USING EXOTIC GUIDANCE FOR PLEIADES-HR IMAGE QUALITY CALIBRATION

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ABSTRACT :

In-flight Image Quality calibration and performance assessment activities depend on specific acquisitions and, for some of them, on dedicated guidance of the satellite platform. The operational constraints may be tedious during the commissioning phase. Moreover, the length of the requested data collection may be conditioned by uncontrolled parameters such as climatic hazard. The new French high resolution earth observing satellite Pleiades-HR will be launched at the beginning of 2010. A specific design and new technologies have been embarked to provide great agility. These capabilities offer new methods to perform the image quality activities. Two are described in this paper. The first one concerns the so-called AMETHIST method to compute the normalization coefficients of the radiometric model. The second one uses the stars to measure the line-of-sight dynamic stability.

1. INTRODUCTION

1.1 Pleiades-HR overview

PLEIADES is the highest resolution civilian earth observing system ever developed in Europe. This imagery program is conducted by the French National Space Agency, CNES. It is the French part of the French-Italian ORFEO program which also comprises COSMO-SkyMed, an Italian high-resolution radar system. It will operate in 2010-2011 two agile satellites designed to provide optical images to civilian and defence users. Images will be simultaneously acquired in Panchromatic (PA) and multi-spectral (XS) mode, which allows, in nadir acquisition condition, to deliver 20 km wide, false or natural coloured scenes with a 70 cm ground sampling distance after PA+XS fusion. Coverage will be almost world-wide with a revisit interval of 24 h for 2 satellites.

The Image Quality requirements were defined from users studies from the different spatial imaging applications, taking into account the trade-off between on-board technological complexity and ground processing capabilities. The Pleiades-HR satellites will benefit from technology improvements in various fields which will allow achieving, at an affordable price, performances once reserved to ambitious military spacecrafts.

The major constraints of weight and agility led to the development of a highly compact satellite (about 1 ton weight), to minimize the moments of inertia. The instrument is partly embedded in a hexagonal shaped bus containing all equipment. The attitude control system uses 4 fibre-optic gyroscopes and 3 star trackers to provide restitution accuracy compatible with the system location specification of 12m for 90% of the products. These attitude sensors are mechanically fixed on the telescope support to minimize the thermo-elastic distortions. The satellite orientation is ensured by 4 gyroscopic actuators.

1.2 Agility

Agility is a characteristic which allows the satellite to acquire off-nadir targets rapidly in a large flight envelope, in order to sequence numerous images. This agility is imposed by several requirements stated by the users. For instance, a 100x100 km2 zone can be acquired by the satellite from the same orbit thanks to a lateral multi-band coverage. As for stereoscopic capacities, 3 images from the same zone can be acquired in a single pass with B/H lying between 0.1 and 0.5. For multi-targets, the time between the end of an imaging segment and the start of the next segment, including stabilization of the line-of-sight is specified less than 10 seconds for an excursion of 10° and less than 26 seconds for an excursion of 60° from nadir viewing. Guidance is mainly performed using roll and/or pitch steering (without slow motion), but fine yaw steering has to be used to respect the principle of acquisition set by the TDI device in the focal plane.

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Figure 1 : The Pleiades-HR satellite

1.3 Image Quality activities

The assessment of the Image Quality and the calibration operation will be performed by CNES Image Quality team during the commissioning phase that will follow the satellite launch. These activities cover many topics gathered in two families : radiometric and geometric Image Quality. Radiometric activities concern the absolute calibration, the normalization coefficients computation, the refocusing operations, the MTF assessment, the estimation of signal to noise ratio and also the tuning of the ground processing parameters in order to fit the images to the users needs. Geometric activities deal with the geometric model calibration, the assessment of localization accuracy, focal plane cartography, multi-spectral and multi-temporal overlapping, static and dynamic stability, planimetric and altimetric accuracy.

These operations require specific control of the payload and, for some of them, dedicated guidance of the satellite platform. The new capabilities offered by Pleiades-HR agility allow to imagine new methods of image calibration and performances assessment. Two of them are described here.

2. NORMALIZATION CALIBRATION ON NON-SPECIFIC LANDSCAPE

2.1 Objective

The aim of normalization is to correct raw images for relative inter-detector sensitivities, so that a uniform landscape gives a uniform image. Normalization residuals may cause vertical stripes.

