The Brazilian Autonomous Star Tracker - AST

ANTONIO GIL V. DE BRUM[1], MÁRCIO A. A. FIALHO[2], M. L. SELINGARDI[2],
NILTON D. BORREGO[3], JOSÉ L. LOURENÇO[3]
[1]CECS/Aerospace Engineering
Universidade Federal do ABC
Av. dos Estados, 5001. Santo André – SP.
antonio.brum@ufabc.edu.br http://www.ufabc.edu.br
[2]Aerospace Electronics Division
National Institute for Space Research – INPE
Av. dos Astronautas, 1758. São José dos Campos – SP.
[3]Wisersoft Informatica
Av. Pensilvânia, 235. Jacareí – SP.
BRAZIL

Abstract: - The main subject of this paper is the star tracker system called AST (autonomous star tracker), currently under development at the Brazilian National Institute for Space Research – INPE. A description of the approach used to estimate the attitude on board the spacecraft, in real time and autonomously, is presented. The methods and techniques described in this paper guided the creation of the embedded software of the instrument in what concerns the attitude estimation and tracking. In it, a pattern recognition procedure is employed to identify stars in the field of view (FOV) of an active pixel sensor (CMOS APS), which comprises a star sensor system of one fixed head. As results, two computer program packages were created. The first one is intended to control the star tracker system operation, and the other is a simulation environment to test the system operation. This simulator environment was called ADAST (Attitude Determination Algorithm Software Test) and it represents an important contribution to the sector, for it comprises a complete simulation environment of a star sensor/tracker system, to be used in both, the understanding of the fundamentals of this equipment operation, and in the design and testing of algorithms that make up the system. The part of the studies concerning the search and track operations, along with their results, are discussed and presented in this paper. Some tests of the AST system are scheduled and are also described. Once tested, the AST will integrate the attitude control system of future Brazilian satellites within the goals of the space program in progress.

Key-Words: - Brazilian satellite, autonomous star tracker, AST, ADAST, attitude estimation software.

1 Introduction

The positioning and appointment of a spacecraft, along with their variations (attitude and orbit dynamics) need to be precisely known and controlled for the proper fulfillment of the space mission goals. For their importance, these items have been the subject of specialized studies aimed at improvements in the processes and methods employed today for their accomplishment ([1], [2] and [3]). The attitude and orbit control subsystem (AOCS) is the primary responsible for carrying out these tasks on board the spacecraft.

As a part of the AOCS, Star trackers are the most accurate attitude sensors currently in use. This technology has evolved from the heavy and very expensive star sensors used in the 70's, which were slow and consumed a lot of energy. These former devices were taking pictures of the stars in the imaging sensor field of view (FOV) and transferred this information to the AOCS, where the information was processed, along with data from other sources, and the attitude of the vehicle was then calculated. This attitude determination process needed a previous attitude estimate to work, and this implied the need for another coarse attitude sensor on board, as a sun sensor. Additionally, because of the delay in the processing of information and, consequently, in the determination of the spacecraft attitude, these sensors operated in conjunction with gyroscopes, used to track the attitude until a new accurate estimate were available. A more detailed description of these devices can be found in [4].

Modern star trackers are light, fast and low power consuming devices. These systems operate autonomously and are capable of offering accurate (arc second) 3 axis attitude to the AOCS many times in a second, even in the condition of no previous attitude knowledge available ("lost in space").

Because of technological advances in the areas of imaging sensors, integrated microelectronics and computing, including image processing techniques, these systems are produced today at a lower cost, offering a complete solution for precise autonomous attitude estimation on board without the need for additional equipment. To accomplish this, image processing methods and techniques are employed in order to extract precise attitude information from the star field images acquired by the sensor. Reference [5] discuss one of these methods. In [6], a discussion is presented on the techniques employed by Galileo Avionica (aerospace company) in the redesign of their Autonomous Star Trackers (ASTR) to fit the requirements of the NASA's New Horizon mission. Among these requirements, the new ASTR was expected to provide autonomous spacecraft attitude estimates at 10Hz at spin rates up to 10 rpm. Finally, as a very good example of one state-of-the-art equipment, the μASC (micro Advanced Stellar Compass) is presented in [7].

The development of all technologies needed to control the attitude of an artificial satellite is an important part of the Brazilian space program. As a part of this effort, in Brazil, since around the year 2000, INPE (the Brazilian National Institute for Space Research) has focused more sharply on the study of methods, techniques and equipment related to stellar sensing. These studies aimed at the development of sufficient expertise to create a star tracker system to operate in the forthcoming Brazilian satellites. The expertise generated has led to the creation of the AST (Autonomous Star Tracker), an state-of-the-art star sensor system, whose development, in terms of the control software, is presented.

As a part of the mentioned effort, in 2003, a simulation environment was created for testing different algorithms related to the internal process of attitude determination from one image. This simulation environment was called PTASE [8].

In 2005, already as part of a specific development project, the desired equipment specifications were defined [9]. Also in 2005, many studies concerning sensor optics were conducted. These studies led to the identification of the most important sensor operating errors, as well as the existing correction possibilities, so that the sensor could achieve the desired attitude determination accuracy and precision [10], [11].

In 2007, with the sensor specifications in mind, a newer and better version of PTASE was achieved [12]. This new version would be the basis for the simulations to be undertaken in the sequence of developments, when all efforts converged to the completion of the system software and all the acquired knowledge was used to create and test the software for the operation of the specified sensor. In this final stage, the aerospace company OMNISYS (headquartered in the city of São Bernardo do Campo, São Paulo) was contracted to collect and turn into a product all the knowledge generated till then.

Thus, in 2009, the simulation environment "ADAST" (Attitude Determination Algorithm Software Test) was created. This simulator has been extensively used since then to validate the algorithms used in the "Attitude Determination mode", particularly the control logic responsible for the passage from the "attitude acquisition" to the "tracking" sub modes, back and forth.

From 2008 to 2010, the first AST prototype was built, and attitude acquisition using the "lost in space" mode was successfully acquired in late 2010. Following this test, the algorithms tested in ADAST were implemented and a new night sky test, this time including the tracking mode, was conducted in February 2011. However, in this test the AST failed to successfully enter into the tracking mode, due to a software bug. This bug has been fixed and the star tracker hardware was improved.

