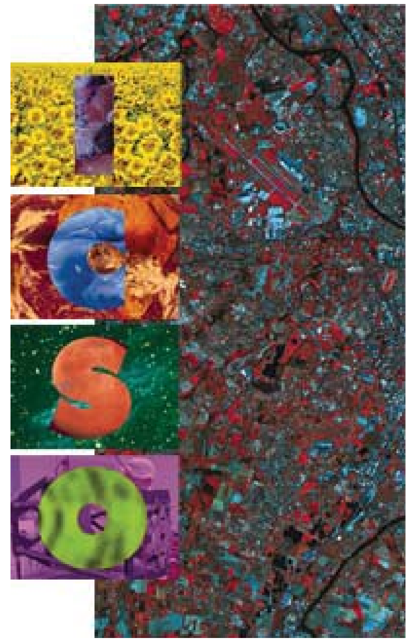
International Conference on Space Optics—ICSO 2000

Toulouse Labège, France

5–7 December 2000

Edited by George Otrio



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International Conference on Space Optics — ICSO 2000, edited by George Otrio, Proc. of SPIE Vol. 10569
105690U · © 2000 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2307893

SED16 AUTONOMOUS STAR TRACKER NIGHT SKY TESTING

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RESUME – Le SED16 est un viseur d'étoiles multi-missions autonome qui délivre sans information préalable l'attitude et la vitesse angulaire sur les trois axes dans un référentiel inertiel. La démarche de qualification de ce viseur d'étoiles inclut cinq étapes de validation utilisant un simulateur d'étoiles optique, un simulateur d'images de synthèse et un banc d'essais ciel réel. Les essais ciel réel constituent l'étape finale de la démarche de qualification. Durant ces essais, l'ensemble des fonctions du viseur ont été mises en œuvre dans des conditions nominales : Acquisition autonome puis poursuite autonome de dix étoiles. Ces tests ont été effectués à Calern sur le site de l'OCA (Observatoire de la Côte d'Azur). Le banc de test et les résultats obtenus sont décrits après un rappel des principales caractéristiques du viseur et de la démarche de qualification.

***ABSTRACT** - The SED16 is an autonomous multi-missions star tracker which delivers three axis satellite attitude in an inertial reference frame and the satellite angular velocity with no prior information. The qualification process of this star sensor includes five validation steps using optical star simulator, digitized image simulator and a night sky tests setup. The night sky testing was the final step of the qualification process during which all the functions of the star tracker were used in almost nominal conditions : Autonomous Acquisition of the attitude, Autonomous Tracking of ten stars. These tests were performed in Calern in the premises of the OCA (Observatoire de la Cote d'Azur). The test set-up and the test results are described after a brief review of the sensor main characteristics and qualification process.*

1- SED16 AUTONOMOUS STAR TRACKER MAIN FEATURES

SED 16 is an autonomous, multi-missions and cost-effective star tracker. SED 16 delivers three axis satellite attitude and the satellite angular velocity to the Attitude Control Sub-system.

The main functions of the sensor are :

- An optronic sensor comprised of the lens and a 1024 x 1024 pixel CCD detector with a cooling device,
- Electronics combining functions for implementing the detector, digital processing and interfaces as well as for shaping the video signal,
- A mechanical structure to maintain the required stability of the lens and the detector,
- A sun shade to protect the star tracker against stray-light,
- A software enabling the 3-axis attitude restitution ; this software incorporates star catalogues as well as recognition and tracking algorithms.

In-house software routines were developed by SODERN to improve tracking accuracy, high angular rate operation, tracking even with a high level of stray-light and to operate with the Moon in the field of view, either in tracking or in acquisition. These routines were validated in-flight on previous star trackers or during the qualification process.

The star tracker's design involves a small number of components. This makes the SED 16 easy to integrate and leads to greater cost-effectiveness.

This new family of star sensors is a breakthrough for attitude measurement due to the performance achieved, their easy integration on the satellite bus, their answer to the satellite's mission requirements as well as their low recurring cost.

