IN-FLIGHT ASSESSMENT OF STAR TRACKER PERFORMANCES: FROM PICARD, THROUGH PRISMA, TO MICROSCOPE

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Abstract: *MICROSCOPE is a CNES-ESA-ONERA-OCA-DLR mission whose main objective is to progress in fundamental physics by testing the Equivalence Principle (EP) with an accuracy of 10^{-15}. The scientific instrument is a differential electrostatic accelerometer developed by ONERA. The 300Kg drag-free satellite will be launched in April 2016 into a 700km dawn-dusk sun-synchronous orbit for a two year-mission.*
The Drag Free and Attitude Control System (DFACS) was designed by CNES. It uses the scientific instrument as a sensor for linear and angular accelerations in addition to classical Star TRacker (STR) attitude measurements. A set of 8 cold gas GAIA-like thrusters is used to continuously overcome the non-gravitational forces and torques. As a result the satellite follows the test masses in their pure gravitational motion. The mission specificity is the stringent attitude and stability requirements at the EP observation frequency (Fep) which is very low compared to classical mission frequency band of interest. Thus DFACS performance relies on sensors accuracy at low frequency.
Evaluation of STR errors at low frequency is very difficult to get from ground tests. The opportunity to perform in-flight measurements appeared on PICARD and PRISMA satellites (same orbit, same star-tracker) and was indeed very interesting.
Several in-flight experiments were carried out on PICARD and PRISMA between 2010 and 2013. STR measurements were acquired during attitude profiles mimicking MICROSCOPE attitude. Thanks to these data, reliable models function of the attitude motion and the star pattern quality were built. The data analysis was eased by the availability of a high number of images from the camera. This paper presents these experiments and illustrates how in-flight tests helped preparing MICROSCOPE and the next mission by providing an insight onto star-tracker performance.

Keywords: *Star tracker, In-flight experiment, MICROSCOPE.*

1. Introduction

MICROSCOPE belongs to Myriade line of platforms[3][4] but is very specific in terms of pointing and stability requirements. In particular very stringent performance is required at low frequencies. To achieve the desired accuracy, a complex DFACS has been designed to manage the 6 degrees of freedom and the propulsion subsystem so that the performance relies on sensors accuracy at low frequency. Does Myriade STR meet Microscope requirements? This paper aims at presenting how in-flight experiments on PICARD[5][6] and PRISMA[7][8] satellites help answering this question. It begins with a presentation of the MICROSCOPE mission followed by a description of the DFACS and the associated star tracker requirements. Then a paragraph is dedicated to on-ground STR performance assessment. The main part of the paper details in-flight experiments, explains the most effective methods to characterize the star tracker performance and finally gives some examples of results.

2. MICROSCOPE mission presentation

2.1. MICROSCOPE: a Microsatellite for the Observation of the Equivalence Principle

MICROSCOPE mission[2] main objective is to test the Equivalence Principle (EP) with an accuracy of 10^{-15}, i.e. more than 100 times better than existing ground experiments accuracy.

The Equivalence Principle postulates the equivalence between the inertial mass and the gravitational mass. A well-known consequence of this principle is that two objects submitted only to the same gravitational field have exactly the same acceleration, regardless of their composition. For the MICROSCOPE experiment, the Earth is the gravitational source and two test-masses of different compositions will be observed in free-fall condition. A particular attention will be brought to the control of the two objects to ensure they are submitted exactly to the same gravitational field.

This experiment is expected to result in a breakthrough in fundamental physics. In fact, a violation of the EP would demonstrate the existence of an atomic interaction which is predicted by current gravity quantum theories. On the other hand, if the EP is verified, the theories predicting a violation of the EP above 10^{-15} could be discarded.

2.2. Experiment principle

The high accuracy acceleration measurements will be performed by a differential electrostatic accelerometer developed by ONERA, called SAGE (Space Accelerometer for Gravity Experiment). It is composed of two concentric, coaxial, cylindrical proof masses with a common center of gravity suspended in a highly stable electrode cage. The external proof mass is made of titanium and the internal of platinum-rhodium.

The experiment principle is to measure the electrostatic forces required from the electrodes to maintain the relative position of the proof masses in the cage. Free fall masses would quickly separate (short direct experiment) while accelerometers are a stable bench (long indirect measurement).

Since both electrode cages experience the same acceleration, the differential measurement is the difference between the gravitational acceleration of the two masses:

$$\vec{S} = \vec{\gamma}_1 - \vec{\gamma}_2 = \delta \times \vec{g} \tag{1}$$

where $\vec{g}$ is the Earth gravitational acceleration and δ is the equivalence principle violation parameter :

$$\delta = \left(\frac{m_{1g}}{m_{1i}} - \frac{m_{2g}}{m_{2i}} \right) \tag{2}$$

In order to confirm the experimental process and the measurement accuracy, a second SAGE instrument with two proof masses made of the same material (platinum-rhodium) is also used.

