SPOT4 (TAKE 5) TIME SERIES OVER 45 SITES TO PREPARE SENTINEL-2 APPLICATIONS AND METHODS

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ABSTRACT

This paper presents the SPOT4 (Take 5) experiment, aimed at providing time series of optical images simulating the repetitivity, resolution and large swath of Sentinel-2 images, in order to help users set up and test their applications and methods, before the mission is launched.

In 2016, when Sentinel-2 constellation is complete, and for at least seven years, users will have access to high resolution time series of images acquired every 5 days, anywhere among the Earth land surfaces. This new dataset will drastically change and enhance the way land surfaces are monitored using remote sensing. Sentinel-2 frequent revisit will assure that a given surface will be observed at least once a month, except in the most cloudy periods and regions. Such a repetitivity will enable to develop operational applications that rely on regular updates of surface reflectances.

New methods and algorithms will have to be developed, in order to handle time series covering very large areas. The methods will need to be robust to the data gaps due to clouds and given the number of images to handle, the methods will have to be automatic. At the Sentinel-2 preparatory symposium in 2012, the user community voiced a high interest to develop such new methods and applications well in advance before the launch of Sentinel-2, enabling a timely start of operational applications as soon as the data becomes available. The SPOT4 (Take 5) experiment is providing the users with time series of observations close to those of the Sentinel-2 mission in terms of temporal revisit and spatial resolution.

When CNES offered to use SPOT4 for technical experiments, at the end of its commercial life, CESBIO proposed to change SPOT4 orbit, in order to place it on a 5 days repeat cycle orbit. CNES started this experiment on the 31st of January 2013, and it lasted until June the 19th, 2013.Time series of SPOT4 images have been acquired every 5th day, over 45 sites scattered in nearly all continents, and covering very diverse applications (land cover and land use, agriculture, phenology, hydrology, snow monitoring, coasts monitoring, habitats characterization and biodiversity...).

Key words: Sentinel-2, SPOT4(Take5), time series, repetitivity, cloud detection, atmospheric correction.

1. INTRODUCTION

When they launch a new satellite mission, space agencies usually set up a preparatory program to provide simulated data to future users, so that they can get ready to start using the mission data as soon as they are available, after the satellite and ground segment commissioning phases. This is usually done using aerial acquisitions that provide simulations of the future images, but in the case of ESA's Sentinel-2 program, this task was complicated because one of the main features of the mission is to bring a huge amount of data with following characteristics :

- Resolution : 10m, 20m, 60m depending on the spectral band
- Coverage : all lands are observed, field of view is 290 km
- Revisit : each land pixel is observed every 5th day with a constant viewing angle
- Spectral : each pixel is observed under 13 spectral bands in the visible, VNIR and SWIR domains

As a result, providing simulation data sets is not easy, and before the SPOT4 (Take5) experiment, the existing data sets only respected two of the four main features :

- ESA provided simulated data resulting from aerial acquisition, with the 13 spectral bands and the proper resolution, but with a very small coverage and no repetitivity
- CNES provided Formosat-2 data sets with the appropriate repetitivity at constant angle, and 10m resolution, but with a small coverage (24*25 km) and only 4 bands and no SWIR
- USGS provides LANDSAT data, with the adequate coverage and a good spectral richness, but the repetitivity is insufficient (16 days) and the resolution is only 30m
- SPOT and Rapid Eye do not provide repetitivity with constant angles and only have 4 or 5 bands.

To cope with this problem, the SPOT4 (Take5) experiment was proposed by CESBIO and accepted by CNES. It consisted in lowering SPOT4's altitude by 2 km to put it on a five days repeat cycle orbit. From this orbit, it was possible to acquire a large simulation data set for Sentinel-2 preparation. This data set has now been acquired and provides the following characteristics :

- Resolution : 20m resolution
- Coverage : 45 sites are observed with a field of view of 60 to 120 km using both SPOT4 HRVIR instruments. Combining observations from adjacent orbits, it was possible to obtain 200 km wide sites.
- Revisit : 5 days with constant viewing angles.
- Spectral : 4 bands, including a SWIR band (Green, Red, NIR and SWIR)

The SPOT4(Take5) experiment was formally decided by CNES on December the 11th, 2012, and started on January the 31st, 2014, after it rallied the 5 days cycle orbit at 819 km 2 days earlier. The experiment lasted until June the 19th 2013, and finally SPOT4 was de-orbited and "plugged" off 10 days later. Each of the 45 selected sites (see next section for a description of the sites), was observed every 5th day, 28 times.

