GEOMETRIC CALIBRATION OF PLEIADES LOCATION MODEL

D. Greslou ; F. Delussy

CNES, 18, avenue Edouard Belin 31401 TOULOUSE CEDEX 4 - (daniel.greslou@cnes.fr ; francoise.delussy@cnes.fr)

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ABSTRACT:

Pleiades is a high-resolution optical Earth observation system developed by the French National Space Agency CNES, for civilian and militarian users. It will operate in 2008-2009 two agile satellites with very high geometric accuracy since latest budgets show that the system could reach, after in-flight commissioning, an absolute location performance better than the current Pleiades specifications set at 12m for 90% of images. Given this level of accuracy, the geometric calibration needs the use of a very high planimetric and altimetric accurate reference data which is obtained with heavy and costly means: generally, only one or two areas are equipped, and complete calibration could take several months after launch. In order to gain time, a first "coarse" calibration will be performed using ground control points and an accurate physical model of the instrument. This first step should allow the system to reach its specifications more quickly.
This paper presents the global methodology planned to calibrate the geometric location model. It also highlight the need of an accurate GCP data base for this treatment and for periodic assessment of the location budget.

1. INTRODUCTION

Pleiades is a high-resolution optical Earth observation system developed by the French National Space Agency CNES, for civilian and militarian users. It will operate in 2008-2009 two agile satellites aimed at delivering images with a high resolution and a large swath.
The location accuracy has to be better than 12m for 90% of the products with no use of ground control point after in-flight-calibration.

This paper gives a quick overview of the Pleiades instrument and describes the use of an advanced viewing direction model during in flight calibration to improve location performances.

2. PLEIADES CONCEPT

The Pleiades mission (Fig. 1) leads to enhance the resolution to submetric values with a swath over 20km. Panchromatic and multispectral images will be provided. These images have to be processed to get a very accurate localisation.

Based on the system requirements and ground processing design, the satellite design has been fully optimized. It is very compact to minimize its moments of inertia. Whereas older generations like SPOT used to put their payload on the top of the bus, the Pleiades instrument is partly embedded in a hexagonal shaped bus containing all equipment.

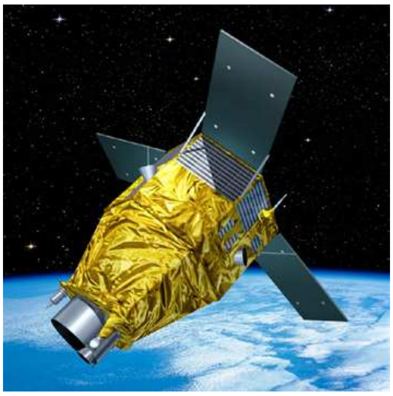

Fig 1: Pleiades Satellite

2.1 Instrument

The instrument design is mainly determined by the requirements for radiometric image quality in the panchromatic band which supplies the images with the sharpest resolution. On the basis of the main image quality requirements, the camera was designed under the constraint of the satellite mass and inertia, which has to weight less than 1 metric ton and fulfill the agility requirements. This lead to a Korsch type telescope with a focal length of 12.90 m and a diameter of 65 cm.

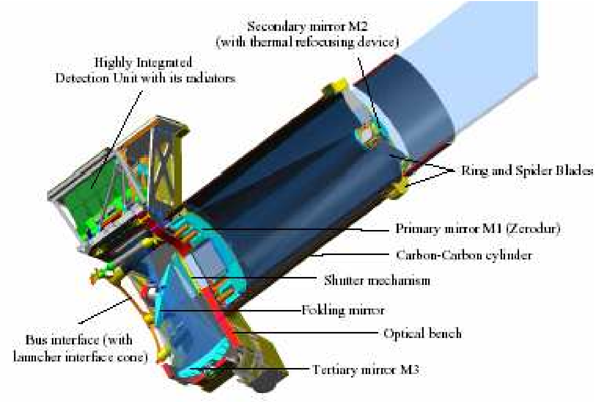

Fig 2: Pleiades camera overview

The front cavity is a light collector constituted by two centred mirrors M1 and M2. In the back cavity, behind M1, there is an intermediate image plane where the beams converge then diverge and are folded up by a long rectangular folding plane mirror (MR) towards the tertiary aspherical mirror (M3) which gives a corrected image at the focal plane (PF).