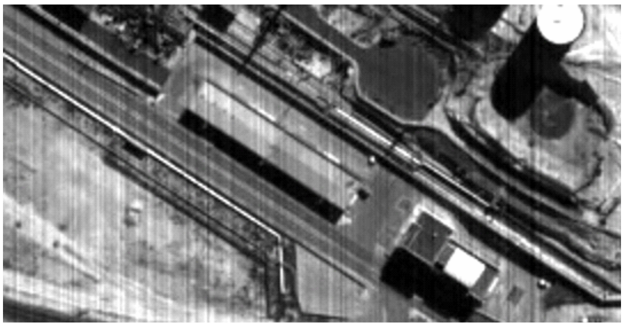

Figure 2 : Raw image

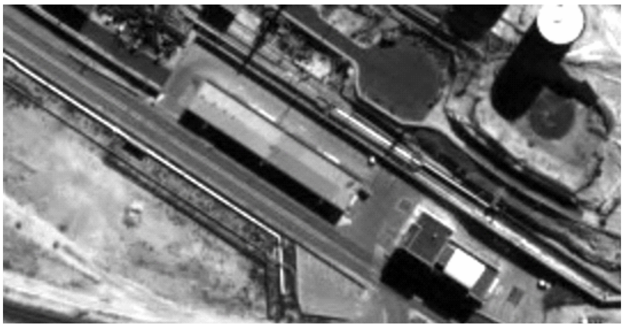

Figure 3 : Normalized image without residuals

2.2 Radiometric model and normalization function

When the camera observes the top-of-atmosphere radiance L, the output digital number X(j,L) delivered by detector j is modelled by the following relation:

$$X(j,L)=A.g(j).L+C(j) \qquad (1)$$

Where : C(j) is the dark current of detector j (L=0)
g(j) is the relative sensitivity of detector j
A is the absolute calibration coefficient

With a linear model, normalization function F can be easily performed to get the normalized digital number Y as a function of X :

$$Y(j,L) = F(X(j,L),g(j),C(j)) = [X(j,L)-C(j)]/g(j) = AL \qquad (2)$$

This relation shows that normalized images are proportional to input radiances.

Dark currents C(j) are computed thanks to specific images acquired over the oceans when the satellite is in the dark (night orbit). To make it simple, starting from this section, only Z=X-C will be used in the normalization model.

Because high resolution optical satellites like Pleiades-HR have to face a lack of signal, which may move the useful signal range towards the non-linear part of the detector response, normalization may have to be run with a non-linear model. Considering the computational constraint, we use for F a piecewise linear function designed to fit the detectors relative responses :

$$Y(j) = a1(j)\, Z(j) \qquad \text{if } Z(j) < Zs(j) \qquad (3.1)$$
$$Y(j) = a2(j)\, (Z(j)-Zs(j))+a1(j)Zs(j) \qquad \text{if } Z(j) > Zs(j) \qquad (3.2)$$

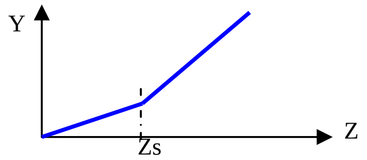

Figure 4 : Pleiades HR normalization model

The calibration consists in computing for each detector j, the triplet p(j)={a1(j), a2(j), Zs(j)} used in the normalization function F / Y(j) = F(p(j), Z(j)).

2.3 Resolution principle

In this non-linear case, we need for each detector the response to different radiances. Then the parameters are computed in the least-squares sense.

Given N different input radiances, let us define Z(k,j) the corresponding response of detector j where index k points to the input radiance value. For each radiance index k, the average response of the whole line is YM(k). The unknown triplet is determined in order to minimize the following least-squares criterion LSC(j):

$$LSC(j) = \sum_{k=1}^{N} \left(\frac{YM(k) - F(p(j), Z(k,j))}{\sigma(k,j)} \right)^2 \qquad (4)$$

where σ(k,j) weights can be used to balance the residuals according to the signal level.

2.4 In-flight normalization method

The difficulty is to acquire in flight images to measure for each detector the response to the same input radiances.

The first approach is to image uniform snowy expanses located in Greenland and Antarctic at different radiances depending on the latitude and the season. These areas are used to compute the linear normalization coefficients of the SPOT family satellites [1]. However, they suffer such a cloudy weather that a typical normalization campaign lasts 2 to 3 weeks to get useable cloud-free scenes at a single radiance level. Adding a constraint to get several radiance levels by means of selecting areas according to the local sun elevation would lead to very tedious operations.