These 45 data sets are aimed at helping users learn to process the information brought by the unique set of Sentinel-2 features, among which the most unusual is the availability of repetitive observations under constant viewing angles at high resolution. New techniques, methods and applications will have to be developed to take full advantage of Sentinel-2 image time series, and SPOT4(Take5) data can be used to test these new ideas.

This paper describes the data set and its processing, provides its first validation results and summarizes the first few lessons learned from the experiment.

2. SITE SELECTION

Given the very tight schedule of the experiment, the site selection was managed differently for the French sites and for the international sites :

- In France, it was decided to issue a call for site proposals to the French scientific community and to French public institutions. 20 sites proposals were received after a one month delay, with participants from 80 laboratories and institutes. 16 sites were finally chosen, 11 of which are in France.
- At the international level, the schedule was too short to issue a call for proposals and we only contacted space agencies with which collaborations were already in place in the optical remote sensing domain. The European Space Agency (ESA), the National Aero Space Administration (NASA), the European Commission Joint Research Center (JRC), and the Canadian Center for Remote Sensing decided to participate, and even shared a part of the cost by funding the provision of Level 1A data produced by Astrium Geo on their sites. These sites were of course chosen by the funding agencies.

This process resulted in a large diversity of landscapes and thematics, as shown below :

- *Large sites :* Using both SPOT4 HRVIR instruments, it is possible to obtain a 120km swath. And by joining sites acquired from 2 adjacent orbits on consecutive days, it is possible to obtain sites with a horizontal extent of 200 km, and a length that is only limited by the number of images our budget let us afford. Three very large sites and 8 large sites have been acquired, obtained from adjacent swaths, and named Sudmipy (160*300 km), BretagneLoire, East and West(160*180 km), and ProvLanguedoc, East and West (160*220 km2). See Table 1 and Figure 1.
- *sites viewed from different angles :* From two adjacent orbits, it is possible to acquire overlapping sites under different viewing angles. 4 sites are concerned by this possibility: Maricopa, Sudmipy, ProvLanguedoc and BretagneLoire. These sites will enable to study directional effects corrections and compositing methods to produce bi-monthly or monthly products.
- *Aerosol validation sites :* Several sites may be used to perform aerosol validation, because they are close to an Aeronet site : Sudmipy, Provence, Tunisia, Morocco, Oklahoma, Ukraine. Although no ground truth seems available on these sites, very high aerosol optical thicknesses have been observed

