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DYNAMIC MTF, AN INNOVATIVE TEST BENCH FOR DETECTOR CHARACTERIZATION

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ABSTRACT

PLEIADES HR are High Resolution satellites for Earth observation. Placed at 695km they reach a 0.7m spatial resolution. To allow such performances, the detectors are working in a TDI mode (Time and Delay Integration) which consists in a continuous charge transfer from one line to the consecutive one while the image is passing on the detector.

The spatial resolution, one of the most important parameter to test, is characterized by the MTF (Modulation Transfer Function). Usually, detectors are tested in a staring mode. For a higher level of performances assessment, a dedicated bench has been set-up, allowing detectors' MTF characterization in the TDI mode. Accuracy and reproducibility are impressive, opening the door to new perspectives in term of HR imaging systems testing.

1. INTRODUCTION

Pleiades-HR satellites, under CNES development, are successors to SPOT satellites series for Earth Observation. They are equipped with one High Resolution (0.7m) panchromatic channel and with a 2.8 meter resolution multi-spectral channel in 4 spectral band. The Optical Payload is designed and integrated by Alcatel Alenia Space.

The high agility satellite, placed at 695 km operates in a push-broom mode.

Fig. 1. Photograph of Pleiades TDI PAN detector

The panchromatic detectors have been developed by e2v technologies (cf. Fig.1). They are composed of 6000 columns x 20 lines, with a pixel pitch of 13μm and are working in TDI mode (Time and Delay Integration). This allows to increase the signal to noise ratio by increasing artificially the integration time.

On Pleiades HR panchromatic detector, the number of TDI line (N_{TDI}) is selectable among 5 values. The

resulting image is consequently the integration of the charges on N_{TDI} single cells.

Detectors spatial resolution characterization in the TDI mode is not easy because of the necessity to simulate the image scrolling with high accuracy & stability. The design of a dedicated test bench & the associated results on Pleiades HR PAN detectors are presented.

2. DESIGN & DIMENSIONING

2.1 Design

The test bench is designed to allow both measurements (staring & TDI modes) in the most similar configuration in order to avoid bias when comparing them.

To estimate the MTF, several methods exist. For this test, we do not search for an MTF evaluation at all spatial frequencies. The frequency of interest is the specific Nyquist frequency:

$$f_{Nyquist} = \frac{1}{2.a} \quad (1)$$

with a = pixel pitch

One easy method for the MTF measurement at a defined frequency is the evaluation of the contrast. Here, we use an object made of black & white fringes. At Nyquist frequency, the image of a fringe has the same width as a pixel. The spatial resolution is directly linked to the capacity to distinguish the black from the white.

The image of this object on a pixel as a function of its position is a sine wave :

Fig. 2. contrast evaluation method

From that result, the Contrast Transfer Function (CTF) is easily calculated :

$$CTF(\nu) = \frac{\phi_{\max} - \phi_{\min}}{\phi_{\max} + \phi_{\min} - 2\phi_{\text{dark}}} \quad (2)$$

with ϕ_{dark} : dark signal level

The set-up is the following [Fig.2]

We use an integrating sphere as light source, the object is in the focal plane of the collimation lens. A mirror is mounted on a rotary stage that will simulate the Earth scrolling. A focalization lens allows the image to be formed on the detector. The object is mounted on a 3 axis motorized system.

Fig. 3. Test bench schematic

For the static measurement, the object is moved step by step following the Y axis. For every step, the level on the chosen pixel is stored.

For the dynamic measurement, the rotary stage is turning at the defined speed (the one corresponding to the detector charge transfer). The acquisition is triggered by the rotary stage. The rotary stage being synchronized with the detector charge transfer speed, an acquisition is composed of a series of maxima & minima, the levels of these max & min depending on the phasing of the fringes vs. the detectors lines. The object is moved step by step following the Y axis to change the phasing. For each step, an acquisition is performed.

Note :

- the tests are made on the detector combined with an electronic chain representative of the flight one. When talking about the detector, we talk of course about the group detector and associated electronic
- rotary stage clock and detector clocks are totally uncorrelated

2.2 Dimensioning

The test bench dimensioning activity takes into account:

- the mechanical design constraints

the 3D modelling has been used to help in establishing the configuration [Fig. 4].

