

Primljeno / Received: 04.11.2019.
Prihvaćeno / Accepted: 04.12.2019.

UDK 528.852
Originalni naučni rad / Original scientific paper

LARGE SCALE MOSAICING AND COMPOSITING OF PROBA-V SATELLITE IMAGES

KRUPNORAZMJERNO MOZAICIRANJE I KOMPOZICIJA PROBA-V SATELITSKIH SNIMAKA

Tatjana Veljanovski, Klemen Čotar, Aleš Marsetič

ABSTRACT

The paper deals with the production of large scale vegetation products derived from PROBA-V 100 m satellite images. Image compositing and mosaicking are needed to create seamless products on a global or continental scale. In the study, we have analysed and compared two compositing methods. Evaluation of the methods was focused on the visual inspection of the product seamlessness, and efficiency in eliminating (reducing) the influence of inadequate pixels that were misclassified by a cloud detection algorithm. During the compositing procedure, we also created a raster quality map and calculated statistical properties of the mosaics in order to assess the quality of the product.

Keywords: *PROBA-V, vegetation products, mosaicking, compositing, Earth observation*

SAŽETAK

U radu je opisana izrada krupnorazmjernih vegetacijskih podloga dobivenih na temelju 100-metarskih satelitskih snimaka PROBA-V. Postupci kompozicije i mozaiciranja snimaka neophodni su pri kreiranju kontinuiranih podloga na globalnom ili kontinentalnom nivou. U radu su analizirana i upoređena dva pristupa kompoziciji snimaka. Evaluacija metoda zasnivala se na vizuelnoj kontroli neprekinutosti podloga i efikasnosti u uklanjanju (smanjenju) utjecaja neadekvatnih piksela koji su pogrešno klasifikovani algoritmom za detekciju oblaka. Tokom postupka kompozicije također je kreirana kvalitetna rasterska karta i izračunata su statistička svojstva mozaikâ s ciljem ocjene kvalitete konačnog proizvoda.

Ključne riječi: *PROBA-V, vegetacione podloge, mozaikovanje, kompozicija, satelitsko posmatranje Zemlje*

1 INTRODUCTION

Large scale monitoring is mainly performed using data from low and medium-resolution satellite sensors (e.g. NOAA, AVHRR, MODIS, SPOT-VGT). Images of these sensors cover large areas on a daily or near-daily basis and are often burdened with clouds, cloud shadows, and other atmospheric disturbances (e.g. haze, cloud edge reflections, etc.). The purpose of compositing is to reduce the influence of cloud cover, view angle and atmospheric effects by creating a single composite image comprised of the data from several individual satellite observations (Holben, 1986; Cihlar et al., 1994). Composites are useful for systematic long-term observations of anomalies in environmental monitoring, from regional to global scales. In particular, the move

from an individual scene-based observation to a best available pixel (BAP)-based observation brings several advantages (Griffiths et al., 2013):

- analyses are no longer restricted to a few “best” images, where low cloud cover often had to be favoured over seasonally suited acquisitions,
- partitioning into scene footprints can be overcome,
- the entire image archive can be exploited in a consistent and systematic way and
- observation frequency, in general, is increased as all non-contaminated pixels from available single images, as well images overlap, can contribute to the composite.

When individual radiometrically and geometrically corrected images are available, and large scale mapping is preferred, compositing and mosaicking apply. As noted above, compositing refers to the process of combining spatially overlapping images into a single image based on selection and aggregation function (best pixel selection from several overlapping images). On the other hand, mosaicking refers to the process of spatially assembling image datasets to produce a spatially continuous image (joining several spatially connected images to create a single homogenous seamless image, covering a larger area than a single satellite image).

Large scale mapping based on wide-swath satellite imagery involves greater variability in data acquisition conditions. The preprocessing of data before compositing is thus concerned with the recognition of cloud contamination, correction of directional reflectance and off-nadir viewing effects, sun-angle and shadow effects, and removal of aerosol and water vapour effects (Holben, 1986).