Table 1. List of SPOT4(Take5) sites

Site	longitude	latitude	Agency	Size (km)
ALPES (FR)	5,769	45,153	CNES	110*110
ALSACE (FR)	7,4658	48,5539	CNES	60*110
AQUITAINE (FR)	-0,953	44,535	CNES	60*110
ARDECHE (FR)	4,484	45,472	CNES	60*60
BRETAGNE LOIRE E (FR)	-2,595	47,45	CNES	110*110
BRETAGNE LOIRE O (FR)	-3,718	48,217	CNES	110*110
RENNES (FR)	-2,05	48,27	CNES	110*110
CHINA (1)	115,993	29,32	CNES	110*110
CONGO (1)	16,898	3,092	CNES	110*60
MADAGASCAR	46,674	-19,582	CNES	110*110
MOROCCO (1)	351,848	31,518	CNES	110*110
PROV LANGUEDOC E (FR)	4,322	43,803	CNES	110*110
PROV LANGUEDOC O (FR)	3,36	43,3768	CNES	60 *170
ROUSSILLON	3,15	42,6	CNES	60 *170
SUDMIPY E (FR)	1,5701	43,7292	CNES	60 *300
SUDMIPY O (FR)	0,201	43,651	CNES	110*240
DORDOGNE (FR)	1,1	44,9	CNES	110*110
TUNISIE	9,342	35,583	CNES	110*110
VERSAILLES (FR)	2,0024	48,7595	CNES	60*60
CCRS	-111,65	57,0208	CCRS	60*60
ARGENTINA	-59,577	-34,196	ESA	60*60
BELGIUM	4.985	50,64	ESA	60*60
CHESAPEAKE	-76,115	37,7926	ESA	60*60
CHINA (2)	116,569	36,831	ESA	60*60
EGYPT	30,826	31,484	ESA	60*60
ETHIOPIA	37,8571	9,1291	ESA	60*60
GABON	10,8063	0,3755	ESA	60*60
JORDAN	36,825	31,831	ESA	60*60
KOREA	126,150	35,1472	ESA	60*60
MOROCCO (2)	352,183	32,9667	ESA	60*60
PARAGUAY	305,084	-25,285	ESA	60*60
CONGO (2)	15,9527	0,9046	ESA	60*60
SOUTH AFRICA	26,61	-27,38	ESA	60*60
UKRAINE	30,11	50,075	ESA	60*60
ANGOLA	20,5761	-15,2522	JRC	60*60
BOTSWANA	23,8145	-22,6868	JRC	60*60
CAMEROON	8,98	4,58	JRC	60*60
BORNEO	115	1	JRC	60*60
HONDURAS	85	15	JRC	60*60
THAILAND	98	19	JRC	60*60
SUMATRA	102,75	0,5	JRC	60*60
TANZANIE	36,2259	-7,2004	JRC	60*60
ZAMBIA	25,7171	-14,3497	JRC	60*60
MARICOPA	-112,409	33,094	NASA	110*60
SOUTH GREAT PLAINS	-98,209	36,645	NASA	110*110

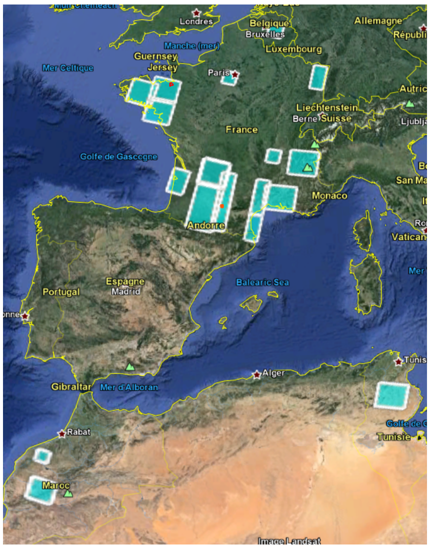

Figure 1. Sites in France and Maghreb

on China (2), Cameroon, and Congo sites, which will provide challenging test cases for aerosol detection.

- *Agriculture, Land Cover, Biomass, Irrigation :* Several sites are intended for use in agricultural applications, in various climate types. Most sites are now members of the JECAM Network.
  - Temperate : France, Ukraine, Belgium; Argentina, China, USA(Oklahoma)
  - Arid : Morocco, Tunisia, USA (New Mexico), Egypt, South Africa
  - Tropical : Madagascar, Paraguay
- *Forest :* Other sites are largely covered by forests :
  - Temperate : France (Several sites),
  - Boreal : Canada
  - Tropical : Gabon, Congo (2sites), Borneo, Sumatra, Thailand, Honduras, Cameroon
- *Meadows, rangelands, habitats, biodiversity, Natura 2000* Other sites are in more natural environments with a mix of meadows, rangelands, forests and some agriculture...
  - Temperate : France (Several sites), China
  - Arid : Tunisia, Morocco
  - Tropical : Tanzania, Zambia, Botswana, Angola, Ethiopia
- *Snow :* A few sites have been covered by snow in winter, or contain mountains
  - Mountains : Pyrenees, Alps, Atlas
  - Plains : Ukraine, USA (Oklahoma), Canada
- *water :* Finally, even if Sentinel-2 is a land mission, it turned out that a lot of the requested sites adressed coastal or inland water issues
  - Inland : Provence, Languedoc, Aquitaine, Loire, Paraguay, China, Egypt, Jordania
  - Sea : Korea, France, USA (Cheasapeake)

