Sentinel 2 Geometric image quality commissioning – First results

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ABSTRACT

In the frame of the Copernicus program of the European Comission, Sentinel-2 will offer multispectral high-spatial-resolution optical images over global terrestrial surfaces. In cooperation with ESA, the Centre National d'Etudes Spatiales (CNES) is in charge of the image quality of the project, and will so ensure the CAL/VAL commissioning phase during the months following the launch.

Sentinel-2 is a constellation of 2 satellites on a polar sun-synchronous orbit with a revisit time of 5 days (with both satellites), a high field of view - 290km, 13 spectral bands in visible and shortwave infrared, and high spatial resolution - 10m, 20m and 60m. The Sentinel-2 mission offers a global coverage over terrestrial surfaces. The satellites acquire systematically terrestrial surfaces under the same viewing conditions in order to have temporal images stacks. The first satellite has been launched in June 2015. Following the launch, the CAL/VAL commissioning phase will then last during 6 months for geometrical calibration.

This paper first provides explanations about Sentinel-2 products delivered with geometric corrections. Then this paper details calibration sites, and the methods used for geometrical parameters calibration and presents the first linked results. The following topics are presented: viewing frames orientation assessment, focal plane mapping for all spectral bands, first results on geolocation assessment, and multispectral registration. There is a systematic images recalibration over a same reference which will be a set of S2 images produced during the 6 months of CAL/VAL. As it takes time to have all needed images, the geolocation performance with ground control points and the multitemporal performance are only first results and will be improved during the last phase of the CAL/VAL. So this paper mainly shows the system performances, the preliminary product performances and the way to perform them.

1. THE SENTINEL-2 SYSTEM

1.1 Mission overview

Sentinel-2 mission is based on two identical satellites that will offer a systematic global coverage of land surfaces from 56°South to 84°North. The cycle of 10 days with 143 orbits per cycle provides a high revisit, every 5 days under the same viewing conditions. The reference satellite altitude is 786kms, and the local time is 10:30 AM at equator. The instrument has a wide field of view, of 290 km, and provides multi-spectral information with 13 bands (covering visible, near infra-red and short wave infra-red), of high spatial resolution: 10m, 20m and 60m.

1.2 Sentinel-2 design

Each of the SENTINEL-2 satellites weighs approximately 1,2 tons, and is designed to be compatible with small launchers like VEGA and ROCKOT. The first satellite Sentinel-2A was launched on 23th June 2015; its nominal life duration is 7.25 years but the batteries and propellant have been provided to accommodate for 12 years, including end of life de-orbiting maneuvers.

The SENTINEL-2 satellite system is developed by an industrial consortium led by Airbus Defence and Space Germany. Airbus Defence and Space France is responsible for the MultiSpectral Instrument (MSI).

The MSI is a push-broom imager based on a Tri Mirror Anastigmat (TMA) telescope. It is opened at F/4 and the focal length is 0.60m. The focal plane is splitted in two parts:

- a Visible and Near Infra Red (VNIR) focal plane made of 12 staggered CMOS detector modules containing 10 spectral bands
- a Short Wave Infra Red (SWIR) focal plane made of 12 staggered Mercury Cadmium Telluride (MCT) detector modules hybridized on a CMOS read-out circuit, containing 3 spectral bands

The staggered arrays are shifted in the telescope focal plane along the satellite velocity direction, as described in figure 1, which induces a double effect of parallax:

- a cross-band parallax angle, within one detector. As described in figure 2, the parallax angle between band 2 and band 9 in the VNIR focal plane is equal to 0.018, and the parallax between band 10 and band 12 in the SWIR focal plane is equal to 0,010. These values are the maximum cross-band parallax values, since band 2 and 9 are positioned at the border of the VNIR detector, while band 10 and 12 are positioned at the border of the SWIR detectors.
- a cross-detector parallax angle, within one band, between odd and even detector modules. As described in figure 2, these values varies from 0.022 and 0.059 depending on the spectral band. It is to be noted that the ten meter bands are positioned in the detectors, so as to minimize the parallax angle.