For the compositing and mosaicking of images from different dates and/or years, it is also necessary to consider the trade-offs between inter- and intra-annual temporal distribution of acquisitions, i.e. possible changes in land cover and phenological effects (Franz et al., 2017). The aim is to obtain satisfying seasonal and annual consistency while achieving complete coverage, i.e. to achieve high radiometric consistency across space and time. Radiometrically stable and consistent datasets over large areas enable analyses aimed at addressing selected time periods.

Several authors have presented various compositing criteria to fulfil different objectives, while minimizing cloud cover and atmospheric contamination (Cihlar et al., 1994; Qi and Kerr, 1997; Cabral et al., 2003; Dennison et al., 2007; Lück and van Niekerk, 2016). Cloud-free pixel selection is typically performed by using maximum value compositing (MVC) if datasets are already prepared as vegetation indices, or by using spectral tests to predetermine the probability of cloud contamination if reflectances are used, for each pixel before compositing (Fraser et al., 2009; Franz et al., 2017). Selection of cloud-free pixels from component images is critical to the success of a compositing method. Further, the compositing period and temporal span of products should be set to such time period that removes most cloud effects. As we will show, this period can heavily depend on geographic location.

The compositing was originally developed for moderate (100 – 500 m) spatial resolution wide-swath sensors that provide near-daily global coverage and environmental monitoring on a continental or global scale (Holben, 1986; Franz et al., 2017). Recent sensors can provide global near-daily coverage in higher (to medium) spatial resolution (10 – 100 m), thus frequent global monitoring at a more detailed observation level.

The paper presents and compares the two most popular compositing methods that are used for the creation of a large-scale and seamless vegetation product from the PROBA-V (Project for On-Board Autonomy – Vegetation) 100 m imagery. Every method has its advantages and limitations, but its common tendency is to eliminate as efficiently as possible any unsuitable or inadequate observation and create a visually pleasing and radiometrically useful raster image. From those composites, a mosaic image that covers the area of Europe was created and vegetation parameters from the created mosaic were determined (Figure 1). The objectives of the study were:

- to apply compositing and mosaicking routines to PROBA-V 100 m resolution data to create large scale seamless vegetation products,
- to access and to evaluate the potential of PROBA-V imagery for large scale mapping and monitoring and
- to compare different compositing algorithms and get insight into their potential for vegetation monitoring.



Figure 1. False colour image (Red-NIR-SWIR composite of Europe in June 2015, obtained from PROBA-V 100 m resolution images

2 MATERIALS AND METHODS

In the study, a procedure for large scale compositing of medium-resolution PROBA-V 100 m imagery was demonstrated, as an extension to existing compositing methods on low-resolution data for global monitoring products (e.g. MODIS or SPOT-VGT products). As processing of large areas requires huge storage capabilities and computer time, this study was limited to the extent of Europe. The potential of PROBA-V imagery for large scale mosaicking was evaluated, as well as the two most prevalent compositing techniques.

2.1 PROBA-V satellite imagery

PROBA-V satellite is an ESA (European Space Agency) mission devoted to the observation of the Earth's vegetation, providing data continuity with the SPOT (French: *Satellite pour l'Observation de la Terre*) satellites and filling the gap to the ESA Sentinel-3 mission. The small satellite is designed to observe in three visible and one short-wave infrared (SWIR) spectral band. To achieve the swath necessary for global near-daily coverage of the Earth, the payload consists of three cameras placed next to each other, where the best spatial resolution of raw data is achieved by the central camera. Data acquired by the satellite are geometrically and radiometrically corrected, resampled to the constant spatial grid and provided freely to users in 100 m (only central camera) and 300 m (combined data from all cameras) resolution on the ground (Dierckx et al., 2014; Sterckx et al., 2014).

PROBA-V S1 TOA and TOC images are geometrically and atmospherically corrected (Maisongrande et al., 2010), have a spatial resolution of 100 m, and are acquired by the central camera of the satellite facing towards nadir. TOC images that were used in our study represent Top of the Canopy (TOC) product. Vegetation products, i.e. Normalised Difference Vegetation Index (NDVI), were also calculated and used for compositing and mosaicking analysis.