3. PRODUCTS AND PROCESSORS

The SPOT4 products were ordered to Astrium Geo as Level 1A products. Level 1A products are very basic products, with just radiometric corrections applied (detector normalization), and relevant meta-data added to enable to ortho-rectify and calibrate them. A new ground segment has been set-up at CNES to produce higher level products :

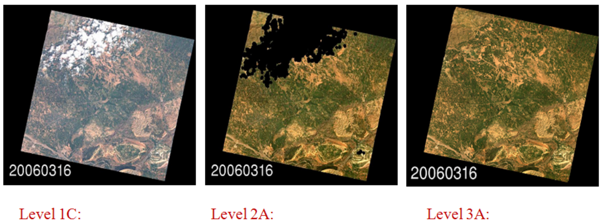

Figure 2. Products delivered by MUSCATE production center within THEIA Land Data Center

- *Level 1C* : ortho-rectified product expressed in Top of Atmosphere (TOA) reflectance
- *Level 2A* : ortho-rectified product expressed in surface reflectance, provided with a cloud/cloud shadows/water/snow mask.
- *Level 3A* : Monthly or bi-monthly composite product made of the Level 2A products obtained during a given time period

The development of this ground segment (named MUSCATE, within the THEIA Land data center, and installed in CNES premises) had already started when SPOT4(Take5) was decided, and it was originally designed to process Landsat and Sentinel-2 data. As all the processors are multi-sensor processors, it was not too difficult to implement a version to process SPOT4 take5.

The Level 1C processor is based on a CNES tool named SIGMA (Bignalet-Cazalet et al. (2010), Baillarin et al. (2008)). It uses the image meta-data, a reference ortho-rectified image and a DEM to simulate the expected image and compare it to the real one. Automatic image matching with correlation is then used to measure the differences and correct for the errors on the image attitude meta-data. The reference image used in the version 1 of SPOT4 (Take5) products is derived from LANDSAT-5 and LANDSAT-7 images. For some sites in equatorial regions, we had to find images acquired 10 years ago, and even sometimes create manually a composite image made from one half from one date and one half of another date. Since the geolocation of LANDSAT-8 has been improved compared to the previous LANDSAT satellites, we intend to produce a new version of SPOT4 (Take5) products in November 2013, using Landsat 8 products as input, at least for all the sites for which a mostly cloud free image will be available in a 6 months archive of LANDSAT-8 images.

The Level 2A was based on a processor developed at CESBIO and named Multi-Sensor Atmospheric Correction Software -prototype (MACCS Prototype). A operational version is also being developed by CNES, named MACCS. One particularity of the level 2A processor is that it uses multi-temporal criteria to build the various masks and to detect the aerosols before the atmospheric correction. The methods have already been described in the literature (Hagolle et al. (2008),Hagolle et al. (2010)), when applied to FORMOSAT and LANDSAT. These methods were designed for Vens and are fully applicable to Sentinel-2. In the case of SPOT4 (Take5), one additional difficulty lies in the absence of a blue band. In classical cloud detection algorithms, when thermal infra-red bands are not available, the cloud detection relies mainly on the presence of a blue band. And the blue band is also the basic band for the estimate of aerosol optical depth, using spectral relationships between blue and red surface reflectances or between blue and SWIR surface reflectances (Remer et al. (2005)). However, the multi-temporal methods are more tolerant to the absence of a blue band and they permitted to obtain good cloud detection performances, as well as good aerosol estimates, as shown in next section.

The Level 3A product is not yet delivered by MUSCATE production center. SPOT4(Take5) will be used to test various compositing methods and to tune their parameters.

4. PRODUCT VALIDATION

4.1. Data quality

SPOT4 was 14 years old when the SPOT4 (Take5) experiment started. Although it was a cutting edge satellite when it was launched, it will of course be largely outperformed by Sentinel-2.