The main features of the Star Tracker are indicated in Fig. 1.

Functional features	
Attitude	3-axis attitude determination
Acquisition	Autonomous (lost in space function), 99.9 % in less than 3 s.
Tracking	Autonomous, 10 stars tracked simultaneously
Polluting objects	Automatic exclusion (debris, satellites, …)
Moon	Able to operate with the Moon in FOV
Standard Sunshades : • D=160 mm / L=160 mm / M=0.48 Kg • D=200 mm / L=240 mm / M=0.67 Kg	Sun / Earth rejection angle : 40 degrees / 32 degrees 25 degrees / 25 degrees
Output data rate	1- 10 Hz
Accuracy at 20°C, 10 HzEOL : • Bias (X, Y and Z axes) • Noise (X and Y axes) • Noise (Z axis)	 10 arcsec 3σ 11 arcsec 3σ 70 arcsec 3σ
Angular velocity	Up to 20 degrees/s at 10 Hz in tracking
Environmental features	
Operating temperature range	-30°C to +60°C
Vibration	25 g rms
Mechanical interfaces	
Size	170 x 120 x160 mm without sun shade
Mass	2.5 kg without sun shade
Mounting plane	SED-B parallel or SED16-A perpendicular to line of sight
Electrical interfaces	
Typical power consumption	8 W
Power supply	20 - 55 V, 50-122 V
Data I/O	RS 422 or 1553 B
Lifetime	15 years in GEO
Reliability	1000 to 2700 fit according to part quality grade and interfaces

Fig. 1 : SED 16 main features

The Fig. 2 represents the SED16 with a line of sight parallel to the mounting plane (SED16-B) associated with a 25° baffle and the SED16 with a line of sight perpendicular to the mounting plane (SED16-A) associated with a 40° baffle.

Fig. 2 : SED16-B and SED16-A

2- SED16 QUALIFICATION PROCESS

The SED16 qualification process is described on Fig. 3 : At each step, the test results are compared to results obtained with simulation tools in order to validate the tools which are also used to assess the star tracker accuracy budget.

2.1 MEV16 test benches

MEV16 is an automated star tracker test bench involving :

- An optical test bench simulating from 1 up to 4 stars. Star magnitude and star spectral distribution are adjustable and this enables us to simulate all kinds of stars.
- A two-axis table (360 degrees per axis) which allows to test star trackers in static or dynamic mode (up to 4°/s).
- A thermal vacuum chamber mounted on the two-axis table with a temperature range of –40°C to +70°C.

MEV16 single-star allows us not only to integrate calibrations and test a star tracker, but also to provide simulation software with reliable, accurate data and to adjust them.
MEV16 multi-stars allows us, for a specific and fixed star configurations, to check star tracker's performances at the beginning of its life.

2.2 SIM16 test benches

There are two SIM16 test facilities :

- SIM16-GI : Is an image generator which allows to play any pre-computed image sequence
- SIM16-BF : Includes real time simplified images calculation and injection in the tracker

The first system SIM16-GI allows to test tracker algorithms with very representative image sequences, including stray light, EOL CCD dark current and sensitivity, objects, planets and Moon in the field of view, CTI effects. The second system SIM16-BF only generates simplified images but allows endurance tests during days, easy simulation of any 3-axis trajectory profile and real time close loop tests at AOCS level for validation or during acceptance (thermal vacuum, final functional test, …).

2.3 Night Sky test bench

This test setup uses a rotating table on which the star tracker is fixed. This bench allows us to check functionality and noise performances of star trackers up to 30 degrees per second in a real sky landscape.

The tracker is operating in ambient temperature and pressure conditions : Specific calibration parameters are used, including distortion law and signal to magnitude conversion factor. Star deviation by the atmosphere has been computed and have been incorporated in the tracker distortion law calibrated in the air. The signal to magnitude conversion factor has been calibrated and corrected using the attenuation computed with LOWTRAN.

