Data fusion with Hydra Star Tracker on Spot6

*Damien PIOT, Lionel ODDOS-MARCEL, Benoit GELIN **
*Alain THIEUW, Patrick GENTY ***
*Pierre-Emmanuel MARTINEZ***, Stephen AIREY, Steeve KOWALTSCHEK *****
** SODERN, 20 avenue Descartes, 94451 Limeil-Brévannes, France*
Email benoit.gelin@sodern.fr
*** ASTRIUM, 31 avenue des cosmonautes, 31402 Toulouse Cedex 4, France*
**** CNES, 18 avenue Edouard Belin, 31401 Toulouse Cedex 4, France*
***** ESA-ESTEC, Keplerlaan 1, Postbus 299, 2200 AG Noorwijk, Netherlands*

Abstract
This paper presents one main characteristic of the multiple-head CMOS sensor based Star Tracker, HYDRA from Sodern: the field-of-view fusion. After explaining this concept, the paper presents the validation of multi-head management during night sky tests, performed during Hydra qualification. Then results from the star tracker on-board SPOT-6 Spacecraft from Astrium are presented and successfully compared to predicted performances. Single head performances and fused quaternion performances are evaluated by PSD calculation with splitting into the different frequency classes and fit very well simulated values. Paper ends with inter-head matrices in-flight calibration and blinded heads management, both compliant with expected behaviour.

1. Introduction

1.1 Spot-6 mission overview

Sodern's HYDRA multi-head star tracker has achieved TRL-9, having been launched success-fully aboard the French Spot-6 Earth observation satellite on September 9, 2012. Spot-6 satellite will be joined in its 435-mile (700-kilometer) polar low-Earth orbit by the identical Spot 7 to be launched in late 2013. Astrium Services has financed the Spot-6 and Spot-7 project aimed at forming a commercial Earth-imaging satellite constellation. Both satellites will be phased at 180° in the same orbit as the French Pleiades constellation (Sun synchronous quasi-polar orbit). The Spot-6 satellite is the first model of the newly developed ASTROBUS 250 platform by Astrium. The architecture of this platform is close to that of the Pleiades satellites. Spot-6 and Spot-7 include four control moment gyroscopes, a fibre-optic gyroscope and the HYDRA three head 3-axis star tracker.

1.2 Star tracker overview

HYDRA is the multiple head CMOS Active Pixel Sensor (APS) star tracker developed by Sodern and co-funded by CNES (French Space Agency), DGA (French Defense Procurement Agency) and ESA (European Space Agency). This paper presents results from the Spot-6 HYDRA on-orbit performance. The Spot-6 HYDRA configuration comprises three Optical Heads (OH) with 28° Sun exclusion angle baffles and two Electronic Units (EU) to achieve redundancy. The Star Tracker (STR) operates at 16Hz with measurements and quaternion delivery both at 16Hz; actually HYDRA can deliver quaternion at a rate up to 30Hz which is a large step ahead compared to other star trackers which operate at 10Hz maximum. The multi-head design allows delivery to the AOCS three individual quaternions corresponding to each OH and based on 15 stars each, and a fused quaternion based on data fusion of the 3 OH Fields Of View (FOV). This is the first star tracker that performs such on board data fusion: it goes further than the usual Optical Head quaternion fusion since the fused solution is based on the 45 stars available in the 3 FOVs. The 3 OHs are mounted on the spacecraft in an almost orthogonal configuration (each Line of Sight is orthogonal to the two others, as shown in figure 1) which allows the best performance (the fused quaternion has the same performance on each axis) and the highest availability (quaternion delivery is maintained even if one OH is blinded by the Sun and one is occulted by the Earth).