In 2011, the AST and its system software were first presented to the scientific community [13].

New night sky tests are scheduled to occur in September/October 2013.

This paper is organized as follows: section 2 describes the attitude determination mode in the embedded AST software, its main phases and some of the algorithms used in it. Section 3 describes the ADAST simulator, with its most relevant configuration windows, and some simulations results. In section 4, the AST current status is presented. , the conclusions and future activities are discussed. Finally, Section 5 contains the conclusions, comments and future activities.

2 Attitude Determination in the AST

2.1 AST main features

The AST is a wide field of view (wide FOV) star tracker (star sensor), with a FOV around 25° × 25°. A star catalog and its pattern recognition software are implemented internally to allow three-axis attitude determination even when the vehicle is in a true “lost in space” condition, which makes the AST an autonomous star tracker. When fully calibrated, the AST should have accuracy of the order of a few arcseconds in the determination of its boresight axis coordinates.

The AST has many operational modes besides the "Attitude Determination mode", being capable of doing other things beyond attitude determination. Here are listed its most important operating modes:

Stand-by mode: default mode after powering up or a reset.

Imaging mode: selected when the AST is intended to be used as a camera, e.g. to take pictures of the Earth, the sky, or other celestial targets. It is also useful for debugging purposes (e.g., finding blemishes and defects in the CMOS APS array).

Attitude Determination mode: in this mode, attitude is acquired and updated continuously.

Calibration mode: used for maintenance and in laboratory calibration.

Only when the AST is in the “Attitude Determination Mode” it operates as a star sensor/star tracker. This mode of operation is the subject of this paper.

2.2 The Attitude Determination Mode of the AST

The AST “Attitude Determination mode” can be further subdivided in the following sub-modes:

Attitude acquisition: In this mode the AST attempts to calculate its own attitude and angular velocity state, from a couple of large images, taken in succession. This sub-mode may be entered either with or without a previous attitude estimate.

Attitude tracking: After successfully acquiring attitude and angular velocity state, the AST logically tracks stars previously seen in the last frames, updating attitude according to the position of these stars in the current frame.

After entering the “Attitude Determination Mode”, the AST begins with the “Attitude Acquisition" sub-mode, remaining in this sub-mode until its attitude and velocity are acquired with enough precision to enter into the attitude tracking sub-mode, where it should remain for most of the time. If by some reason, tracking of stars is lost, the AST returns to attitude acquisition sub-mode. The AST is an autonomous star sensor, meaning that it is capable of acquiring attitude even in the absence of previous attitude information, e. g., in a true “lost in space” mode. However it can benefit from the availability of an attitude estimate provided by the attitude and orbit control computer (AOCC), since this will allow a faster attitude acquisition. Figure 1 depicts the internal states transitions of the “Attitude Determination Mode”.

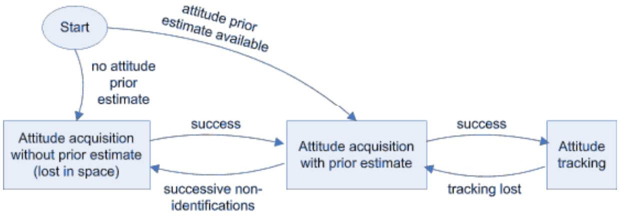


Figure 1 - Internal state transitions diagram of the “Attitude Determination Mode”.

When in the “Attitude acquisition without a prior attitude estimate” state, also known as “lost in space” state, once the first acquired image is processed and a successful attitude is calculated from it, the AST switches to the “Attitude acquisition with prior estimate”, using that first attitude as an attitude estimate for the processing of the next image. The star sensor only exits the “Attitude Determination Mode” when receiving a command from the AOCC to switch to another operating mode or in case of a reset or power cycling.

From the hardware point of view, the main difference between “attitude acquisition” and “attitude tracking” sub-modes is in the way that the FPGA that controls the image sensor is programmed to acquire images in each case. In the “attitude acquisition” sub-mode the FPGA is programmed to take a single rectangular image, with arbitrary dimensions up to the dimension of the image sensor itself (1024×1024 pixels), whereas in the “attitude tracking” sub-mode, the hardware is programmed to image only inside some small fixed size square windows, that can be positioned anywhere on the image sensor. In the current implementation, there are 12 windows each measuring 12×12 pixels. When the AST is operating in the “attitude tracking” sub-mode these windows are programmed to the expected location that the tracked stars should be in the next frame, prior to frame acquisition. This difference between “Attitude Acquisition” and “Attitude Tracking” sub-modes is illustrated in Figure 2. For a successful attitude acquisition, the AST FOV should be unobstructed and situated in a spacecraft section that does not rotate or rotates slowly.

2.3 The attitude acquisition phase

In the "Attitude acquisition" phase, the star sensor acquires a first image and processes it, in order to obtain its attitude.

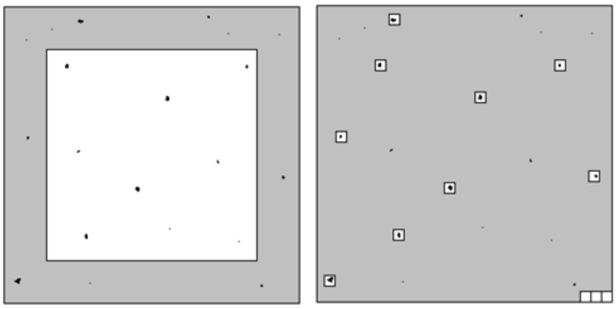

a) imaging in sequential mode
b) imaging in tracking mode

Figure 2. Image acquisition during a) "attitude acquisition" and b) "attitude tracking" sub-modes. The larger outer squares represent the image sensor useful area. Dark dots represent stars. Grayed-out areas are areas ignored by the FPGA that controls the image sensor.