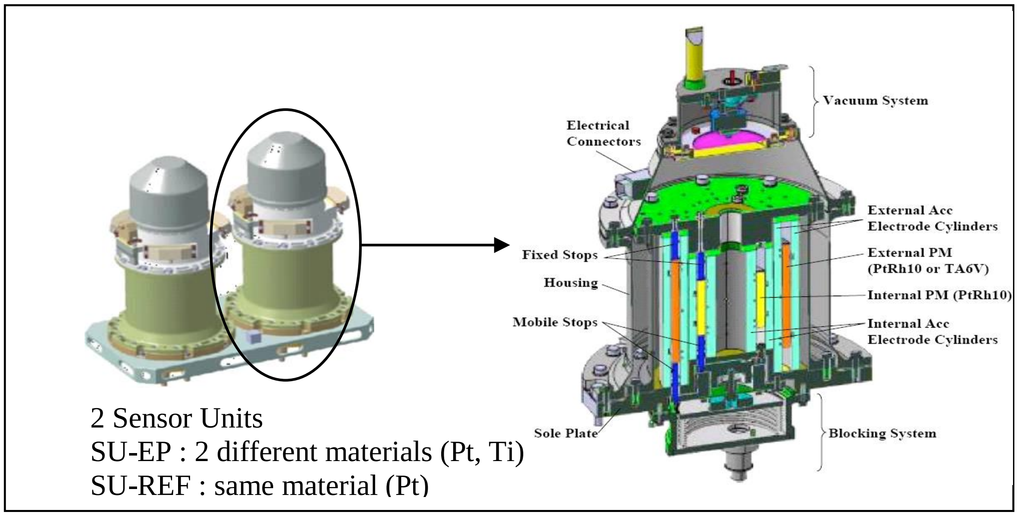


Figure 1. T-SAGE : Twin Space Accelerometer for Gravity Experiment

2.3. Orbit and pointing

MICROSCOPE will fly on a dawn-dusk sun synchronous orbit at 700 km of altitude. The EP measurements will be carried-out during two types of measurement sessions:

Inertial sessions:
The satellite is inertially pointed (i.e. it just follows the one degree per day drift of the orbital plane). The main axis of the accelerometer is in the orbital plane. The EP violation signal is expected to be a sine at the rotational frequency of the $\vec{g}$ in satellite frame Fep = Forb ≈ 0.17 mHz. These sessions last about 8 days.

Rotating sessions:
The satellite is in rotation around the orbit normal at the frequency Fspin ~ 0.8 mHz. During these sessions the EP signal is modulated at the frequency Fep = Forb + Fspin. These sessions last 1.5 days.

In addition, specific sessions are dedicated to the accelerometer calibration. Based on an inertial pointing, they consist in performing angular oscillations of 0.05 rad (2.9 deg) at Fcal ~ 1.3 mHz.

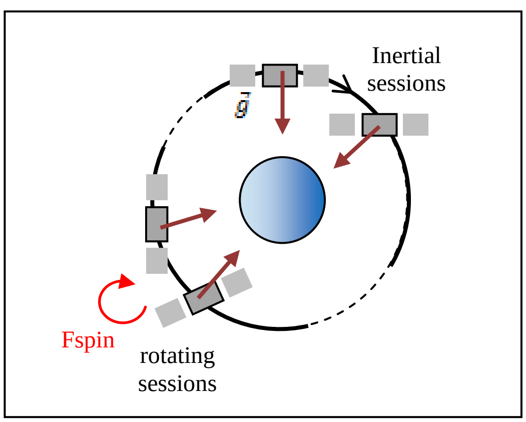


Figure 2. Microscope measurements sessions

3. Drag Free Attitude Control System (DFACS)

3.1. DFACS architecture

To achieve the ambitious scientific performance, the satellite has to protect the payload from all non-gravitational forces disturbing measurements. This is the function of the Drag Free Attitude Control System (DFACS) specifically developed for MICROSCOPE by CNES.

Since the EP violation signal should be a sine at Fep frequency, the DFACS most stringent requirements are at Fep. On linear axes, the residual linear accelerations in mission mode must be less than 10^{-12} m/s² in the bandwidth of scientific interest. The angular control is also submitted to stringent requirements to limit angular to linear coupling, due to the test-masses miscentring.

To meet these stringent requirements, the DFACS relies on the payload accurate accelerations measurements for both linear and angular control. Linear accelerations are directly used by the drag free control whereas the attitude estimation is the result of an hybridization between STR measurements and angular accelerations[1]. Then a set of 8 cold gas GAIA-like thrusters allow to accurately realise the commanded torque. The DFACS control loop is illustrated in Figure 3.

