

Sentinel 2 Global Reference Image

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ABSTRACT

Sentinel-2 is a multispectral, high-resolution, optical imaging mission, developed by the European Space Agency (ESA) in the frame of the Copernicus program of the European Commission. In cooperation with ESA, the Centre National d'Etudes Spatiales (CNES) is responsible for the image quality of the project, and will ensure the CAL/VAL commissioning phase.

Sentinel-2 mission is devoted the operational monitoring of land and coastal areas, and will provide a continuity of SPOT- and Landsat-type data. Sentinel-2 will also deliver information for emergency services. Launched in 2015 and 2016, there will be a constellation of 2 satellites on a polar sun-synchronous orbit, imaging systematically terrestrial surfaces with a revisit time of 5 days, in 13 spectral bands in visible and shortwave infra-red. Therefore, multi-temporal series of images, taken under the same viewing conditions, will be available.

So as to ensure for the multi-temporal registration of the products, specified to be better than 0.3 pixels at 2σ , a Global Reference Image (GRI) will be produced during the CAL/VAL period. This GRI is composed of a set of Sentinel-2 acquisitions, which geometry has been corrected by bundle block adjustment. During L1B processing, Ground Control Points will be taken between this reference image and the sentinel-2 acquisition processed and the geometric model of the image corrected, so as to ensure the good multi-temporal registration.

This paper first details the production of the reference during the CALVAL period, and then details the qualification and geolocation performance assessment of the GRI. It finally presents its use in the Level-1 processing chain and gives a first assessment of the multi-temporal registration.

Keywords: Sentinel 2, In-Orbit commissioning, geometric performances, Global Reference Image, Level-1 products, oscillations

1. INTRODUCTION

Sentinel-2A was successfully launched on June, 22nd 2015, from the Centre Spatial Guyanais (Kourou).

In the frame of the ESA-CNES cooperation agreement, CNES contributes to the image quality commissioning phase for providing calibrations and performances assessment, both in radiometric and geometric topics. In radiometry, the activities conducted are the following: vicarious calibration, pixel response non-uniformity calibration, dark signal measurements, SNR and MTF measurements, compression rates evaluations, water/land and cloud masks parameterizations, crosstalk and ghost assessment, Level1 products validation, Level2 demonstration product. These

activities are presented in papers [4] and [5]. In geometry, the following activities have been performed: dynamic analysis, LOS calibrations, pointing bias calibrations, geolocation, multi-spectral registration performances assessment, and swath and pixel size assessment, Global Reference Image over Europe constitution, multi-temporal registration performances and extended mode performances assessment. These activities are presented in paper [3] and also this one.

This paper focuses in two main topics:

- the resolution of the roll oscillation issue,
- The constitution of the Global Reference Image and the multi-temporal registration performances associated.

1.1 Sentinel-2 design and main features

A presentation of Sentinel-2 missions, design, product and geometric processing is needed for fully understanding this paper. The reader can refer to papers [2] and [3] for this presentation. We still recall here very briefly the main features of the mission and design.

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.

The Multi-spectral instrument is a push-broom imager based on a Tri Mirror Anastigmat (TMA) telescope. The focal plane is split in two parts, a Visible and Near Infra Red (VNIR) focal plane made of 12 staggered detector modules containing 10 spectral bands, and a Short Wave Infra Red (SWIR) focal plane made of 12 staggered detector modules, containing 3 spectral bands. There are very small values of stereoscopic angle between bands and detectors, 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 [1].

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.

1.2 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 calibrated on-ground and re-calibrated in-flight.

Three main activities, done during in-orbit commissioning (IOC), have a direct impact on these geolocation and registration performances:

- First, the resolution of the oscillation anomaly (see paragraph 2) was mandatory to reach any of these performances
- Then, the calibration of the orientation of Viewing Frames, and the focal plane mapping, have a direct impact on the geolocation and registration performances. These calibrations are described in [3]
- Finally, a major activity foreseen during IOC is the production of the Global Reference Image (GRI) and the ground processing parameters tuning, such as the parameters of the space-triangulation, and the automatic correlation process. This activity, as well as preliminary multi-temporal registration performances, is described in paragraph 3.

2. OSCILLATIONS

First image dynamic analysis showed that, during image acquisition mode, Sentinel-2 undergoes an unexpected on-board oscillation due to a solar array movement, which was having great impact on geometric performances.

This oscillation has two frequencies:

- 0.84Hz, amplitude 50 micro radians,
- 0.03Hz, amplitude 100 micro radians.

