A test and calibration environment for the Brazilian star tracker

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Abstract. For many spacecraft to accomplish their mission goals there is a need to have an accurate control of their spatial orientation (attitude), so that instruments aboard the spacecraft, such as remote sensing cameras, telescopes, and other scientific payload be correctly pointed to their targets. For that purpose, many spacecraft employ sophisticated attitude control systems, fed by a variety of attitude sensors: sun sensors, horizon sensors, gyroscopes, star trackers, etc. Among the attitude sensors capable of providing an absolute attitude measurement, star trackers are considered the most accurate. This work presents an overview of the test and calibration infrastructure built for an autonomous star tracker (AST) being developed by the Electro-Optics group of INPE, result of an effort to increase the competence of the country in attitude control systems.

1. Introduction

Many spacecraft, especially those developed for Astronomy and Astrometry, require a precise control of their attitude (orientation in space) to accomplish their mission goals. To do so, they employ a variety of attitude sensors, which provide to the spacecraft attitude control system information about the spacecraft orientation in space. Star trackers are among the most accurate attitude sensors available for spacecraft [1, 2]. Most of them consist of a computerized camera with embedded software capable of obtaining an attitude solution from sky images taken by them, using the observed stars as attitude references. This work presents the calibration and test environment built for testing current and future autonomous star trackers (ASTs) for future Brazilian space missions.

Star trackers are also known in the literature as star cameras or star sensors, even though, according to many, the latter term is broader as it also includes star scanners [1, 2]. In this work we will use these terms interchangeably.

This paper is organized as follows: Section 2 provides a brief introduction to the star sensor that is being developed at INPE; Section 3 describes the main calibration environment that was built to calibrate this star sensor; Section 4 presents a portable scene simulator, which can be used to optically stimulate the AST during hardware in the loop tests; Section 5 concludes this work.

2. Star trackers for protoMirax

2.1. Star tracker development

The development of an autonomous star tracker (that is, a star tracker capable of obtaining an attitude solution without any external processing) began at INPE with the development of image processing
and star identification (star-ID) algorithms. Soon after, hardware development started with the definition of the AST architecture and selection of key components (processor and image sensor). An engineering model was built using components with commercial temperature range (0 °C to +70 °C) that had space qualified equivalent versions [3]. After that, it was decided to validate the star tracker design in a stratospheric balloon flight. Since the engineering model was not suitable for a balloon borne stratospheric flight, it was decided to build three models of a new version with electronic components suitable for operation in the stratosphere, with wider temperature range (−40 °C to +85 °C for most components). Two of these models will fly aboard the protoMirax balloon borne experiment [4], while the third will serve as a backup unit. Figure 1 shows one of the models being assembled, then being prepared for a thermo-vacuum test and installed in protoMirax for mechanical interface verification.

Simultaneously with the star sensor’s hardware development, we have worked in the development of its embedded software and test and calibration resources. Reference [5] presents the simulation software that has been developed to test the transition between the attitude acquisition and attitude tracking modes.

2.2. Star tracker specifications
The autonomous star tracker (AST) being developed at INPE is a wide field of view star sensor with a single optical head. The main features of the two star tracker models that will fly aboard the protoMirax experiment are given in Table 1.

| Description          | Specification                                      |
|----------------------|----------------------------------------------------|
| Mass                 | < 4.5 kg                                           |
| Volume               | 180 x 140 x 317 mm³ (baffle included)              |
| Power                | 4 W (typical), 15 W (max.)                         |
| Field of view        | 25.4° x 25.4°                                      |
| Star catalog         | 1612 stars, up to magnitude 5.                     |
| NEA (random error)   | yaw, pitch: < 3.3 arcsec roll: < 20 arcsec        |
| Processor            | SPARC, 32 bits, 9.6 MIPS @ 12 MHz                 |
| Memory               | 4 MB RAM + 1 MB storage                            |

A more detailed explanation of our star sensor main characteristics, hardware and software is provided in reference [3].
3. Main calibration infrastructure
An autonomous star tracker is able to meet its specifications only if a detailed mapping of the distortions introduced by its optics is performed. From this mapping, a set of calibration parameters is derived. These parameters are used by the AST firmware to compensate the distortions introduced by its optics. Also, if its radiometric response is accurately measured, it becomes possible to use stellar brightness (as seen by the AST) as an efficient filter during star identification, improving AST performance and reliability.