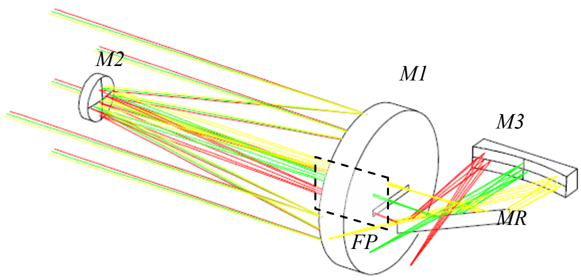

Fig 3: Korsh concept for Pleiades

The viewing directions of the detectors undergo the distortion of the instrument, which is approximately 2% at the edge of the field of view.

Note, at least, that one micro-radian roughly corresponds to 1 meter at the ground surface.

2.2 Focal plane layout

The Pleiades focal plane layout is represented on the figure below.

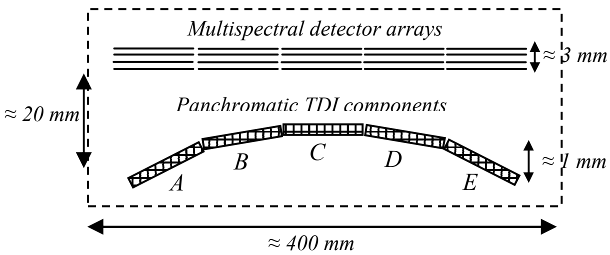

Fig 4: Focal plane layout

It contains:

- a panchromatic band composed by 5 TDI components whose elementary detector measures 13µm. Each TDI array has 20 lines of 6000 detectors. They are disposed on focal plane not in a straight line but along a curved shape which reduces significantly optical distortions effects on TDI synchronisation.
- a multi-spectral channel composed by four-colour CCD whose elementary detector measures 52 µm. The blue, green, red and near infrared filters are positioned in front of each of the 4 retinas of this CCD. A four-colour linear array has 4 lines of 1500 detectors.

In fact the focal plane is not plane : of the 5 linear arrays of each retina, 2 operate by reflection and 3 by transmission around a beam-splitting mirror device which allows all the points in the field to be acquired almost simultaneously. This is represented on the figure below.

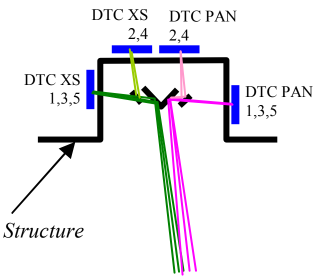

Fig 5:Inter-array concept

2.3 Viewing-direction frame

The viewing-direction frame $R_V = (X_V, Y_V, Z_V)$ is defined from the viewing-directions of some physical pixels :

- Z_V axis is the viewing-direction of the barycentre of the central array PAN pixels
- Y_V axis is defined as the projection on normal plan to Zv of the mean of the difference of the viewing-directions located on the central PAN array, symmetrically towards its centre
- X_V defined so that (X_V, Y_V, Z_V) is direct

Before launch, R_V is measured and the quaternion $q\_R_{SAT}\_R_V$ is defined. This quaternion is used to compute image acquisition guidance.

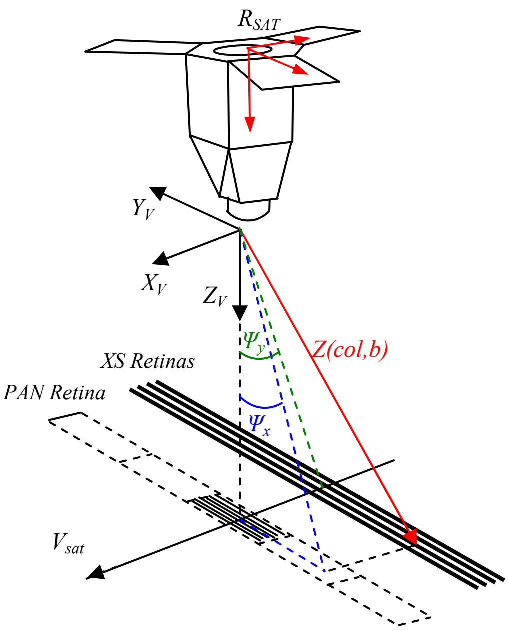

Fig 6: Viewing-direction frame R_V

The viewing-direction of each physical pixel on focal plane is then defined in R_V with the 2 angles (ψ_x, ψ_y) shown in fig *6*. Roughly ψ_x is linear towards the pixel column number and ψ_y is constant.

Computation of all these viewing-directions is based on a model of the focal plane and instrument assessed on ground (cf. [1]).