2.1 Phenomenon

This oscillation is seen by the on-board attitude measurement sensors and thus should theoretically not impact the image quality: if the on-board perturbation was correctly restituted by Gyro-Stellar Estimator (GSE) algorithm and taken into account by ground processing, oscillations would be corrected on images (Figure 1)

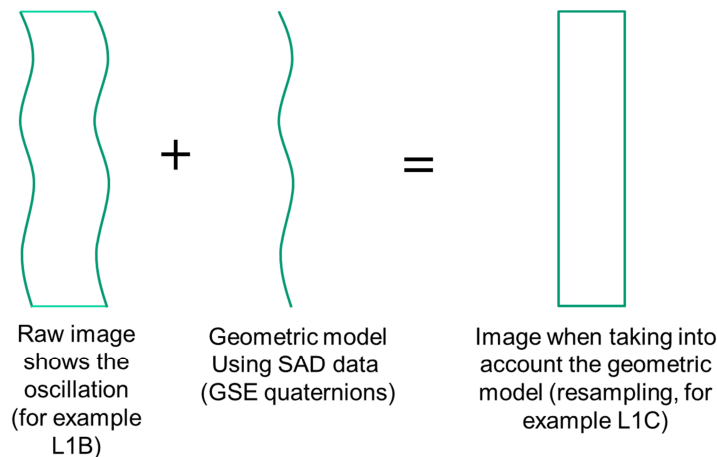


Figure 1: Correction of oscillation in the images through geometric modelling

But after Sentinel-2 image processing, after taking into account the geometric model, there was still a residual dynamic perturbation that appeared on the images, leading to image deregistrations which amplitude was up to 10 times the specifications.

Image quality and AOCS analysis (see following paragraph), conducted in parallel, showed that attitude restitution datation was delayed with respect to image datation, causing this residual deregistration after geometric processing. This

delay was due to two causes: the anti-aliasing filter on IMU data was introducing a dephasing which was dependent on the frequency of the perturbation; then, there was an uncertainty in the datation of the rate computed from IMU angular measurements (Figure 2).

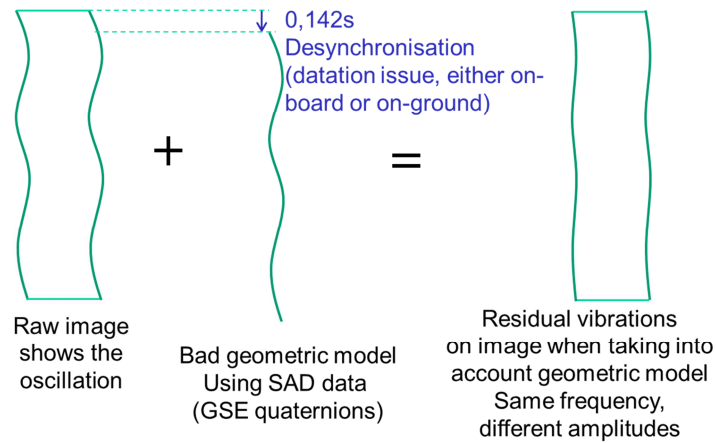


Figure 2 : Residual oscillations on image

The main tool of image quality to determine the dynamic perturbations occurring during acquisition is the inter-band correlation: due to the stereoscopic angle between channels in the focal place, the different colors do not see the same place on ground at the same time, undergoing different perturbations, which we measure by image correlation (Figure 3).

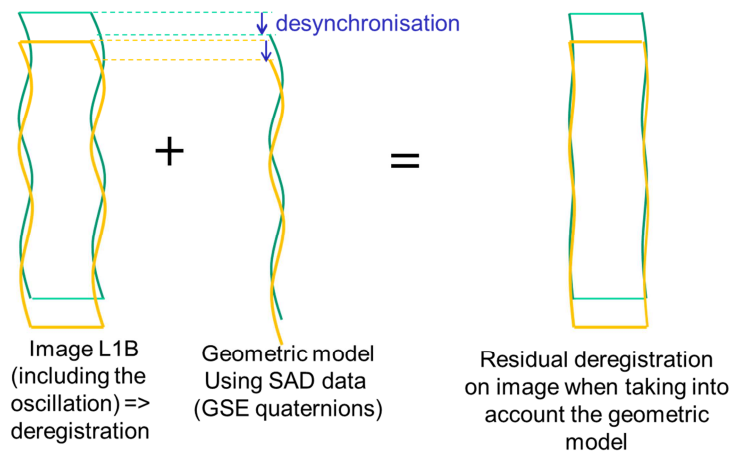


Figure 3 : Residual deregistration on image

The desynchronisation (the time delay) was first temporary corrected through a Ground Image Processing Parameter (GIPP) delaying image datation. Then, as a definitive correction, the attitude restitution algorithm was re-coded on-ground and integrated as a plug-in in the ground processing.

