: SAS field of view](image)

Since the field of view of all the three SAS are interrelated, simulations have to be ordered and only one SAS geometry should vary at a time, using the set defined in Table 3 page 12. In order to find
all the minimal cones of visibility, a constant $\beta$ angle has been first fixed arbitrarily to 30 deg for the SAS on the $Z^+$ side in order to guarantee a sufficient intersection with the field of view of the other sensors (continuous coverage). Then the two other $\beta$ angles have been successively scattered.

A first group of simulations has been performed with a full field of view ($\beta = 0$) on the critical SAS on $X^-$ side, and varying the $\beta$ angle of the SAS on $X^+$ side. Table 6 shows all these assumptions as well as the number of cases leading to a non-converged MAS (in the column “Results”). Figure 20 shows the details of the results, with the mean values for each $\mathbf{rCe}$ matrix written on top of the figure and presented by the green-dashed line.

<table>
<thead>
<tr>
<th>$\mathbf{rCe}$ case number</th>
<th>$\beta$ [deg]</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Z^+$</td>
<td>$X^+$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6: First group of simulations

No set of simulations show any case of MAS non-convergence, but some of these are close to the specifications (simulation number 152 has a convergence time of about 22000 s, and simulations numbers 35 and 143 have a high maximal misalignment). Since the MAS convergence must be guaranteed, an arbitrary maximal acceptable value for this $\beta$ angle is chosen, set to 30 deg including a large safety margin.
Once the maximal acceptable value of $\beta$ angle on $X^+$ is fixed, the field of view of the $X^-$ SAS is decreased regularly. Table 7 shows the assumptions of the second group of simulations as well as the number of case leading to a non-convergence.

<table>
<thead>
<tr>
<th>$r\overrightarrow{C}$e case number</th>
<th>$\beta$ [deg]</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z^+$</td>
<td>$X^+$</td>
<td>$X^-$</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 7: Second group of simulations

Figure 21 shows the detailed results. One can see the non-convergence cases, either with a convergence time higher than 25000 s (these cases are drawn even so), or without detected convergence (these cases are not drawn in the figure). In case of convergence, the maximal misalignment after the MAS convergence seems not to be affected by the limited SAS field of view. However, looking at the mean convergence time for each $r\overrightarrow{C}$e matrix (green dashed lines in Figure 21a), it seems that the convergence time increases exponentially with respect to $\beta$.

Figure 21: Second group results

Regarding the results in both Table 6 and Table 7 and considering a safety margin, a specification could be stated. In order to get a coherent safety margin on all the sensors, we have set all maximal $\beta$ angles to 30 deg, and verified the MAS convergence by running the complete set of simulations as described in Table 2 page 12.

The results of the simulations set with a 30 deg field of view on each SAS are presented in Appendix K. All the cases lead to the convergence of the MAS, except the case number 10. As the study has to provide results in which the MAS has a reliability of 100%, the specification above is not proper. After extracting all the initial parameters values, a single simulation has been performed (up to 50000 s) to understand what happened in this case exactly. Figure 22 shows the absolute angular pointing error with respect to the time. Actually the MAS converge at 32700 s, approximately one
and an half orbit later\(^1\). This could be acceptable if the battery level is sufficient for the Taranis safety, since during the MAS the solar panel is not always standing against the Sun (the battery is thus charging during the MAS), however a convergence after 25000 s leads to a high risk of battery dump [6]. Moreover, the battery model is not yet implemented in the Escape© simulator used in this study, and a working specification must be provided as a conclusion of this study. Figure 23 shows the map of performances for the Sun observer which has a larger "eclipse area" than the reference case (Figure 8a page 8), as well as the satellite Sun direction during the third phase of the MAS (dashed line during non converged MAS, and continuous line after convergence occurs). One can see that the Sun direction is out of the SAS visibility during a large time range (dashed line in the white area), or seems to enter into the SAS visibility not long enough. Actually this is coupled with an other phenomenon. As luck would have it, when the Sun direction crosses the SAS

\(^1\)The Taranis orbit lasts approximately 5800 s.