This allows to define a coarse location for each element, avoiding the mechanical conflicts.

- the optical parameters: aperture, spectral bandwidth, ...

The bench MTF has an impact on the precision we will get. In fact, the measured MTF is the product of the bench MTF and the detector MTF. The better the bench MTF is, the better the precision will be. Optical simulation is used to select the configuration

Fig. 4. Test Bench 3D modeling

- components & process specification: object, rotary stage, magnitude adjustment requirement ...

An accuracy budget is made to evaluate the influence of each parameter and consequently to put the stress on the tightly points.

The most critical point is related to the speed stability. In fact, in the TDI mode, the MTF evaluation is impacted by the effect of the inaccuracy in the image and charge transfer speeds synchronization (desynchro MTF) and by the scrolling effect (smearing MTF):

$$MTF_{TDI} = MTF_{\text{smearing}} \cdot MTF_{\text{desynchro}} \quad (3)$$

With the following hypothesis :

- speed constant in time : V
 - measurement at Nyquist frequency: f_N (cf. (1))
 - 4 phases TDI detector
- $\Rightarrow N_p=8$: charge shift by step of $1/8^{\text{th}}$ of pixel
- T_i = integration time or charge transfer cadence

we get the formulae:

$$MTF_{\text{smearing}} = \frac{\sin(\pi \cdot f_N \cdot V \cdot T_i / N_p)}{\pi \cdot f_N \cdot V \cdot T_i / N_p} \quad (4)$$

and

$$MTF_{\text{desynchro}} = \frac{\sin(N_{TDI} \cdot \pi \cdot f_N \cdot (a - V \cdot T_i))}{N_{TDI} \cdot N_p \sin(\pi \cdot f_N \cdot (a - V \cdot T_i) / N_p)} \quad (5)$$

We analyse the impact of the non perfect synchronisation of the image speed :

$$V = V_{\text{theo}} + \delta V \quad (6) \quad \text{with} \quad V_{\text{theo}} = \frac{a}{T_i} \quad (7)$$

and we define m by

$$\frac{V}{\Delta V} = \frac{1}{m} \quad (8)$$

The conclusion of the calculation is:

- the speed error has a very small impact on the smearing MTF : a difference of 3% on the velocity as an impact smaller than 0.05% on the smearing MTF.
- the de-synchronisation of the image speed and the charge transfer speed has a great impact on the precision of the measurements, especially when N_{TDI} is high.

This impact is greatly increased as we want to make an average on values get on n fringes to increase the signal to noise ratio (SNR). With m defined by (8), this factor is equal to :

$$\frac{\sin(n \cdot \pi / m)}{n \cdot \sin(\pi / m)} \quad (9)$$

Finally, in order to get a good precision and to allow a good SNR, we specified the need for a speed stability better than 0.1%.

The rotary stage is consequently the key element of the bench. It should allow :

- a very fine speed adjustment accuracy
- a stability of the rotary stage speed better than 0.1%

- to trigger the acquisition

The final choice has been made for a high precision air-bearing rotary stage with a fast control electronic (maximum resolution = $1.25 \cdot 10^{-6}^\circ$!!).

The accuracy budget give also the sensibility to the optical adjustments. The main points are the magnitude adjustment and the object tilt.

3. ALIGNMENTS & TESTS

3.1 Alignments

Fig. 5. Test Bench photograph

3.1 Alignments

The detector working in staring mode, the alignment is performed. The reference is the rotation axis of the mirror.

The fine positioning in tip/tilt has been performed by auto-collimation on the detector and on the successive optical & mechanical parts (mirror, detectors, lens holders and object).

For the magnitude very precise adjustment an innovative method has been used. This is based on CTF acquisition for different position of the object, looking on the de-phasing on the object position corresponding to the extrema.

Fig. 6 shows a zoom on the image of the fringes on the detector when the alignment, the magnitude, and the focus are adjusted :

- no residual tilt (fringes are parallel to the lines)
- magnitude is adjusted : the width of the image of the fringes is equal to the width of the lines
 - focus is correct : no blurring

Fig. 6. image of the fringes aligned with the detectors lines

Note about Fig.6 :

- colours are artificial
- the figure is turned of 90° vs. the physical detector lines or fringes axis
- the X-axis represents the columns of the detector. A zoom is made on 100 columns over the 6000 of the device.
- the Y-axis is the number of the detector lines (width =13µm) – the 20 TDI lines are those numbered 10 to 29 on the figure

This allows the MTF in the staring mode to be evaluated.