The new approach is to make all the detectors view the same points of the scene, following the same trajectory on the ground, one after the other. The region of interest is therefore no longer a uniform region, but rather a non-uniform varied region to measure the response to several input radiances. The equalization is thus performed in a single pass. The so-called AMETHIST method [2] is based on a specific guidance also called normalization steered viewing mode.

2.5 "Rotated retina" guidance

As the sensor consists of rectilinear arrays, a 'rotated retina' guidance is required and was defined [3] thanks to a 90° yaw angle, with acquisition performed in the direction of the rows. In the classical push-broom viewing mode (Fig 5) successive lines of the image correspond to successive part of the scene.

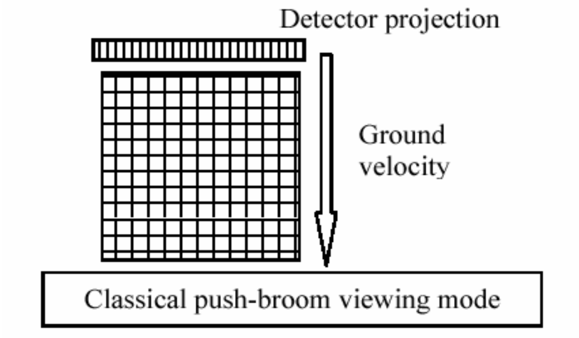

Figure 5 : The push-broom principle

In the normalization steered viewing mode (Fig 6) successive lines of the image correspond to the same part of the scene with a translation of one detector ground projection. This induces a deformation of the raw image, with the useful data distributed according to series of diagonal lines (Fig 7).

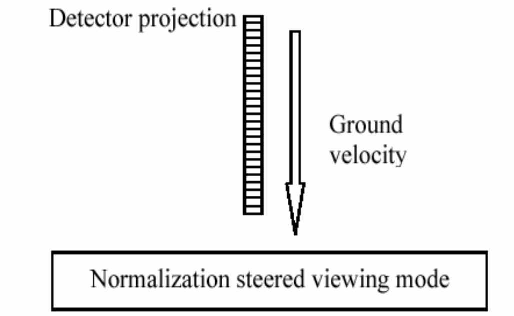

Figure 6 : Rotated retina guidance

After a pre-processing that globally shifts each column of the raw image, we get an image that contains all needed information as shown in Fig 7. This means that every row contains the set of detectors response to the same landscape.

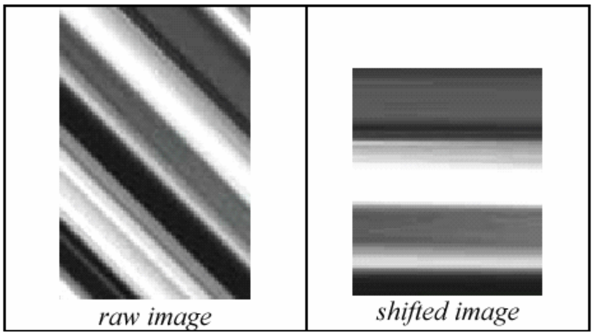

Figure 7 : raw image acquired with a 90° yaw angle and the corresponding useful area

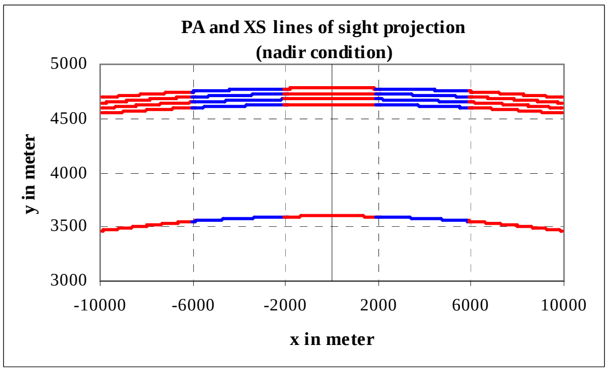

Figure 8 : PA and XS sensors projection

AMETHIST guidance law is optimized to superimpose on the ground several predefined detectors (for instance, the centre of each array). Because of the focal plane architecture and camera distortion effects, the only way to make the consecutive projections of the line of sight superimposed is to perform two quasi-circular trajectories, one for the PA retina and one for the XS retina,. Nevertheless, the PA arrays tilt causes geometrical residuals of about 4 PA pixels. Hence, the whole detectors do not perfectly see the same landscape, but the TDI device average the acquired data and compensate most of these residuals effects.