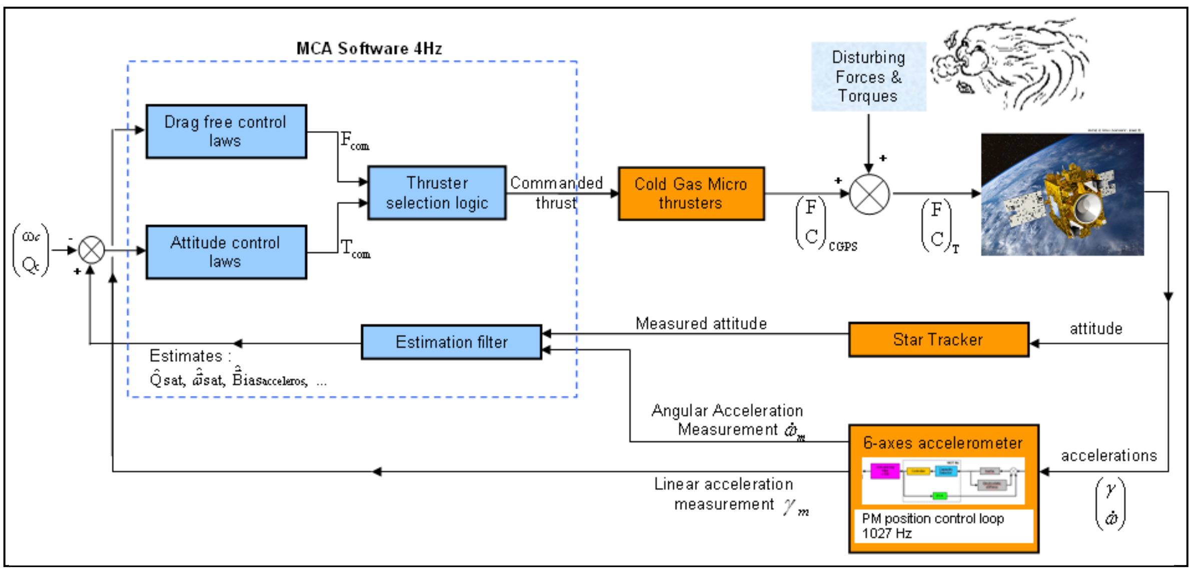


Figure 3. DFACS control loop

3.2. STR requirements

The pointing error must be very low, indeed less than few tenth of microrad at Fep. This stringent requirement applies on both attitude control and attitude estimation.

The attitude estimation is performed by a hybridization filter using angular acceleration and STR measurement. This filter relies on STR performance at low frequencies, and particularly around Fep. STR performances are then required at Fep and its harmonics. Due to recombination and non-linear effect, errors in Fep neighborhood also affect the attitude estimation at the EP violation signal frequency. Therefore STR performances at k*Fspin are required in rotating mode. In inertial mode, the pixel-to-pixel variation frequency (Fpix ~ 0.45 mHz) is also identified as a singular frequency. The order of magnitude of the required STR performances is around 10 microrad at Fep and around 30 microrad at Fspin and Fpix.

STR classical performance figures such as Noise Equivalent Angle (NEA) and Relative instrument Accuracy (RA) make sense for a higher frequency range. The low frequency errors are more difficult to assess since specific test facilities are needed.

4. STR performance assessment on ground

4.1. Simulations

The simplest way to assess STR performance is of course simulation. A simulator, developed for the need of another high-performance mission, was specifically designed to estimate the low frequency errors of star trackers, taking into account errors such as optical distortion, relativistic and angular acceleration errors and catalog errors. It appeared as a good starting point to build a Myriade STR error model. But this simulation tool requires representative parameterization for the STR software as well as for the hardware. Unfortunately, such set of parameters was not available for Myriade STR. Nevertheless, simulations were carried-out with a reference STR and a macroscopic analogy was drawn between both STR.

The results could not be directly extrapolated to the Myriade STR but provided an insight onto different phenomena such as orbital aberration, optical distortion and pixel-to-pixel effects: frequency, line of sight / transverse axes performance ratio, etc. It proved to be useful to predict what can be expected from real sky tests.

4.2 On-ground test

In order to improve the STR error characterization at low frequencies, on-ground “backyard” tests were performed. Myriade STR under test was mounted to an Aluminum bracket. Attitude was recorded at 2Hz during about 3 hours.

Since the STR follows the Earth rotation rate (15 arcsec/sec), the test was representative for quasi-inertial pointing but provided no information on rotating mode (~1000 arcsec/sec).

The only but very noticeable phenomenon was the pixel-to-pixel variation, which came from stars passing lines and columns in the CCD. This result was compared to simulations in order to define a “performance factor” between the reference STR used for the simulation and Myriade STR. But the question of how this gain can be extrapolated to other phenomena remained.

In conclusion, the backyard test allowed to estimate the pixel-to-pixel effects. But these data were not sufficient to prove that Myriade STR meets MICROSCOPE requirements. It has to be completed with tests on different star regions (rich and meager) with different rotating rates. Such tests have not been conducted because of their complexity and cost. Furthermore, an opportunity to conduct in-flight experiments appeared.

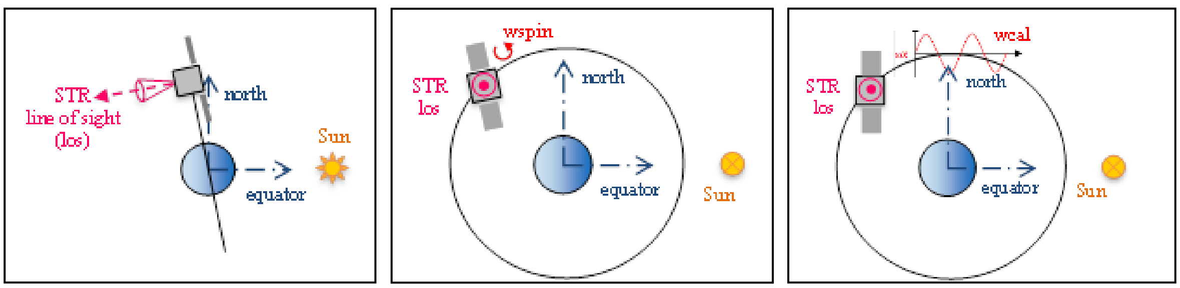
5. In-flight experiment

5.1 Experiments description

Between 2010 and 2013, opportunities of in-flight measurement appeared during end-of-life experiments on PICARD and PRISMA. These opportunities were indeed interesting since both satellites had a similar orbit (700 km dawn-dusk sun synchronous orbit) and the same STR as MICROSCOPE.