During the tests, the CCD is regulated at a temperature of +15°C instead of the nominal –10°C which simulates end of life dark current.

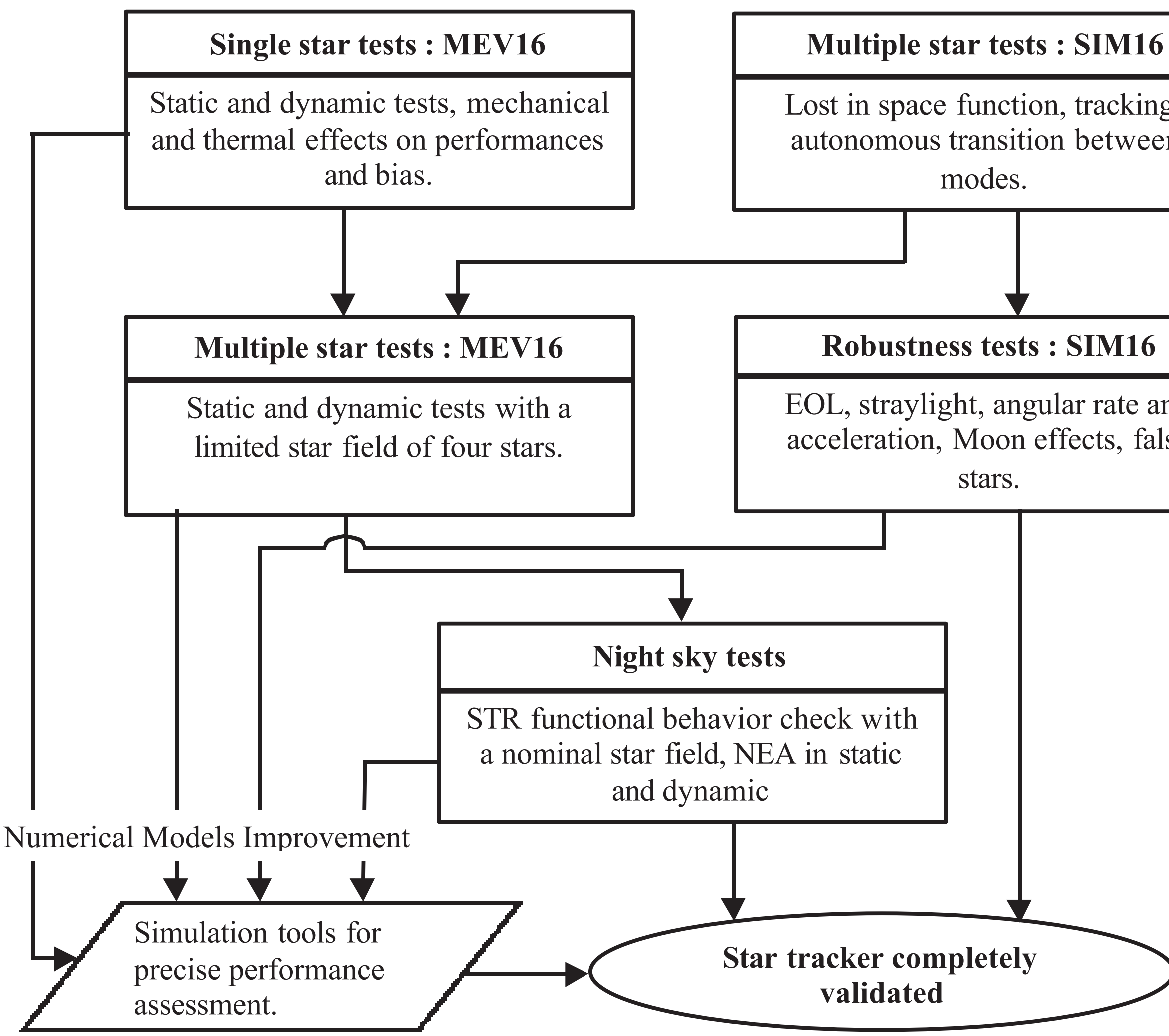

Fig. 3 : SED16 qualification process

3- NIGHT SKY TEST SETUP

The night sky test bench is an equipment which allows to operate the Star Tracker in static and dynamic conditions. It includes a single axis table which supports the star tracker and an electronic bench to control either the table motion and the star tracker powering and communication. The star tracker is mounted on a base plate (see Fig. 4) which allows to tilt its optical axis with regard to the vertical (0°, 10°, 20° and 30°). The overall is fixed on a rotating table by a brace, the table axis is adjusted to the local vertical using a spirit level. Signals are transmitted via rotating contacts to the electronic interface with star tracker :