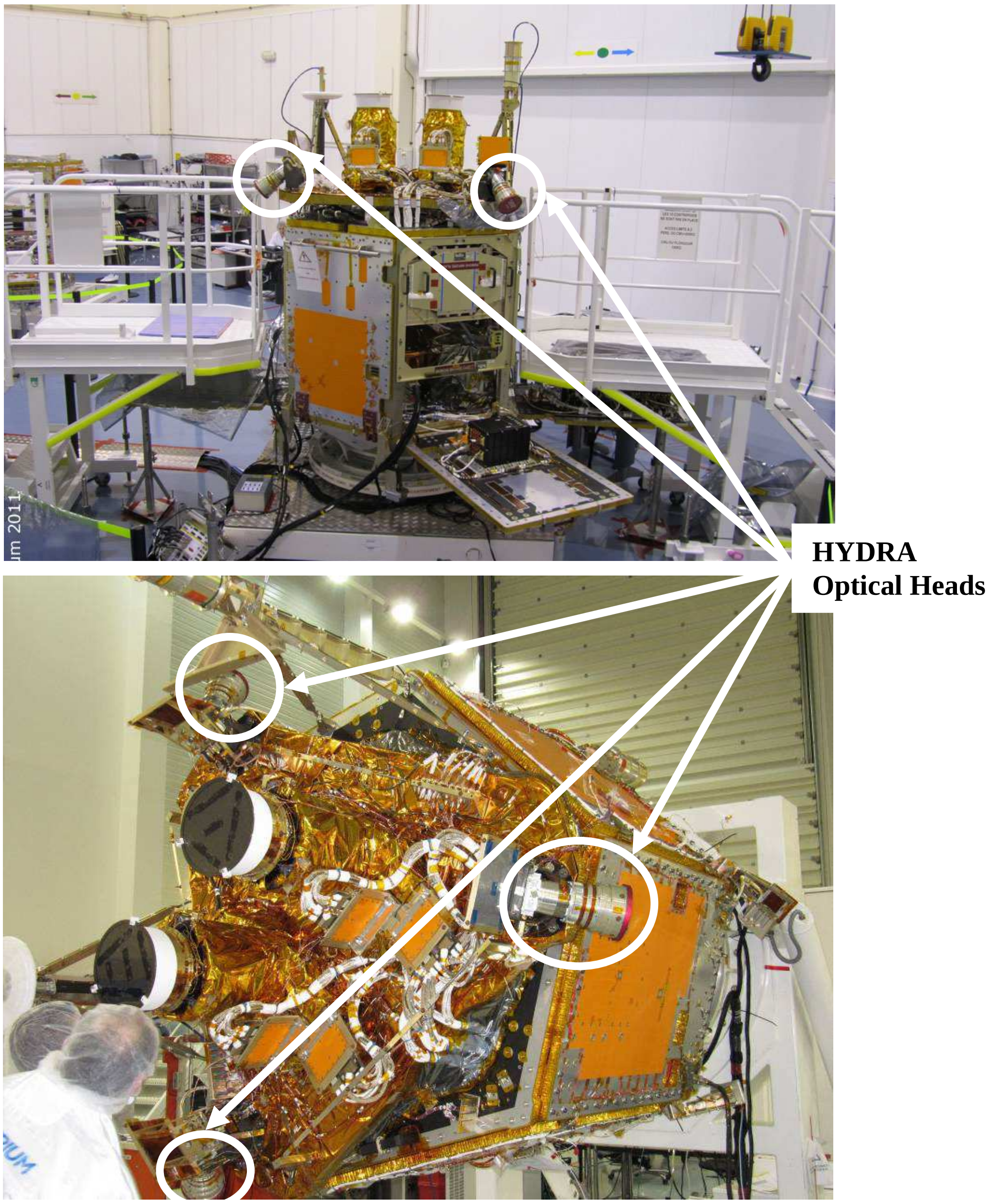

Figure 1: View of the Spot-6 satellite.

2. FOV fusion

2.1 Single FOV concept

A single FOV concept is used for the multi-head attitude computation. This means that all the star directions are expressed in the reference frame of one OH, and then attitude is computed from all of them. This task is called "fusion".

Multi-head management is flexible with respect to the number of OH included in the multi-head fusion. For example, the participation of an OH can be dynamically enabled or disabled during attitude tracking. In the latter case, the single head attitudes of this head (that is to say the attitude computed from the stars measured by this head and only these) are still computed and delivered to the AOCS. An OH can be switched on and inserted into the multi-head system during recurrent attitude tracking. In the particular case of occultation or blinding of an optical head, the STR automatically detects the event and suspends the use of this OH data in the fusion; when the event ends up, the participation of this head in the multi-head data fusion can be delayed for a number of cycles.

The OH the fusion is performed in is the so-called internal reference OH. This head is preferentially a user defined OH called the external reference OH if this head is in tracking, or the oldest available OH being in tracking if the external reference OH is off or in stand-by. A default external reference OH is defined by a software parameter but this head can be dynamically changed by means of a command while Autonomous Tracking Mode is running.

