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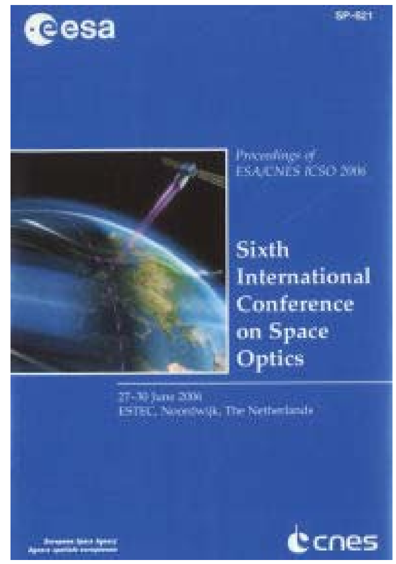

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REDUCTION OF LOW FREQUENCY ERROR FOR SED36 AND APS BASED HYDRA STAR TRACKERS

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ABSTRACT

In the frame of the CNES Pleiades satellite, a reduction of the star tracker low frequency error, which is the most penalizing error for the satellite attitude control, was performed. For that purpose, the SED36 star tracker was developed, with a design based on the flight qualified SED16/26. In this paper, the SED36 main features will be first presented. Then, the reduction process of the low frequency error will be developed, particularly the optimization of the optical distortion calibration. The result is an attitude low frequency error of 1.1'' at 3 sigma along transverse axes. The implementation of these improvements to HYDRA, the new multi-head APS star tracker developed by SODERN, will finally be presented.

1. INTRODUCTION

1.1 Why minimizing the low frequency error

In order to obtain a good image localization for Earth observation satellites, an accurate onboard attitude knowledge is necessary, usually given by star trackers. Among the star tracker error classes, the bias can be in-flight calibrated, and the noise is usually filtered with gyroscopes data by the AOCS (Attitude and Orbit control System). So, the most penalizing error class for the attitude control of the satellite is the low frequency error. That's why in the frame of the Pleiades program, an effort was brought to reduce that error class.

1.1 Presentation of SED36 star tracker

The SED36 star tracker was developed by SODERN for Pleiades, the new Earth observation satellite developed by the CNES. It is based on the SED26 (see [1]), which is a space qualified ITAR free sensor (International Traffic in Arms Regulation); the same objective, detector, electronic and software are used. The SED36 has been separated into three parts in order to minimize thermal coupling effects: the optical head, which is mounted directly on the instrument, the electronic box and the baffle. The main features of this star tracker are indicated in Table 1.

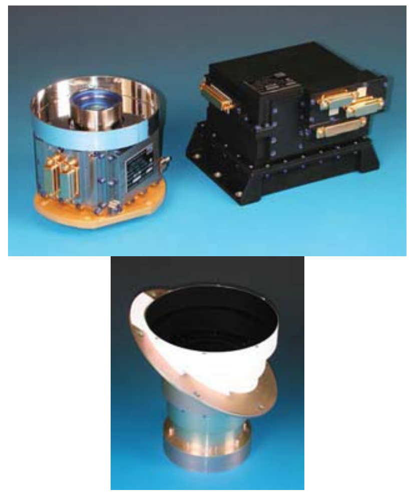

Fig. 1. SED36 star tracker: the optical head (up – left), the electronic box (up – right), and the baffle (down)

Table 1. SED36 main functional features

Attitude	3-axis attitude
Acquisition	Autonomous <4 s.
Tracking	12 stars tracked
Baffle	Sun rejection angle : 30 °
Output data rate	1- 10 Hz
Accuracy at 20°C, 8 Hz, v=1°/s, EOL (End of Life) LEO (Low Earth Orbit) 5 years : Bias LFE (Low Frequency Error) Noise	 10'' XY / 10'' Z 1.1'' XY / 6.3'' Z at 3σ 8'' XY / 50'' Z at 3σ
Operating temperature range	20°C ± 3°C
Mass : Optical head Electronic box Baffle	 1.3 kg 1.5 kg 0.9 kg
Dimensions : Optical head Electronic box Baffle	 Ø = 130mm / h = 110mm 160 x 130 x 110 mm Ø = 220mm / h = 255mm
Typical power consumption Optical head Electronic box	At 20°C mounting plane 1.4 W 7 W
Data I/O	1553 B (RS422 option)
Power supply	20-50V (50-100V option)

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2. IMPROVEMENT OF THE LOW FREQUENCY ERROR

In this chapter, the different steps of the optimization of the low frequency error of the SED36 star tracker will be developed.