This anomaly had a great impact on the calendar of geometric image quality activities during in-orbit commissioning, since correcting the oscillations and getting stable attitude restitution was a pre-requisite to geometric calibrations, to Global Reference Image activities, and to performances measurement.

2.2 Characterisation of the oscillations

Spectral and temporal analysis on attitude quaternions showed on-board oscillations:

- At $f=0.031$ Hz ($T=32$ s), vibrations on roll and pitch (green thread);
- at $f=0.8$ Hz ($T=1.2$ s), vibrations on roll (blue tread).

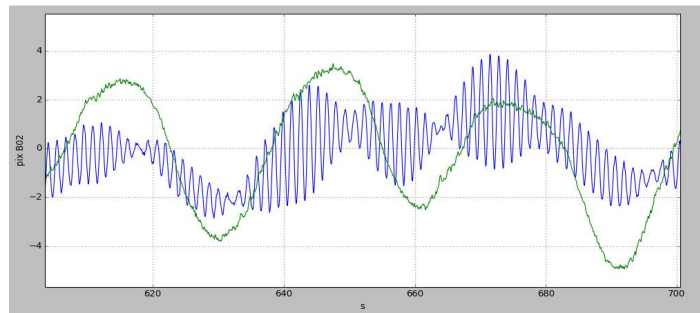


Figure 4: temporal analysis on attitude quaternions

Measured on images by inter-band correlation, the corresponding measured image de-registration was:

- varying along the orbit
- depending on spectral bands correlated
- of a maximum of 4 pixels in column, with a line period of more than 800 pixels (Figure 5)

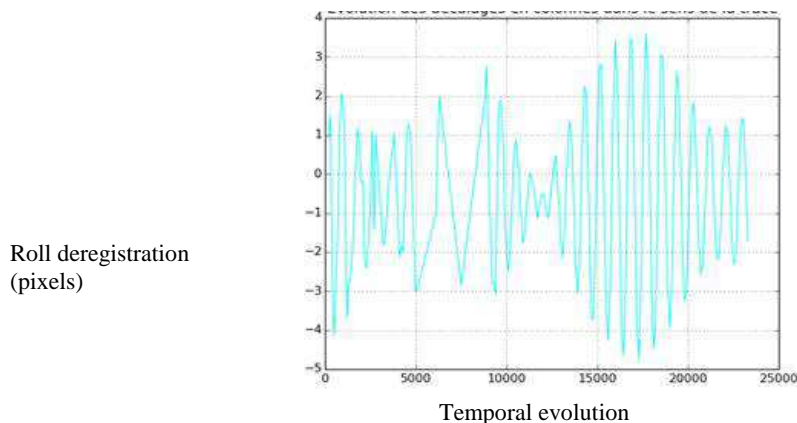


Figure 5: Example of B3/B4 correlation over Sweden.

When using the on-board attitudes data for correcting oscillations by resampling, the de-registration levels are reduced by about a half. The maximum level of de-registration was around 2 to 3 pixels (Figure 6), but varying a lot depending on the position over the orbit and the spectral bands correlated. These level of deregistration was seen on all the products tested.

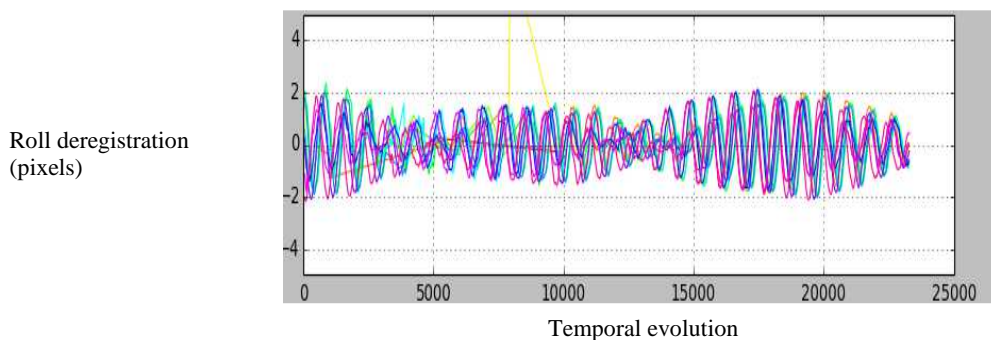


Figure 6: Example of B3/B4 correlation over Sweden on several detectors, using on-board attitude data

A residual oscillation after image resampling was not normal: if the oscillation has been correctly seen by on-board attitude measurement, it should not appear in the images after resampling.