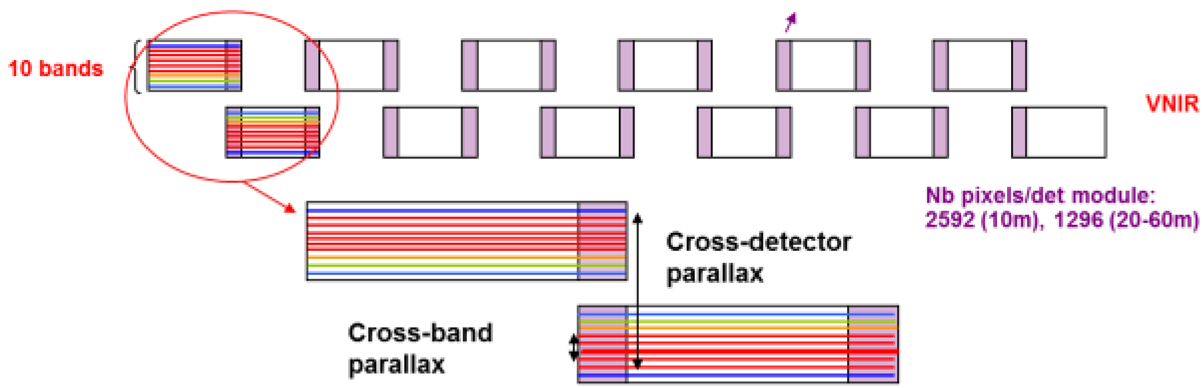


Figure 1. MSI VNIR focal plane, including 12 staggered detectors modules and ten spectral bands.

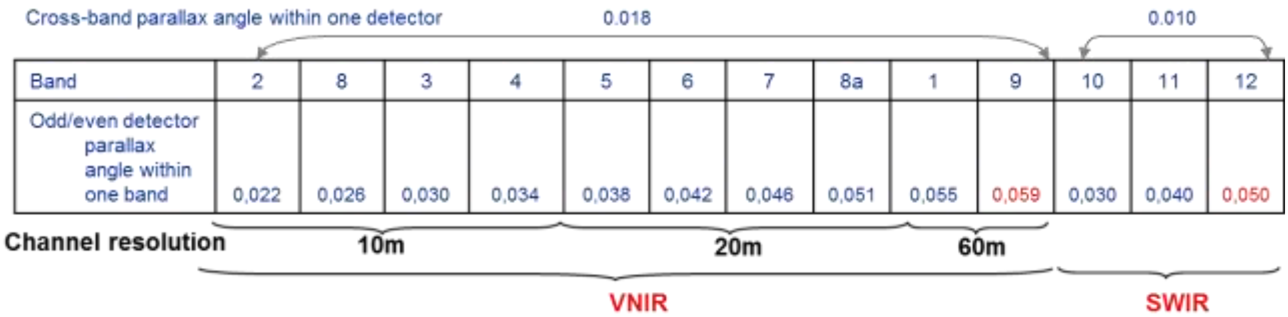


Figure 2. Parallax angles for each band, each detectors.

These are very small values of stereoscopic angle, but it still means registration performances sensitivity to both terrain elevation modelling errors, and high frequency platform perturbancies. Such effects of the stereoscopic angle on the geometric image quality are described in [2].

The accurate on-board determination of the satellite position and the absolute dating are supplied by a dual frequency Global Navigation Satellite System (GNSS) receiver. The knowledge of the satellite fine attitude is provided by the hybridization of the measurements performed by an inertial measurement unit involving gyroscopes and 3 star trackers; these sensors are mounted on the instrument structure so as to reduce thermo-elastic deformations between their reference frames and the line of sight. This information is sent with the instrument telemetry for further precise geometric processing on ground. The satellite is steered around the yaw axis so as to balance the earth rotation.

Orbital accuracy will be maintained by a dedicated propulsion system.

Image data are compressed on-board using a multi-resolution compression algorithm based on wavelet decomposition. This function operates in real time and delivers a fixed rate bit-stream with a compression ratio optimized for each spectral band in order to keep the quality of the images. The mean compression ratio is close to 3.

1.3 Sentinel-2 products

The system product breakdown is the following:

- the Level-0 and Level-1A are system products which correspond to respectively raw compressed and uncompressed data (limited to internal calibration purposes),
- the Level-1B is the first public product: it comprises radiometric corrections (dark signal, pixels response non uniformity, crosstalk, defective pixels, restoration, and binning for 60m bands); and an enhanced physical geometric model appended to the product, but image is not resampled.
- the Level-1C provides ortho-rectified image in UTM projection, top of atmosphere reflectance with a sub-pixel multi-spectral and multi-date registration; a cloud and land/water mask is associated to the product. Note that the cloud mask also provides an indication about cirrus. The ground sampling distance of Level-1C product will be 10m, 20m or 60m according to the band. The final Level-1C product is tiled following a pre-defined grid of 100x100km², based on UTM/WGS84 reference frame,

The Level-2A provides surface reflectance after cloud masking and atmospheric correction for high resolution spectral bands (in the same geometry as the Level-1C).