The in-flight experiments consisted in acquiring STR data during attitude profile representative of MICROSCOPE mission. Three kinds of measurement sessions were defined:

- Inertial session representing the inertial pointing of MICROSCOPE: for these sessions the pointing was in fact quasi-inertial, the satellite followed the drift of the orbital plane (1 deg/day~0.2µrad/sec). See Fig.4.1
- Rotating session representing the rotating mode of MICROSCOPE: the satellite was spinned around the orbit normal. See Fig.4.2
- Sinus session representing the calibration mode of MICROSCOPE based on an inertial pointing during which oscillations were successively done around each satellite axis. See Fig.4.3



4.1 : inertial session **4.2 : rotating session** **4.3 : sinus session**

Figure 4. Attitude profile during in-flight experiment measurement session

These sessions were adapted to PICARD and PRISMA characteristics, in order to be as representative as possible of MICROSCOPE configuration.

On MICROSCOPE, the STR is composed of two Optical Head (OH) arranged on -X panel, both pointed toward the orbit normal in the anti-solar direction.

PRISMA also has one STR with two optical heads arranged on the same panel but tilted of 70 deg one from another. To represent MICROSCOPE, PRISMA experiments were done with one STR pointed toward the orbit normal. See Fig 5.

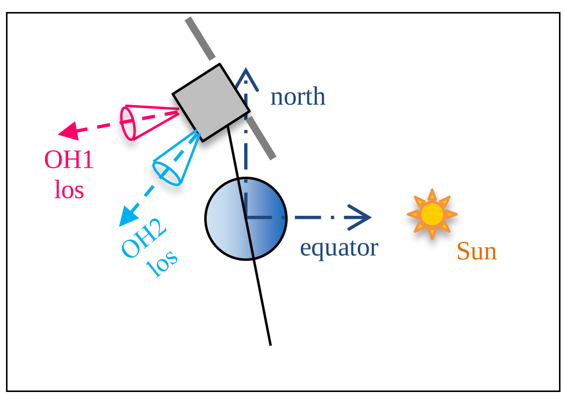


Figure 5. Inertial attitude profile on PRISMA

On PICARD, the two optical heads of the STR were pointed in two opposite directions in the orbital plane (see Fig.6). Thus, each optical head was used on half an orbit and was brighten by the Earth on the other half. This configuration was quite different from MICROSCOPE since the

STR Line Of Sight (LOS) was not normal to the orbit. This was not a problem for the inertial or sinus sessions but it had to be taken into account for the rotating session analysis. In fact, field of view errors are different depending on whether the spin axis corresponds to the STR LOS or not.

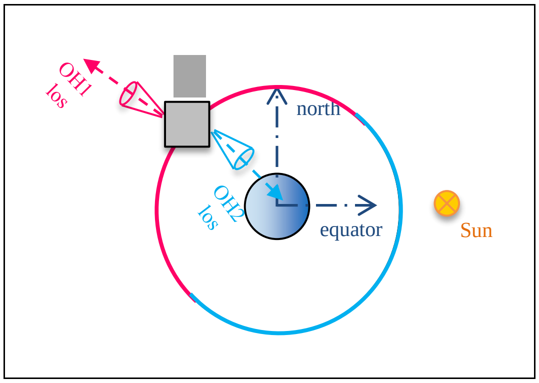


Figure 6. Inertial attitude profile on PICARD

On PRISMA, due to power constraint (with the required pointing, solar panels were not perpendicular to the sun direction anymore), the measurement session length did not exceed 6 orbits. There was not such constraint on PICARD since the required pointing was closed to the nominal one, so each measurements sessions were planned on 20 orbits (~1.5 day).

In order to improve the reliability of the results, each session was realized several times for each STR optical heads, at different dates, for different phases, in order to point diverse star regions. In total, more than 300 hours of measurements were acquired during in-flight experiments.

5.2 Measurements analysis

The experiments objective was to assess the STR low frequency error. The main difficulty was to make sure that the signal comes from STR measurement error and not from another source like control error. Since the attitude and control system design was strongly different between PICARD and PRISMA two analysis methods were applied.

- Differential measurement on PRISMA

On PRISMA, the STR was the only attitude sensor and the measurements of both optical heads were used for attitude estimation. The only way to extract the STR measurement error was to analyze the differential measurement between both heads when simultaneously available. More specifically, the analysis focused on the low frequency variation of the differential measurement around the mean value.

- Absolute measurement on PICARD

On PICARD, the presence of a third sensor, the Sun Ecartometry Sensor (SES), made the measurement analysis easier. The SES gave a very accurate 2-axes attitude measurement of the sun direction. The STR was only used for the attitude estimation around the third direction.

Since the control error could be neglected (the random noise was estimated to 15 µrad (3σ) and the harmonic error lower than 1 microrad), it was justified to consider the satellite perfectly pointed in the orbital plane. So STR measurement errors were estimated from the variations of the angular distance between the SES LOS and the STR axes.

- Harmonic analysis

As explained before, MICROSCOPE STR requirements apply on harmonic error at specific frequencies: Fep, Fpsin, Fpix, Fcal.

Naturally, the Fast Fourier Transform (FFT) tool seemed to be the most appropriate approach to evaluate the harmonic signals. But the use of FFT requires a perfectly discretized signal with a constant sample time and no measurement gap. On PICARD, as well as on PRISMA, the STR were periodically blinded by the Earth. The period of continuous measurements was long enough to estimate the error at Fpix and Fcal but for Fep and Fspin another method was needed.

For a signal which was not continuous, harmonic components were estimated by mean square approximation. This method presented only one limitation: it could not be used to estimate the harmonic error at the measurements gap frequency (low observability).