The single–star error items taken into account in the low frequency error budget, as well as their typical value for SED16/26 compared with SED36 are given in Table 2.

The Low Frequency errors can be sub-divided into two categories:

- the orbital errors, whose variations are in the orbit timescale; these errors usually depend on the thermal environment,
- and the field of view errors, which depend on the position of stars in the star tracker field of view. These errors are spatial errors, so their temporal frequency depends on the angular motion rate of the satellite.

Table 2. Low frequency error items and typical values

At 3σ along XY axes		SED16/26 [-20;+50°C]	SED36 20°C +/-3°C
Field of view errors	Distortion residue	± 9’’	± 3’’
	Residual scale factor	± 5’’	± 0.8’’
	Star catalogue errors	± 3’’	± 1’’
Orbital errors	Residual thermal drift	± 10’’	± 0.6’’
	Residual relativistic aberration	Negligible (corrected)	Negligible (corrected)

2.1 An optimized thermo-mechanical design

The first step in order to reduce the attitude low frequency error is to minimize the thermal effects. Indeed, the thermal drift of the optical axis has the same value and direction for all the tracked stars, so it is not averaged among the number of stars. Moreover, approximately one half of this error is due to the contribution of thermal dissipation of the baffle, when it is exposed to sun light. So, SED36 has been separated into three parts, in order to minimize thermal coupling effects. The optical head is directly mounted on the Pleiades instrument in order to achieve the best accuracy and avoid additional frame transformations, whereas the baffle is mounted on the satellite structure.

The other half of the thermal drift error is due to thermal conductive coupling at the optical head mounting plane. This is why the electronic box has been separated from the optical head, to minimize power dissipation at the optical head interface. Moreover, one of the major constraints to achieve the required accuracy is to have a very stable thermal regulation at the satellite interface, about 20°C ± 3°C. Taking into account this thermal stability and the nature of the Pleiades instrument interface (SiC), a judicious choice of materials and of geometrical configuration was performed in order to minimize thermal differential dilatations. The aluminium main structure of SED16/26 was replaced by a titanium/AlSiC combination, very well matching with the main instrument SiC interface, while keeping a very rigid and stable mounting.

Then, software improvements were developed, in order to go one step further in minimizing the low frequency error.

2.2 A more accurate calibration of optical distortion

The second main error item of Table 2 is the residual optical distortion error. On SED16/26 star trackers, a third order polynomial law is used, which gives residual errors after correction of about ±9’’ at 3σ. This law is calibrated on the BCG16 (Banc de Calibration Géométrique) test bench available in SODERN, with simulated stars of equivalent colour temperature of 6000K, and with a mounting plane temperature of +20°C. It has been decided to perform a dedicated study in the frame of a CNES contract, in order to develop a more accurate distortion calibration method.

- Test bench accuracy

The first step was to evaluate the test bench accuracy, and the sensibility of the existing correction to the spectral types of the stars, and to a mounting plane temperature variation.

The repeatability of the distortion calibration on BCG16 test bench is measured to about ±1” at 3σ, and the absolute angular precision of the rotation table to ±1” 3σ. Consequently, the calibration limit of the bench over duration of the test is ±2”; this is the precision limit of any distortion calibration method that can be implemented. Nevertheless, it is possible to average a deterministic periodic part of the error of the rotation table, by positioning the calibration stars in judicious positions in the field of view.

Moreover, taking into account the spectral distribution of stars of the Tracking mode catalogue, the effect of chromaticity on the distortion residue appears to be negligible. Indeed, in almost the whole celestial vault, most tracked stars have a colour temperature close to 6000K (simulated colour temperature used for law calibration), and for other stars the influence of chromaticity is averaged on the attitude.
Lastly, when the temperature of the mounting plane varies about ±3°C compared to the calibration temperature of 20°C, a potential degradation of ±0.5” 3σ should be added to the obtained performances.