Figure 22: Absolute angular error - MAS

Figure 23: Map of performances - SAS field of view of 30 deg - Path of the simulation number 10
visibility area, the Earth eclipses the spacecraft. Figure 24 shows the Sun direction components in the body fixed frame (in black) as well as the estimated Sun direction from the observer (in red). The background indicates is gray when the Earth eclipses the spacecraft, and in white when the Sun lights the spacecraft.

![Graphs showing Sun direction coordinates](image)

**Figure 24:** Sun direction coordinates - Body fixed frame - Simulation number 10

One can see that when Taranis could acquire the Sun at time 12400 s, it is shadowed by the Earth. After that time, the Sun is out of the SAS field of view (from 12400 s to 26700 s), then the Sun is acquired for a short time, not sufficiently longer, before Taranis loses it again at 27200 s. The same short appearance occurs between 29800 s and 30100 s, before the spacecraft get sufficient information at 32400 s (just after the Earth eclipse) to point toward the Sun.

Finally it was decided to change the 30 deg specification to 20 deg after verifying that the same parameter values as the case of the simulation number 10 above leads to a MAS convergence as a result. The results of the simulations set with a 20 deg field of view on each SAS are presented in Appendix L. This time, all the case show a MAS convergence, and we are able to set a specification for Myriade.

<table>
<thead>
<tr>
<th></th>
<th>Convergence time</th>
<th>Maximal misalignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>13650 s (+2.6%)</td>
<td>25 deg</td>
</tr>
<tr>
<td>Mean +3σ</td>
<td>20770 s (+4.7%)</td>
<td>32 deg</td>
</tr>
<tr>
<td>Max value</td>
<td>20161 s (+6.7%)</td>
<td>34 deg</td>
</tr>
</tbody>
</table>

**Table 8:** Results - β = 20 deg - Comparison with reference case
3.4 Sunlight reflection and masking effects of $X^-$ antenna

The MAS aims to point the $X^-$ side toward the Sun. Thus this side is the most critical. The Taranis design places the antenna in Figure 25a close to the SAS as shown in Appendix B where the sensor is in red and the antenna in orange. As mentioned in Section 2.3, the antenna surface is first discretized as shown in Figure 25b, where the rear part is absent to decrease the calculation time since it can not reflect any light energy toward the SAS. The reflection coefficient is about 30% ($\rho = 0.3$), and the behavior of the surface is something between the uniform distribution and the scattered specular distribution. However all the distributions presented in Section 2.3 have been tested. Only two cells of the SAS can be lighted backwards by the antenna: cells number 2 and number 3 (cell number 1 is red in Figure 25b). The second cell is the most lighted by the antenna considering their respective positions. Figure 26 below shows the results of the computation on $\text{rCe}$ only for the second cell (note: the color scale upper limit is 0.27 instead of 1).

One can see the difference from left to right, where the direction between $dS_1$ and $dS_2$ in Figure 14 (page 13) becomes more and more important in the calculation. The maximal values (in white) are respectively: 0.2074, 0.2628 and 0.2224. These peaks are located around a Sun azimuth angle of 270 deg, when basically the Sun, the cell and the antenna are roughly aligned in this order.
The other effect is the masking from the antenna. A simple computation on MACSIM by changing the geometry of the baffle is needed to create the corresponding rCe. An additional surface with the shape of the antenna has been added to the data from which the matrix is computed. Figure 27 shows the masking effect on the SAS model on cells number 2 and 3 (the other cells are not affected by the antenna shadow).

![Figure 27: Sun lightning coefficient - SAS with antenna masking effect](image)

Combining these effects, just by adding the resulting matrices, we can get the whole rCe matrix in each case. Figure 28 shows the results in the case using the scattered specular model for the reflection. Appendices E, F and G shows the rCe results for each case.

![Figure 28: Sun lightning coefficient - Antenna effect with Scattered Specular model](image)

The maximal light intensity from both the Sun and the reflection on the antenna are now comparable. The antenna effect seems to be weak compared to the Sun, but the map of performances of the Sun observer is more relevant to appreciate the real impact.
Thus the antenna creates a additional area\textsuperscript{1} where the flight software declare the spacecraft in eclipse, as shown in Figure 29 below, and disturbs the performances around $-X$ axis (white rectangle, by comparison with Figure 8a page 8). In addition, a significant loss of performances (white circle) has appeared at the opposite side of the antenna with respect to $-X$ axis. This is probably due to the Sun observer algorithm which computes the Sun direction from the cell electric current defining a cone of solutions. Thus a slight change in the intensity is capable to deflect the solution sufficiently to get this performance loss.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure29.png}
\caption{Map of performance - Antenna effect with Scattered Specular model}
\end{figure}

Appendices E, F and G show also the map of performance of the Sun observer for each reflection model.