For the objectives of the study, we used the whole set of PROBA-V 100 m S1 TOC images acquired between March 2014 and May 2016, that cover two vegetation growing seasons. The spatial extent was determined by the PROBA-V X-tile coordinates 17, 18, 19, 20 and Y-tile coordinates 2, 3. That gave us eight different tiles in total.

2.2 Image compositing

The most common compositing method selects the dates with the maximum value of the NDVI (Holben, 1986; Qi and Kerr, 1997). It is supposed to minimize cloud cover, enhance the vegetation signal, and avoid off-nadir viewing angle data (Holben, 1986; Qi and Kerr 1997). Using this algorithm, three possibilities exist for determining the final value of the pixel used in the composite. First, if no data is available from any of the images, a value of zero is assigned. Second, if data from only one image is found, pixel values of that image are used. Third, if co-located pixels are present for multiple images, the pixel with the maximum value of NDVI is chosen for the final image. Image's acquisition date or pixel time is used to determine if an image qualifies for the given composite which can be generated for a predefined time span: yearly, monthly, bi-weekly, 10-days grid composites or dynamic (whenever enough information is acquired to produce a new output composite image). Compositing period for products should be set to such time period that removes most cloud effects. However, many other approaches that emphasise the best observation in satellite time series were developed.

In this study, one composite image was created for each calendar month using Max pixel NDVI and Median pixel compositing methods. As a result, slight deviations in a number of used

observations per month are present, depending on the length of the month. Another variable that specifies the number of observations per pixel is a swath of the satellite, its orbit and the latitude of acquisition. Consequently, pixels that are located further towards the North or the South Pole have a higher number of observations. On the average between 6 and 11 observations are available per pixel per month, depending on pixel geographical location and land cover type (PROBA-V images are not fully processed over large water bodies, like oceans).

The compositing methods used in this study operate on a pixel-wise way and do not consider the neighbouring pixels in the compositing process. The statistics are calculated from the stack of pixels on the same coordinates, though acquired at different dates. A quality mask supplied with the satellite data is used to remove pixels inadequate for the retrieval of vegetation parameters – those classified as cloudy, saturated or covered with snow. However, the pixels were not evaluated regarding the viewing angle. Images used in the study were acquired only by the central camera that points in the nadir direction, where the maximum off-nadir angles are less than 30 degrees in any direction.

Although only two methods were considered in the paper, many different approaches exist (Dennison et al., 2007; Lück and van Niekerk, 2016). From the published literature, we identified the following compositing methods as the most used:

- Median pixel value (calculated independently for every spectral band),
- Mean pixel value,
- Max NDVI index (the observation that produces the highest NDVI value is selected; selection is the same for all spectral bands),
- Max DVI index,
- Max EVI index,
- Min RED band reflectance,
- Min RED followed by max NDVI (firstly pixel values are ordered by the reflectance value in red band from min to max and the first few of them (arbitrary values of 3, 5, 7...) are used to select the observation that produces the highest NDVI) and
- Max DVI followed by min RED.

2.3 Masking inadequate pixels

To filter out all potentially inadequate and thus undesired, useless, pixels (cloudy, snowy, and saturated) a corresponding image quality map, provided along acquired imagery, was used. The image compositing procedure reads the quality map and depending on the defined selection removes undesired pixels. Different combinations of quality flags can be masked out:

- only background pixels,
- cloudy pixels,
- cloudy and snowy pixels,
- cloudy, snowy and shaded pixels and
- all that might degrade the quality of the final product.

Mask-out areas are dilated with a small structural element (3x3 squared kernel; the parameter otherwise adjustable to fit the satellite image spatial resolution) before the mask is applied to the image. The dilation is performed to include bordering pixels into the mask and to fill small discontinuities or gaps in the mask. In the PROBA-V quality mask, the boundary between the detected cloud and its shadow is one pixel wide and usually still contains erroneous values. Dilation procedure can significantly reduce this issue.

2.4 Continental vegetation products

Compositing and mosaicking are used in the development of continental vegetation products. From all the gathered observations one image mosaic was created for each month that covers Europe and is a composite of images acquired in that month. The compositing and mosaicking workflow that was used to derive large scale vegetation products is shown in Figure 2.