Since the spacecraft may be rotating, to be able to enter into the "attitude tracking" phase, knowledge of the spacecraft angular velocity **ω** is required. For this, the AST acquires a second image, and computes a new attitude from it using the first attitude as an attitude estimate. Using these two attitudes and the time difference between the acquisition times of the images used to calculate these attitudes, the star sensor is able to calculate the spacecraft angular velocity **ω**. The AST then acquires a third image, calculates its attitude and compares this measured attitude with the attitude for this third image predicted from **ω** and the previous attitude. If both have a good agreement, it means that the knowledge of current attitude and attitude evolution is good enough to enter the "attitude tracking" phase, described in section 2.4. In the next paragraphs, a discussion about the mathematical model used in the attitude acquisition phase is presented.

We assume here that the vehicle angular velocity is small ($\boldsymbol{\omega}$ < 1 deg/sec) and time intervals between successive images are small enough (a few seconds or less). This is usually the case for most contemporary applications (AST specification is $\boldsymbol{\omega} \leq 0.5$ deg/sec; time intervals were studied and simulated to check the model adequacy).

Taking: S/C = spacecraft;

$\boldsymbol{\omega}$ = star sensor angular velocity in the inertial reference frame [12] in matrix form = S/C angular velocity, since the star sensor is fixed in the S/C;

$\mathbf{A}$ = star sensor attitude matrix in the inertial reference frame;

$\mathbf{I}$ = identity matrix;

$\boldsymbol{\omega}_\mathbf{E}$ = estimate of ω;

$\mathbf{M}^T$ = transpose of matrix **M**;

t = time;

$d\mathbf{A}/dt = -\omega.\mathbf{A}$, assumed model of attitude evolution. (1)

2.3.1 1st step - Acquisition and processing of the 1st image

i) 1st image is taken at $t = t_o$. If no previous attitude estimate is available ("lost in space" case), this image is a large image with 1024×1024 pixels. If a previous attitude estimate is available, this first image can be smaller (384×384 pixels).

ii) 1st image is processed and the attitude at the instant of acquisition of this image $\mathbf{A}(t_o)$ is calculated after stars in this image have been identified. If no previous attitude estimate is available, the Star Identification Algorithm (SIA) works in the "lost in space" condition, otherwise it uses the provided attitude estimate to speed up the identification process.

iii) If attitude successfully obtained, proceed to the next step, otherwise repeat this step.

iv) If a previous attitude estimate was available and too many attempts to acquire attitude with this estimate have failed, then ignores this estimate for the next attempts, thus, effectively entering into the "lost in space" state.

2.3.2 2nd step - Acquisition of a 2nd image and computation of the spacecraft angular velocity

i) At $t = t_o + \Delta t_o$, the 2nd image is taken (384×384 pixels)

ii) This second image is processed and $\mathbf{A}(t_o+\Delta t_o)$ is calculated after stars in this image have been identified, like in the previous step. In this step the AST uses the previous attitude ($\mathbf{A}(t_o)$) as an attitude pre-estimate, which significantly reduces the time required for stellar identification;

iii) $\boldsymbol{\omega}_\mathbf{E}$ is calculated with the use of the following attitude evolution model:

$$\boldsymbol{\omega}_\mathbf{E} = [\ \mathbf{I} - \mathbf{A}(t_o+\Delta t_o).\mathbf{A}^T(t_o)\ ] / \Delta t_o \qquad (2)$$

iv) If successful, proceeds to the next step, otherwise goes back to the 1st step.

2.3.3 3rd step - Verification of the accuracy of ω and A estimates:

i) Let $t \leftarrow t_o + \Delta t_o$ = acquisition time of the last image.

ii) Let $\mathbf{A}(t) \leftarrow \mathbf{A}(t_o + \Delta t_o)$ = attitude calculated from the last image.

iii) Use $\boldsymbol{\omega}_\mathbf{E}$ and $\mathbf{A}(t)$ to predict vehicle attitude at $(t + \Delta t)$, where Δt is the time difference between the acquisition time of the last (usually the second) image and the acquisition time of the next image to be taken. According to the model in (1), this predicted attitude $\mathbf{A_p}(t + \Delta t)$ is given by:

$$\mathbf{A_p}(t + \Delta t) = [\mathbf{I} - \boldsymbol{\omega}_\mathbf{E} \Delta t]\, \mathbf{A}(t); \qquad (3)$$

iv) A new image is taken at $t+\Delta t$ (in this case, a smaller one, 384×384 pixels). After its processing $\mathbf{A}(t+\Delta t)$ is calculated.

v) By comparing the predicted attitude $\mathbf{A_p}(t + \Delta t)$ with the measured attitude $\mathbf{A}(t + \Delta t)$ it is possible to know if $\boldsymbol{\omega}$ and $\mathbf{A}$ are known with sufficient precision to enter into the “attitude tracking” sub-mode.

vi) If $\mathbf{A}(t + \Delta t)$ and $\mathbf{A_p}(t + \Delta t)$ do not agree to the required precision to enter into the “attitude tracking” phase, then let: $t \leftarrow t + \Delta t$, $\mathbf{A}(t) \leftarrow \mathbf{A}(t + \Delta t)$, and repeat this step from the point where a new $\mathbf{A_p}(t + \Delta t)$ is calculated.

If the obtained estimate at the end of the 3rd step is good enough, the tracking phase can be started. Otherwise, the process has to be repeated until an estimate with enough accuracy is obtained. Here, "enough accuracy" means good enough to allow positioning the tracking windows in such a way that the image of the stars that will be tracked will be in the center or close to the center of these tracking windows when the next image is taken. For tracking windows with 12×12 pixels, the required accuracy is around ±2 pixels. This small adjustable margin of error was considered in this work. Note that the decision of making the tracking windows larger can lead to a review of this margin, taking it to ±3 or ±4 pixels.

The attitude estimate used in the 1st step does not need to be complete; an estimate of the star sensor boresight axis suffices for speeding up the attitude acquisition process.

The algorithms employed in computing the attitude from a single image (image processing, star identification and attitude determination algorithms) are discussed in [8] and [13].

2.4 The attitude tracking phase

The transition from the “attitude acquisition” to the “attitude tracking” phase depends on the precise knowledge of the vehicle attitude. The AST should seek to enter the tracking mode whenever possible and keep its operation in this mode.