To perform a detailed optical and radiometric characterization of the AST, the following calibration infrastructure was built and installed in a clean room environment. Its main components are:

- Star Simulator, composed of:
  - Spectrally Tunable Light Source (STLS);
  - a neutral density filter wheel;
  - a pinhole;
  - a collimator;
- AzEl (Azimuth Elevation System), composed of:
  - AzEl 2-axes precision gimbal;
  - AzEl controller and driver;
- Industrial Computer, running these two programs:
  - Star Sensor Test Program (SSTP);
  - Star Simulator Control Program (StarSim);
- DC Power Supplies;

A diagram of the main calibration infrastructure is shown in Figure 2. In this figure the abbreviation *Comm.* is used to indicate communication / signal cables:

![Diagram of main calibration infrastructure](image)

**Figure 2.** Calibration environment for star sensors.
3.1. Star Simulator

The Star Simulator, shown in Figure 3, is capable of generating a synthetic star with a custom spectrum in the wavelength range 380-970 nm and visual magnitude range from 0 to 5, thus allowing to study the effects of chromatic aberration in the star tracker response. The system main components are a spectrally tunable light source (STLS), a pinhole and a collimator. A spectroradiometer is also used to stabilize the STLS output in a closed loop controlled by the Star Simulator Control Software (StarSim in Figure 2). The design of the Star Simulator was based on the STS (Spectrally Tunable Source) designed by Fryc et al. [6, 7]. Reference [8] provides a detailed explanation of the theory behind STLS and StarSim.

The STLS is composed of an LED (light emitting diode) driver with 96 channels that can be individually controlled, LEDs and an integrating sphere. In total, 43 different types of LEDs with different spectral responses are being used in STLS. These are soldered into white painted circular printed circuit boards (PCBs) that are installed on black metallic supports (LED heads) which are then attached to the integrating sphere, as shown in the right panels of Figure 3. A filter wheel with an empty slot and neutral density filters is installed at the exit of the integrating sphere, in the optical path from STLS to the pinhole. The neutral density filters are inserted in the optical path only when the system needs to synthesize dim stars.

The current version of StarSim uses a black-body approximation to the spectrum of the simulated star. In this version, the user specifies the simulated star magnitude and effective temperature, from where the spectrum is derived. The system then interactively adjusts the voltages applied at each LED channel until the measured spectrum inside the integrating sphere matches the spectrum needed to obtain the desired star spectrum at the collimator exit. However, the spectral output of this system is not perfect. There are some spectral distortions, albeit small, introduced by the collimator mirrors, neutral density filters, spectroradiometer optical fiber and spectroradiometer calibration curve errors. To remove the spectral distortion introduced by these sources, the system will be calibrated with a set of traceable standard light sources and a more sensitive spectroradiometer (which will not be incorporated into the system). Also, future improvements to StarSim are planned, such as the ability to synthesize any arbitrary spectrum, previously stored in a database.
3.2. AzEl (Azimuth and Elevation System)

The Azimuth and Elevation System (AzEl) is a precision gimbal with two motorized axes, the azimuthal axis and the elevation axis. This system allows to measure with great accuracy the geometric distortions introduced by the star tracker optics, by rotating the star tracker while a simulated star is generated by the star simulator. To decouple measurements from vibrations on the ground, AzEl and the Star Simulator are installed on a large optical table, as shown in Figure 4. AzEl main specifications are given in Table 2.

| Description           | Specification |
|-----------------------|---------------|
| Range                 | ±180 °        |
| Resolution            | 0.00001 °     |
| On-axis accuracy      | 0.0006 °      |
| Repeatability         | ±0.0003 °     |
| Wobble                | 10 µrad       |
| Max speed             | 10 °/s        |
| Motorization          | Infranor (Brushless DC Motor) |

The AzEl controller can receive commands through an Ethernet cable. The commands can be sent manually via a web-browser by accessing AzEl controller’s IP address, or automatically by software, such as when SSTP controls AzEl. This makes it possible to perform basic tests or to elaborate complex automated tests using AzEl.