The same calculations have been performed concerning the structure panel as shown in orange in Appendix A, with a reflective coefficient of 10\% ($\rho = 0.1$) since it is black-painted \cite{1}. Figure 30 shows the different calculations results. The maximal $r\text{C\text{\textordfiddle{e}}}$ value for the reflection are respectively: 0.0032, 0.0063 and 0.0096. The results show that the effect is negligible compared to the Sun lighting and the natural SAS field of view. This is mainly due to the distance between this structure panel and the SAS on $Z^+$. Indeed, as shown in Section 2.3, $dr\text{C\text{\textordfiddle{e}}}$ is proportional to the inverse of the squared distance between the reflective surface and the sensor. Concerning the masking (green circle in Figure 30a), the height of the structure panel is not sufficient compared to this distance to interfere with the SAS.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure30.png}
\caption{Masking and Reflection - Structure panel on $Z^+$ - $\rho = 0.1$}
\end{figure}

\footnote{Nearly an elliptic cone of 20 by 40 degrees.}
In order to observe the impact of the antenna on the MAS performances, one set of simulations has run for each reflection model. Table 9 and Table 10 gather the results of the three sets of simulations as well as those from the reference case. All the results are detailed in Appendices H, I and J.

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Uniform</th>
<th>Lambert</th>
<th>Specular</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean value</strong></td>
<td>13308</td>
<td>13139</td>
<td>13496</td>
<td>13566</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(−1.3%)</td>
<td>(+1.4%)</td>
<td>(+1.9%)</td>
</tr>
<tr>
<td><strong>Mean +3σ</strong></td>
<td>19829</td>
<td>19463</td>
<td>19710</td>
<td>20258</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(−1.8%)</td>
<td>(−0.6%)</td>
<td>(+2.1%)</td>
</tr>
<tr>
<td><strong>Max value</strong></td>
<td>18840</td>
<td>18201</td>
<td>19229</td>
<td>22384</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(−3.4%)</td>
<td>(+2.1%)</td>
<td>(+18.8%)</td>
</tr>
</tbody>
</table>

Table 9: Antenna disturbances results - Convergence time

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Uniform</th>
<th>Lambert</th>
<th>Specular</th>
</tr>
</thead>
<tbody>
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<td><strong>Mean value</strong></td>
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<td>25</td>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td><strong>Mean +3σ</strong></td>
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<td>32</td>
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<td>32</td>
</tr>
<tr>
<td><strong>Max value</strong></td>
<td>35</td>
<td>33</td>
<td>34</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 10: Antenna disturbances results - Maximal misalignment

One can see that the MAS seems to converge with any kind of reflection. Concerning the convergence time, all the mean values are really close to each other (the difference with the reference is under 2% in each case), but the specular model seems to give really scattered results, since the maximal value is close to the acceptable limit and the Mean + 3σ value is 2.1% higher to the reference and the maximal value 18.8% higher than the reference. One solution to avoid any specular behavior could be to cover the antenna with a black and mat paint. The maximal misalignment results show no significant differences between the cases and the reference case.
Conclusion

As a conclusion, this paper has shown the robustness of the Sun observer for a MYRIADE spacecraft like Taranis about sunlight disturbances from devices in the surrounding environment of the Sun Acquisition Sensors (SAS).

The first task was to create a simulator for the Acquisition and Survival Mode (MAS) allowing to implement two different kinds of disturbances. As the complete SAS behavior is described by a four-dimensional matrix computed through a MACSIM routine, it has been decided to reuse it in the ESCAPE© simulator. The SAS model was then compared to experimental results from the producer of the SAS (EADS Astrium) and validated. Then a simulations strategy was decided in order to give relevant information about the MAS according to different parameters. Finally the model of two kinds of disturbances were created. If the masking effect used only the MACSIM routine, the light reflection on surfaces was performed from scratch with MATLAB© routines.

