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MODEL OF THE LINES OF SIGHT FOR AN OFF-AXIS OPTICAL INSTRUMENT PLEIADES

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ABSTRACT

The future Earth observation missions aim at delivering images with a high resolution and a large field of view.

These images have to be processed to get a very accurate localisation. In that goal, the individual lines of sight of each photosensitive element must be evaluated according to the localisation of the pixels in the focal plane.

But, with off-axis Korsch telescope (like PLEIADES), the classical model has to be adapted. This is possible by using optical ground measurements made after the integration of the instrument. The processing of these results leads to several parameters, which are function of the offsets of the focal plane and the real focal length.

All this study which has been proposed for the PLEIADES mission leads to a more elaborated model which provides the relation between the lines of sight and the location of the pixels, with a very good accuracy, close to the pixel size.

1. INTRODUCTION

The future Earth observation missions aim at delivering images with a high resolution and a large field of view.

Fig. 1. PLEIADES satellite

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The PLEIADES mission (Fig. 1) leads to enhance the resolution to submetric values with a swath over 20km. Panchromatic and multispectral images (Fig. 2) will be provided. These images have to be processed to get a very accurate localization. In that goal, the individual lines of sight of each photosensitive element must be evaluated according to the localisation of the pixels in the focal plane.

Fig. 2. Simulated images

The theoretical model used to describe the lines of sight is a polynomial function, which takes into account the focal length and the optical distortion of the system. This approach works when the optical design is centered.

For others systems, when the optical axis has no link with a physical pixel, this previous model doesn't fit. This occurs with Korsch telescope (like PLEIADES) working with an off-axis field of view. The classical model has to be adapted.

2. PLEIADES CONCEPT

The optical architecture of the telescope results from the optimization of radiometric performances compatible with volume restrictions.

The front cavity is a light collector constituted by two centered mirrors (Fig.3.): the primary mirror (M1) and the secondary mirror (M2). In the back cavity, behind M1, is located 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).

As for the beams coming from M3 towards the focal plane not being blocked by MR, the field of view is slightly shifted perpendicular to the image line. Thus, MR is shifted from the M1-M2 optical axis and M3 is off-axis as shown on Fig. 4.

The telescope field of view allows the simultaneous imaging of a panchromatic line (PAN) and four multispectral lines (XS) with a slight field separation compliant to mission requirements [1].

Fig. 3. Schema of the PLEIADES optical elements in the (Y_i, Z_i) plane

Fig. 4. Schema of the PLEIADES optical elements in the (X_i, Z_i) plane

The mirrors have been already manufactured, as seen on Fig 5 and Fig 6.

Fig. 5 Manufactured zerodur mirrors two M3 and two MR

Fig. 6 Measurement configuration for M1+ M2

The focal plane is analysed in 30,000 samples in PAN and 7,500 in XS. The PAN band is constituted of 5 TDI mode CCD arrays, which the image section has 6000 columns of active pixels each $13\mu\text{m}$ square. The colored bands (XS) are constituted of 5 CCD four linear arrays, which each line of pixels has 1,500 photo-elements each $52\mu\text{m}$ square.

3. DESCRIPTION OF THE DATAS

3.1 Lines of sight

The coordinate system R_i usually used to describe the lines of sight is defined by the three axes shown on Fig.-3.

Z_i : orientated from the center of the primary mirror towards the center of the secondary mirror.

Y_i : parallel to the optical axis between the tertiary mirror and the focal plane

X_i : so that the instrumental coordinate system (X_i, Y_i, Z_i) is direct.

The lines of sight are determinate by the two angles R_{xi} and R_{yi} shown on Fig.7, in the instrumental coordinate system $R_i : (X_i, Y_i, Z_i)$.

Fig. 7. Line of sight in the instrumental coordinate system Ri

3.2 Position in the focal plane

We can define two coordinate systems :

The optical coordinate system R_{opt} which is linked to the instrumental coordinate system R_i as seen on Fig. 3. The center of this coordinate system O_{opt} is the image of the optical axis.

The focal plane coordinate system R_{PF} which is linked to the physical retinas as shown on Fig. 8.

Fig. 8. Focal plane

The differences between the two coordinate systems can be characterized by the offsets of the center of the focal plane O_{PF} regarding the optical center O_{opt} along the two axis X_{PF} (x_{Oopt}) and Z_{PF} (z_{Oopt}), and by the tilt of the retina (θ) around the Y_{PF} axis and the tilt of the focal plane around the X_{PF} axis (β).

The coordinates of a pixel can be theoretically defined either by x_{opt} , y_{opt} in the optical coordinate system R_{opt} , or x_M , z_M in the focal plane coordinate system R_{PF} .

4. POLYNOMIAL MODEL

The theoretical model which links the line of sight (defined in R_i) towards the position of the pixel in the focal plane (defined in R_{opt}) is described by Eqs. 1 for each direction.

$$\begin{aligned} \tan R_{xi} &= + \frac{x_{opt}}{F} \cdot (1 - D(r)) \\ \tan R_{yi} &= - \frac{y_{opt}}{F} \cdot (1 - D(r)) \end{aligned} \quad (1)$$

$$D(r) = a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4 + a_5 r^5$$

$$r = \sqrt{x_{opt}^2 + y_{opt}^2}$$

The model used is a polynomial function with five coefficients a_1 , a_2 , a_3 , a_4 , a_5 to take into account the distortion of the instrument, and the focal length F .