- Comparison of the performances of several distortion calibration laws

Then several distortion calibration laws have been compared, in order to evaluate the ratio between the performance that can be reached and the corresponding constraints. The calibration laws studied are:
- high order X/Y polynomials. On SED16/26 star tracker, a third order law is nominally used. One can expect a better precision by simply increasing the order of the polynomial,
- Zernike polynomials. These polynomials are in polar coordinates instead of the Cartesian ones. They are usually used to model the optical aberrations, so they are supposed to be appropriate to correct the distortion effect,
- correction by dividing the star tracker field of view into several small areas. Indeed, when observing the distortion residues after a correction by a third order polynomial law, the error seems to exhibit low frequency variations. So, by dividing the star tracker field of view into small areas, one can correct the star positions by a constant value in each area, along X and Y axes. By principle, this method should lower the distortion residues; the achievable performance will only be limited by:
- the frequency variation of the residues to correct; the higher the frequency is, the smaller the areas size should be,
- the implementation constraints such as the available memory size to store the needed parameters, the timing constraints of the flight software, and the duration of the calibration test,
- and the test bench accuracy previously evaluated.

The comparison of these calibration laws has been performed thanks to measurements done on the BCG16 test bench on 4 SED16 star trackers, with about 1000 points in the field of view (in order to have an accurate estimation). A specific algorithm has been implemented under Matlab for that purpose, in order to calculate the laws and to evaluate the corresponding residues.

The results are the following: high order X/Y polynomials have almost the same efficiency as Zernike polynomials. When the order of the polynomial increases, the value of the residues decrease, with however a limit : indeed, after the 10th order, the calibration law becomes very close to calibration points, but can have high frequency variations between these points, making the correction less efficient.
With the correction using several small areas in the field of view, the correction is more efficient. When the number of areas increases, the value of the residues decrease, and the only limitation is the test bench accuracy.

Fig. 2 compares the 3σ values of the distortion residues for the different types of corrections, in function of the number of needed parameters. The values shown are the averages of the performances obtained among the 4 SED16 star trackers. The red curve refers to the XY polynomials, the blue one to the small areas method, and the black one to Zernike polynomials.

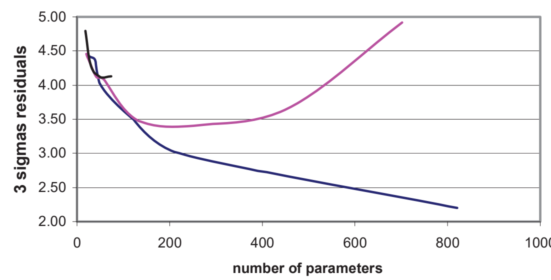

Fig. 2. Distortion residues in function of the number of parameters.

- Evaluation of the constraints

Since the calibration using small areas in the field of view is the most efficient, its implementation constraints have been evaluated, in order to assess the maximum allowable number of areas (and so the minimum performance achievable):
- the number of parameters to be stored (correction coefficients to apply in each area), is compatible with the memory size available on SED36 star tracker, even with a high number of areas,
- the execution time of this additional correction by the flight software is neither a major constraint whatever the number of areas, because some operations are performed in hidden time, during the CCD (Coupled Charge Device) reading,

- the main limitation on the number of areas, concerns the duration of the calibration process on the test bench. Indeed, if the measurement lasts more than about ten hours, there can be some risks of long term drift of the bench due to small room temperature variations for instance.

But when the number of areas increases such as the limit of the test bench accuracy is reached, the calibration measurement lasts less than ten hours, so it is compatible of the maximum duration constraint.

In synthesis, the calibration method which presents the best performances is the method using small areas in the field of view of the star tracker, and its implementation constraints are compatible with SED36 design.

- Implementation of the correction by areas in the star tracker flight software and in the test bench software

The method using small areas has then been implemented in the star tracker software. The correction process is presented in Fig. 3. In order to have an efficient correction, a third order polynomial law still needs to be applied before the correction by areas; it is then a two step correction. Moreover, in order to avoid a step on the attitude restitution when a tracked star shifts from one calibration area to an adjacent one, an interpolation law is used between the adjacent areas.