The fusion requires the knowledge of the transformation quaternions between each OH's reference frames. Unless inhibited by software parameterization, these relative orientations are calculated continuously from the single head attitudes by a self-calibration process [1].

The FOV fusion and the multi-head management offer immunity from Sun and Earth blinding. They also take part in autonomous recognition and adaptation to internal failures such as loss of an optical head, data link or thermal control. Moreover full accuracy is met about all three axes. These capabilities allow large simplifications in the AOCS design, in particular in on-board software and ground operations.

2.2 Inter-head transformation quaternions

Several events, either at STR level or at OH level, can modify inter-head transformation quaternions: switch on, switch off, reset, switch between tracking mode and stand-by mode, blinding or occultation… Whenever possible, last estimated values of inter optical head transformation matrices are held until a new calculation is available. If it is not possible, either because parameters prevent it or if STR is reset for example, then missing transformation quaternions are switched to calibration values.

For example, if an OH is occulted or blinded while Autonomous Tracking Mode is running then last estimated values of transformation quaternions between this head and other heads are held. When occultation or blinding end up, self-calibration filter is reset with new measurement if a reset flag is up. If this reset flag is down (default tuning) then self-calibration filter is not reset.

At any time, if an EU hot reset occurs, RAM parameters remain unchanged so RAM inter-head matrices default values (initially loaded from EEPROM but potentially modified by previously sent Memory Write Telecommand) are used.

3. Multi-head management during night sky tests

Blinding and occultation tests have been performed during night sky tests, in order to confirm STR good behaviour. For these tests some parameters were not set to their present values. In particular the number of stars per OH was 7 in 3-head configuration.

In 3-head configurations, tracking is never lost when one or two optical heads are blinded or occulted or both (one blinded and one occulted). On the occulted or blinded head, the number of measured stars is null. After blinding or occultation, the number of stars increases back to 6-7 stars.

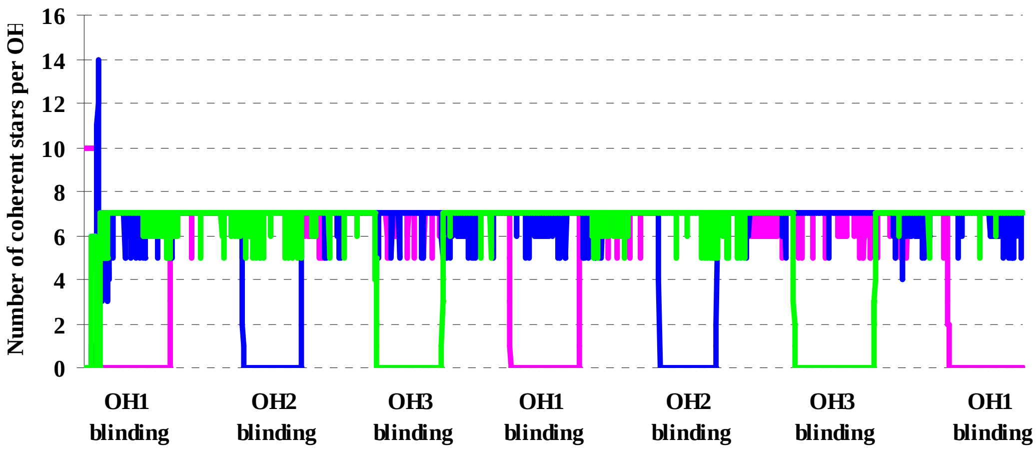

Figure 2: Blinding of one OH among 3 during night sky tests

This behaviour is the same for each configuration: one or two blinded or occulted heads, in quasi static condition or at 2.5°/s around cross-boresight axes.

If a simultaneous blinding (it would be the same for occultation) of the 3 optical heads occurs, then the STR returns to acquisition mode, reacquires attitude as soon as one head at least is no more blinded, and comes back to attitude tracking mode in which it recovers all other heads when their blinding ends up (see Figure 3 and Figure 4).