To sum up, image de-registrations amplitude was up to 10 times the specifications. The residual oscillations was also decreasing the geolocation by a factor 2 with respect to the specification, and degrading the multi-temporal registration up to 10 times the specification.

2.3 Investigations and corrections on datation

Several analyses were made to understand why the oscillations were still showing on the images when correcting them using the attitudes measurement on-board. Soon, it became clear that the on-board gyro-stellar estimator was measuring the perturbations at the correct amplitude and frequency, but that there was a datation issue, which was either in the image datation or in the images datation. The following investigations have been made by image quality:

- Line_Period value.

Image datation is determined using the Line Period value and the number of lines in the image. Theoretically equal to 1,566ms, it has been estimated in-flight by linear regression over 10 different products, and found equal to 1.565873622ms with a 1ns precision. This value has been confirmed by AIRBUS DS, and the model has been updated with this value in ground processing parameters.

- Constant delay

Image quality analysis, performed on several images (see Table 2) and by two methods, show that the image is always in advance with respect to the attitude data (ie attitude data is always late with respect to the image), with a magnitude of 0,14s.

Product name	Relative orbit number	Acquisition Date	Method 1 : Space-triangulation	Method 2 : Local estimation
Sweden-Togo	22	04/07/2015		138,3ms
France	51	06/07/2015		141,6ms
Portugal	37	15/07/2015	132ms on 60000lines	142,3ms
Australia B3/B4 (10m bands)	131	12/07/2015	147ms	141,3ms
Australia B5/B6 (20m bands)				139,9ms
Europe	122	11/07/2015		141,9ms

Table 2: Result of datation analysis on several products

Method 1 was using a space-triangulation algorithm between two bands, with an unknown on the datation parameter.

Method 2 was comparing the delay between inter-band image correlation and image colocation, since colocation uses on-board attitudes. The dephasing between both was corresponding to the delay between image and attitude data.

Finally, precise determination by correlation then proved that 142ms was the value reducing best the oscillations, showing a residual level of oscillations around 0.3 pixels p-p. Since it was possible to correct image datation in the GPP through parameterization (GIPP), it was decided to do so temporarily.

- Ground processing investigations

The above analysis made it clear there was a datation issue, either in image datation or in attitude datation; the question was to know if it was due to an on-board cause or to an on-ground anomaly. To discard all possible sources of errors in the ground processing, large verifications have been performed in the Ground Prototype Processor (GPP). No anomalies of significant impact have been found in the ground processing.

2.4 A new gyrostellar estimator (GSE) algorithm on ground

After AOCS investigations, this delay proved to be due to attitude datation. It was decided to code again the attitude restitution on-ground, so as to correct for this datation issue: hybridation was done again from raw star tracker measurement and raw gyroscopes measurements. The quality of this attitude restitution was evaluated on the images by inter-band correlations. This new gyro-stellar estimator was now allowing doing an almost perfect correction of the on-board phenomenon occurring on-board, as can be seen in Figure 7:

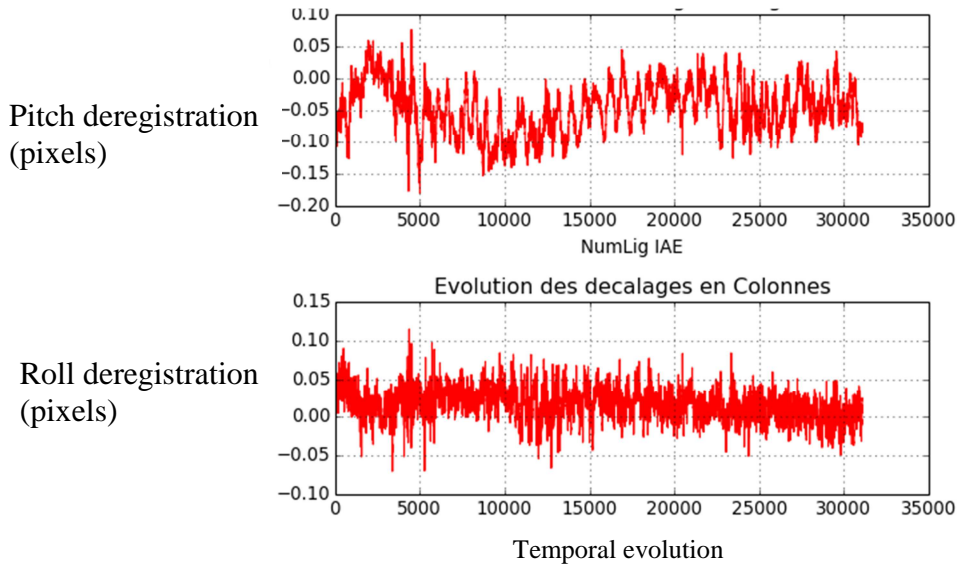


Figure 7: Example of residual oscillation – B3/B4 correlation

On 8 products, the residual deregistration has been assessed on several coupled of bands: the results are presented in Table 3.

<i>couples</i>	<i>d_dynamic</i>	
B4_B8	0.129	10m pixel
B4_B3	0.115	
B4_B2	0.140	
B5_B6	0.117	20m pixel
B5_B7	0.133	
B5_B11	0.106	
B5_B12	0.152	
B5_B4	0.132	
B5_B8a	0.139	
B8_B8a	0.022	
B3_B6	0.127	

B5_B1	0.149	60m pixel
B2_B10	0.206	
B8_B9	0.017	
B9_B1	0.162	
MAX	0.20	
MAX w/o B10	0.16	

Table 3: Residual deregistration due to oscillations, measured on several couples

This is considered as a very good result. The larger value on B10 is not to be trusted much, because the correlation noise on this band is high, since it is located in a water absorption band: the radiometric content is very different from the other bands, leading to correlation errors.

After this validation, the new GSE was integrated in the GPP as a plug-in in end of august 2015, leaving the floor to all the others geometric calibrations and performances assessment.

Some of the main activities during IOC are described in [3]: the orientation of viewing frames determination, the focal plane mapping; the geolocation performances and the multi-spectral performances. In the next paragraph, is described the constitution of the Global Reference Image and the multi-temporal performances assessment, which can be done after all the calibrations have been done.

3. GLOBAL REFERENCE IMAGE

All this section is dealing with the multi-temporal registration performances, which is to be reached after L1B geometric processing. So, the first section of this paragraph presents the products and the geometric processing at L1B. The second section presents the Global Reference Image constitution. The last part presents the results of a study assessing preliminary the multi-temporal registration performances on a subset of products.

3.1 Sentinel-2 L1 products and L1 geometric processing

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,

In the frame of the ESA-CNES cooperation for the Sentinel-2 program, ESA has delegated to CNES the technical definition of the Sentinel-2 Level-0/1A/1B/1C Ground Prototype Processor (GPP) as well as the follow-up of its industrial development. An overview of the Level-1 processing, which combines radiometric and geometric corrections, to achieve the levels of products described previously, is described in [2].

After decompression of the image source packets transmitted by the MSI and extraction of ancillary information, radiometric processing [4] takes place: normalization, dark signal and detector relative sensitivity correction, SWIR pixels re-arrangement, cross-talk correction, defective pixels interpolation, restoration and binning. Then geometric processing takes place.

The goal of the geometric correction is to perform the temporal and spectral registration of all the images taken over any target. To reach this objective, the physical geometric model, which associates a viewing direction to any pixel, has to be refined according to an absolute reference: the Global Reference Image (GRI). This physical geometric model combines position, attitude and time-stamp information, transformation matrices between different reference frames: satellite, instrument, focal planes and detectors, and for each elementary detector a viewing direction. Then, the processing chain takes advantage of the GRI, well geo-referenced, to correct the physical geometric model of each image taken (Figure 8. Sentinel-2 physical geometric model refinement based on automatic correlation with reference data