2.6 Computing normalization parameters from steered viewing mode images

Regardless of geometrical disturbances, we may use each single row of the shifted image as a measurement of the detectors responses to the same input radiance L. This approach would lead to a great sensitivity to radiometric noise and mis-registration. This is why an histogram matching method is preferred, because it will not be sensitive to a single pixel location : the only hypothesis is to put in front of each detector the same collection of radiance levels. If all detectors behaved the same way, all histograms $h_j[Z]$computed on each column j would be identical. Differences between column histograms are due to relative sensitivities among detectors (Fig 9). After normalization, all histograms should be identical.

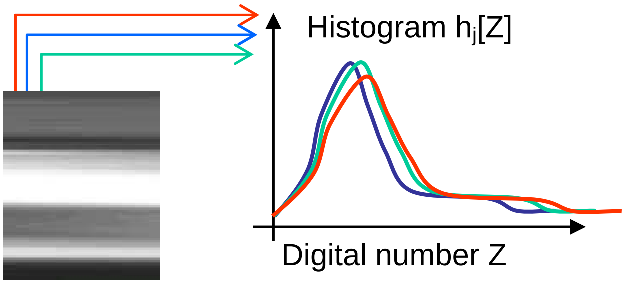

Figure 9 : Histogram extraction of each column

The collection of input radiances and corresponding detectors responses needed to compute the normalization parameters according to relation (4) can be deduced from the normalized cumulative histograms $hc_j[Z]$. For each detector j, the hc_j varies from 0 to 1. Let us define the centile Z(k,j) as follows :

$$\forall q_k \in]0,1[, \ hc_j[Z(k,j)] = q_k \qquad (5)$$

The latter means that q % of all pixels in column j have a digital number inferior to Z(k,j). In relation (4), YM(k) is the average values of Z(k,j) for the whole detectors.

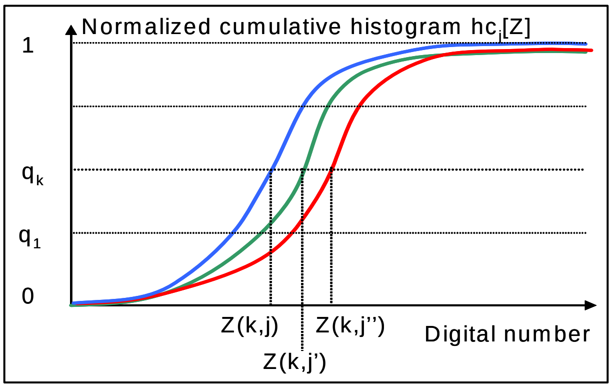

Figure 9 : centiles of cumulative histograms

2.7 Results based on image simulation

Pleiades-HR images were simulated taking into account the geometry of the 'rotated retina' guidance, the cartography of the focal plane and the radiometric characteristics of the sensor. Several varieties of landscape such as cities, forest, agricultural fields but also homogenous landscape such as snowy expanses were tested.

The first result is the method sensitivity to the wideness of the histograms. The widest they are, the most accurate are the radiometric model. It is difficult to obtain these required radiometric dynamics on a single-pass. This means that we need to cumulate data from several pass, maybe 2 or 3, targeting landscapes covering different level of radiances. For instance, we could choose ocean for low level, countryside for medium level, and snowy expanses for high level. In this scope, the calibration operations remains very light compared to the previous approach based on numerous uniform landscape acquisitions.

The second result is that the geometrical residuals induced by the guidance approximation create radiometric residuals on normalized images when the landscape contains too high-frequency variations. The consequence is that urban-like landscape should be avoided for calibration.

Finally, following chart (Fig 10) gives the standard deviation of the normalization residuals for both linear and piece-wise linear model (computed according to AMETHIST method).