- Centroid images analysis

For in-depth analysis, centroid images were recorded during the measurement sessions. It helped understanding the field of view errors by establishing correlations between sky characteristics (e.g. stars distribution, bright stars positions) and harmonic errors.

5.3 In-flight experiments results

This paragraph aims at illustrating the information obtained from in-flight experiment data analysis. One result example is detailed for each kind of measurement session.

- Inertial session

On PRISMA, with an inertial pointing, the STR radiator was submitted to the Earth albedo at the orbital frequency (Forb). A high thermo-elastic effect resulted from this thermal configuration, disturbing the STR measurements. A systematic error up to 40 microrad at Forb was observed on the STR transverse axes. PICARD measurements proved to be more relevant since the inertial pointing corresponded to the mission nominal pointing. So the configuration was optimal to assess the STR harmonic errors.

One result example is illustrated on Figure 7. The left plot represents the error around the LOS, whereas the right plot illustrates the results regarding the LOS stability. The blue dots correspond to the angular distance between STR LOS and SES LOS. The pink line represents the mean square harmonic approximation result. The error amplitude at Fep and at 3*Fep are given on the graph below. These graphs show a very high stability of the STR line of sight, the fluctuation amplitude at Fep is lower than 10 microrad. As expected the variation around the LOS are slightly higher.

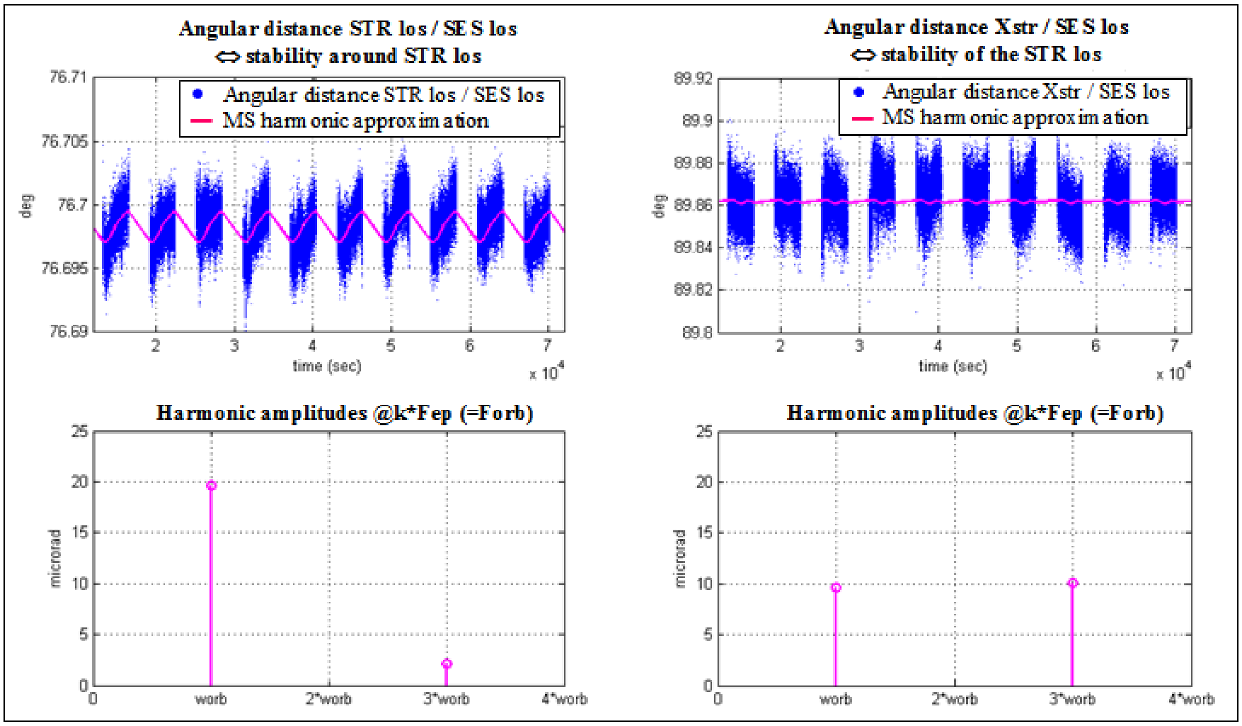


Figure 7. Harmonic error during inertial attitude profile on PICARD

- Rotating session

For the rotating sessions, PRISMA experiment results were more relevant for MICROSCOPE than PICARD ones since the rotating axis was the STR LOS. Figure 8 illustrates the attitude profile: the satellite rotated around one STR LOS, pointed normal to the orbit. The second STR, pointed 70 deg from the first one was blinded by the Earth at Fspin.

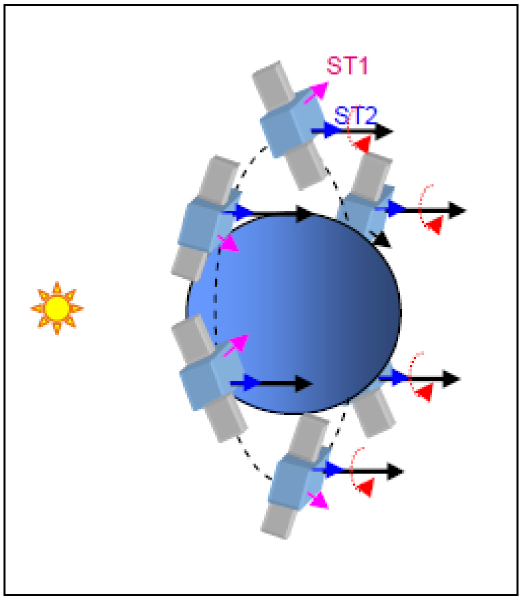


Figure 8. Rotating attitude profile on PRISMA

This session was realized several times in order to obtain a large variety of results, highlighting the field of view influence on the STR performance. Around the LOS, the field of view error at k*Fpsin were dominating. Depending on the stars distribution, the main harmonic errors was found at 2*Fspin or at 4*Fspin as illustrated on Figure 9.