This approach works when the optical design is centered i.e. symmetrical, towards the optical axis (Cassegrain telescope for instance). In that case, the position of the pixels is defined in the optical coordinate system R_{opt} .

5. OFFSETS OF THE FOCAL PLANE

5.1 Correction of the polynomial model

For others systems, when the optical axis has no link with a physical pixel in the focal plane, this previous model Eqs. 1 doesn't fit. The position of the pixels is defined in the focal plane coordinate system R_{PF} . This occurs with Korsch telescope (concept chosen for PLEIADES instrument Fig. 9) working with an off-axis field of view to be able to have a compact design with a plane folding mirror.

Fig. 9. Korsch concept for PLEIADES

The classical model has to be adapted by taking into account the offsets of the focal plane (x_{Oopt} , z_{Oopt}), the tilt of the retinas θ and the tilt of the focal plane β . Then the directions of the line of sight can be expressed regarding the position of the pixels in the R_{PF} coordinate system and these correction parameters (see Eqs. 2).

$$\tan R_{cxi} = \frac{f(\theta, \beta, x_{Opt}, z_{Opt}, x_M, z_M)}{F} \cdot (1 - D(r))$$

$$\tan R_{cyi} = \frac{g(\theta, \beta, x_{Opt}, z_{Opt}, x_M, z_M)}{F} \cdot (1 - D(r)) \quad (2)$$

$$r = R(\beta, x_{Opt}, z_{Opt}, x_M, z_M)$$

An additional correction, more classical, is to take into account the real focal length, which depends on the realization of the mirrors. In fact, this real focal length depends on the defocusing of the center of the focal plane along the Y_{PF} axis. So, in order to be consistent with the previous parameters, we introduce another offset y_{Opt} .

The directions of the line of sight become Eqs 3.

$$\tan R_{cxi} = \frac{f(\theta, \beta, x_{Opt}, y_{Opt}, z_{Opt}, x_M, z_M)}{F} \cdot (1 - D(r))$$

$$\tan R_{cyi} = \frac{g(\theta, \beta, x_{Opt}, y_{Opt}, z_{Opt}, x_M, z_M)}{F} \cdot (1 - D(r)) \quad (3)$$

$$r = R(\beta, x_{Opt}, y_{Opt}, z_{Opt}, x_M, z_M)$$

The model has been improved by five correction parameters.

5.2 Determination of the correction parameters

These correction parameters (x_{Opt} , y_{Opt} , z_{Opt} , θ , β) have to be evaluated using optical ground measurements made after the integration of the instrument.

From the measures made on the instrument, the line of sight of several pixels are evaluated in the instrumental coordinate system R_i regarding their position in R_{PF} . By minimization of the quadratic difference between the measured values and the modeled values, the correction parameters can be calculated.

6. SIGHT COORDINATE SYSTEM

The previous model Eqs. 3 links the lines of sight to the position of the pixel in the focal plane coordinate system, taking into account its offsets.

But the expressions of the lines of sight are related to the instrumental coordinate system, which is the coordinate system used for the ground measurement, because it is defined by the position of the mirrors.

In flight, this coordinate system doesn't exist. An other coordinate system has been defined : the sight coordinate system R_v , whose three axes which depend on the line of sight of the physical pixels.(Fig. 10).

Z_v : line of sight of the barycentre of the PAN pixels of the central CCD arrays named C.

Y_v : projection in the plane which is perpendicular to Z_v of the mean of the difference of the lines of sight of pixels located on the CCD arrays C, symmetrical towards O_{PF} .

X_v : so that the sight coordinate system (X_v , Y_v , Z_v) is direct

Fig. 10. Line of sight in the sight coordinate system R_v

As the model is defined in the instrumental coordinate system, a transfer matrix must be evaluated to be able to express the model in the sight coordinate system. This transfer matrix $MAT_{R_i R_v}$ depends on the correction parameters, because it is linked to the offsets and tilt of the focal plane. It is the product of three rotate matrix.

A preliminary matrix will be determinate with the processing of the ground measurements. But , this matrix should be optimized in flight with the measures made in the sight coordinate system to increase the accuracy of the model.

7. RESIDUAL ERROR OF THE MODEL

In the rest of the study, the model is evaluated in the optimized sight coordinate system, to get the best accuracy for the model.

The residual error is the difference between the values calculated with the model and the real values.

To evaluate this error, 3000 cases of manufactured systems have been studied. This takes into account the real positions and curvatures of the mirrors, and the accuracy of the alignment. To follow the study, four cases have been selected. These four cases are those which lead to the highest variation of each correction parameter (x_{Opt} , y_{Opt} , z_{Opt} , θ).