2.4 Geometric calibration

The ground geometric calibration of a satellite system is performed in several steps with incremental backwards loops.

At first the calibration is performed on the first-rate parameters which errors may have different sources:

- ephemeris data, spacecraft position
- attitude data, spacecraft orientation (roll, pitch and roll)
- spacecraft clock which defines the links between image data and ephemeris and attitude

This process allows to verify the alignment of different frames and adjust existing biases, in particular:

- AOCS frames (star-tracker and gyros frames alignment)
- R_V image frame

The R_V calibration is made using scenes containing ground control points : it is performed with a space triangulation optimisation.
Frame adjustments are a synthesis of results obtained on a large and representative sample of cases. Generally this step is sufficient to allow the system to reach its absolute location performance.

Subsequently, an additional calibration is performed to reduce second-rate errors and to improve the geometrical accuracy of the system.
These step may be useful to allow the satellite system to reach its local coherence (i.e. regularity of the sampling of the pixels in both directions) and multispectral registration specifications to satellite to specifications
This is obtained in particular by a calibration of each detector viewing direction. This method is based on dense matching methods using very high geometric accurate reference data images which elaboration may need important efforts and means. Moreover, it is necessary these data, more commonly named “supersites” (cf. [2]) have to be as similar as possible to the images of the system to calibrate, in order to minimise landscape differences and so, bad correlations. It is advisable to prepare these supersites during the commissioning phase: so they could not be available immediately. In order to gain time, an alternative method to this second step has been analysed: this is described on chapter §3 below.

3. COARSE FOCAL PLANE CALIBRATION

Contrary to usual focal plane calibration techniques, this method is based on exploitation of « limited » ground equipment and reference data (GCP) and on an accurate physical viewing-direction model.

3.1 *Viewing-direction model*

[1] shown that the viewing-directions of the Pleiades Instrument could be approached by an analytical model with very high accuracy.
This model is derived from a polynomial function generally used with optical centered designs and taking into account only focal length and optical distortion parameters. Due to its off-axis field of view, modelling of this Korsh telecope needs the definition of some correctives parameters. It provides a relationship between the viewing directions defined by the angles ψ_x, ψ_y , and the location of pixel on the focal plane.

$$\psi_x = f(\theta, \beta, x', y', z', col, b, D, L)$$
$$\psi_y = f(\theta, \beta, x', y', z', col, b, D, L)$$

where :

- L refers to all focal plane layout parameters : positions of bands and arrays, angular tilts between arrays, inter-array characteristics…see fig. *4*
- $D = (a_1, a_2, a_3, a_4, a_5, f)$ refers to instrument parameters like optical distortion coefficients and focal length f
- $(\theta, \beta, x', y', z')$ are the focal plane integration offsets : (x', y', z') are translation components and (θ, β) angles rotations
- (col, b) are respectively the pixel number in the retina and its spectral band

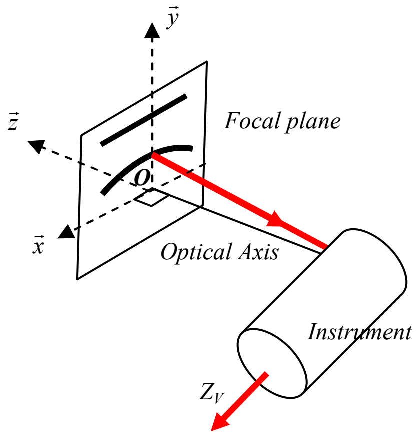

Fig 7: Perfect integration of the focal plane

- (x',y',z') are the components of the vector $\overrightarrow{OO'}$ where O is the intersection of the optical axis with the nominal focal plane, and O' the intersection of the optical axis with the « real » focal plane
- θ is the rotation angle around $\vec{z}$ axis.
- β is the rotation angle around $\vec{y}$ axis.

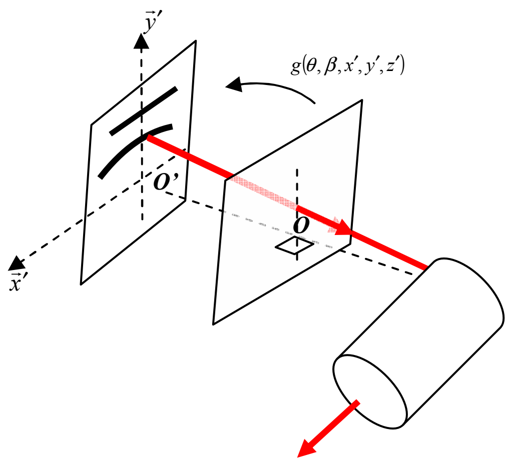

Fig 8: « Real » integration of the focal plane

(L,D) are parameters which can be measured and assessed on-ground with very high accuracy: that is not the case for (θ,β,x',y',z').