The accuracy of AzEl is of paramount importance for the correct calibration of the star trackers. Therefore, its performance was demonstrated by the manufacturer by tests performed after installation at INPE and through calibration certificates of its angular encoders and test instruments, including certificates provided by accredited laboratories in Europe. These tests and calibration certificates demonstrated that after being installed at INPE, the system accuracy was well within its specification and was better than 1 arc-second for the movement range to be used during star tracker characterization. Considering that random errors from statistically independent sources add quadratically and errors from AzEl are statistically independent from centroiding errors in the star tracker, it is possible to conclude that AzEl inaccuracies should not have a great impact on the star tracker’s yaw/pitch error budget of 3.3 arcsec (rms) presented in Table 1.
3.3. Industrial computer

The main calibration infrastructure is controlled by an industrial computer. In routine calibration, this computer runs two programs: SSTP and StarSim (described in section 3.1). SSTP (Star Sensor Test Program) is the main program that controls the main calibration infrastructure. It is possible to configure in SSTP test scripts to perform lengthy characterization procedures overnight (such as a detailed mapping of the geometric distortions introduced by the star tracker optics and S-curve error measurements [9]).

SSTP can also be used in an observatory or open field setting for night sky tests. Figure 5 shows a screenshot for SSTP. In this screenshot, the AST was in imaging mode, and an out of focus indoor scene captured by the AST can be seen.

![SSTP screenshot](image)

**Figure 5.** SSTP screenshot showing an image acquired by the AST.

3.4. DC Power Supplies

Two programmable direct current power supplies are installed in the same rack where the industrial computer is installed. One of them is used to power the Star Simulator’s STLS. The other is used to power the star sensor under test. These DC power supplies can be controlled by the industrial computer through an IEEE-488 bus and are able to report the power consumption of the loads attached to them. This enables SSTP to log the power consumption of the star tracker during tests.

3.5. Future improvements

To enable AST calibration under vacuum and at non-ambient temperatures, a thermal vacuum chamber with an optical window is being installed on AzEl. This vacuum chamber, shown in Figure 6, has a thermal shroud in which a cooling/heating fluid can be circulated, allowing tests to be performed with temperatures ranging from about \(-20 \degree C\) to \(+50 \degree C\). The optical window has stringent flatness, parallelism and homogeneity requirements to not distort the wavefront or change the propagation direction of the light beam generated by the Star Simulator collimator. When ready, this system will allow to characterize the AST and future star trackers in a condition much closer to the ones found in an orbiting spacecraft.

Besides the thermo-vacuum chamber, a data acquisition system is also being developed. This data acquisition system will gather important information during the tests, such as pressure and temperature
measurements inside the vacuum chamber, AST thermistor measurements, information about AzEl’s position, and also about the Star Simulator. All such data will be gathered into a log file to facilitate analysis of each test’s results.

**Figure 6.** Vacuum chamber for AST characterization. Left: zoomed-in view. Right: installed on AzEl.

4. **Portable Scene Simulator**

The Portable Scene Simulator (Figure 7) was built to enable functional tests of the AST during integration into protoMirax or in a spacecraft, or during hardware in the loop tests. It has a microdisplay that works just like a conventional LCD monitor, and a collimating optics. It was designed to be inserted inside the AST stray light baffle.

**Figure 7.** The Portable Scene Simulator and how it is coupled to the star tracker.

An in-house software was developed to generate the scenes displayed on the Portable Scene Simulator. This software can accept input quaternions representing the AST attitude at rates up to more than 60 Hz in a modern personal computer, generating a new simulated sky scene for each quaternion received. This makes it possible to integrate the Portable Scene Simulator with a spacecraft attitude and orbit simulator, enabling hardware in the loop tests with the AST.
This scene simulator does not replace AzEl and the Star Simulator, since it is not accurate enough to calibrate the AST, but it enables functional tests of a star sensor in the absence of a real sky. It is also valuable for allowing tests simulating adverse conditions, such as Moon, or Earth in the FOV.

One idea to calibrate this scene simulator is to use the star tracker itself, after it has been calibrated using AzEl and night sky tests. Reference [10] provides methods that may be useful in calibrating the scene simulator.

5. Summary
This paper has shown an overview of the laboratory setup that was assembled during the AST project to characterize, calibrate and test the many AST prototypes and models. This setup will be used to perform the final calibration of two AST models before their flight aboard the protoMirax experiment. After protoMirax, our plan is to use this laboratory environment to test, characterize and calibrate future star trackers for future space missions.

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