Once the static alignment is performed, the adjustments in the dynamic mode are made:

- synchronization
- adjustment of the rotary stage speed

The measurements show a very sane behavior of the test bench. In fact [cf. Fig. 7] :

- the set-up allows to distinguish between speeds differing from less than 5.10^{-4} °/s

⇒ 1st : that means we can define a speed with this precision

⇒ 2nd : the speed - once defined - is quite stable vs. detectors clocks

- the global behaviour is very reproducible : stability of the following period in time

A few explanation :

Fig.7. represents, for 2 different speed of the rotary stage, the contrast observed as a function of the run :

- the rotary stage is running continuously
- each run, 1000 acquisition are made in the TDI mode for 20 lines (each of the 1000 measurements results from the accumulation of charge on the 20 consecutive lines)

- 400 measurement points of the 1000 correspond to the fringes. An average on the 100 maxima & minima is made, giving the mean contrast for each run

Fig. 7. Test Bench sensitivity to the speed
23.4795 vs. 23.4800 °/s

The contrast is changing from one run to the consecutive one due to a constant phase shift between the trig clock of the rotary stage & the main clock of the detector (the evolution of the contrast is not linked to a difference in speed between these two clocks).

The stability of this difference in time, and the reproducibility of the behaviour is representative of the test bench stability.

3.2 Results

a) capacity in doing MTF measurements in TDI mode

The test bench has got a sane behavior and allows a great accuracy in the rotary stage speed setting. The main success criteria is nevertheless the capacity to make measurements in TDI mode. On Fig.8, we see one of the measurement, at the maximum contrast, for one specific column.

When the sampling card receives the trigger from the rotary stage, 1000 acquisitions are launched, each 100µs. Each point on the graph results from the integration of the signal on 20 lines.

The stability of the maxima & minima between the first and the last fringes: demonstrate that :

- the fringes speed and the charge transfer speed are equal (difference < 0.05 %)

- the speed is stable

Fig. 8. MTF in TDI mode – visualisation of object (400 fringes) + zoom in

b) reproducibility

One of the other very impressive result is the stability of the test bench in time and the reproducibility of the measurements.

On Fig.9, are shown 2 measurements made with a 15 days time interval. It deals with CTF values (Y-axis) as a function of the column number(X-axis).

We can observe a extremely good over-positioning of the measurements points : maximum of difference in this case <0.6% !!

Fig. 9. reproducibility over 15 days of the CTF evaluation in the TDI mode

c) relative measurements: staring mode vs. TDI mode
Measurements in TDI mode stand as a critical point as well for the accuracy of measurements and for the repeatability.

But the real success criteria is the ability to compare the measurement in staring mode versus the TDI mode. We reach a repeatability in the difference evaluation better than 1%.

From this point of view, the tests are successful too ! (values are not significant as they are really linked to the detector)

d) new perspectives

the test bench allowed also the characterization of the detectors TDI mode sensitivity to other parameters like wavelength, aperture, number of TDI lines, input light power, ...

This drives to a global review of the tests during the integration & characterization of the instrument. The results allow in fact to define more precisely the tests configuration and to refine the success criteria.

Such tests could be generalized for the future generation of High Resolution detectors and extended to instruments.

4. CONCLUSION

A very accurate test bench has been developed allowing detectors' relative behavior in the TDI mode vs. the staring mode characterization with a high accuracy and a great reproducibility. With a short term view, the data we got allow a better estimation of the "in-orbit" Pleiades HR instrument behavior. This drives to more precise tests, with criteria adapted to the new performances understanding.

This type of measurements is not new but the quality of the performances reached is marking a step in the test accuracy. With a longer term view, this open the door to a better characterization, a better understanding of the "in-orbit" behavior at detector level, and possibly at instrument level.

In particular, a study of the de-synchronization effects on HR instruments could now be conceivable.

5. REFERENCES

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