[1] demonstrate that calibration of the only five (θ,β,x',y',z') parameters after the integration of the focal plane allows to reach good performances : it shows that accuracy of this calibrate model, obtained from ground measures, and compared with a numerical model, could reach *6 μrad* in the worst case (maximum error of 3000 simulated manufactured instruments), i.e. *6 pixels* (*1 pixel* = *1μrad* = *70cm* at Nadir). This performance has been assessed taking in account errors ground measurements that are not negligible in the error budget. We can expect that accuracy of this model will be better than announced.

3.2 *Parameters sensibilities*

Figures *9* and *10* below show the different sensibilities of (ψ_x,ψ_y) towards each of the 5 parameters of the model (ψ_x is plotted in black plain line, ψ_y in red dashed line) versus focal plane position ('A', 'B', 'C', 'D', 'E' are the five PAN-TDI components in the focal plane).

Theses figures are interesting because they give the impact -in terms of shape and magnitude- of a parameter gap on (ψ_x,ψ_y) angles. That can be useful for analysis and interpretation of residual error during commissioning.

On the upper figure *10,* we can notice that the θ angle has no impact on (ψ_x,ψ_y) : that due to the definition of the R_V frame which depends on (ψ_x,ψ_y) values.

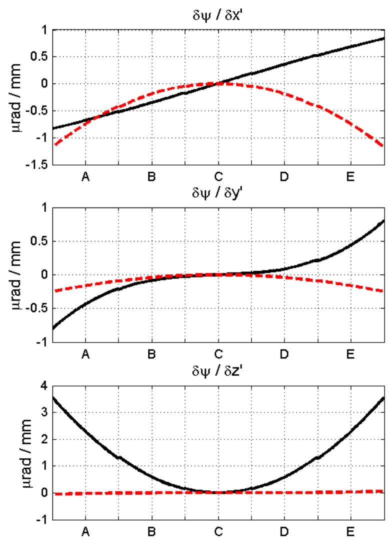

Fig 9: Viewing direction sensibility to (x',y',z')

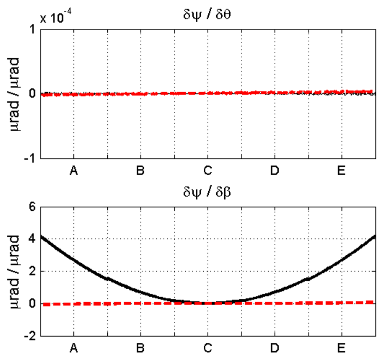

Fig 10: Viewing direction sensibility to (θ,β)

3.3 *In-flight calibration process*

This chapter deals with the in-flight calibration process of the geometric model and the performances it will be able to reach.
This calibration is performed after a first step doing the adjustment of the principal biases (ephemeris, attitude, ...).

Simulations have been done from 2 viewing-direction models defined with 2 sets of parameters. One is considered as the “real” model (in-flight model), the second simulates the on-ground assessed model which has to be calibrated.

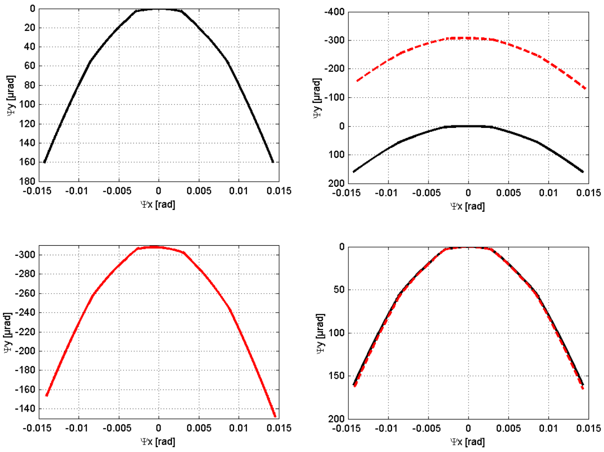

Fig 11 : (ψ_x, ψ_y)

On the upper-left figure, the plot is $\left[\psi_{y\_1} = f(\psi_{x\_1})\right]_{R_V}$ of the panchromatic initial on-ground model. By definition, this plot is a even function. On lower-left figure, the plot represents $\left[\psi_{y\_2} = f(\psi_{x\_2})\right]_{R_V}$ of the panchromatic in-flight model. Differences between the 2 plots depends on $(\theta, \beta, x', y', z')$ parameters gaps which have been chosen, here, at a maximum level. In particular, we can notice that the second plot is no longer even (that is due essentially to the θ angle). We can also notice the ψ_y bias (up to *300* μrad, corresponding to *300 meters* !) on upper-right figure where we plotted the two functions on a same window.