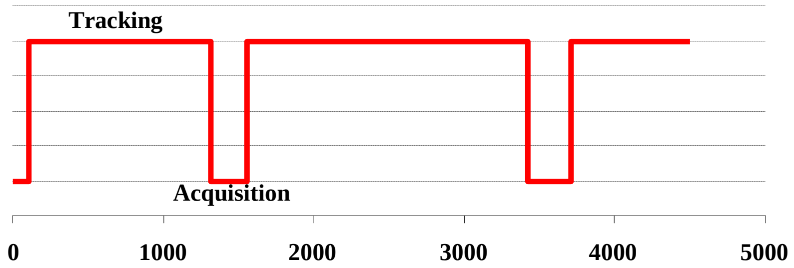

Figure 3: Mode swing during blinding of 3 OH (night sky tests)

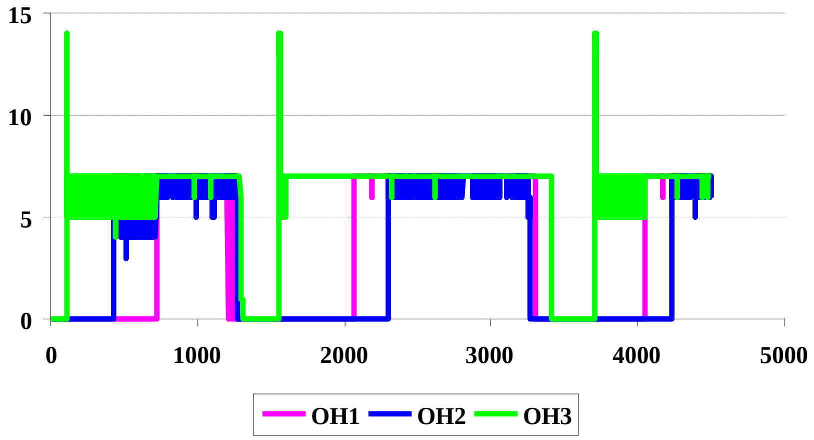

Figure 4: Number of coherent stars during blinding of 3 OH (night sky tests)

Figure 4 displays the number of coherent stars in tracking for each optical head. The 3 heads were blinded at the beginning of the test sequence so the acquisition was making many attempts. After each simultaneous blinding, OH3 blinding ended first followed by OH1 then OH2, or OH2 then OH1. Entrance in tracking is single head, hence the high value of stars tracked by OH3 during first few measurements. As soon as a head was no more blinded its number of coherent stars increased to 6-7 stars. Conversely, as soon as it was fully blinded its number of coherent stars dropped to zero.

Conclusion of the test: the behaviour of the star tracker is perfectly compliant with the expected behaviour: in 3-head configuration attitude tracking is never lost when one or two optical heads are blinded or occulted or both (one blinded and one occulted).

4. Hydra on-board Spot-6

4.1 Single head performance

The performance has been analyzed for standard LEO (Low Earth Orbit) angular rate (0.06°/s) [2].

The analysis method for the attitude performance is as follows:

- Since orbital control could degrade the measured performance, data sets have been chosen so that no manoeuvre was performed during the recording periods. This constraint limits the size of data sets.
- The four components of raw quaternions are fitted with a fifth order polynomial law. The fit quaternion is considered as the true quaternion. The choice of this kind of law has been done in agreement with Astrium.
- The measurement error is considered as the difference between the measurements and the fitted quaternion (the bias and the bias stability are not included in the measurement error since they are included in the fit).
- The Power Spectral Density (PSD) is computed for each axis and the different error terms are computed by frequency filtering through Fourier transform.

For the Low Frequency Spatial Error (LFSE or Field Of View error), this method does not discriminate errors coming from the STR and from the satellite (base plate shift, variation in the angular rate…); the calculated error is therefore a worst-case at star tracker level. Consequently a second method has been used in addition to extract LFSE by a filtering with a moving average. This method is probably more accurate than the PSD through Fourier transform since the number of samples is limited (however, both methods give the same order of magnitude as it is shown below).

The total error is then split into the different error classes. Table 1 gives the temporal Noise Equivalent Angle (NEA), Table 2 the High Frequency Spatial Error (HSFE) and Table 3 the Low Frequency Spatial Error (LFSE).

Table 1: Single head measured and expected temporal NEA

	Temporal NEA (at 3 sigma)			**Temporal NEA at 10Hz (at 3 sigma)**
	Measurement	**Performances assessment (1)**	**As built performances (2)**	**Measurement**
	arcsec/Hz$^{1/2}$	**arcsec/Hz$^{1/2}$**	**arcsec/Hz$^{1/2}$**	**arcsec**
Around X_{OH}	0.68	0.95	0.73	2.1
Around Y_{OH}	0.65	0.95	0.73	2.1
Around Z_{OH} (LOS)	6.0	7.6	5.7	18.8

Measurement: in-orbit measurement
Performances assessment: BOL simulated performances with worst case parameters
As built performances: BOL simulated performances with typical or on-ground measured parameters

The temporal NEA is easy to get as its frequency domain is clearly defined. Note that all values are expressed in arcsec/Hz$^{1/2}$, which is equivalent to 1Hz. For comparison to other star trackers, the last column gives the performance in arcsec at 10 Hz.