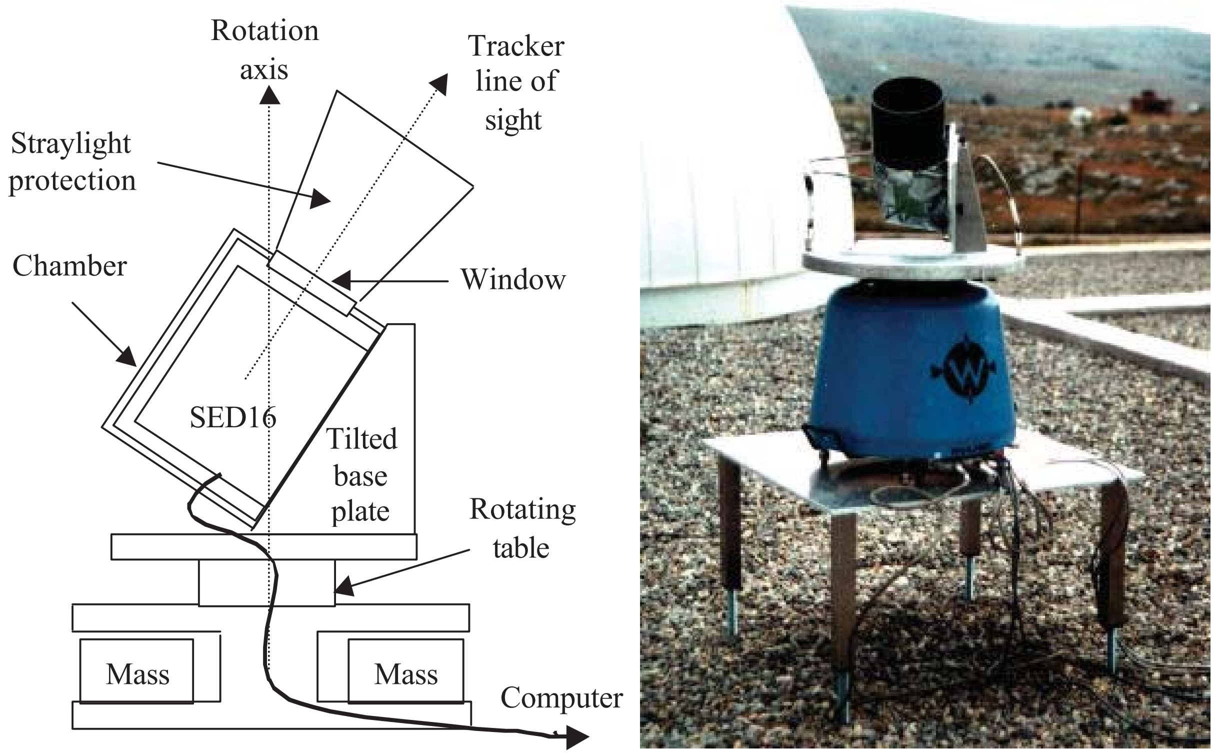

Fig. 4 : Night sky test set-up

The electronic bench and test software includes low level communication functions which allows to directly operate the star tracker sending telecommand or pulling up telemetry on a case by case basis, as well as high level macro-functions which allow to run complete test sequences and process the data. During the test sequence proceeding, the operator can check the star tracker behavior using the real time control panel which reflects most useful part of the star tracker telemetry. Nevertheless, all the operating mode telemetry is recorded and can be directly checked or processed afterward to calculate absolute angular position, noise or any kind of statistic on the measured stars.