1.4 Sentinel-2 geometric image quality requirements

The main geometric image quality requirements are summarized in table 1.

Geometric image quality performance	Ground processing hypothesis
A priori accuracy of image location: 2km max (3σ)	No processing
Geolocation Performances Accuracy of image location: 20m (3σ)	After image processing without control points
Geolocation Performances Accuracy of image location: 12.5m (3σ)	After image processing with control points
Multitemporal registration: 3m (2σ) for 10m bands 6m (2σ) for 20m bands 18m (2σ) for 60m bands	After image processing with control points
Multispectral registration for any couple of spectral bands: 3m (3σ) for 10m bands 6m (3σ) for 20m bands 18m (3σ) for 60m bands	After image processing with control points

Table 1. Geometric image quality requirements

Image quality requirements are to be met by the Level-1 products, using the ancillary data provided by the satellite, and the data and models either calibrated in-flight or before the launch. Geolocation performances are then the combination of board contributors and ground contributors.

The main board contributors to geolocation performances are:

- Orbital position errors
- Attitude restitution errors
- MSI thermo-elastic stability with respect to the mean orientation of the Viewing Frames calibrated during in-orbit commissioning
- Datation errors

The main ground contributors to geolocation performances are:

- Lines of Sight (LOS) calibration residuals.
- Precision of the GRI
- Ground Control Points (GCP) contribution extracted from GRI.
- Residual errors of on-board contributors after the space-triangulation process
- DEM error

Geometric calibrations during in-orbit commissioning (IOC), especially the calibration of the orientation of viewing frames, and the focal plane mapping, have a direct impact on the geolocation and registration performances.

2. GEOMETRIC CALIBRATIONS DURING COMMISSIONNING

Two main activities during IOC are described hereunder: the orientation of viewing frames determination and the focal plane mapping in order to meet geolocation performances and registration performances.

These calibrations have been done after analysis on oscillations issue described in [1]. Briefly: spacecraft oscillations coming from solar array movement imply images with oscillations. If attitudes datation was consistent with image datation, as oscillations frequency is low, it would have been possible by using the geometric model to correct these oscillations for level 1C. But there was an error of 142ms on attitudes datation so that oscillations were not fully corrected on L1C products. This error on datation has been first dealt in geometric model until a new gyrostellar algorithm has been installed on-ground, (beginning of September) correcting this datation issue.

2.1 Orientation of viewing frames and geolocation performance

3.1.1 Method

Absolute calibration of the viewing frames or calibration of the absolute alignment biases consists in determining the mean pointing bias. This calibration is achieved by refining the geometric models of a large number of scenes, using well-located reference images: Pleiades 1B database. S2 scenes are long segments acquired on various sites intersecting with many Pleiades images. These sites are distributed all over the world: the aim is to cover the maximum number of longitude and latitude ranges so as to:

- determine any possible change in alignment biases as a function of criteria such as latitude (analysis of possible thermoelastic effects),
- avoid being too dependent on weather conditions.

For all the scenes, the geometric models are then refined by space-triangulation to determine an average biases set per scene (pitch, roll and yaw biases). An analysis of the alignment biases thus estimated for all scenes and all GIQ sites then allows to:

- determine a mean bias to update viewing model parameters,
- observe a possible evolution of biases according to such criteria as latitude, date…

For Sentinel-2, this method is used for the calibration of VNIR viewing frame. The B4 spectral band of these Sentinel-2 images will be systematically correlated with the well located reference images of Pleiades, in order to refine the geometric model of the VNIR frame.

3.1.2 References: Pleiades database

Pleiades database is composed of about 500 Pleiades 1B images, cloud-free, distributed all over the world. There geolocation is under 5meters. More than 20 S2 orbits are systematically acquired over which there are about 20 Pleiades images spread over the field of view and along the orbit. Figure 3 shows the distribution over Europe of these images.