First of all, its a-priori geolocation accuracy, using only meta-data, is poor, with geolocations errors reaching 1500m for some images (before ground control points are used to refine it to subpixel accuracy). Second, the image coding is limited to 8 bits, it is thus necessary to change gains according to the sites and seasons. To tune the gains for each image, CNES has implemented a model based on the histograms of images already acquired during SPOT's history, but this model is not perfect, and cannot be perfect when in a given site, some users are interested in the snow cover in the mountains and others by wheat fields in the lowlands. As a result, saturations have been observed on some images, while on other ones, the useful dynamic range of the data is very small. Sometimes, for large swath sites obtained with both HRVIR instruments, saturations may be observed on the right part of the image but not on the left part, or vice versa. A saturation mask is provided with the Lavel 1C and Level 2A products, and users are strongly advised to use it.

Finally, the SWIR band detectors are very sensitive to heavy ion collision, which can, from time to time, permanently damage a detector. After 14 years of space life, SPOT4 had lost a large percentage of its SWIR detectors, which are cleverly interpolated using information from their neighbours and the correlation of SWIR band to the B2 band.

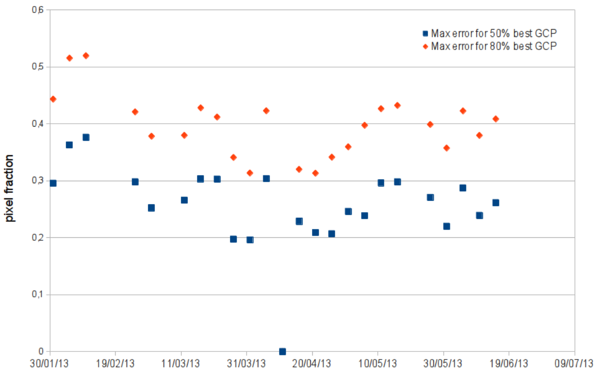

Figure 3. Multi-temporal registration performances obtained for Morocco(1) site, with regard to the image of April 14th (the dot with registration error equal to zero).

4.2. L1C validation

The main difficulty in the level 1C processor lies in the image ortho-rectification. The figure 3 shows the multi-temporal registration for one of the sites (Morocco). For most images, 50% of the measurements show that the registration performance is better than 0.3 pixel (6.66m), and 80% better than 0.5 pixel (10m), which is a good performance, given the initial geolocation error that could reach 1500m, and accounting for errors in the measurement of performances. However, a few flat and very cloudy rain forest sites caused us difficulties, with very little image details to obtain reliable ground control points. On these sites (Borneo, Sumatra, Gabon, Congo(2)), the registration performance is degraded and may reach 10 pixels !

4.3. L2A validation

Up to now, we did not have time to set up an independent data set to provide a quantitative validation of cloud masks and cloud shadows masks. Our validation lies in a visual verification of quick-looks, as shown in Figure 4. Although not perfect, the cloud mask detects very faint clouds and also detects their shadow. Some cloud classification errors have been observed when the assumption on a slow variation of surface reflectance is wrong, for instance when a wet bare soil dries up and becomes brighter and whiter, but this is quite uncommon. In some cases, mainly because of saturations, cloud and snow have been confused, but this should not happen with Sentinel-2, whose data are coded with 12 bits.

Validation of aerosol detection has also been performed using the Aeronet network of Aerosol in-situ measurements. The performances obtained are very good and close to the state-of the art performances obtained with MODIS instrument (Remer et al. (2005)). Standard deviation of the optical thickness, on sites for which at least one image per month was available are close to 0.5 (see Figure 5). On a few sites for which the weather was very

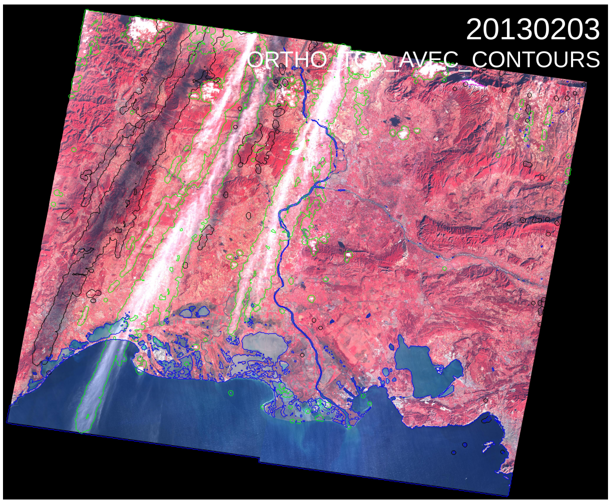

Figure 4. On this SPOT4(take5) image acquired in Provence, the cloud mask is outlined in green, the cloud shadows mask in black, the water mask in blue and the snow mask in pink. One can note that faint clouds and cloud shadows are well detected).