4- FUNCTIONAL TESTS RESULTS

The purpose of these tests was to check that the star tracker acquisition and tracking did not failed and to verify that operating mode behavior was nominal : Number of tracked stars, number of measured and coherent stars, measured attitude and angular rate noise (for constant angular rates only). The test conditions were rather representative of end of life conditions since the detector temperature was 15°C instead of –10°C during flight.

4.1 Constant angular rate tests

Most tests were performed at a constant angular rate : See Fig. 5. The sequence in this case used the star tracker "autonomous pointing mode" which consisted of two measurements in "acquisition mode" in order to measure star tracker initial attitude and angular rate, followed by measurements in "tracking mode" (from 1024 to 8096) but always interrupted by a telecommand. The tests were performed up to 30°/s : See Fig. 6. The acquisition was always performed at the same angular rate as the tracking even when this was out of range of the tracker specification : The only noticed consequence was that at high angular rates (15°/s to 30°/s) the attitude and angular rate measurement could take a few more image integration than the two expected.

	Tracker angle with respect to rotation axis (local vertical)					
	0°	30°	0°	30°	0°	30°
Angular rate	1 Hz		5 Hz		10 Hz	
0°/s	X		X		X	
0.1°/s				X		
1°/s	X					
2°/s		X		X		X
5°/s				X		X
8°/s				X	X	X
10°/s				X		X
15°/s				X		X
20°/s				X		X
25°/s						X
30°/s						X