In order to simulate the first step calibration (cf. §2.4) , we plotted on lower-right figure the function $\left[\psi_{y\_2\_cal} = f(\psi_{x\_2\_cal})\right]_{R_{V\_cal}}$ which represents viewing directions (ψ_x, ψ_y) in a viewing direction frame R_{V_cal} calibrated: we notice there is no longer ψ_y bias, and function is symmetrical. This is obtained, for example, after a first adjustment of both pitch and yaw angles.

The second in-flight calibration step consist in assessing $(\theta, \beta, x', y', z')$ “real” parameters from GCPs measures.

In fact only 4 parameters are adjusted because the θ angle come unobservable (cf. lower-right figure *11* and upper figure *10*).

The Fig 12 below shows the residuals errors $\Delta\psi_x, \Delta\psi_y$ of panchromatic detectors before (black-plain line) and after calibration (red-dashed line).

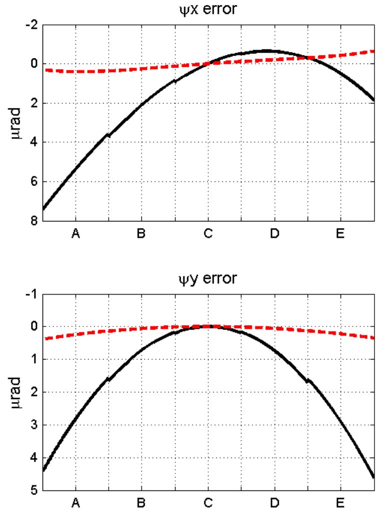

Fig 12: Residual errors reduction

In this case, the residual error has been reduced from *8*μrad to *1*μrad. This is has been obtained using ***10*** GCP of very high quality (***1*** m. rms) evenly distributed in the field.

Others cases had been simulated with a number of GCP by scene and also with a GCP data-base less accurate (*3*m. rms.) but results are not so convincing.

n_{GCP}	5	10	20	20	30
Rms (m)	0.1	0.3	1	2	3
ψ_x max error (µrad)	1.2	0.2	1	2	5
ψ_y max error (µrad)	0.3	0.2	0.2	0.5	4

In some cases, the accuracy of calibrated model is even degraded (GCP rms greater than *10*m). This is due to bad estimations of parameters (β, y', z') which aren’t easy observable because theirs effects on (ψ_x, ψ_y) are low (cf. §3.2).

Moreover, estimation of (β, x', y', z') parameters in an pre-adjusted frame do not allow to go back to the real (β, x', y', z') physical values because they have already been partly taken into account in the first calibration. Nevertheless, this process can be useful to supervise hypothetical temporal fluctuations of these parameters.

3.4 *Conclusion*

This alternative method of focal plane calibration is worth studying. First analysis shows that the use of an accurate viewing directions model combined with an accurate GCP data base allows to reduce focal plane residuals errors.
As a matter of fact, it seems relevant to consider a global calibration with an adapted weighted process, allowing the estimation of both attitude/ephemeris and focal plane corrections.

4. CONCLUSION

The use of an accurate focal plane model can be interesting at the beginning of the commissioning phase in order to increase absolute location performance and even to allow system reach its local coherence and multispectral registration specifications (due to a better relative model between the spectral bands) on the one condition to have a very high accurate GCP data base.
This preliminary analysis shows that results are significant once are available about ten 1m. rms. GCPs.

This model can be more useful as an analysis tool to better understand, interpret supervise and adjust focal plane error residuals during satellite life, in particular after the accurate calibration of each viewing direction with a supersite.

As a conclusion, and this paper is an illustration of this, we can say that means to calibrate and supervise very high location accurate systems are rare and precious. In a near future, Pleiades will need GCP data-base of very high quality, both to calibrate geometric model and to assess periodically location performances.

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