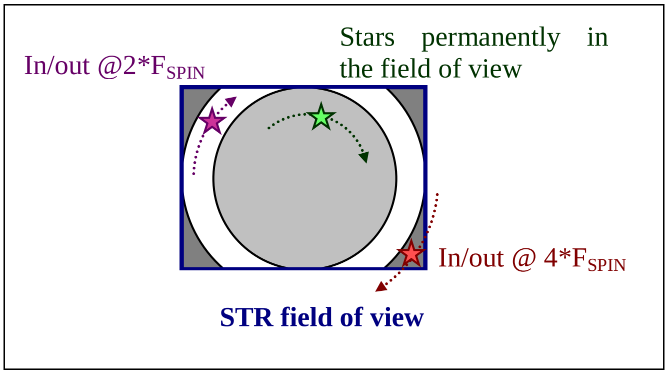


Figure 9. Sensor field of view in rotating mode : stars in/out frequency

Examples of both situations are plotted on Figure 10. It shows the fluctuations of the STR LOS during two sessions: the first one performed on October 2011 and the second one, one month later. For the first session, the centroid images analysis showed the presence of bright stars coming in/out at 2*Fspin, whereas for the second sessions bright star in the field of view corner were responsible for the error at 4*Fspin.

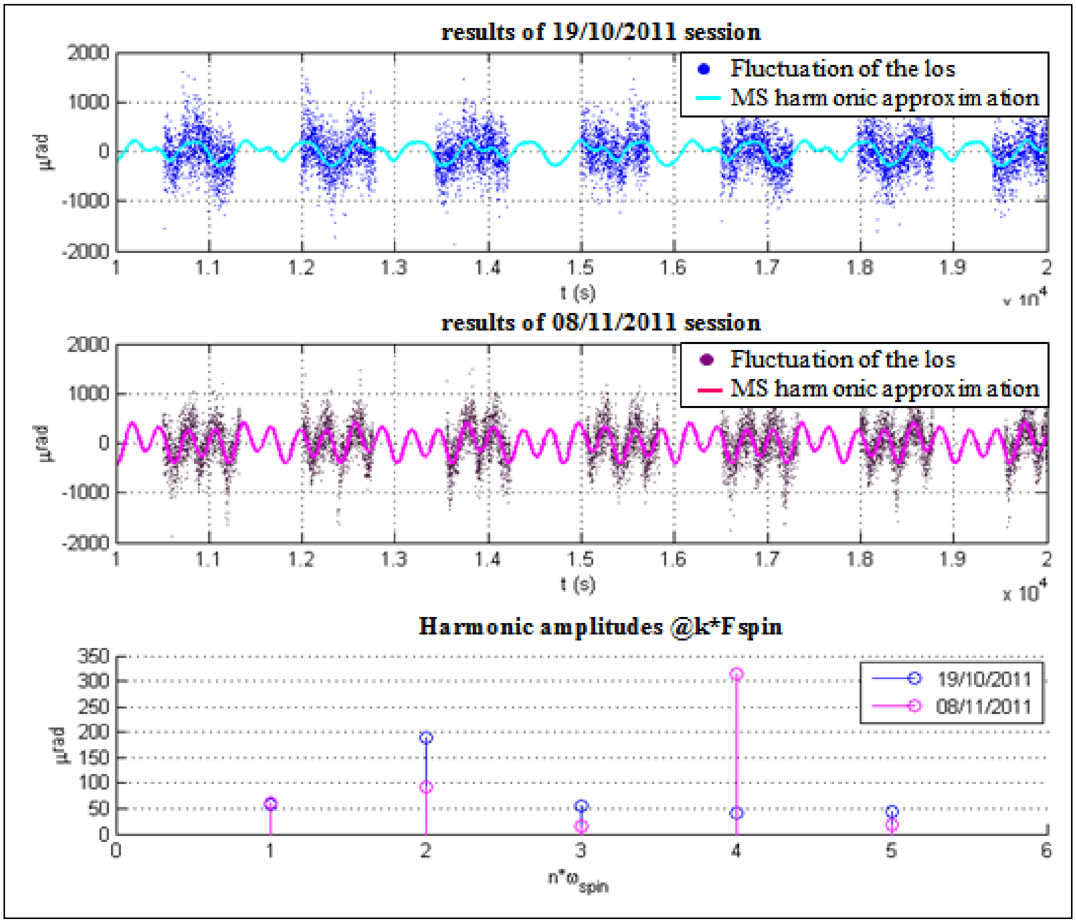


Figure 10. STR LOS harmonic error in rotating mode on PRISMA

The fluctuations around the transverse axes are illustrated in Figure 11. The perturbations at Fep due to the thermo elastic effect specific at PRISMA configuration is clearly visible. It has to be noted that field of view errors at Fspin do not affect the STR performance around transverse axes.