At this stage, the S/C attitude and angular velocity are accurately known. This information is used to predict the set of stars that are going to be visible in the sensor FOV at the instant of the next image acquisition as well as to calculate their positions (centroids). The brightest stars that will be inside the FOV in the next frame are selected for tracking, and around each of them is positioned a tracking window. Confirming the presence of these stars in their expected windows, is an indication that the S/C attitude is maintained within the required accuracy. In this stage the attitude and the angular velocity estimate $\boldsymbol{\omega}_\mathbf{E}$ are constantly updated. This section describes the mathematical model used in this sub-mode, an adaptation of the method called "predictive centroiding" [15].

2.4.1 **Start** - instant t: $\boldsymbol{\omega}_\mathbf{E}$ and $\mathbf{A}(t)$ are known:

The next image, composed of many tracking windows, will be taken at instant $(t + \delta t)$, where t is the current moment and δt is a time interval of the order of milliseconds, usually the integration time required for image acquisition plus a small processing time.

i) For the instant $(t + \delta T)$, the predicted attitude matrix, $\mathbf{A_P}(t + \delta t)$, is calculated using a first order approximation:

$$\mathbf{A_P}(t+\delta t) = [\mathbf{I} - \boldsymbol{\omega}_\mathbf{E}.\delta t].\mathbf{A}(t) \qquad (4)$$

Usually, for most of the practical applications, $\| \boldsymbol{\omega}_\mathbf{E}.\delta t \| < 10^{-3}$ rad. This means that (4) must be accurate to this order of magnitude (milliradians), or better, to perform one step prediction.

ii) With $\mathbf{A_P}(t + \delta t)$, a search is made in the star catalogue for stars that will be inside the FOV.

- Being $\hat{\mathbf{s}}_i$ the unit vector associated with the i-th catalogued star and $\hat{\mathbf{u}}_\mathbf{est}$ the boresight axis extracted from $\mathbf{A_P}(t + \delta t)$, the dot product $\hat{\mathbf{s}}_i \cdot \hat{\mathbf{u}}_\mathbf{est}$ is calculated, if this product is greater than the cosine of the FOV semi-diagonal, then the star might be inside the FOV, otherwise it is surely outside and is skipped.
- If $\hat{\mathbf{s}}_i \cdot \hat{\mathbf{u}}_\mathbf{est}$ is greater than the cosine of the FOV semi-diagonal, then the expected centroid coordinates for that star are computed:

$$x_i = x_o - (f / d) \cdot (\hat{\mathbf{a}}_\mathbf{1} \cdot \hat{\mathbf{s}}_i)/(\hat{\mathbf{s}}_i \cdot \hat{\mathbf{u}}_\mathbf{est}) + \text{distortion\_x}(...) \qquad (5\ a)$$

$$y_i = y_o - (f/d) \cdot (\hat{\mathbf{a}}_2 \cdot \hat{\mathbf{s}}_i)/(\hat{\mathbf{s}}_i \cdot \hat{\mathbf{u}}_{est}) + \text{distortion\_y}(...) \tag{5b}$$

Where: (x_i,y_i) are the expected centroid coordinates in pixels; (x_o, y_o) is the center of the array (usually (512, 512)); f is the focal length of the sensor objective; d is the pixel size (assuming same width and height); $\hat{\mathbf{a}}_1$ and $\hat{\mathbf{a}}_2$ are the cross-boresight axes predictions obtained from $\mathbf{A_P}(t + \delta t)$. Distortion introduced by the optics or misalignments must be modeled, hence the distortion_x(...) and distortion_y(...) functions.

- If (x_i,y_i) is within the CMOS APS sensor array and not too close to the array edges and corners, where observation may be incomplete or blocked, then the i-th star is added to the list of stars to be tracked.
- The search continues until the catalog ends or the list of stars to be tracked is full.
- The star catalogue used is sorted by magnitude, so brighter stars will be verified first.

iii) With the list of predicted centroid positions (x_j,y_j), $j = 1,...,n \leq 12$, the tracking windows are programmed in the FPGA in such a manner that these centroids lie in their centers. Unused tracking windows must be placed in places where they don’t disturb the windows that will be used, like near the corners of the sensor array.

iv) The FPGA is commanded to start image acquisition in tracking mode.
Since only pixels inside the tracking windows are imaged, the resulting image size is much smaller than those acquired in the “attitude acquisition” phase, being only 12 × 12×12 = 1728 pixels, *versus* more than one hundred thousand pixels for images acquired for attitude acquisition. Hence processing time is much shorter.

v) After the image acquisition is completed, a "star confirmation algorithm" is executed. This algorithm checks if the tracked stars are indeed inside their corresponding tracking windows, computing their centroid locations and brightness from these windows. For each star, if its brightness and centroid position differs too much from their expected values, the star is deemed not observed or unconfirmed.

vi) If too many tracked stars were rejected in the previous step, then AST assumes that attitude tracking was lost, going back to the “attitude acquisition” phase. On the other hand, if a sufficiently high number of tracked stars was confirmed, then the AST attitude is updated using the centroid locations obtained from the image processing. This updated attitude is denoted $\mathbf{A}(t + \delta t)$. With this updated attitude, a refinement in the value of $\boldsymbol{\omega}_\mathbf{E}$ is achieved.

$$\boldsymbol{\omega}_\mathbf{E} = [\,\mathbf{I} - \mathbf{A}(t+\delta t).\mathbf{A}^\mathbf{T}(t)\,] / \delta t \tag{6}$$

vii) From here on, we take $t \leftarrow (t+\delta t)$ and repeat the process. Thus the stars are tracked in their apparent movement inside the sensor FOV. As some stars leave the sensor FOV, new stars are automatically included in the list of stars to be tracked, as they enter the sensor FOV.

It is important to note that the software that controls this phase is designed to work well even in the case of vehicle attitude loss (or accuracy loss). In this case, the system leaves the tracking mode, returning to the acquisition mode with prior attitude estimate, or, even, it may go back to the initial "lost in space" condition, when the vehicle attitude data is lost, unknown, or insufficient, as depicted in Figure 1.