Figure 3 : Pleiades database over Europe

3.1.3 Results

The geolocation performance is directly the distance in meters between references and S2 images.

At the beginning of life, just after launch, i.e. without correcting the geometric model with new viewing frames biases, the geolocation was estimated to 2,5km.

At the beginning of July a calibration of the star trackers on board allows to reach a geolocation performance of 700m. These 700m are the value which should be corrected with new viewing frames.

- First calibration

As explained in [1] a datation bias of 142ms has to be put, either on attitudes datation or on image datation in order to minimize oscillations on L1C products. In July, there was no way to put this delay on attitudes, so it was put in image datation (see red array on Figure 4). In order to correct the 700m of errors (green array), and taking into account the datation bias (red array), a bias in pitch of 250m has been put in the geometric model towards north (blue array).

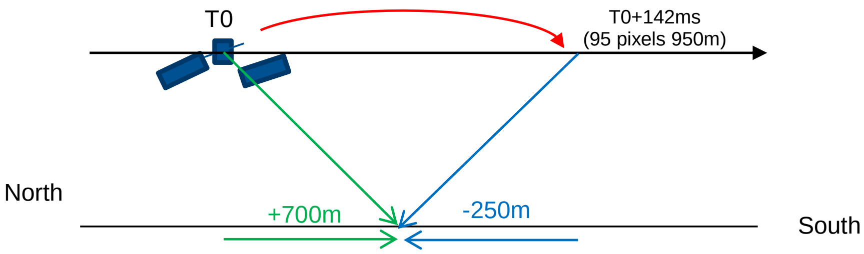


Figure 4 : biases to correct the geometric model

After this first calibration of the geometric model, geolocation performance was about 20 meters on products in August.

- Second calibration

At the beginning of September a new gyrostellar estimator algorithm was implemented in ground production in order to correct the time shift on attitudes datation as explained in [1].

So the previous bias in datation in the geometric model can be removed: datation of the image and of attitudes are well-phased. When removing this datation bias, geolocation is degraded if bias in pitch is not corrected. So an absolute new bias in pitch of about 700m (green array) was put in the geometric model to have a good geolocation performance (which makes a relative bias of 950m from the previous state).

Just after calibration of the viewing frames, on about 30 products, wrt to Pleiades images as external references the geolocation was around 10m@2sigmas. This value should be taken with precaution because it is a first value just after calibration. The real value of geolocation will be given after the 6 months of commissioning, and according to IGN evaluation after creating the GRI (Ground Reference Images, see [1]).

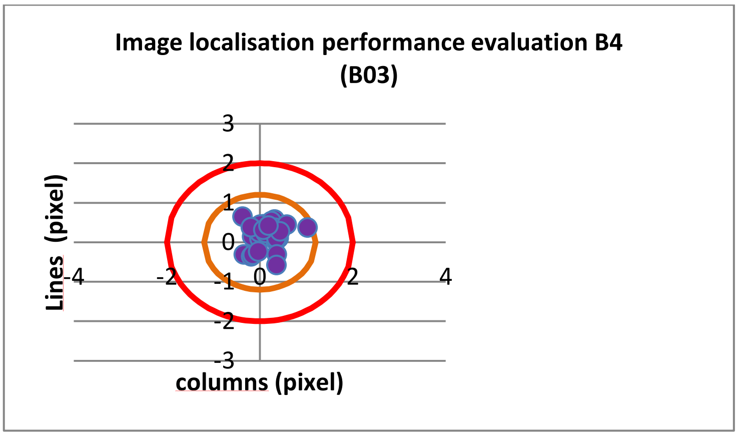


Figure 5 : geolocation of about 30 products in September

What can be kept in mind is that geolocation is really good, and far under specifications.

- First observations on temporal evolution

A temporal evolution was observed during July and August on viewing frames biases :