The “performance assessment” values (1) are the predictions with simulation tools, calculated in Beginning Of Life (BOL) conditions without straylight (conditions of the measurements) and taking into account worst case values for readout noise, star spot size and photometric sensitivity. Theses values are expected slightly higher than the measurement since they include margins, which is the case.

The “as built performance” values (2) are the same but consider typical values (or values measured during the acceptance tests) for the read out noise, the star spot size, and the photometric sensitivity. The performances are computed on the whole celestial vault. The as built performance fit perfectly the measurement which demonstrates the good prediction of the performance.

Table 2: Single head measured and simulated HFSE

	HFSE (arcsec, at 3 sigma)	
	Measurement	**Performances assessment**
Around X_{OH}	2.1	2.0
Around Y_{OH}	2.8	2.0
Around Z_{OH} (LOS)	15.8	15.7

The simulated HFSE in the measured conditions (beginning of life without straylight) is expected very low in such conditions which increases the difficulty to evaluate it accurately with the PSD method. The measured HFSE matches the simulated one around X and Z axes and is slightly higher around Y. It should be noted that the simulated values are not the worst case as it corresponds to a global statistic on the vault whereas the measured one is extracted from a measurement of a small part of the vault. The slight discrepancy around Y does not inform the result and the HFSE is considered as validated here.

Table 3: Single head measured and simulated LFSE

	LFSE (arcsec, at 3 sigma)	
	Measurement (PSD // moving average)	**Performances assessment**
Around X_{OH}	0.5 // 0.3	0.7
Around Y_{OH}	0.7 // 0.5	0.7
Around Z_{OH} (LOS)	3.3 // 2.2	4.7

As explained previously, the PSD method is not very accurate to estimate the spatial errors at high and low frequencies. It seems that the PSD method overestimate the LFSE contribution compared to the moving average method, but both methods give about the same results.

Despite the applied method is expected to give worst case values because it can include errors that do not come from the star tracker, the measured LFSE is fully in accordance with the performances assessment. Even better values are found, about 0.4arcsec (3 sigma) on X&Y axis.

This error class is very important for the performance of the spacecraft since LFSE cannot be filtered by gyroscopes contrary to HFSE and temporal NEA that can be filtered. A low value is often required by prime's and HYDRA confirms here its very low contribution.

For all the frequency domains, the measured performances fit with the simulated values.

4.2 Fused quaternion performance for 3 available OH

The same analysis performed for single head performance is done for the fused quaternion when the three optical heads are available. The total error is also split into the same error classes but expressed in the same reference frame (RS or satellite reference frame). Table 4 gives the temporal NEA, Table 5 the HFSE and Table 6 the LFSE.

Table 4: Fused quaternion measured and simulated temporal NEA

	Temporal NEA (at 3 sigma)			**Temporal NEA at 10Hz (at 3 sigma)**
	Measurement	**Measurement**	**As built performances**	**Measurement**
	arcsec/Hz$^{1/2}$	**arcsec/Hz$^{1/2}$**	**arcsec/Hz$^{1/2}$**	**arcsec**
Around X_{RS}	0.43	0.63	0.48	1.3
Around Y_{RS}	0.28	0.63	0.48	0.9
Around Z_{RS}	0.40	0.68	0.50	1.3

The fused quaternion offers an excellent temporal NEA around each axis; this is the advantage of HYDRA fused quaternion. The measured values are lower than the simulated performances (performed in the same favourable environment conditions).

Table 5: Fused quaternion measured and simulated HFSE

	HFSE (arcsec, at 3 sigma)	
	Measurement	**Performances assessment**
Around X_{RS}	1.4	1.4
Around Y_{RS}	2.0	1.4
Around Z_{RS}	1.7	1.4

The measured HFSE is also improved by the fused method and is close to the simulated performances. The same shift as for single head performances is observed around Y axis and the same remarks concerning the accuracy of the PSD method and the limited part of the vault for the measurement can be given. The measured HFSE fits globally the simulated one.