The algorithms employed in updating the attitude from a single frame during "attitude tracking" phase are very similar to those used in the "attitude acquisition" phase, except that the star identification algorithm is replaced by a "star confirmation algorithm" as described in the preceding paragraphs.

3 The Simulation Environment

A complete simulation environment for the AST operation in the “Attitude Determination” mode was developed by Omnisys Engineering, with the help of Wisersoft and support of INPE and UFABC. This environment was called "ADAST", and was developed to test algorithms used when the AST operates as a star sensor / star tracker, including image processing algorithms, star identification algorithms and attitude determination algorithms. One of the main goals during its development was to test the “attitude tracking” phase, a new development that had not been tested by previous simulators, such as PTASE ([8], [12]) and SIATS [16]. Another important goal accomplished by ADAST was to test the control logic responsible for switching between the “attitude acquisition phase” to the “attitude tracking phase” and vice-versa.

Using the star catalog itself, and parameters entered by the user, ADAST is able to generate synthetic images of the sky very similar to those expected to be seen by the AST. These images are fed to the attitude determination chain (image processing, star identification and attitude determination algorithms), exercising algorithms to be implemented in the AST embedded code.

ADAST uses PTASE base code to simulate expected images in the FOV of a sensor with AST characteristics. To do this, all items related to image acquisition with APS sensors (image integration times, image data transfer, spacecraft rotation), and all algorithms related to the attainment of an optimal attitude estimate (initial image acquisition, image processing and centroid calculation, systematic errors correction, stars identification, preliminary attitude determination, optimal attitude estimation, angular velocity estimation, transition between attitude acquisition and tracking phases - with or without use of preliminary estimate of attitude) are taken into consideration by the program.

Software PTASE was developed to implement and test attitude determination algorithms, as well as to simulate the starry sky seen by the sensor FOV ([8], [17]). In its operation, the program internally accesses a star catalog specially developed for this application from the catalog generated by the astrometric mission Hipparcos [18]. References [8] and [12] discuss and present the details of these implementations in the PTASE simulation environment. Reference [16] discusses the algorithms themselves.

3.1 ADAST (Attitude Determination Algorithm Software Test) brief description

ADAST simulates the sensor image acquisition. This is possible through the understanding of the imaging process, as performed with use of CMOS APS sensors, and it requires estimates of the time intervals involved in the process (integration, transferring, processing, etc.).

When set to operate in the search/acquisition mode, the images are simulated according to adjustments in size (512×512, 1024×1024, etc.), integration times (milliseconds), rotational condition of the vehicle (angular velocity: intensity and direction), and star sensor initial attitude. As an example, to get a simulated image focused on Antares, the alpha star in the Scorpius constellation, we use the inertial coordinates of the star (right ascension and declination) as input

for the pointing direction of the sensor optical axis (ANTARES: RA = 16h 29m 24s; DEC = −26.43°) when setting the initial attitude. In this case, the integration time and the image size have also to be adjusted. Naturally, for larger integration times, the stars seem brighter in the image. Additionally, larger images imply larger image processing times.

The simulator uses input data in degrees. Thus, for centering on Antares we must set: right ascension (RA) = 16h 29m 24s = 247.35° and declination (DEC) = −26.43°. Figure 3 shows a simulated image with Antares on its center and the attitude input needed to get this image (in the "Set APS Sensor Axis Point" window). ADAST also permits to save images created in this way (in bitmap format). This possibility of saving images is important for the program validation.

3.2 Attitude Determination from a Simulated Image

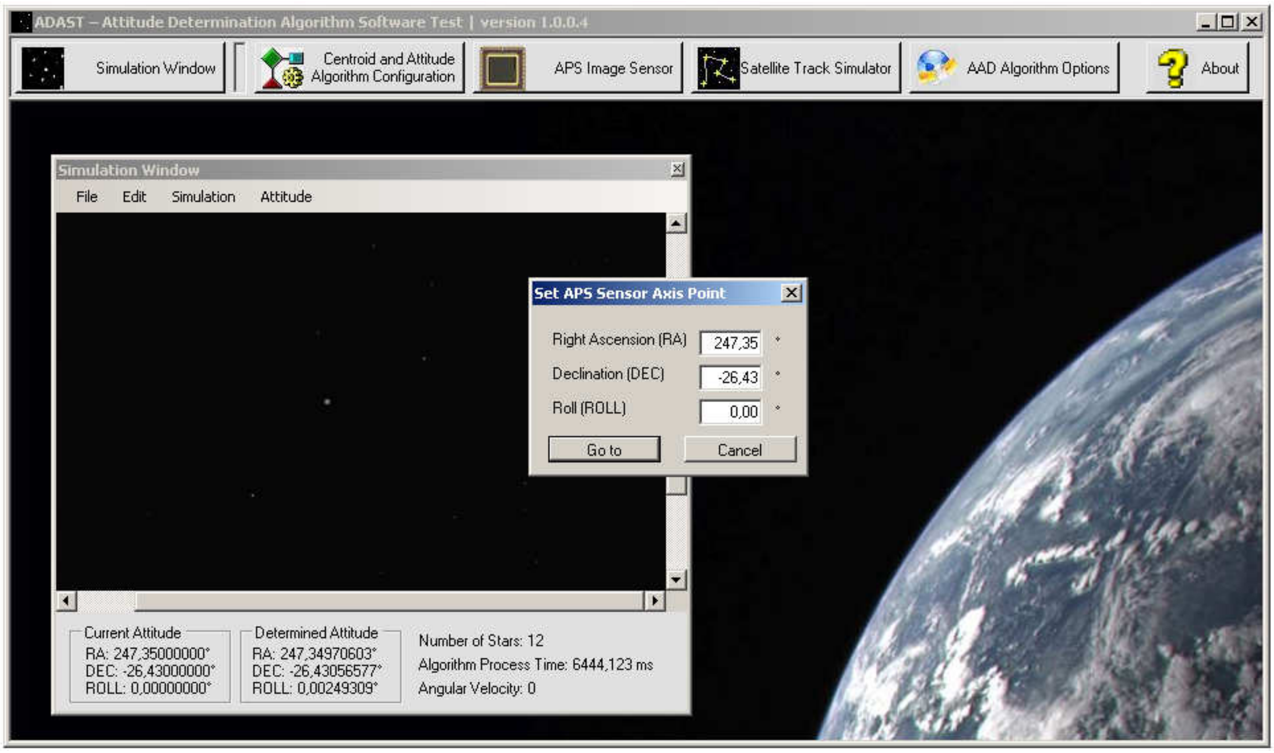
With respect to the former example, when the program generates and shows a simulated image, it automatically runs its internal algorithms of image processing, stars identification and attitude determination. Figure 3 shows this program feature. In the image of Antares, as produced by the simulator, we see in the lower part of the simulation window the "true" attitude ("Current Attitude"), the attitude as determined by the internal processing algorithms ("Determined Attitude"), and other data related to the image processing, such as the total processing time (6.444 seconds), the number of stars in the image (12), and the angular velocity setting (0 degrees/second).