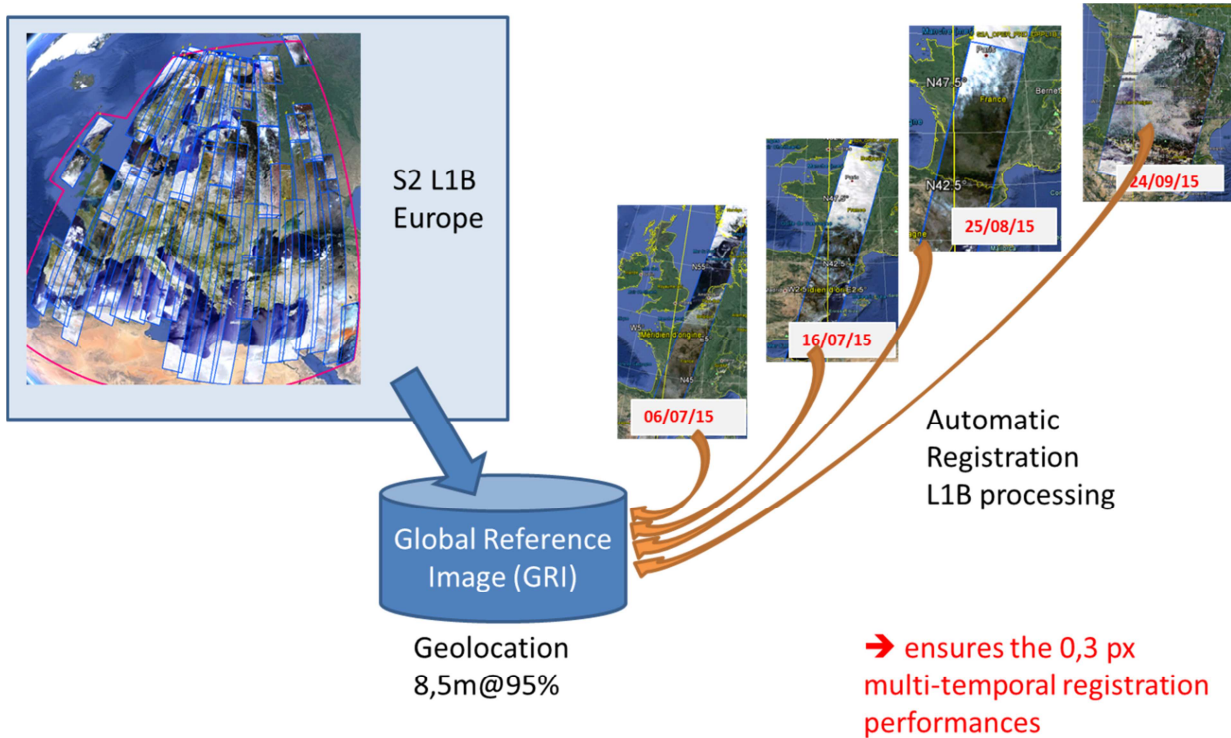


Figure 8. Sentinel-2 physical geometric model refinement based on automatic correlation with reference data

The processing is based on an automatic image matching process which provides accurate ground control points between a given band of the image to refine and a reference image, allowing to dynamically calibrating the viewing model and so to attitude and position profiles.

Because of the parallax between odd and even detector modules and between bands, the registration is sensitive to the Digital Elevation Model (DEM) used for the processing. A DTED1-class DEM is necessary to reach the required performances. The refined geometrical model is then propagated to all the bands.

The geometric model refinement also implements an automatic registration between VNIR and SWIR focal planes based on multi-spectral correlation (based on similar method). This complementary refinement could be used during commissioning phase.

Once the geometrical model of the image is refined, the final ortho-rectification is performed using an optimized resampling process combining:

- a tiling process, partitioning the final images in several tiles according to the cartographic pre-defined grid,
- a geometric process computes the inverse grid that gives for each point of the output image its location in the focal plane,
- a radiometric process computes for each point of the grid its radiometry using Splines interpolation functions (in radiance),

- a final operation converts the radiance into the reflectance (knowing the sensor sensitivity). This operation is done on the fly at pixel level.

Finally a cloud (opaque/cirrus) and land/water mask is computed.

3.2 Global Reference Image

A key improvement in the overall process is the usage of the Global Reference Images database. This database is made of Sentinel-2 mono-spectral images whose geometrical model is refined. It is initialized during the commissioning phase over Europe under the responsibility of CNES, and realized at IGN-Espace (Institut Geographique National).

During IOC, a set of monospectral cloud-free L1B over Europe are processed with a dedicated method, already used for SPOT5-HRS, based on a large space-triangulation [6] (bundle block adjustment on a large area), using tie points between the different images and GCP in order to improve jointly the geometric models of images. The process takes also advantage of the overlap between Sentinel-2 orbits.

Two GRI over Europe are to be delivered by CNES during the commissioning phase: the intermediate GRI, which is already available (October 2015), and the final GRI, covering all European orbits, which is foreseen for end of December.

The intermediate GRI is composed of 19 L1B products (Figure 9). The geometrical model of the 19 GRI products was refined by space triangulation using tie points between images and Ground Control Points (GCP). The figure below represents location precision of each GRI product before and after refining. Red lines represent distance to the reference before geometric model correction and blue lines represent this distance after space triangulation.