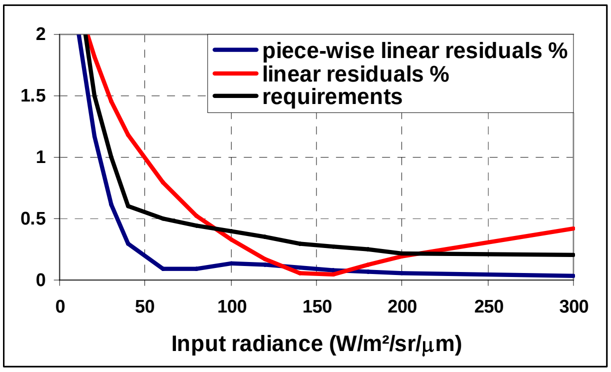

Figure 10 : normalization residuals

3. LINE OF SIGHT DYNAMIC STABILITY ASSESSMENT THANKS TO THE STARS

3.1 Objective

The dynamic stability of the line of sight is to be assessed during the commissioning phase. These measurements contribute to the in-flight image geometric budget. The expected attitude disturbances for Pleiades-HR are characterized by very low amplitude (less than 0.25 PA pixel) and numerous frequencies in the range [40-1000] Hz. Several methods may be performed to estimate some of these micro-vibrations from the images but it remains difficult to achieve a good accuracy specially for the high frequencies.

3.2 Principle of star acquisition

The idea of our method is to use the stars as references. By definition, a star is stationary in an inertial frame. If the satellite sensor remains pointed at the star, it will create a bright column in the image whose straightness depends on the line-wise behaviour of the potential micro-vibrations.

Mainly, this kind of acquisition has several operational interest. First of all, the images are guarantee cloud-free which is very important when a huge amount of data is required. Then, these acquisitions are made from night-orbit without disturbing the satellite commercial mission, given that, both commercial acquisitions and calibration operations share the same system resources.

3.3 Stars characteristics

For the sensor, the star is a source point characterized by its magnitude and spectral response. From now on, we will consider the spectral responses available in of our stellar catalogue (HIPPARCOS) compatible with the spectral band of Pleiades-HR panchromatic mode ([480-820] nm) and we will make the hypothesis that the provided magnitude can be converted in equivalent panchromatic input radiance for the sensor. The conversion in PA digital number is performed thanks to the numerous sensor characteristics such as the optic diameter, spectral bandwidth, time of integration, detector quantum efficiency, TDI lines number and electronic gain. In an inertial acquisition scheme the star is seen by only a few lines of the TDI matrix as shown in Figure 11.

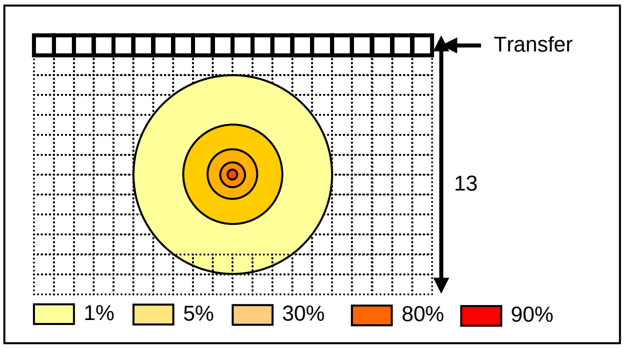

Figure 11 : Source point seen in the PA TDI device

The number of pixels illuminated in the matrix depends on the modulation transfer function of the instrument whose level is expected to be 0.10 at Nyquist frequency. Given that for a N line TDI matrix, a single line response is only 1/N of the total, and that for a source point most of the signal is concentrated on one or two lines, the integrated signal of the star is rather low. The expected maximum digital number in a PA image versus the magnitude of the input star is given in Figure 12.

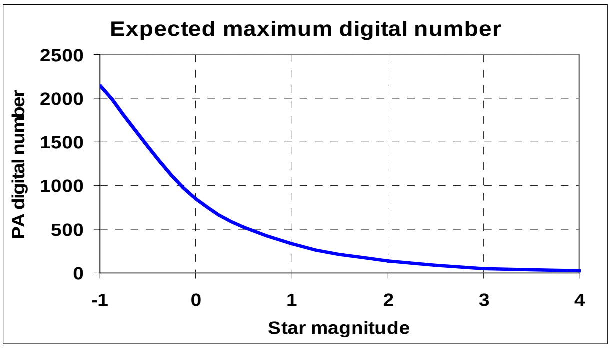

Figure 12 : Maximum digital number versus magnitude

The radiometric signal-to-noise ratio required to use the ‘star’ pixels is about 10. Considering the sensor radiometric performance, a digital number level higher than 25 LSB is required for those pixels. The corresponding magnitude limit is 4 according to Fig 12.