3.3 Settings for the Search and Track Modes

By pressing the "AAD Algorithm Options" button in the upper menu bar of the program main window (Figure 3) a window opens with settings for the "search mode" and the "track mode" (Figure 4). The "search mode" corresponds to the “attitude acquisition phase” of the embedded AST code, while the "track mode" corresponds to the “attitude tracking” phase of the AST. Figure 4 shows the defaults for both modes of operation and how they can be adjusted in the window "AAD Algorithm Options". In the "Start Options" tab, the user can set if the simulation will start in a "lost in space" mode, or if an estimated attitude will be provided for initial attitude acquisition. In the "Seach Mode" tab we can see that separate settings can be defined for the "lost in space" case (with no initial attitude estimate) and "other" cases (with an initial attitude estimate)

3.4 Simulation of the sensor operation

The "Simulation Window" is the place where the simulations are viewed and controlled. In the "Simulation" menu, when the item "Satellite Path" is marked, the simulation of the acquired images along the FOV trajectory will be generated and presented. These images are rendered according to



Right Ascension (RA) 247,35 °
Declination (DEC) -26,43 °
Roll (ROLL) 0,00 °

Current Attitude
RA: 247,35000000°
DEC: -26,43000000°
ROLL: 0,00000000°

Determined Attitude
RA: 247,34970603°
DEC: -26,43056577°
ROLL: 0,00249309°

Number of Stars: 12
Algorithm Process Time: 6444,123 ms
Angular Velocity: 0

Figure 3 - ADAST main window, with the simulation window open (in the background, showing Antares). On the foreground is a dialog window where the optical axis coordinates are being adjusted to coincide with Antares.

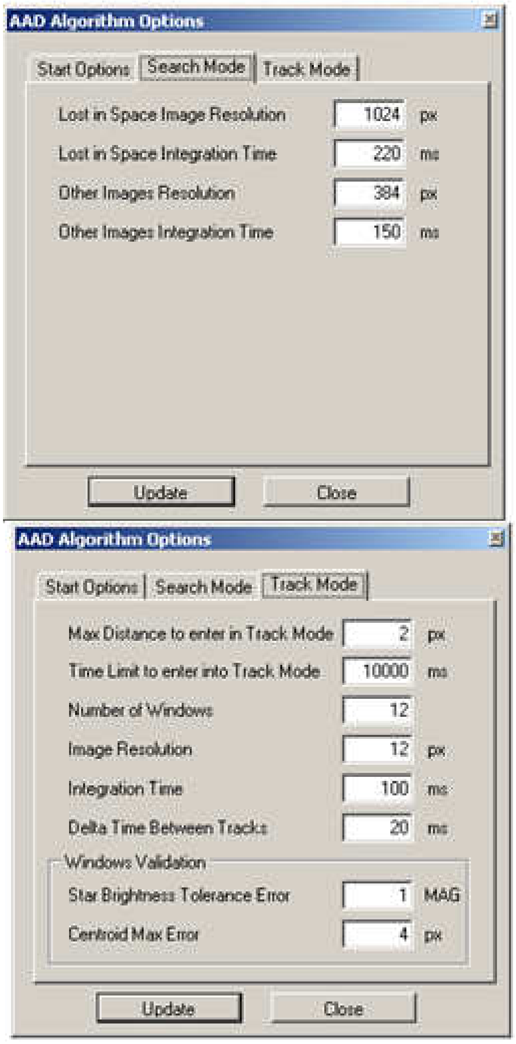
the definitions adjusted by the user in the "APS Image Sensor" window (size, time intervals, etc.). To start a simulation, one must select the "Start" item on the same menu.

To simulate images acquired in the presence of vehicle angular velocity around an arbitrary axis **e**, $\mathbf{e} = [\mathbf{e}_1\ \mathbf{e}_2\ \mathbf{e}_3]^T$, one has to adjust that in the program. These settings are accessible through the "Satellite Track Simulator" button on the program's main menu. Figure 5a shows the settings used for the simulation shown on figure 5b. The angular velocity used was 0.5 degree/sec, corresponding to the worst case predicted in the AST design. In this simulation, the integration time was modified to 600 milliseconds, to better register the movement of the stars inside the sensor FOV. As expected, we can observe the trails formed as the stars move through the field of view. Such trails are expected to be larger, the larger the product of angular velocity and integration time. Also it is noticeable that the image processing and attitude determination algorithms remained in operation. However, in the specific case shown, the internal algorithms were unable to determine the attitude from the image ("Not defined"), and the angular velocity ("Angular Velocity: 0,000000000°/s"). This has occurred because, in these worst cases, the star "spots" in the image became significantly stretched impairing the calculation of the stars centroids. For these cases, the use of special processing techniques allows the calculation of stars centroids with better accuracy, and increases the efficiency of the attitude determination process. One of these techniques is presented in [10] and has been considered for possible implementation.

3.5 Simulation of the Attitude Determination mode

To perform a simulation of the "Attitude Determination" mode of the AST, one has to select the "Search and Track Algorithm" option, inside the simulation window, in the "Simulation" menu, can be used to start the simulation of the sensor operation, which can be performed with or without a previous attitude estimate. Once a simulation is started, a new window named "Search and Track Status" opens with information about the simulation, as shown in Figure 6. Before starting the simulation, one should remember to set correctly the angular velocity, rotation axis and star sensor's initial attitude.