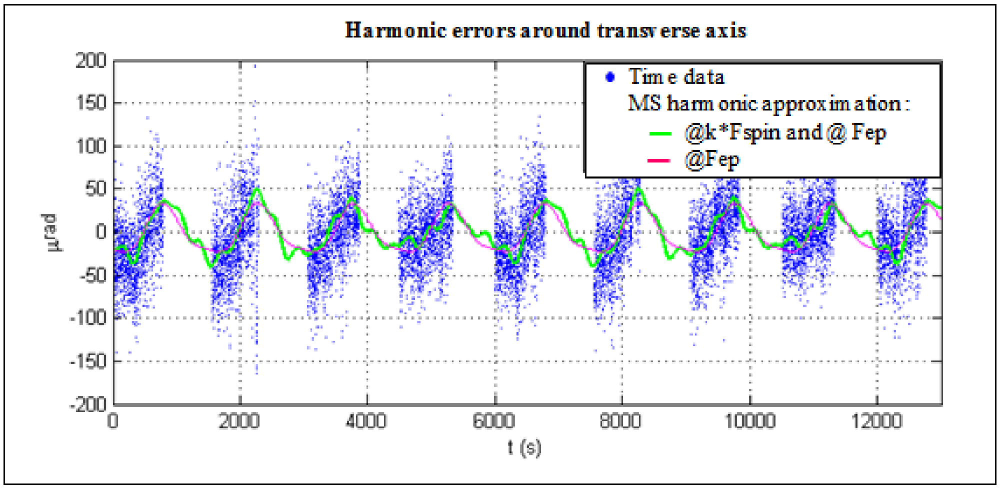


Figure 11. STR transverse axes harmonic error in rotating mode on PRISMA

- Sinus session

Sinus session represents the calibration mode of MICROSCOPE. It is based on an inertial pointing during which oscillations are carried-out around a satellite axis. As for rotating session, the main harmonic errors come from the field of view modifications.

The centroid images analysis highlighted the correlation between the coming in and out of a bright stars and a high error of the LOS at the oscillation frequency (noted Fosc or Fcal).
Figure 12 shows two centroid images taken at one minute interval during a sinus session on PRISMA. The brightest star, circled in red on the centroid image, comes in and out the field of view at each oscillation, inducing a high harmonic error at this frequency.

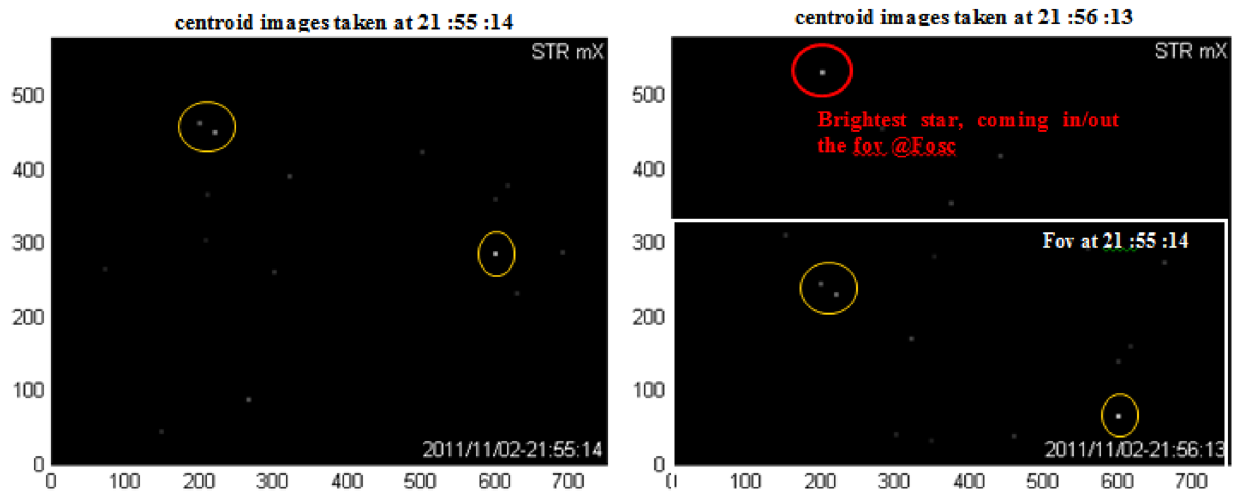


Figure 12. Centroids images taken during rotating session with PRISMA OH2 (02/11/2011)

It is worth noted that when the brightest stars remains in the field of view, the STR harmonic error are very low. On the results plotted on Figure 13, the LOS and transverse axes fluctuations are respectively lower than 35 microrad and 10 microrad.