Table 6: Fused quaternion measured and simulated LFSE

	LFSE (arcsec, at 3 sigma)	
	Measurement (PSD // moving average)	**Performances assessment**
Around X_{RS}	0.4 // 0.2	0.5
Around Y_{RS}	0.5 // 0.4	0.5
Around Z_{RS}	0.5 // 0.3	0.5

As explained for the single head performances, the method probably provides overestimated values for LFSE. Nevertheless, LFSE values fit very well the calculated budget.

In conclusion, the excellent results offered by Hydra fit the predicted performance assessment. The fused solution provides, a LFSE of 0.4arcsec (3 sigma), a HFSE of less than 2 arcsec (3 sigma) and a temporal NEA of 0.4 arcsec/$Hz^{1/2}$ (3 sigma). All values are given for the 3 axis in BOL conditions without straylight.

4.3 Inter-head matrices

The transfer quaternions between the optical heads estimated by HYDRA Kalman filter are not included in the basic telemetry sent by Spot-6. Specific telemetries have been downloaded to check the estimation. Hereafter are presented some cases of the estimation by HYDRA of the transfer quaternions (more exactly, the difference compared to a mean transfer quaternion is presented).

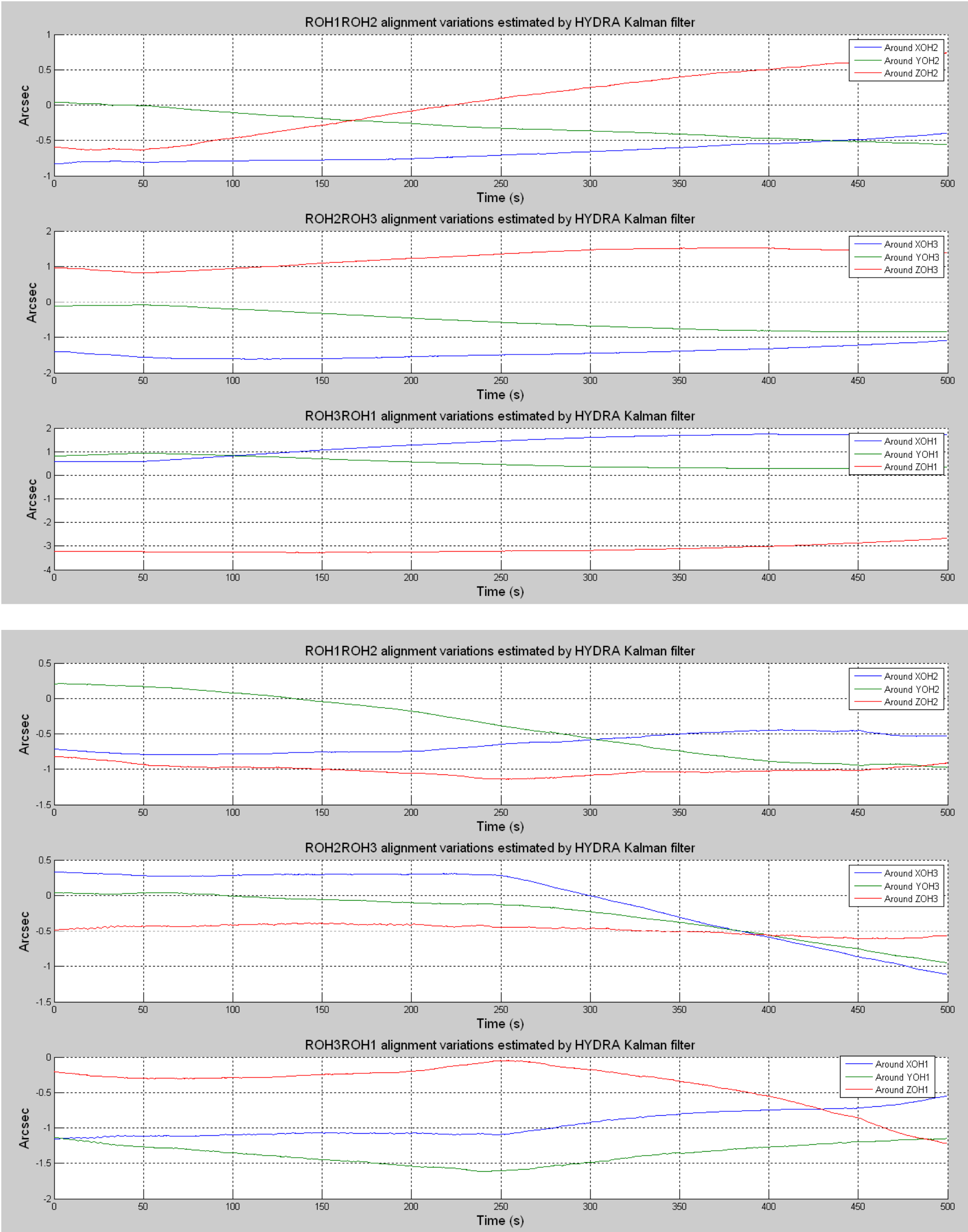

Figure 5: Estimated inter-head quaternions

For these examples, the single head quaternions are not available in the TM. It is not possible to directly compare to the instantaneous transfer quaternions but the estimation is able to smoothly follow low variations of a few arcsec.