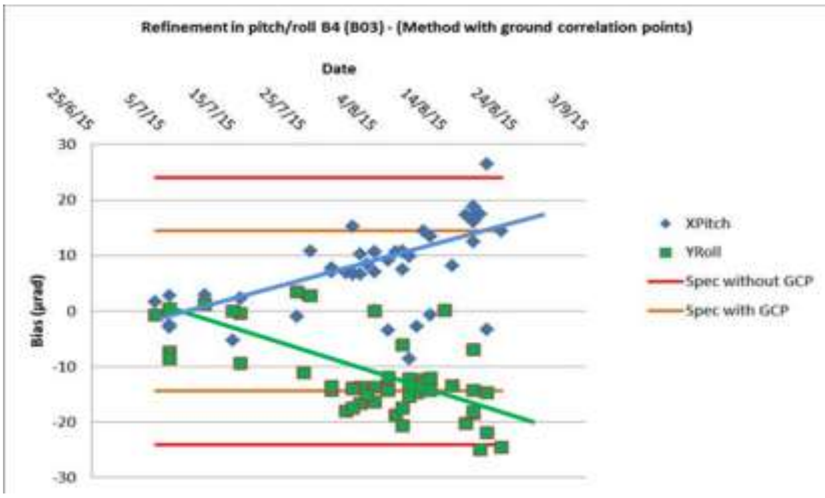


Figure 6 : temporal evolution of the viewing frames bias

A drift of 10 µrad/month was observed in pitch and in roll, which made a total movement of 29 µrad in 2 months (23m on ground).

These drifts are probably beginning-of-life effects due to water desorption. They will be followed during coming months in order to evaluate if a new biases calibration will be needed. But at the end of September, these drifts seem no more present.

2.2 Absolute focal plane calibration

The focal plane calibration consists in re-estimating the lines of sight of the detectors from the various retinas, i.e. estimating distortion and possible discontinuities between the different arrays of the focal plane to improve internal image consistency. Such accurate measurements are not possible on ground before launch. In flight, an absolute method is used: this method is based on the correlation between an image acquired by one of the retina to be mapped and an absolute reference, which is in S2 case BDortho reference over France or long orthogonal Pleiades images.

For Sentinel-2, the absolute method will be used for VNIR B4 spectral band.

Using BDortho and Pleiades images guarantees planimetric and altimetric accuracy consistent with requirements because there are close geometric references to ground truth. Moreover they cover the full swath so that calibration of all detectors can be done.

3.2.1 Method: see figure 7

The BD ortho and Pleiades images considered as a reference are rectified into the geometry of the sensor retina to be calibrated (B4 spectral band). To this end, the direct geometric model of the perfectly known reference images and the digital model of the surface (altimetric reference) are used, before going back to the geometry of the B4 spectral band to be calibrated via its inverse geometric model, given and known at some instant "t".

Two sets of images are then obtained: the image from the B4 spectral band to be calibrated, which represents the physical reality of the system, and a reference image (or set of reference images), rectified in the geometry of the estimated sensor. These rectified images are then correlated. The aim here is to measure the deviation parallel and perpendicular to the track.

The measurement of the deviations is filtered, to eliminate erroneous values of the correlation coefficient obtained, and averaged for each column: this is the calculation of a mean row. The average row and column deviations, the correlation coefficient, the number of filtered and measured points, are computed for each pixel value.

These raw image measurements resulting from correlation are reduced in the focal plane to angular units, e.g. radians, taking into account the aperture angle for each detector: this varies along the track as a function of the roll angle.

Deviations (in the form of polynomials or other functions) are modelled per retina or per array. This modelling is then added to the current model of lines of sight, in such a way as to minimise the row and column deviations between the absolute reference and the image of the sensor being calibrated.