bad, the performance may be degraded to 0.1, due to not enough available data to obtain a correct initialization of the algorithm. In the case of Sentinel-2, the availability of a blue band will enable to combine a spectral criterion to the multi-temporal one, and to increase the robustness of estimates when long data gaps are observed due to cloud cover. The multi-temporal criterion itself will also yield enhanced results because the blue band is less sensitive to vegetation cover variation.

An additional validation experiment has been led by our colleague at NASA and University of Maryland. They compared the averaged of cloud free pixels surface reflectances for (0.05x0.05 degrees) pixels acquired on the same date by MODIS and by SPOT4 (Take5). The agreement of the direct comparison is poor, but after applying a correction for directional effects using Vermote et al. (2009) model, the agreement is excellent, with only a 1%bias, and a RMSE equal to 0.01 or 5% of the measured reflectance, validating at the same time MODIS and SPOT4 absolute calibration, cloud detection and atmospheric correction 6.

5. CONCLUSION AND LESSONS LEARNED

The acquisition phase of SPOT4(Take5) experiment has now ended, but the core part of the experiment is only starting since most of it lies in the training of users and in the development and test of accurate methods, processors and applications. The data distribution has only started 1.5 month ago, in the middle of the summer, and it is obviously too early to obtain feedback from users. However, some interesting conclusions can be drawn from our own processing of the data.

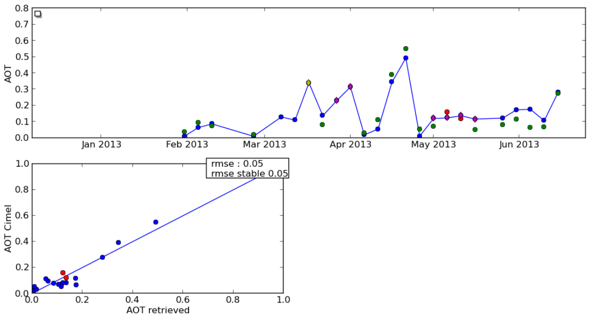

Figure 5. Validation of MACCS aerosol optical thickness estimates using the AERONET site in Ouarzazate (Morocco). The top plot shows the retrievals obtained by MACCS (lines), and by AERONET (dots). The bottom plot shows the comparison of MACCS and AERONET optical thicknesses, for the measurements obtain in stable conditions, with a limited amount of clouds and stable aerosol content. The red points correspond to unstable situations

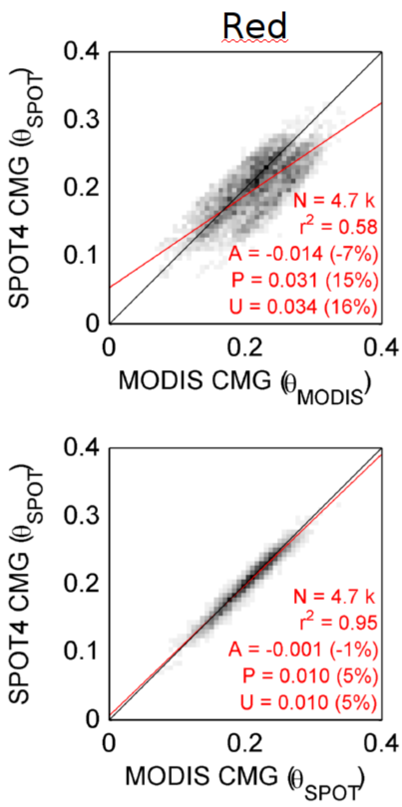

Figure 6. Comparison of SPOT4(Take5) surface reflectances with MODIS reflectances averaged at 5 km resolution, on Maricopa site, for all dates, top, before directional correction, bottom, after directional correction (M.Claverie).