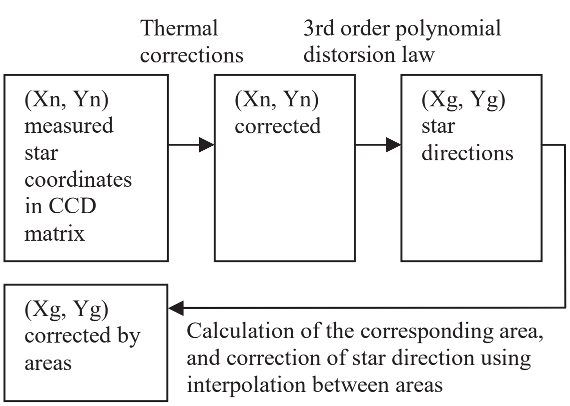

Fig. 3. Flight software distortion correction process.

The test bench software has also been modified in order to perform an automatic calibration measurement process for this specific correction. The calibration measurements are performed on BCG16 test bench, measuring several points per calibration area. The following precautions are taken into account during the process:

- the measurement points are positioned in the pixel centres in order to minimize the barycentre interpolation error,
- the measurement points are positioned in a manner to average a periodic part of the rotation table error: the angular separation between two points is equal to half a period of the error,
- the test bench software avoids positioning a measurement star on potential defective pixels or defective columns of the CCD matrix, in order not to bias the calibration. The coordinates of these pixels are calibrated before the distortion calibration measurement,
- during the measurement process, the position of the central pixel of the CCD is measured periodically, in order to monitor any test bench long term drift. In case a drift is detected, the intermediate measurements are performed again, and the positions of calibration points are corrected,
- the calibration is performed on a larger field of view in order to cover all the useful field of view during flight.

- Method validation

After implementing the calibration method using small areas, it has been validated on the EM (Engineering Model) SED36 star tracker, on the BCG16 test bench.

Fig. 4 presents the distortion residues in the field of view using a representation with small arrows, and Fig. 5 presents the error histograms measured along X or Y axes.

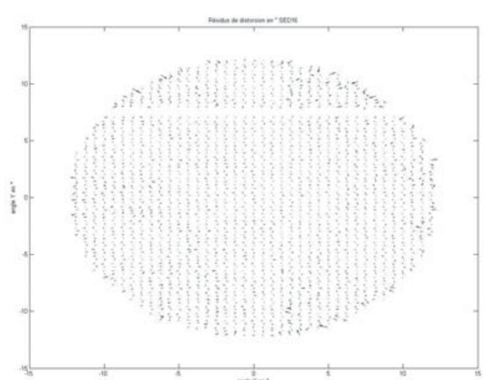

Fig. 4. Distortion residues after correction on EM SED36

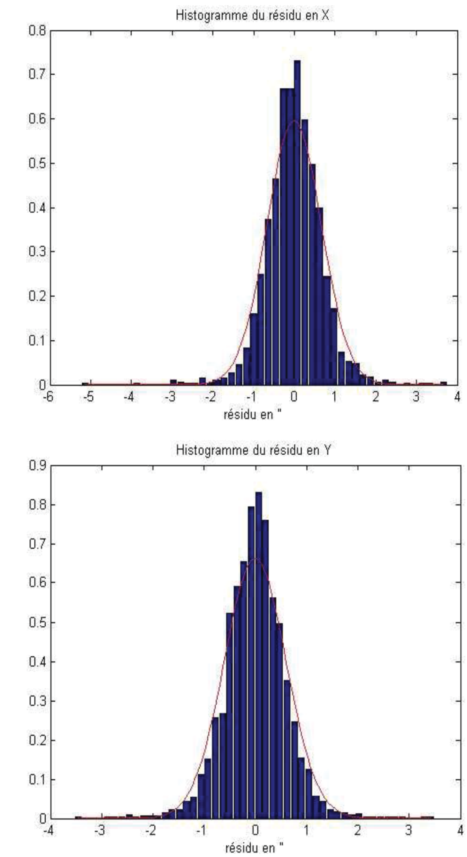

Fig. 5. Histograms of residual errors along X axis (up) and Y axis (down)

The single-star distortion residue measured during this validation is ±2” at 3σ along X or Y axis. This allows reaching a global calibration precision of ±3” at 3σ for the single star distortion error (see Table 2), when taking also into account the influence of the variation of mounting plane temperature, or the test bench accuracy.