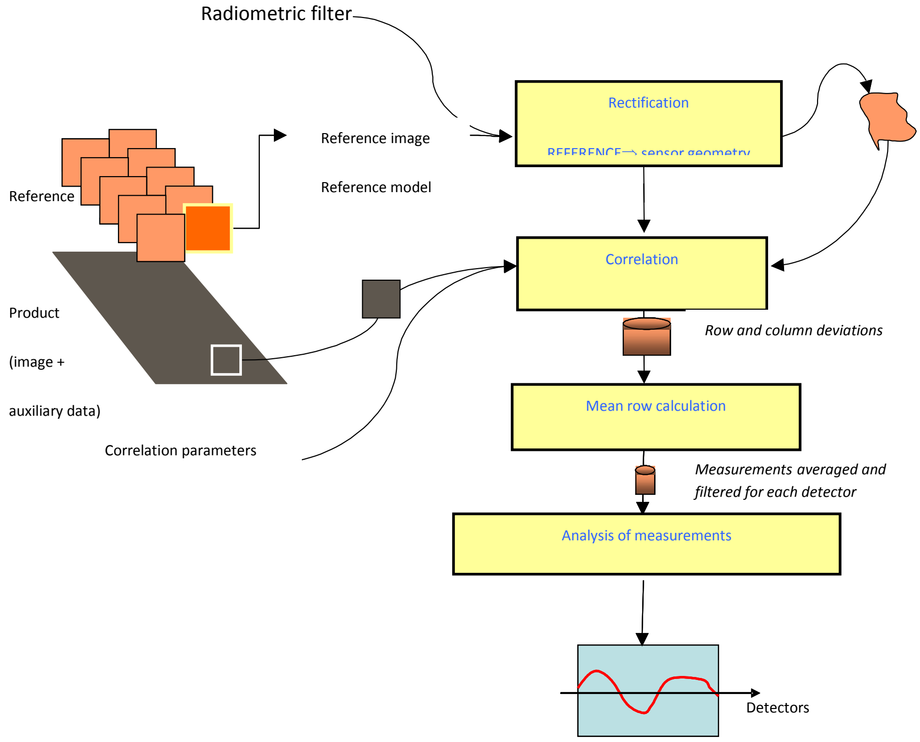


Figure 7. Detailed method for mapping the focal plane

3.2.2 Results

First calibration has been done at the end of July in order to correct the geometric model computed on ground.

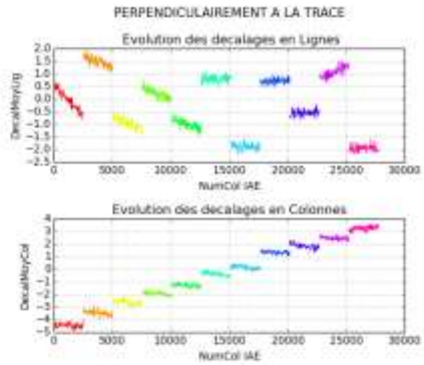


Figure 8 : first absolute focal plane cartography with geometric model defined before launch – each color is one retina

After correction of the geometric model the residuals errors were less than 0,2 pixels.

When the new GSE algorithm has been put, new biases of the viewing frames have been put in the geometric model which modified absolute focal plane cartography (see paragraph on relative focal plane cartography for more explanations). Lines of sights have been calibrated again.

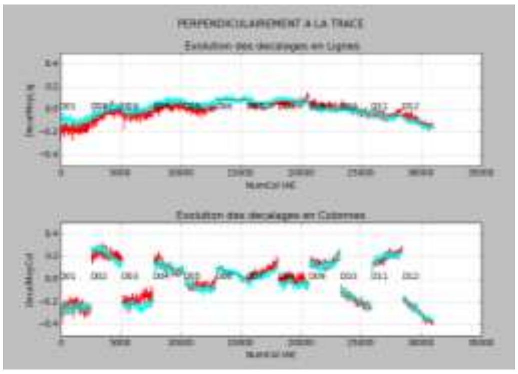


Figure 9 : with old calibration, new viewing frame biases

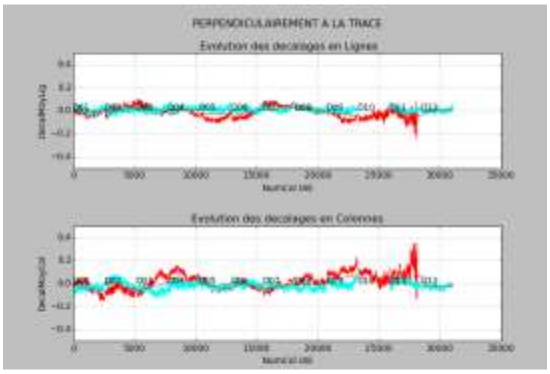


Figure 10 : with new calibration

Residual on absolute focal plane cartography is so evaluated to 0.2 pixels.

2.3 Relative focal plane calibration and registration performances

The relative method for focal plane calibration uses the absolute method, but takes a well-calibrated existing band as a reference. This method is used to calibrate SWIR focal plane from VNIR focal plane and more generally to calibrate the different multispectral bands to ensure consistency between channels LOS. Calibration parameters are thus estimated by correlating the various bands with each other. But the correlation reaches its limits when the spectral bands are very different. A study has been carried out before the commissioning phase to determine the best pairs for correlation. The following pairs are used for calibration:

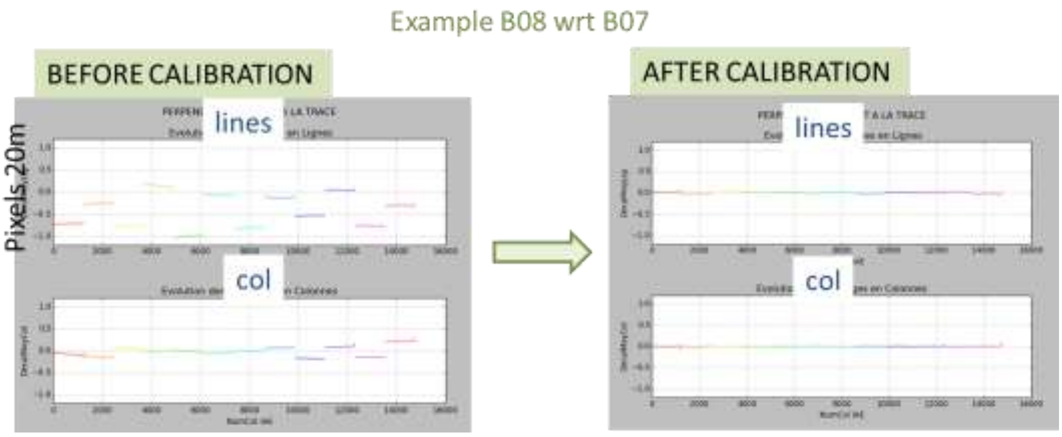
- B4 spectral band is used as a reference to calibrate the focal plane of the B2, B3, B5 and B8 spectral bands

- B5 spectral band is used as a reference to calibrate the focal plane of the B1, B6, B7, B11 and B12 spectral bands;
- B8 spectral band is used as a reference to calibrate the focal plane of the B8a and B9 spectral bands;
- B2 spectral band is used as a reference to calibrate the focal plane of the B10 spectral band.

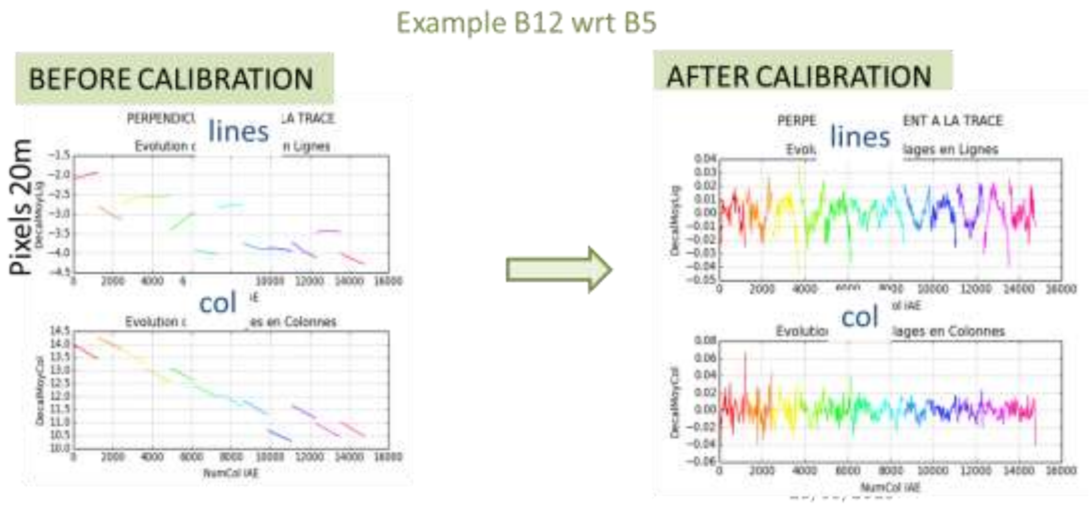
Images used for calibration were cloud free images, mainly on desert like MiddleEast and Australia. LOS measurements are repeatable from one product to another.

3.3.1 First results (end of july)

Correlations have been done on all these bands at the end of july in order to correct the residual LOS errors coming from the ground measurements. The LOS was very well calibrated on ground : only few gaps have been corrected (except on SWIR bands where the focal plane is not the same as the VNIR one, so the gaps were higher).



Example on SWIR pixels



For particular case of B10 (cirrus bands) correlations have been done over high mountains (dry weather) in order to see the land.