3.4 Dedicated star guidance

The satellite guidance has to fulfil the main condition which is that the star remains stationary long enough in the TDI matrix to ensure a dynamic measurement. However, the target acquisition guarantee depends on the satellite pointing accuracy. Thanks to many dedicated onboard equipments, Pleiades-HR performs a pointing accuracy better than 30 micro-radians in a 30° off-nadir cone. For specific off-nadir viewing such as those needed to point the stars, this accuracy is expected to be better than 100 micro-radians. A dedicated pitch steering is to be found, on one hand to scan the sky with an excursion higher than the satellite pointing accuracy and, on the other hand, to approach the inertial pointing scheme. The pitch angular rate for a standard acquisition is about 10000 micro-radians/s. A slowdown of this rate by 200 fulfils our conditions. A 50 micro-radians/s pitch rate allow to scan the 100 micro-radians pointing accuracy in 2 seconds. The 13 lines TDI matrix defines a 13 micro-radians viewing angle which is scanned in 0.26 seconds. This time of acquisition corresponds to about 2600 PA image rows, which is sufficient for our measurement. Moreover, the 20 available lines of the TDI device could be used, after a specific payload control, to increase the observation period.

The total acquisition duration, including image recording and payload tranquilization is less than 4.5 seconds. About 10 stars may be shot per night-orbit so that a hundred acquisitions is achievable per day without disturbing the nominal satellite mission.

3.5 Star image simulations

The dedicated star guidance has been implemented through PA image simulations. Radiometric parameters were set to :

- MTF at Nyquist frequency = 0.10,
- signal-to-noise ratio for a 100 W/m^2/sr/µm radiance=150
- TDI device monitored with 13 lines
- Compression rate = 2.5 bits/pixel

The simulations cover a set of input star magnitude and a set of line-wise and column-wise direction micro-vibrations. The magnitude are in the range [0,4]. Each micro-vibration is an addition of several sinusoidal signals. A temporal shift is introduced between the two directions of the micro-vibration. As an example, simulated microvibrations with less than 0.20 µrad cumulative magnitude have been used to assess the measurement accuracy.

An example is given in Fig 13 for a magnitude 0.

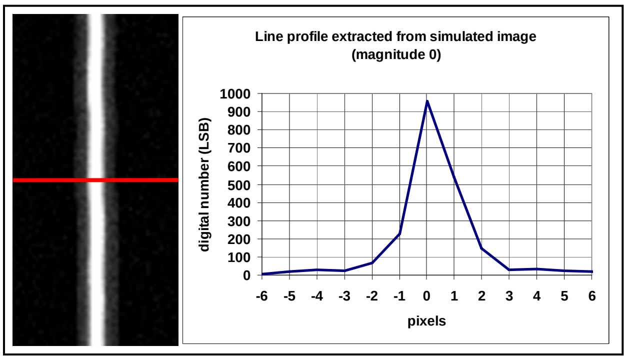

Figure 13 : Image simulation and one row profile

3.6 Micro-vibration measurement

For each row, as shown on Fig 13, the star line-wise absolute location can be given by the digital number profile barycentre, generally close to the profile peak. This approach gives relative stability wathever the instrument PSF symmetry : the only required hypothesis is the PSF temporal stability.

The barycentre profile measurement accuracy depends on the digital number level of the peak closest neighbours. Obviously, this level is related to the star magnitude. Anyway, the measure is always noisy. The noise can be filtered by a low-pass filter (as shown on Fig 14 for a magnitude 1) given that we want to preserve frequencies lower than 1000 Hz (expected micro-vibrations).