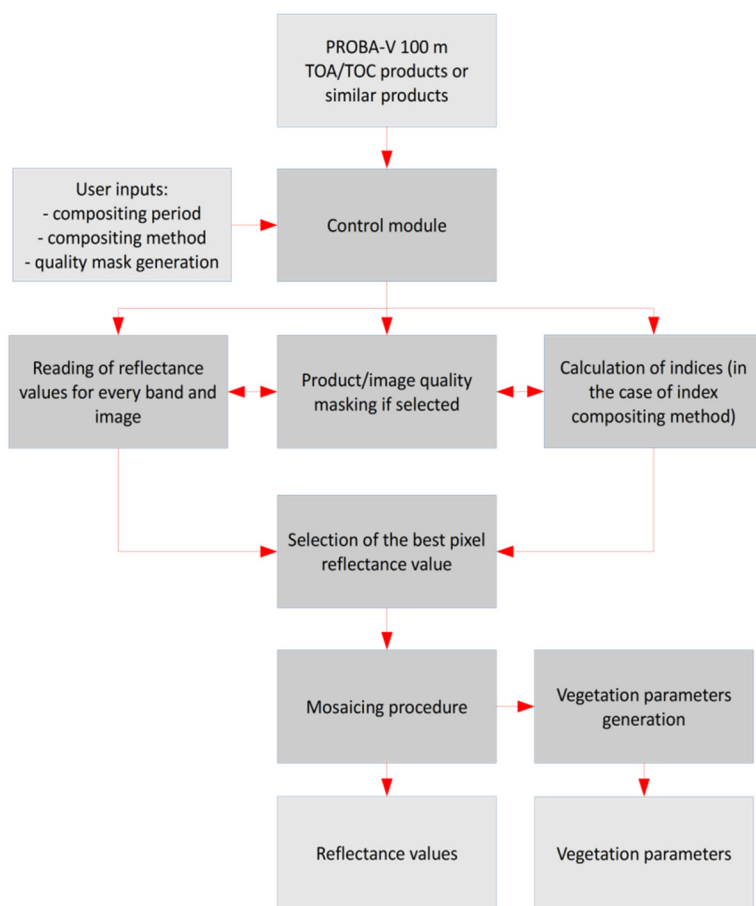


Figure 2. Workflow of the image compositing and mosaicking approach for the development of large scale PROBA-V 100 m vegetation products

3 RESULTS

This section presents the results obtained with the compositing and mosaicking of PROBA-V data. First, the results produced with two most used compositing methods were compared, then the compositing quality was analyzed through the computation of valid observations and percentage of invalid data.