After many sets of simulations performed with different SAS configurations in order to simulate the masking effect on the SAS, we have shown that the Sun observer robustness is guaranteed (as well as the MAS convergence) if no device interfere with the SAS field of view. In this way, the study has identified the safety SAS field of view, defined by an angle of 20 deg away from the SAS plane on each side. This result may be valid for all the MYRIADE spacecrafts using the same MAS tuning.

The sunlight reflection on the devices are strongly dependent on the surface characteristics and the distance to the sensor. Thus no general study can be performed, but one antenna on the X^-side of Taranis had raised a question since it is close to a SAS and since its surface is relatively bright. The reflection model with different assumptions was used to simulate its effect on the MAS performances, as well as the masking effect of this antenna. The study has shown that the Sun observer could get a performance loss, but the MAS performances seem to be safe from the antenna disturbances. However, the scattered specular reflexion case has shown a maximal convergence time 20% higher than the reference case, but the antenna reflexion is easily to thwart by using a black and mat paint.

The masking and sunlight reflection was also simulated concerning the first question raised in the project concerning the structure panel on the Z^+ side. The study has shown that all the effect of this structure panel are negligible since the distance to the sensor is large and since the surface is mat.

All these results are promising for MYRIADE, but the MAS model used so far does not take into account the Earth albedo effect. Even if the comparison with MACSIM has shown only a slight change with or without albedo, a deeper investigation seems to be needed.
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APPENDIX A: Positioning of the SAS on $Z^+$ side
APPENDIX B: Positioning of the SAS on $X^-$ side
APPENDIX C: Acquisition and Survival Mode SIMULINK© diagram

Red: Command / Orange: Observer / Green: Orbit, Environment and Perturbation
Magenta: Sensors / Cyan: Platform / Blue: Actuators
Appendix D: Sun observer settings - Detailed results

**Convergence time (AQM) - Criterion: 40 degrees**

![Convergence time graph](image1)

- Mean: 13381s
- Mean+3σ: 19661s
- Max: 18518s

**Maximal misalignment (AQM) after convergence confirmed**

![Maximal misalignment graph](image2)

- Mean: 22deg
- Mean+3σ: 28deg
- Max: 28deg

Sim. - Mean - M +3σ - Spec.
APPENDIX E: \( \mathbf{rC} \)\( \mathbf{e} \) Matrix and Sun Observer Map of Performance:
Antenna - Uniform case

\[ C_{\text{sun cell nb.1}} \]

\[ C_{\text{sun cell nb.2}} \]

\[ C_{\text{sun cell nb.3}} \]

\[ C_{\text{sun cell nb.4}} \]

Map of performances for AQM Sun direction observer
Absolute angular error \( \varepsilon \) [deg]

\( \varepsilon_{\text{max}} : 94.8595 \text{ deg} \quad \varepsilon_{\text{min}} : 0.012155 \text{ deg} \)
APPENDIX F: $\mathbf{C_{\text{Ce}}}$ Matrix and Sun Observer Map of Performance:
Antenna - Lambert case

Map of performances for AQM Sun direction observer
Absolute angular error $\varepsilon$ [deg]

$\varepsilon_{\text{max}} : 86.5332$ deg  $\varepsilon_{\text{min}} : 0.01275$ deg
APPENDIX G: \(\bar{r}\bar{c}_e\) Matrix and Sun Observer Map of Performance: Antenna - Scattered specular case

\[
\begin{align*}
C_{\text{sun Cell nb.1}} & \quad C_{\text{sun Cell nb.2}} \\
C_{\text{sun Cell nb.3}} & \quad C_{\text{sun Cell nb.4}}
\end{align*}
\]
APPENDIX H: Antenna Results Details: Uniform case

Convergence time (AQM) - Criterion: 40 degrees

Maximal misalignment (AQM) after convergence confirmed

0 simulation(s) ignored

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APPENDIX I: Antenna Results Details: Lambert case

![Convergence time (AQI) - Criterion: 40 degrees](image1)

Mean: 13496s  Mean+3σ: 19710s  Max: 19229s

![Maximal misalignment (AQI) after convergence confirmed](image2)