First of all, the initial geolocation accuracy of SPOT4 was quite bad during this experiment, and we had to tune the image matching parameter to allow searching matches at a long distance from the expected position. This extended research zone increases the probability to find wrong matches, and in regions were it is difficult to find a large number of ground control points, it results in poor registration accuracy. However, on all sites but 4 equatorial rain forest sites, the performances after L1C processing are quite good. This difficulty however forced us to review and enhance all the standard image matching parameters we were using so far, increasing the robustness of results

The MACCS Level 2A processor yielded very good results, without needing much tuning work to adapt it from LANDSAT or Formosat-2 data, which had been used to test it. The masks are very accurate and the atmospheric correction is quite good, when the number of cloud free images is sufficient and when the selected aerosol model is correct. Some work will be needed to find a method to select the aerosol model for each region, for instance from climatologies of from new weather analyses that provide aerosol optical thickness estimates for several types of models (MACC or GEOS5 models). Sentinel-2 will offer more spectral bands to improve the results, and the presence of 2 blue bands (440 and 490 nm) will enable to combine Multi-temporal and Multi-spectral criteria over vegetated zones.

The SPOT4(Take5) experiment also brings valuable statistics on the expected cloud free repetitivity based on 45 sites. This spring's weather in France, where half of the images were acquired had a particularly bad weather. Some places in the east of France had 30% less sunshine duration than average, and most of the country was at least 10% below. In this case, the lessons learned are important, as on a few sites (Alsace, Ardeche, Bretagne, and also China(1) or equatorial sites), only 2 to 4 cloud free observations were obtained from February to end of May. The weather was not bad everywhere, and very nice time series have been obtained on several sites such as Morocco, Provence, Angola..., and even in Congo(1), a couple of almost cloud free images were obtained. This shows the importance of a high repetitivity, and the urgent need to launch the second Sentinel-2 satellite very shortly after the first one.

However, this data set is now open to the scientific community, and also to private companies, according to a very open license. The data may be downloaded from the THEIA web site : `http://www.ptsc.fr/en/products/spot4-take5`. A blog about image time series is also edited by CESBIO, and a large part of the posts is dedicated to SPOT4(Take5) experiment : `http://www.cesbio.ups-tlse.fr/multitemp/` . News concerning reprocessings, validation results or applications will be provided there regularly

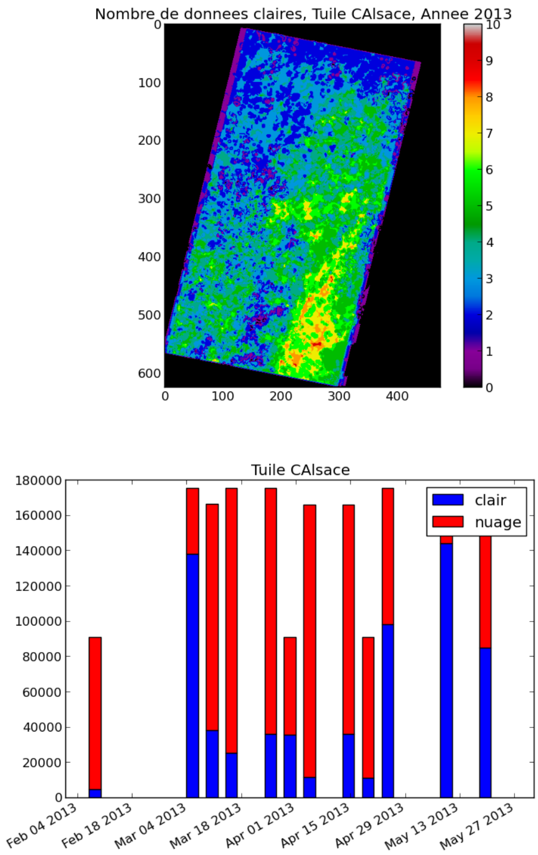

Figure 7. The top plot shows a map of the number of cloud free observations, according to MACCS cloud mask, for the Alsace site, for the months of February, March, April and May. The bottom plot shows in blue the percentage of cloud free pixels for each date, the missing dates are dates with no cloud free pixel

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