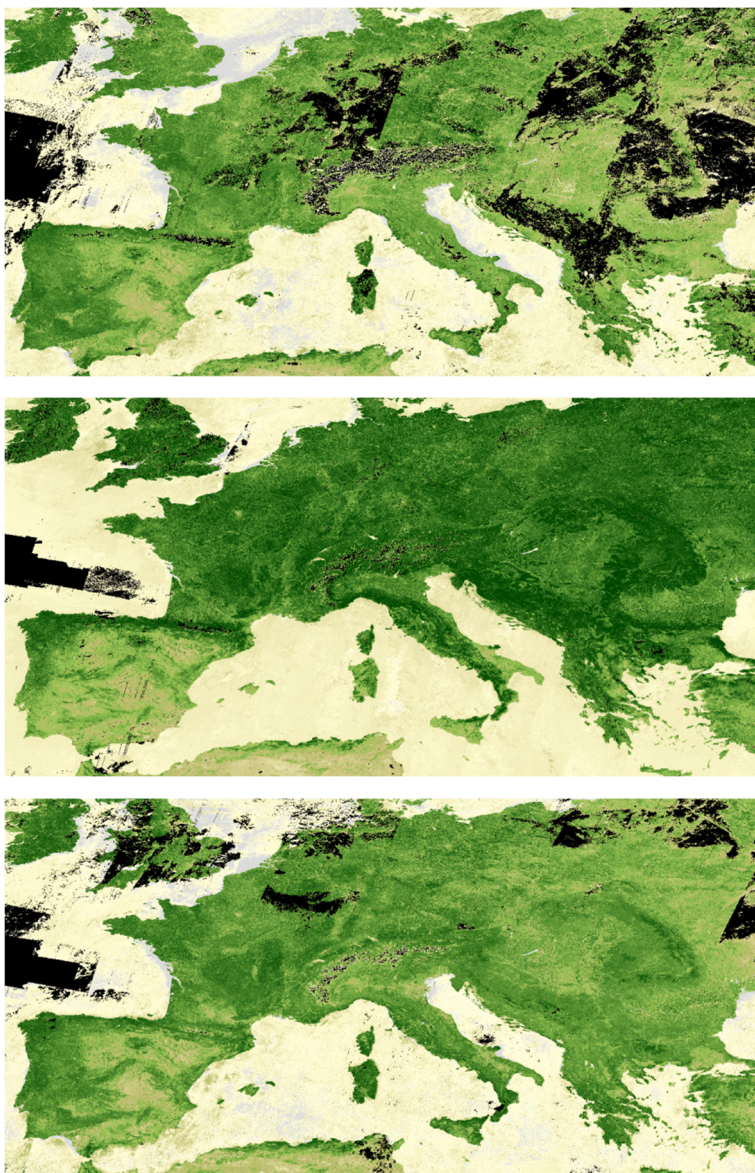


Figure 3. Monthly mosaics of the NDVI vegetation index for January 2015 (top), April 2015 (middle) and November 2015 (bottom), for the area of Europe. Grey areas represent very low, negative NDVI values and black are no-data areas or invalid NDVI values. Shades of green follow the NDVI intensity: darker tones represent higher NDVI values with healthier vegetation conditions

3.1 Continental vegetation products

The collected PROBA-V 100 m observations were used to create image mosaics that geographically cover the area of Europe. Each monthly mosaic is assembled from the tiled monthly composites based on images acquired in that month. Because the study was primarily interested in the status of the vegetation, the pixels marked as snow during the compositing procedure were eliminated. Figure 3 presents three examples of monthly NDVI mosaics.

3.2 Comparison of mosaics with respect to the compositing method

Maximum NDVI compositing method is the standard compositing approach used with PROBA-V and SPOT-VGT imagery. Thus, we selected this approach as reference to which other compositing methods are compared to. Max NDVI compositing method selects the greenest pixel for which it is assumed that is not burdened by atmospheric effects (exceedingly high values of vegetation index usually represent atmospheric features). This method provides a composite that represents the state of the most highly developed vegetation during the compositing period.

Max NDVI was compared to the Median compositing method which calculates the median of the pixel values of all images involved in the mosaic. These median values compose the final NDVI composite.

Important criteria for the evaluation of the compositing method performance are visual appearance, integrity, and homogeneity of the final product. A good method minimizes abrupt changes in pixel values and smoothes seamlines between patches during mosaicking. Visual comparison between two compositing techniques - median compositing and max NDVI - is given in Figure 4.

Some differences between the two compositing approaches can be observed, where three areas (in rows) present variable geographic settings to showcase the performance and capabilities of the two techniques. Median method (left column) in general produces images that have a higher degree of seamless integration of valid observations, is thus more pleasing to look at, but the values that are hazy and not masked out can have a substantial impact on the final product. For the max NDVI approach (right column) it is typical that the image has patchier look with steeper gradients between patches. Also, in this case the shaded areas that are not masked out can generate erroneous pixel values. However, it is less sensitive and performs better with hazy pixels. Median compositing approach proved better over large water areas, if homogeneity is important also on large water bodies.

Authors were also interested in the degree and distribution of discrepancies in the NDVI composites. Comparison of the mosaics obtained with the considered methods is given in Figure 5.

Both mosaics reach a good degree of seamlessness, while the medium approach better addresses the balancing between satellite swath paths (more pronounced over waters). The NDVI mosaic values obtained by the max NDVI approach are clearly higher (considering identical scale, these

values are coloured in darker green). Slight differences in the pattern of the vegetation features on land can be observed, but this can be mostly attributed to a difference in contrast and not the pattern itself. On the other hand, the water (sea/ocean) areas exhibit noticeable discrepancies. From the viewpoint of the visual impression of the comparison, the result of the median compositing would be favourable. This statement is, however, limited to areas with a sufficient amount of atmospherically unburdened (i.e. non-hazy) observations.