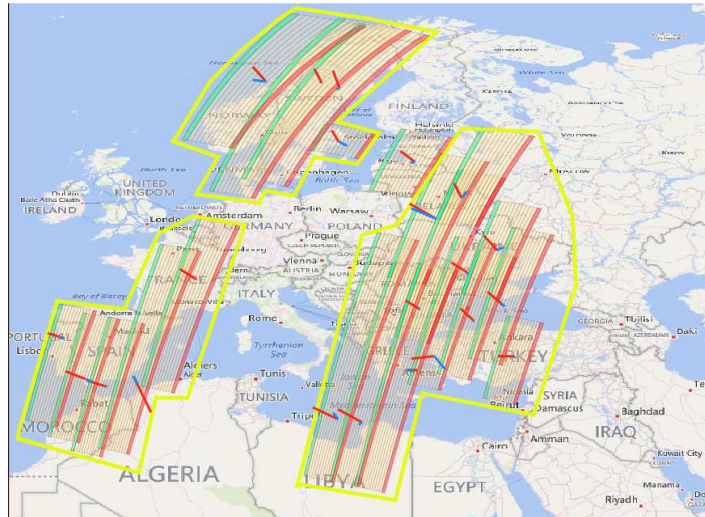


Figure 9: Coverage of the intermediate GRI

Before correction, 95% of pixels were below 13,5m to the reference, whereas after correction 95% of pixels are below 8,5m to the reference. Those results are expected to be improved further, because they were obtained with preliminary calibration.

The ongoing cover of the final GRI is represented in Figure 10. It is composed of 42 L1B products.

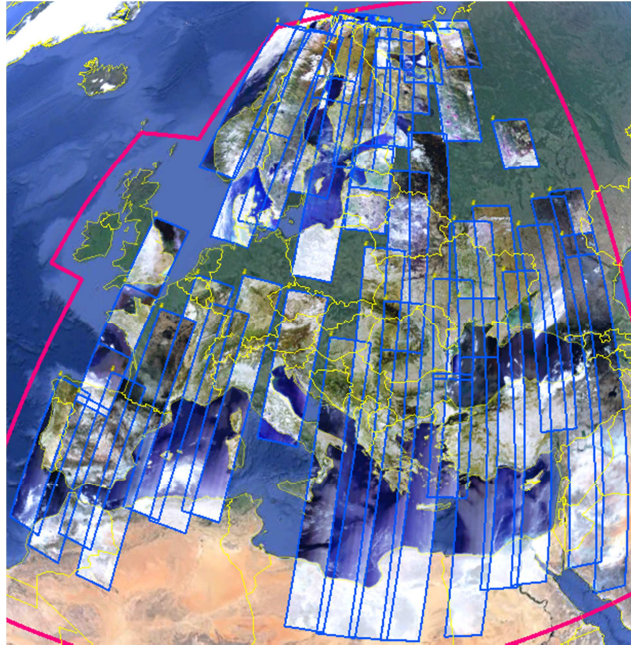


Figure 10: Current coverage of the on-going GRI

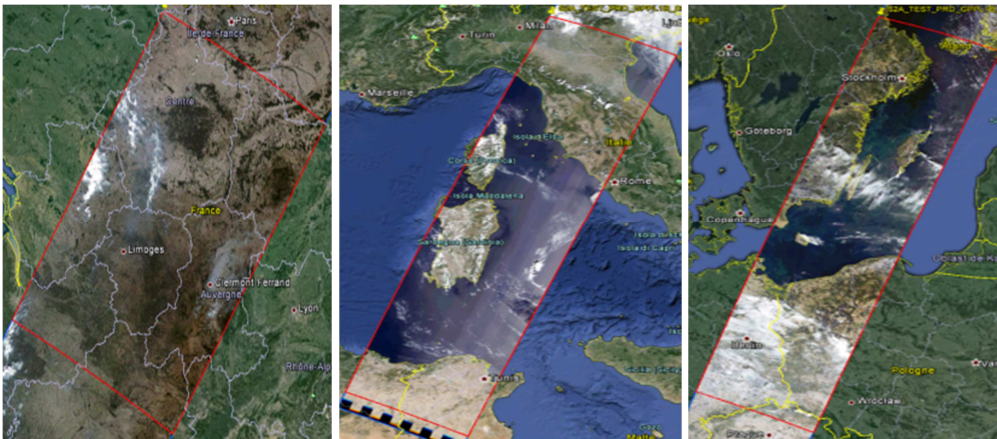
The overall cover of ongoing GRI represents 54% of the required area for the final GRI.