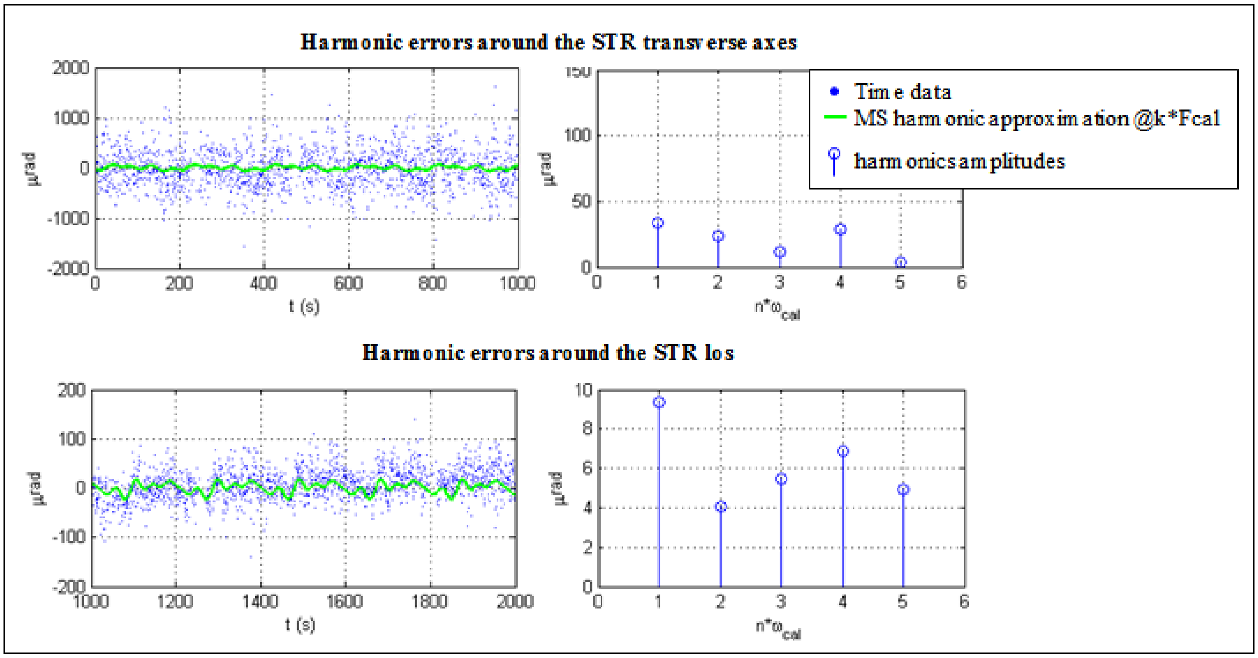


Figure 12. STR harmonic error in sinus mode on PRISMA

Following these results, a field of view predicting tool has been developed for MICROSCOPE in order to anticipate the STR performance during the accelerometer calibration session.

6. Conclusion

The new generation of engineers is fond of numerical model and simulation tools. The simulation approach is going to take the place of the experimental one which has become too slow and too expensive. The main conclusion of this job is the notable complementarity between both.

Simulations provide a first order of magnitude of expected effects impacting STR performance. To be reliable, these results need to be confirmed and complemented by real sky tests, on-ground or in-flight. On-ground tests can be easily adapted to the desired STR configuration but they suffer from implementation difficulties and limitations in terms of attitude profile. In-flight tests are very valuable because they offer the most representative conditions for STR measurements acquisition. If experimental data are essential to validate and improve numerical STR models, simulation results are nevertheless essential to define and analyze real sky tests.

In-flight experiments carried out on PICARD and PRISMA provided reliable STR performance estimation, which could not have obtained from ground tests. These 300 hours of in-flight experiments allow MICROSCOPE project to confidently decide to keep the standard Myriade STR onboard.

MICROSCOPE is now in its final integration phase. The launch is scheduled for April 2016 for a two years mission.

Finally, we would like to acknowledge the valuable and effective cooperation of PRISMA OHB Sweden team as well as PICARD operational team in the realization of the in-flight experiments.

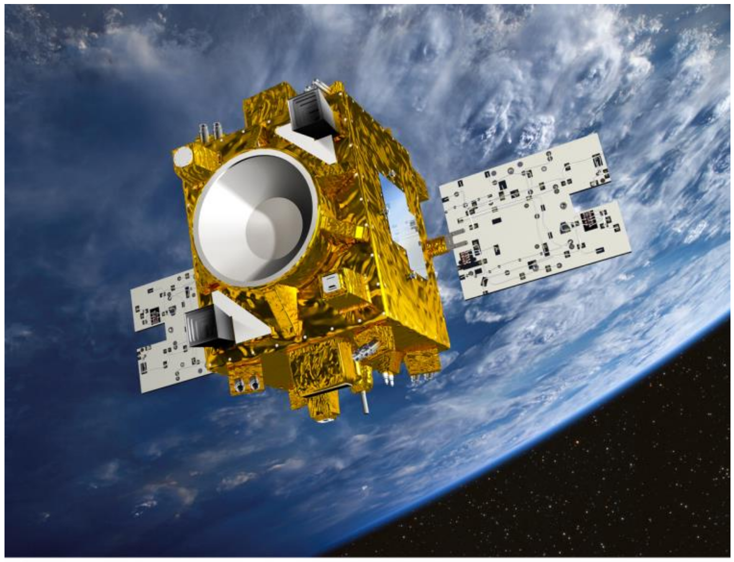


Figure 13. MICROSCOPE satellite

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8. Acronyms

DFACS	Drag Free and Attitude Control System
AOCS	Attitude and Orbit Control Subsystem
EP	Equivalence Principle
SAGE	Space Accelerometer for Gravity Experiment
Fep	Equivalence Principle observation Frequency (frequency of the expected violation signal)
Forb	Orbital Frequency
Fspin	Spinning Frequency
Fpix	Pixel-to-pixel variation Frequency
Fcal, Fosc	Oscillations Frequency during Calibration session
STR	Star TRacker
Reference STR	Reference STR used for simulation (well-known device with qualified simulation models)
Myriade STR	Standard Myriade STR (equipment under evaluation for Microscope)
OH	Optical Head
LOS	Line Of Sight
NEA	Noise Equivalent Angle
RA	Relative instrument Accuracy
SES	Sun Ecartometry Sensor
mHz	milliHerz (10^{-3} Hz)
microrad	micro-radian (10^{-6} rad)
arcsec	arcsecond (1/3600 deg)
DOF	Degree Of Freedom
FFT	Fast Fourier Transform (FFT)