Fig. 5 : Constant angular rate functional tests

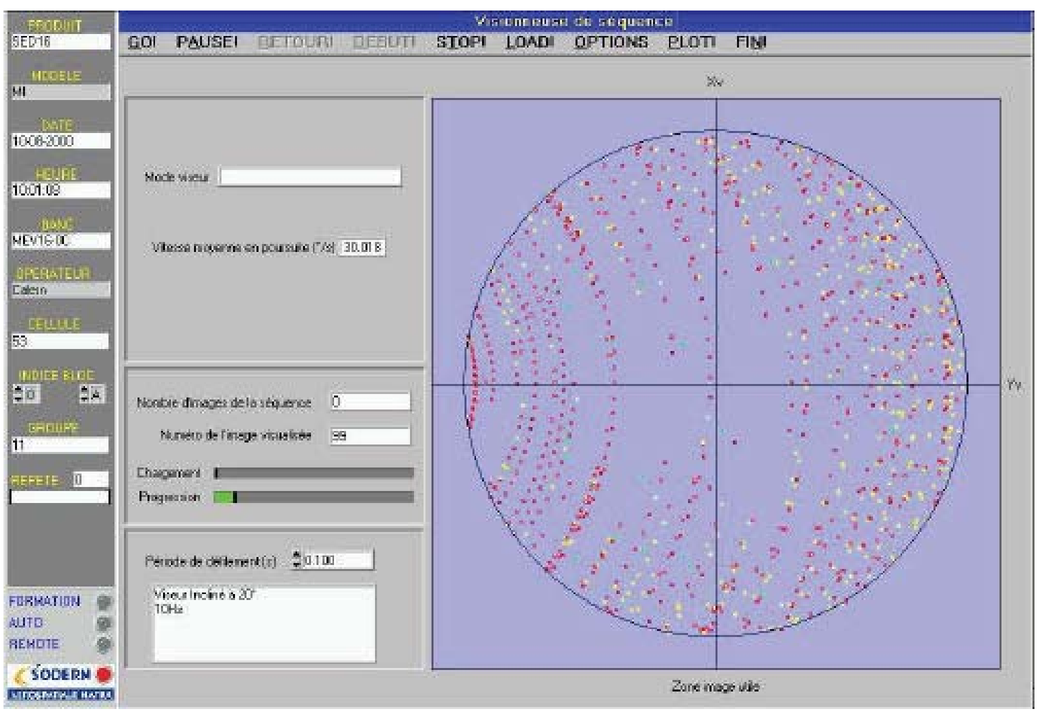

Fig. 6 : Star tracker measured stars at 10 Hz and 30°/s

4.2 Acceleration tests

Other tests were performed, at 5 Hz and with a tracker angle of 30° with respect to vertical, in order to check the star tracker robustness to acceleration rates : In this case, the star tracker first acquisition was performed at a constant angular rate and when in tracking, the table angular rate was modulated using Sine or linear ramps. The purpose of this test was to check that tracking was maintained over all the acceleration range (no return to acquisition) with a sufficient number of coherent stars. A high range of acceleration rates have been tested (see Fig. 7) and no tracking failure occurred up to 5°/s² : See Fig. 8.

<table>
<tr><th>Angular rate (°/s)</th><th>Acceleration rate (°/s²)</th></tr>
<tr><td rowspan="5">3±2</td><td>0.1</td></tr>
<tr><td>1</td></tr>
<tr><td>2</td></tr>
<tr><td>4</td></tr>
<tr><td>5</td></tr>
<tr><td>5±3</td><td>1</td></tr>
</table>

Fig. 7 : Acceleration functional tests

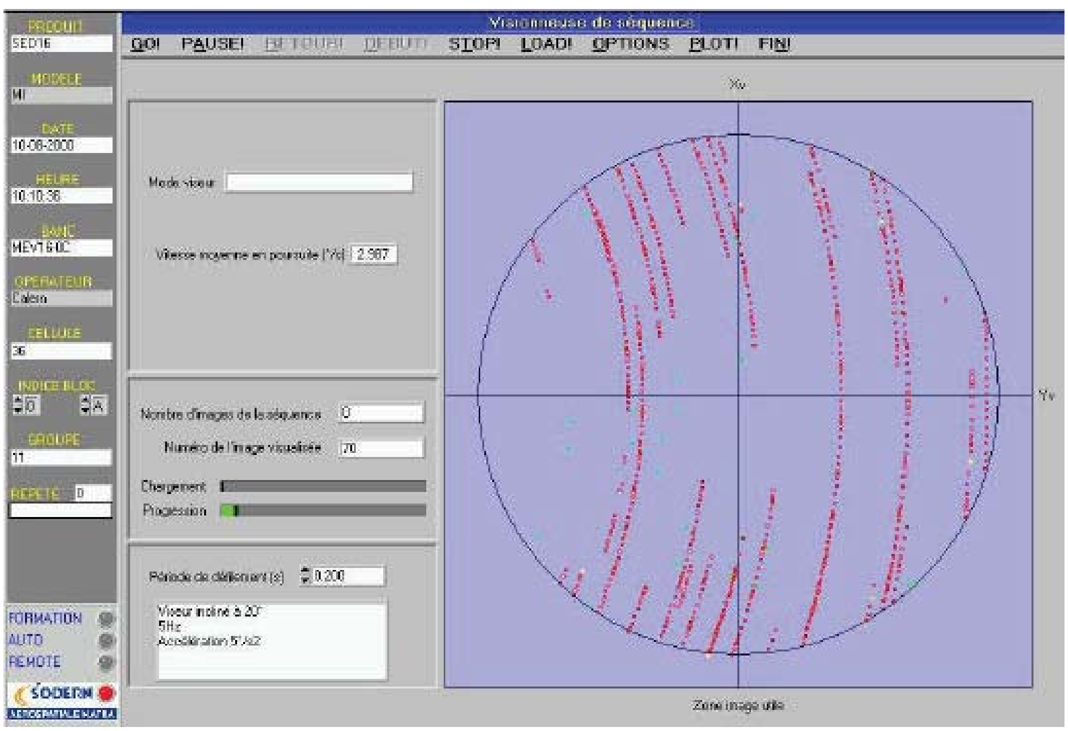

Fig. 8 : Star tracker measured stars at 5 Hz and 5°/s²

4.3 Endurance tests, celestial vault scanning and robustness tests

The purpose of last functional tests was endurance verification : In this case it was necessary to reproduce an important number of measurements, either in acquisition or in tracking. The tests used the "autonomous pointing" mode which starts with 2 measurements in acquisition mode followed by an autonomous switching to tracking mode, the two endurance sequences were :