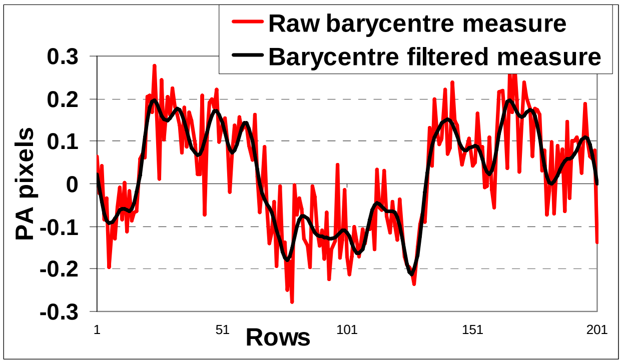

Figure 14 : Raw and low-pass filtered barycentre profile

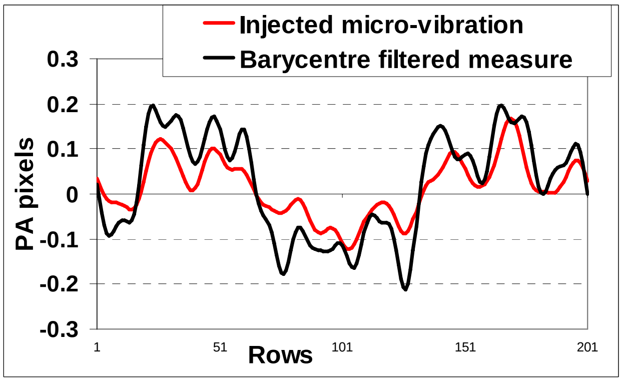

Figure 15 : Low-pass filtered barycentre profile and injected micro-vibration

The absolute location, measured along the line-wise direction, is very closed to the injected micro-vibration as shown in Fig 15. The profile spectra presented below for a magnitude 1 (Fig 16) give an idea of the micro-vibration restitution accuracy in amplitude and frequencies. The maximum amplitude deviation is less than 0.02 PA pixel. Frequency resolution (4.7 Hz in our example) is given by the observation length.

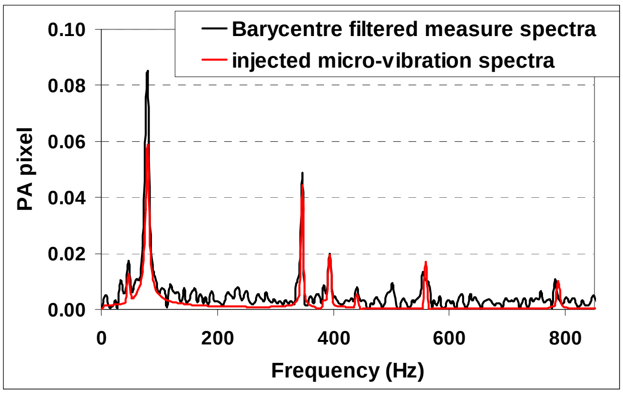

Figure 16 : measured and injected micro-vibration spectra

3.7 Stars selection

A requested RMS amplitude accuracy better than 0.10 PA pixel can be reached with stars brighter than magnitude 2.5 according to Fig 17.

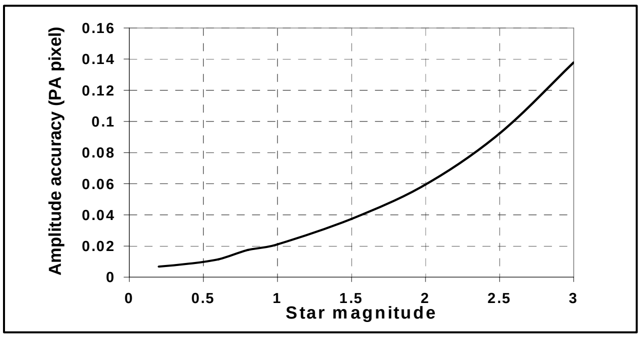

Figure 17 : RMS amplitude accuracy versus star magnitude

About 90 stars fulfil this condition, but if we focus on stars brighter than magnitude 1 to ensure a very good accuracy, about 15 are available (Fig 18) which is enough given that a same star may be shot several times along the night-orbit.

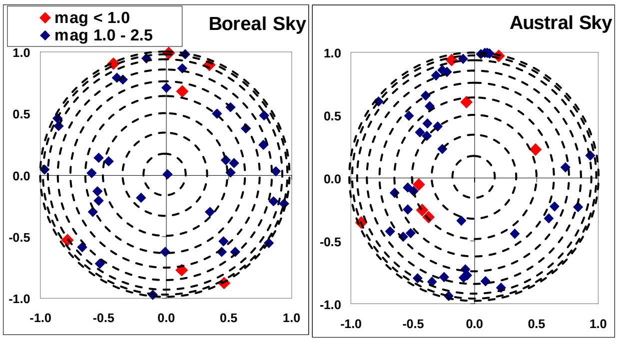

Figure 18 : Stars candidate for dynamic stability assessment

4. CONCLUSIONS

Brand new image calibration methods have been designed and are still studied thanks to Pleiades-HR satellite agility. These capabilities offer large operational benefits. Many other specific acquisitions will be carried out during the commissioning phase. For instance, radiometric absolute calibration will be performed using the moon as a photometric benchmark. As for the stars, they could also be used to assess absolute calibration, MTF or accurate viewing directions.

ACKNOWLEDGEMENTS

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