3.3.2Viewing frames biases impact on LOS calibration

At the beginning of September a big bias in pitch has been put, following the implementation of the new GSE algorithm (see Absolute viewing frame calibration paragraph). This bias (delta from previous bias with which lines of sight were initially calibrated) was 950 meters on-ground. With this new bias, LOS calibration was degraded:

Example on one pair in relative calibration:

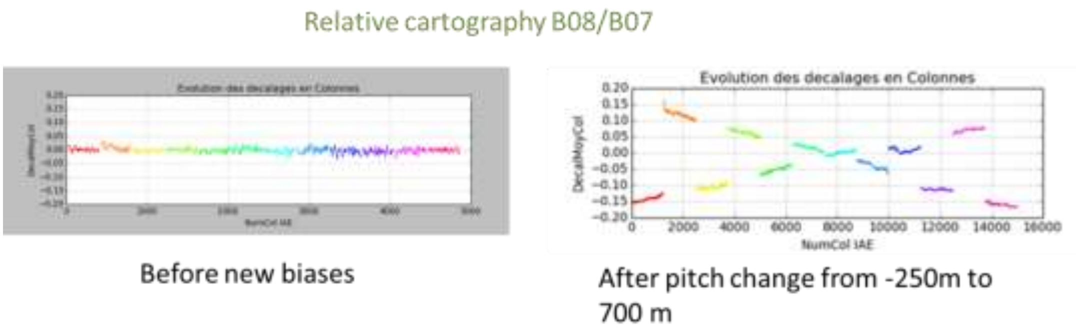
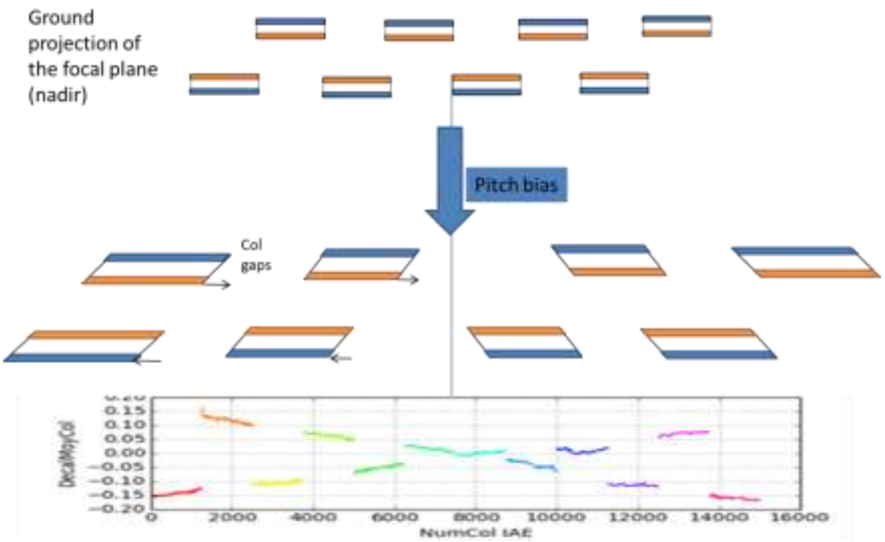


Figure 11 : impacts of viewing frames biases on relative cartography

- ⇨ Projections of detectors, evolving in the field of view, with these biases, causes the effect we see on the registration :



So, with a big bias update, new LOS calibration has to be done. Same kinds of effects are seen with yaw bias, or roll bias. The effect is smaller on registration when the B/H between channels is smaller. There is also an effect on absolute calibration which should be done again when a big bias is put (this should not happen again).

Inter-band coregistration performance is composed of residual of:

- dynamic effect (+/- 0.075 pixel) (residuals of oscillations, see [1])
- static effect (residual of LOS calibration)

After new LOS calibration (done mid-September) the multispectral registration performance is better than the 0.3 coarser pixels. A precise number will be given later in the commissioning.

3. CONCLUSION

Viewing frames bias calibration has been perform to meet geolocation performance: geolocation on S2A is really good without GCP. The geolocation with GCP, as well as multitemporal registration, will be evaluated over the GRI (Ground Reference Image), described in [1], and evaluated during the following months.

Focal plane mapping has been done to meet multispectral registration performance.

Sentinel-2 geometric requirements are met after 3 months of calibration. The calibrations may be done again if there is a temporal evolution (seasonal or beginning of life effects). The end of commissioning is at the end of December 2015 so the final values for all specifications will be given at that time.

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