3.3 Preliminary multi-temporal registration performances

Multi-temporal registration performance specification is 0.3 pixels.

Before the availability of the intermediate GRI, two L1B products were converted to GRI format and the registration performance was estimated using L1B products acquired at different dates. The principle of the method is the following:

1. Selection of test cases to estimate the multi-temporal registration performance. Nine products (Figure 11) were selected with various features, for instance cloud free, with a lot of water, cloudy, very cloudy and desert:



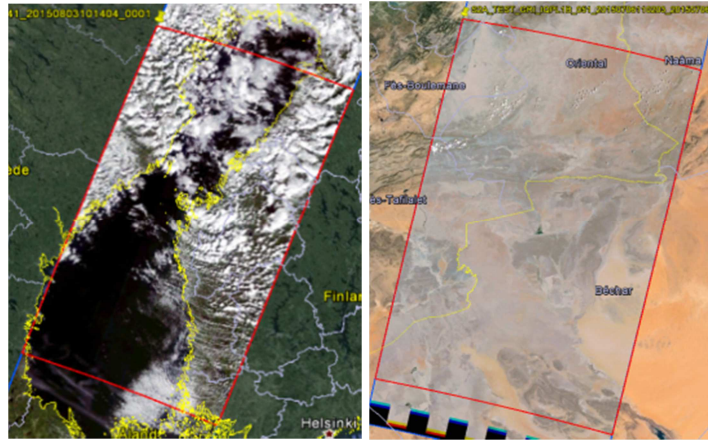


Figure 11: Different landscape selected for the study

2. Tuning of parameters. Correlation and refining parameters used in L1B processing in GPP have been tuned to comply with features of Sentinel2 products.
3. Geometrical model refining of L1B products using tie points between images and GRI and space triangulation.
4. Estimation of multi-temporal registration performance after refining. This estimation is performed using image resampling of refined products and statistical analysis of tie points between images and GRI.

Results on this 9 products, represented by mean location error and circular error for 95% of pixels are detailed in Table 4:

Test case	Refined product acquisition date	GRI acquisition date	MEAN before registration (pixels)	MEAN after registration (pixels)	CE95% (pixels)
Cloud free	16/07/2015	06/07/2015	0.49	0.051	0.11
Water	24/07/2015	03/08/2015	0.42	0.081	0.15
Cloudy	16/07/2015	06/07/2015	0.29	0.16	0.36
	25/08/2015	06/07/2015	1.23	0.16	0.36
	03/08/2015	03/08/2015	0.23	0.12	0.24
	13/08/2015	03/08/2015	0.22	0.11	0.21
Very cloudy	23/08/2015	03/08/2015	0.34	0.29	N/A
	13/08/2015	03/08/2015	N/A (A bias of 30m in lines and columns was introduced so	0.35	N/A

			as to check the capacity of the registration algorithm to correct large geolocation errors under difficult conditions)		
Desert	25/08/2015	06/07/2015	1.27	0.061	0.13

Table 4: Measured registration performances to the GRI

As shown in the table, for cases cloud free, water, cloudy and desert, 95% of pixels have a distance to the reference below 0,36 pixel. Their mean distance to the reference is below 0.16 pixel. This value can be considered as the preliminary performance for L1B and L1C multi-temporal registration, when enabling geometric refining over GRI during L1B processing. For very cloudy images, the measure of 95% of points is difficult to estimate since number of valid points in the correlation verification is very low. However, the mean distance to the reference is quite good (below 0.35 pixel) despite the low rate of usable pixels for correlation.

Those excellent results prove that tuned correlation parameters are generic and robust to difficult cases.

Until end of December 2015, there will be L1B and L1C productions with geometric refining with respect to the GRI, in the GPP. Future efforts consist in checking the multi-temporal registration over a few products, and to adapt the parameters of correlation and refining in L1B processing, if needed.

4. CONCLUSION

The first two months of the image quality geometric commissioning were needed for the oscillation anomaly resolution.

Then, a fine calibration was performed, including the viewing frames orientation calibration, and the focal plane mapping.

The multi-temporal registration is guaranteed by a registration during Level-1 processing, over a set of reference images composed of mono-spectral L1B images: the GRI. The constitution of this GRI, over Europe, has started and is foreseen to be done by end of December.

First assessment show that Sentinel-2 performances are excellent: the geolocation is very stable; the multi-spectral registration performances are also excellent, even with a very small oscillation residual; the multi-temporal registration promise to be outstanding.

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