2.3 An update of the star catalogue

After having optimized both the contribution of thermal errors and the distortion residues, another low frequency error contributor which can be easily reduced is the star catalogue error. This error is mainly due to the star proper motion, the position measurement error of the reference astronomical catalogue being negligible. The catalogue error equals ±3” at 3σ for a duration of 15 years, the star positions in the catalogue being given at the 01/01/2000.

As the Pleiades mid-mission is scheduled for year 2013, the in-flight SED36 tracking catalogue was updated by propagating stars positions up to 01/01/2013. The same stars were kept, only their positions were corrected with the proper motion information available in the reference astronomical catalogue. Simple validations of the modification have been performed, the original mission catalogue being considered as in-flight validated on board SED16 and SED26. After this update, the star catalogue error is reduced to ±1” at 3σ for the duration of the Pleiades mission.

2.4 An increase of the number of tracked stars

Finally, in order to better average the field of view errors, the number of tracked stars is also increased to 12 instead of 10 nominally on SED16/26.
It has been checked that the SED36 star tracker could still operate with 12 measured stars at the required 8Hz frequency.
It has been also verified that in more than 99% of the celestial vault, there are more than 12 stars in the field of view of the star tracker that are referenced in the star catalogue.
Finally, this improvement allows an additional reduction of the field of view error on the attitude of about 10% (with the hypothesis of a uniform star weighting).

2.5 Attitude performance achieved

Taking into account all the above described improvements, an assessment of performances has been performed with the single-star errors presented in Table 2, in order to evaluate the low frequency error on the attitude of the SED36 star tracker.

The result is a low frequency error of:
- ±1.1” along XY axes and ±6.3” around Z axis at 3σ for SED36,
- instead of about ±10” along XY axes and ±30” around Z axis at 3σ for SED16/26 star tracker.

It is recalled that this type of improvement can only be achieved in case of stable thermal regulation (±3°C) at the satellite interface of the optical head.

3. APPLICATION TO HYDRA STAR TRACKER

HYDRA (see [2]) is the new generation multi-head APS (Active Pixel Sensor) star tracker developed by SODERN. In case of good mounting plane thermal regulation at the satellite interface, the same kind of optimisations can be applied to HYDRA.

Concerning the software improvements like the distortion calibration method, and the update of the star catalogue, they have been taken into account during HYDRA development. Moreover, the optical heads are tracking up to 15 stars in their fields of view.

Concerning the thermo-mechanical behaviour, the baffle will be thermally isolated from the optical head, and the electronic box is separated from the optical heads.

In addition to its high accuracy, HYDRA will also allow the use of gyroless AOCS, because of its high robustness to any kind of disturbances. Indeed, it will be robust to solar flares and South Atlantic Anomaly crossing, or to sun blinding of one optical head for instance.

Table 3. HYDRA main functional features

Attitude	3-axis attitude
Acquisition	Autonomous <2 s.
Tracking	15 stars tracked
Baffle	Sun rejection angle : 30 ° or 40°
Output data rate	Up to 30 Hz
Accuracy at 20°C, 30 Hz, v=1°/s, EOL LEO 5 years : Bias LFE Noise	 10'' all axes 1'' all axes at 3σ 10'' all axes at 3σ
Operating temperature range	20°C ± 3°C for improved LFE -30°C to +60°C otherwise
Mass : Optical head Electronic box Baffle	 0.9 kg 1.7 kg 0.3 kg
Dimensions : Optical head Electronic box Baffle	 H=150xL=115xl=115 mm^3 H=105xL=142xl=142 mm^3 H=126xΦ=150 mm^2
Power consumption : 3 optical head and 1 electronic unit, detector at 0°C, and 20°C interface temperature	12W
Data I/O	1553 B (RS422 option)
Power supply	20-50V (50-100V option)

Fig. 6. HYDRA, the new APS multi-head star tracker from SODERN

4. CONCLUSION

In the frame of the SED36 development dedicated to the Pleiades satellite, some hardware and software improvements have been performed on SED16/26 star tracker product line, in order to reduce to 1.1" at 3σ the low frequency error on the attitude along transverse axes. In particular, a more accurate distortion calibration method using small areas in the star tracker field of view has been developed.
The same kind of improvements will be achieved as well on HYDRA, the new generation multi-head APS star tracker developed by SODERN. In addition to its high accuracy, HYDRA will also bring very high robustness to any kind of disturbances, and will offer a cost effective, low mass and low power consumption solution system.

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