- 128 pointing, with 16 measurements in tracking mode, at 5 Hz and 5°/s
- 64 pointing, with 1024 measurements in tracking mode, at 5 Hz and 0.1°/s

The second sequence was also dedicated to a scanning of a significant part of the vault : 120°x80° which corresponds approximately to 15% of the vault. This allowed to check the star catalogs in acquisition and tracking in rich and poor star zones.

Additional tests were performed to check the algorithms : Acquisition and tracking were performed for instance with obscuration of half of the field of view. This allowed to check that significant design margins exist and that robustness of the tracker design could face some unexpected operating conditions.

5- PERFORMANCE TESTS RESULTS

The detailed performance analysis was performed on some of the functional test sequence : Quasi-static test sequence (natural rotation of the Earth only) and dynamic test sequence at 5 Hz and 2°/s. The analysis consisted to compare the estimated noise using the same simulation tools and models as the one used to compute star tracker performances in orbit. Simulation took into account specific test conditions like temperature of the CCD and beginning of life dark current but did not include any error term induced by atmosphere which are difficult to estimate. The measured Noise Equivalent Angle (NEA) performances were calculated through the processing of the star tracker delivered telemetry : Single star coordinates and tracker angular rate.

The first verification was performed at single star level (see Fig. 9). The measured values are slightly better or equivalent to the estimated performances.

Mi	Estimated standard deviation (σ_{x-y})	Measured standard deviation (σ_{x-y})
1.55	3.3 arcsec	2.7 arcsec
3.67	8.2 arcsec	8.3 arcsec
4.00	10.2 arcsec	9.0 arcsec
4.69	17.0 arcsec	15.3 arcsec

Fig. 9 : Quasi static single star Noise Equivalent Angle (NEA)

For the same sequence (quasi-static), the attitude NEA has also been estimated with exactly the measured star field and compared to measured values : Again, a good coincidence is obtained between both values (see Fig. 10).

	Estimated attitude NEA	Measured attitude NEA
σ_{x-y}	1.4 arcsec	1.5 arcsec
σ_Z	9.9 arcsec	8.9 arcsec

Fig. 10 : Quasi static attitude Noise Equivalent Angle (NEA)

The last comparison has been performed in a dynamic case with different orientations of the star tracker line of sight with respect to the vertical (see Fig. 11).

	Estimated NEA		Measured NEA	
Angle Z / vertical	X - Y	Z	X - Y	Z
0°	2.7 arcsec	18.2 arcsec	2.5 arcsec	15.4 arcsec
20°	3.3 arcsec	22.5 arcsec	3.5 arcsec	18.8 arcsec
30°	3.3 arcsec	22.5 arcsec	3.1 arcsec	15.9 arcsec

Fig. 11 : Dynamic attitude Noise Equivalent Angle (NEA) at 5 Hz and 2°/s

6- CONCLUSION

The night sky tests performed with the SED16 gave the best evidence of the star tracker functional and accuracy performance, and this without taking into account the perturbation of the atmosphere. Many tests have even been performed at SODERN, near Paris, where the conditions for straylight and aerosols are probably one of the worst in France. Additional tests are now foreseen in a more adequate location in order to get exact performances of the tracker, probably better than estimated. This location could be at a high altitude in one of Hawaï observatory in cooperation with US customer.

The first flight models has now been delivered and other flight model deliveries are now scheduled at a rate of more than one model per month. The first flight model is dedicated to the SPOT 5 satellite, which is part of the French Earth observation program.