7.1 Theoretical residual error

The theoretical residual error has been evaluated considering perfect conditions of measurement. Fig 11 shows this error evaluated in Ri and Rv coordinate system, for each direction according to the position of the pixel in the focal plane.

Fig. 11. Theoretical error for case 1

The field variations are similar in both coordinate systems. A three order residual error can be seen for the direction Rx (ξ_x) and a second order residual error for the other direction Ry (ξ_y).

The maximum values calculated with the four cases are set out on table 1.

Residual error of the model		Max of the four cases
$\tan(\xi_x)$	rms	2.31E-07
$\tan(\xi_y)$	rms	1.96E-06
$\tan(\xi_x)$	Max	5.28E-07
$\tan(\xi_y)$	Max	3.96E-06

Table 1. Theoretical

7.2 Simplification of the model

As the final need is the knowledge of the lines of sight in the Rv coordinate system, the model can be simplified. The parameter θ corresponding to the tilt of the retina can be canceled, after the determination of the correction parameters. This approach works only when we are working in the Rv coordinate system, namely in flight.(Fig. 12)

Fig. 12. Theoretical error for case 1 with θ canceled

As seen on table 2, the error is slightly perturbed.

Residual error of the model		Max of the four cases
$\tan(\xi_x)$	rms	2.35E-07
$\tan(\xi_y)$	rms	1.97E-06
$\tan(\xi_x)$	Max	5.54E-07
$\tan(\xi_y)$	Max	3.97E-06

Table 2. θ canceled

7.3 Real conditions of ground measurement

As the measures are never perfect, we have to take into account the errors due to the conditions of the ground measurement. There are several errors :

- on each direction of the line of sight : a constant error due to the alignment of the theodolite (used to measure the lines of sight) towards the instrument and a random error.
- on the pixel position : a random error

The constant error increases the error in the Ri coordinate system, but in the Rv coordinate system (Fig. 13), this error is eliminated by the optimization of the transfer matrix MAT_Ri_Rv. The residual error of the model, as seen on table 3, is slightly perturbed. On the other hand, the values of the two parameters x_{Opt} z_{Opt} include a constant error.

Fig. 13. Error for case 1 with the constant error measurement and θ canceled

Residual error of the model		Max of the four cases
$\tan(\xi_x)$	rms	2.41E-07
$\tan(\xi_y)$	rms	2.21E-06
$\tan(\xi_x)$	Max	5.63E-07
$\tan(\xi_y)$	Max	4.50E-06

Table 3. Constant error measurement and θ canceled.

The random errors can't be eliminated as the constant error, in the Rv coordinate system. To evaluate its impact, as it is a random error, 1000 cases have been simulated for each of the four worst manufactured systems cases.

For each random case, each of the five PAN CCD arrays is assumed to be perfectly straight..

Fig. 14. Error for case 1 with the constant plus random error measurement, and θ canceled

The random error increases the residual error, presented in table 4. for the two directions, because it perturbs the values of the correction parameters

Residual error of the model		Max of the 4000 cases
$\tan(\xi_x)$	rms	2.39E-06
$\tan(\xi_y)$	rms	2.48E-06
$\tan(\xi_x)$	Max	5.84E-06
$\tan(\xi_y)$	Max	5.71E-06

Table 4. Constant plus random error measurement and θ canceled.

Nevertheless, the maximum value calculated fits to a rather pessimistic case, which has a weak probability to occur.

It is more realistic to keep in mind the rms value.

The typical error obtained is less than $2.5 \mu\text{rad}$, close to the pixel size.

8. POSSIBLE IMPROVEMENT OF THE MODEL

Two ways for improving the accuracy of the model have been studied.

8.1 Number of measures in the field

The whole previous study has been run, considering 37 measures in the field. By increasing the number of measures to 49, the decrease of the error is about 5%, which is not a very big benefit.

Considering measurement duration, it is not realistic to propose more than 49 field positions.

8.2 A sixth parameter in the model

A sixth correction parameter has been added to the model in order to correct the second order residual error observed on the direction ξ_y . It reduces the theoretical error as seen on Fig. 15.

Fig. 15. Theoretical error for case 1 with six parameters

But, when we take into account all the conditions of the ground measurement, the residual error of the model increases as seen on Table 5, and reaches about the same level obtained with the five parameters.

Residual error of the model		Max of the four cases
$\tan(\xi_x)$	rms	2.59E-06
$\tan(\xi_y)$	rms	2.25E-06
$\tan(\xi_x)$	Max	6.85E-06
$\tan(\xi_y)$	Max	4.86E-06

Table 5. Error with six parameters, with ground measurement errors.

The theoretical improvement observed with the sixth parameter has been nullified by the error due to the inaccuracy of the ground measurements. The interest of adding a sixth parameter doesn't seem justified.

9. CONCLUSION

All this study which has been proposed for the PLEIADES mission leads to a more elaborated model which provides the relation between the lines of sight and the location of the pixels, with a very good accuracy, close to the pixel size.

The chosen model depends on five correction parameters. Theses parameters will be determinate from the ground measurements performed on the instrument.

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