The current phase in the "Attitude Determination" mode is shown in the upper part of the "Search and Track Status" window (Figure 6). The "LOST IN SPACE", "WITH ESTIMATED ATT", "CALC ANGULAR VELOCITY" and "GOING TO TRACK MODE" boxes corresponds to phases in the "attitude acquisition" sub-mode, while "TRACK MODE" corresponds to the "attitude tracking" sub-mode. In the example shown in Figure 6, one can see that the “attitude tracking” phase had already been reached ("TRACK MODE" box is marked with a yellow border), and that the tracking windows of the stars identified in the search mode were operational (small squares around the stars). In the upper middle of this window is shown a detailed view of the contents of two tracking windows. Below these two tracking windows is shown a text report containing the information generated during simulation. This information can be saved to a log file for further analyses and validation of the results ("Save Output to File...").

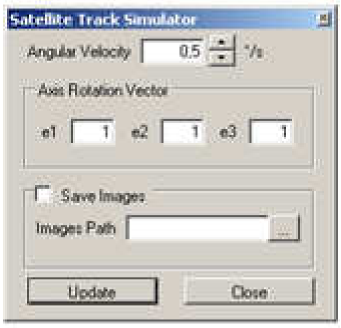


Lost in Space Image Resolution 1024 px
Lost in Space Integration Time 220 ms
Other Images Resolution 384 px
Other Images Integration Time 150 ms

Max Distance to enter in Track Mode 2 px
Time Limit to enter into Track Mode 10000 ms
Number of Windows 12
Image Resolution 12 px
Integration Time 100 ms
Delta Time Between Tracks 20 ms
Windows Validation
Star Brightness Tolerance Error 1 MAG
Centroid Max Error 4 px

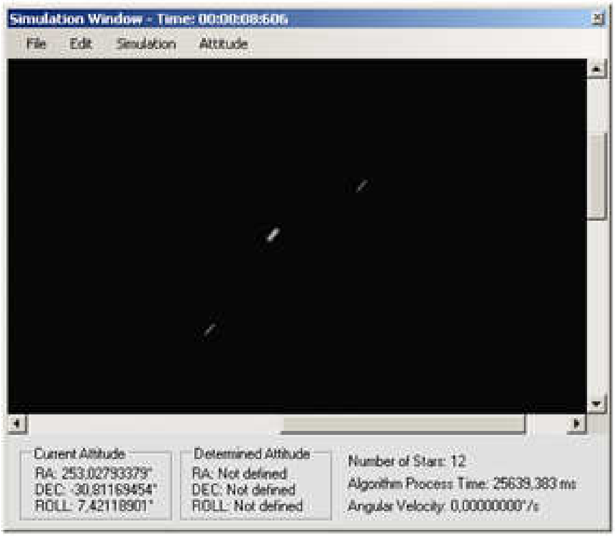
Fig. 4 - Defining the conditions of the Search and Track modes.

By analyzing the results of many simulations, the proper operation of the ADAST simulation environment as well as of the algorithms proposed for the AST could be verified. Hence, the part of the validation verifiable via computer simulations has been successfully performed.



Angular Velocity 0,5 °/s
Axis Rotation Vector
e1 1 e2 1 e3 1
☐ Save Images

a) settings for rotation simulation



Current Attitude
RA: 253,02793379°
DEC: -30,81169454°
ROLL: 7,42118901°

Determined Attitude
RA: Not defined
DEC: Not defined
ROLL: Not defined

Number of Stars: 12
Algorithm Process Time: 25639,383 ms
Angular Velocity: 0,00000000°/s

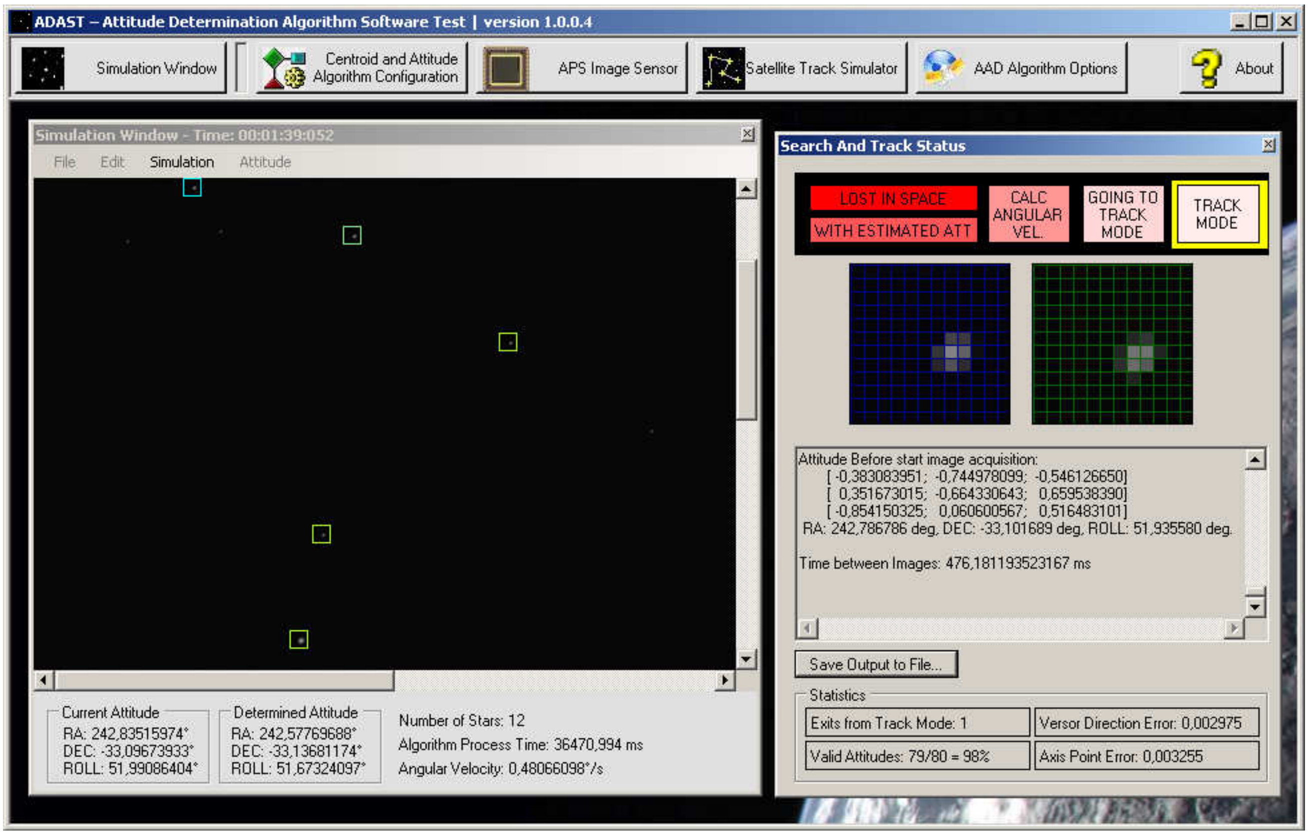
b) motion blurred image of Antares generated by ADAST