Mean: 25deg  Mean+3σ: 33deg  Max: 34deg

Sim.  Mean  M+3σ
APPENDIX J:  Antenna Results Details: Scattered Specular case
APPENDIX K: Specification Results Details: Safety SAS field of view - 30 deg

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Convergence time (MAS) - Criterion: 40 degrees

Mean: 14036s  Mean±3σ: 21708s  Max: 21257s

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Maximal misalignment (MAS) after convergence confirmed
1 simulation(s) ignored

Mean: 25deg  Mean±3σ: 32deg  Max: 34deg
APPENDIX L: Specification Results Details: Safety SAS field of view - 20 deg

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**Convergence time (MAS) - Criterion: 40 degrees**

- Mean: 13850s
- Mean+3σ: 20770s
- Max: 20161s

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**Maximal misalignment (MAS) after convergence confirmed**

- 0 simulation(s) ignored
- Mean: 25deg
- Mean+3σ: 32deg
- Max: 34deg
Appendix M: Mathematical principle of the condition of intersection

The goal of this principle is to verify if a given segment (light ray) crosses the inner surface $S$ of a contour (see Figure below). We assume that the coordinates of the two points (an origin "O" and a target "T") are known as well as the coordinates of the contour summits.

Knowing all these coordinates and the unit vector perpendicular to the plan that includes the contour ($\mathbf{n}$), we can set:

$$O = \begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix} ; \quad C = \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} ; \quad I = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} ; \quad \mathbf{n} = \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

Thus the Cartesian equation of the plane $\Pi$ and the straight line $\Delta$ are described by:

$$\Pi : a.x + b.y + c.z + d = 0$$

$$\Delta : k.\mathbf{u} + \begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix}, \quad k \in \mathbb{R} ; \quad \mathbf{u} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} x_c - x_o \\ y_c - y_o \\ z_c - z_o \end{bmatrix} \times \left( (x_c - x_o)^2 + (y_c - y_o)^2 + (z_c - z_o)^2 \right)^{-1/2}$$

The light ray from $O$ to $C$ is stopped by the surface $S$ if the intersection $I$ of the segment $OC$ and the plane $\Pi$ exists and if $I$ is included in the surface $S$.

If $\mathbf{u} \cdot \mathbf{n} = 0$, then the straight line $\Delta$ is parallel to the plane $\Pi$ and the light ray from $O$ to $C$ is free. As we apply this principle into a numerical calculation we verify the condition $\mathbf{u} \cdot \mathbf{n} < \arccos(\epsilon)$ instead, with $\epsilon = 1 \times 10^{-6}$ rad ($= 6 \times 10^{-5}$ deg). In this case the algorithm consider that the surface $S$ does not stop the light ray. If $\mathbf{u} \cdot \mathbf{n} \geq \arccos(\epsilon)$, then $I$ exists and:

$$\exists! \ k \in \mathbb{R} \ subject \ to : \begin{cases} a.x_i + b.y_i + c.z_i + d = 0 \\ x_i = k.u_1 + x_o \\ y_i = k.u_2 + y_o \\ z_i = k.u_3 + z_o \end{cases}$$

Thus we can find the value of $k$:

$$k = \frac{-(a.x_o + b.y_o + c.z_o + d)}{a.u_1 + b.u_2 + c.u_3} = \frac{-(a.x_o + b.y_o + c.z_o + d)}{\mathbf{u} \cdot \mathbf{n}}$$

Depending on the sign of $k$, three cases emerge. If $k \leq 0$ then $O$ is between $\Pi$ and $C$, and $I$ does not belong to the segment $OC$. If $k \geq \|\overrightarrow{OC}\|$ then $C$ is between $\Pi$ and $O$, and $I$ does not belong to the segment $OC$ as well. In these two cases, the light ray from $O$ to $C$ is free.

Finally, if $0 < k < \|\overrightarrow{OC}\|$, then the segment cross the plane $\Pi$, and the light ray is stopped by $S$ if $I$ belong to this surface$^2$.

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$^1$ $\|\overrightarrow{OC}\|$ is the length of the segment $OC$

$^2$ This is verified with the MATLAB function "inpolygon"