4.4 Blinding

A trajectory section of Spot-6 shows blinded OHs management. OH2 is blinded by the Sun and OH3 is occulted by the Earth. Figure 6 gives the number of coherent stars on each OH.

On the first part of the trajectory, optical heads 2 and 3 are blinded, which explains that no coherent stars are detected. They become available after the first third of the trajectory. On optical head 1, the number of coherent stars remains stable, which allows computing the fused quaternion through the entire trajectory.

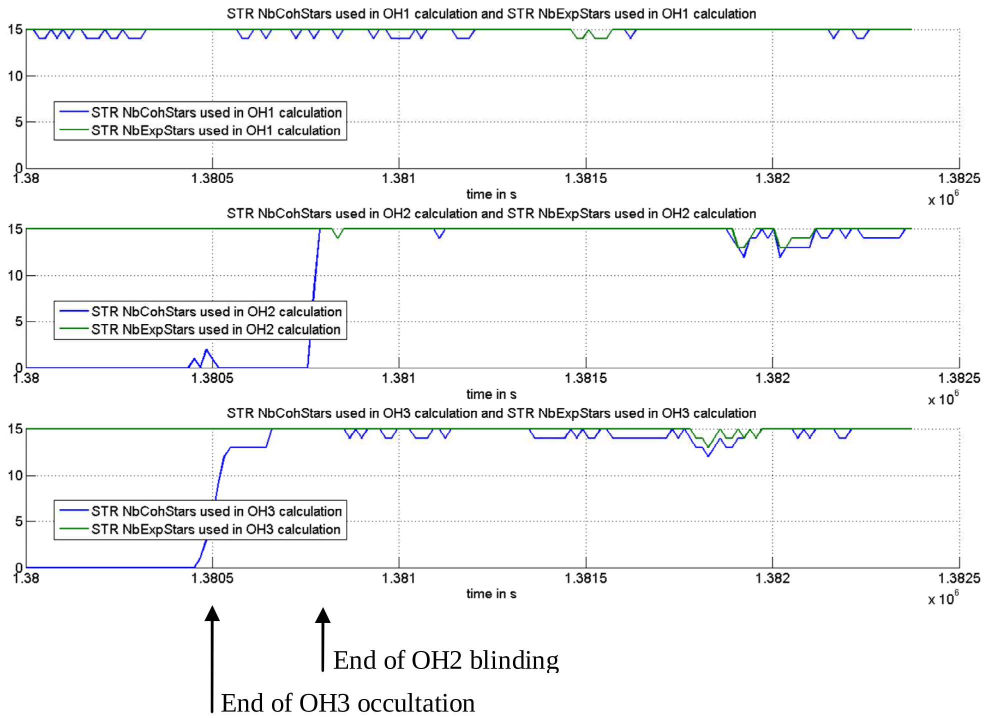

Figure 6: Number of coherent stars during OH2 Sun blinding and OH3 Earth occultation

5. Conclusion

One main characteristic of the Sodern multiple-head Star Tracker HYDRA, on-board Astrium SPOT-6 spacecraft launched on September 2012, has been presented: the field-of-view fusion. Data collected during the first months of SPOT-6 mission have been analyzed and successfully compared to predicted performances. Fused quaternion offers improved performances around the three axes. Multi-head management, in particular blinded heads management, already validated during night sky tests, has been also validated on-board SPOT-6. This confirms that field-of-view fusion and multi-head management allow for the best performances and the highest level of robustness.

References

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