Fig. 5 - Simulated image of Antares for the condition where the vehicle has angular velocity of 0.5 degrees/sec around axis **e** = $[1\ 1\ 1]^T$, in inertial coordinates.

4 AST Current Status

Two AST units are being built for a new protoMirax mission under preparation. ProtoMirax ([19],[20]) is a stratospheric balloon experiment that is scheduled to be launched at the end of 2014 / beginning of 2015. This balloon flight will provide a unique opportunity to verify and validate the AST in an environment that is very close to the space environment (low atmospheric pressure, large temperature variations, ionizing radiation, remote operation).

Before building these units that will fly in the protoMirax experiment, two laboratory units of the AST were built. One of these is an advanced breadboard where the electronics and part of the embedded software where thoroughly tested. These tests verified correct operation of the AST processor, memories, FPGA and basic software (bootloader and operating system). The other laboratory unit is an engineering model of the AST. This engineering model is a complete star tracker built with commercial grade components that



Current Attitude
RA: 242,83515974°
DEC: -33,09673933°
ROLL: 51,99086404°

Determined Attitude
RA: 242,57769688°
DEC: -33,13681174°
ROLL: 51,67324097°

Number of Stars: 12
Algorithm Process Time: 36470,994 ms
Angular Velocity: 0,48066098°/s

```
Attitude Before start image acquisition:
      [ -0,383083951;  -0,744978099;  -0,546126650]
      [  0,351673015;  -0,664330643;   0,659538390]
      [ -0,854150325;   0,060600567;   0,516483101]
 RA: 242,786786 deg, DEC: -33,101689 deg, ROLL: 51,935580 deg.

Time between Images: 476,181193523167 ms
```

Exits from Track Mode: 1
Versor Direction Error: 0,002975
Valid Attitudes: 79/80 = 98%
Axis Point Error: 0,003255

Fig. 6 - Simulation of the "attitude determination" mode.

allowed us to perform tests that depended on the image sensor and optics. This engineering model was extensively used during laboratory and observatory tests (resulting in many successful attitude acquisitions). It was also very useful for testing the laboratory infrastructure that will be used for calibrating and testing the units that will fly aboard the protoMirax experiment.

5 Conclusions and Future Steps

The software created to control the AST operation is described together with the software simulator developed, the ADAST, which performs the simulation of the star sensor environment and implements the approach chosen as solution to the attitude determination problem with use of a star sensor with the same characteristics as the AST. Two ADAST functions were verified with use of simulations. Using the AST engineering model, we successfully acquired attitude from the "lost in space" condition. Attitude acquisition during tracking mode in the AST engineering model was attempted but could not be achieved due to a implementation bug in the embedded software. This software bug was identified and corrected and a new test is scheduled to occur in September 2013.

One of the main qualities of the software developed is the simplicity of the dynamic model used, which results in lightness and computational speed.

Although developed for the AST, the ADAST can also be configured to simulate other star sensors.

The software was created to function well in the situation of up to 0.5 degrees/sec of rotation of the sensor (fixed in the spacecraft). The main difficulty in simulating the operation occurs for the extreme cases where the combination of angular velocity and integration time is large. For these cases, the images of the stars in the sensor FOV becomes in most cases a streak, whose centroid is difficult to calculate. Simulations related to these cases have shown that the operation of the algorithm also depends on the region of space considered, because of the greater or lesser number of stars brighter than the detection threshold present in the sensor FOV. Even in these cases, for most of the regions concerned, the algorithm behaved well, in terms of positive identifications of the stars present in the FOV. In the worst cases, when the loss of vehicle attitude occurred, the sensor operation was redirected to the search in the "lost in space" condition, where the imaging settings are properly defined to facilitate the process of positive identification when no previous attitude knowledge is available.

The model used in the attitude tracking sub-mode simulation assumes that the angular velocity is constant, both in direction and in magnitude. The situations where the presence of external or internal torques could originate some angular acceleration have not been addressed. The small time intervals between the acquisitions of successive images justify this approach. The evaluation of the effects introduced by the presence of non-constant angular velocities as a function of the time between successive images in the search and track modes is recommended for future investigations.

The phase of validation of the algorithms implemented in the ADAST using the actual sensor hardware is already underway, with some important achievements, such as real time attitude determination using the actual star sensor hardware. Efforts to improve attitude accuracy and success rates are currently in progress. For the near future, further tests in laboratories and in astronomical observatories are planned, as well as a balloon flight aboard the protoMirax experiment.

For the future, improvements in the star tracker software are expected. In special, the identification software could be improved by the insertion of new search techniques, like those discussed in [21].

By aggregating all the knowledge acquired about the state of the art of star sensors, the ADAST represents an important acquisition for the engineering and space technology sector in Brazil and establishes a new standard for studies and developments in this area in this country.

The AST represents an important achievement of the Brazilian space program. With it, Brazil gets closer to its aim of mastering the technologies needed to completely control the attitude of an artificial satellite.

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