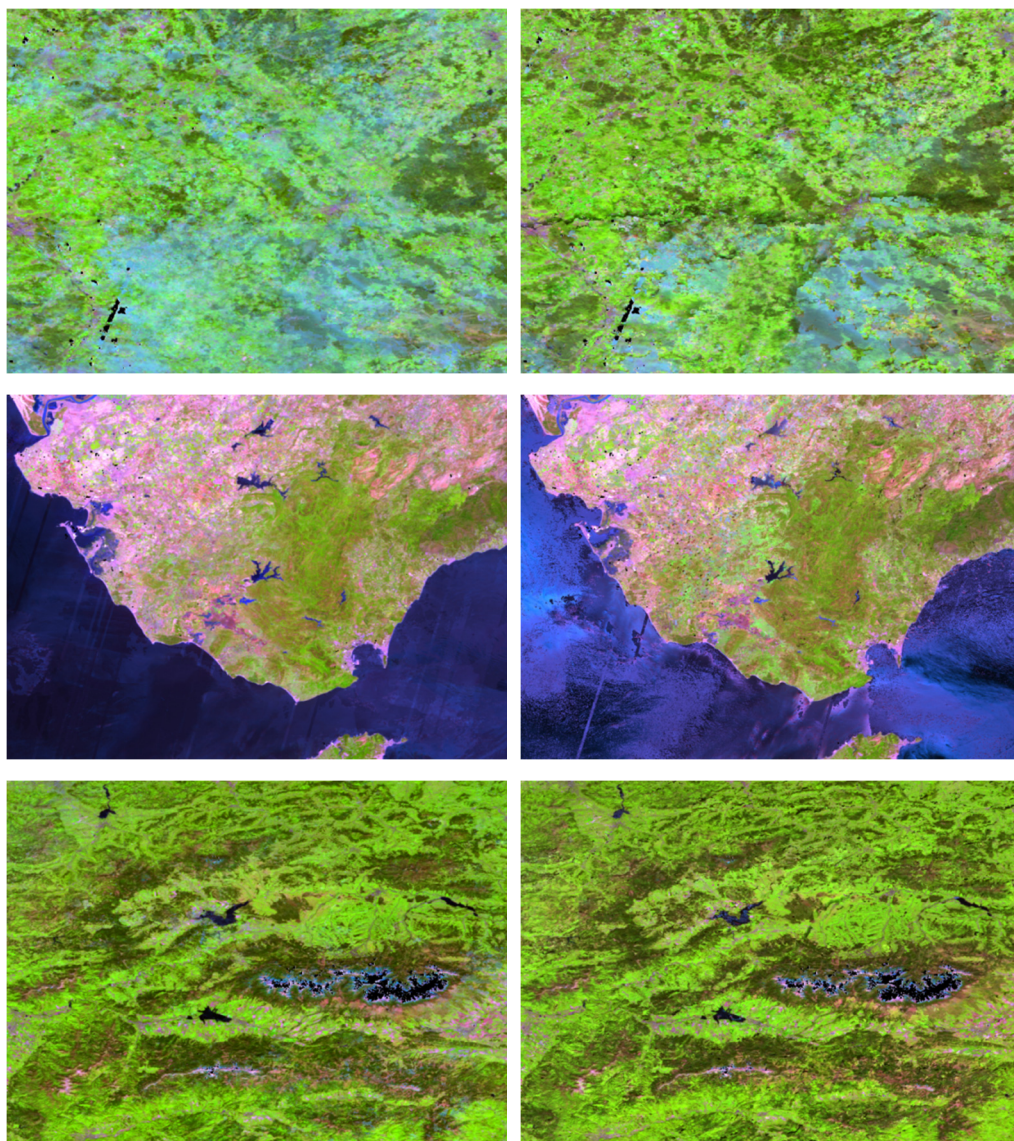


Figure 4. Visual comparison of compositing results of three different regions for median compositing (left column) and max NDVI (right column) compositing method applied to PROBA-V 100 m datasets

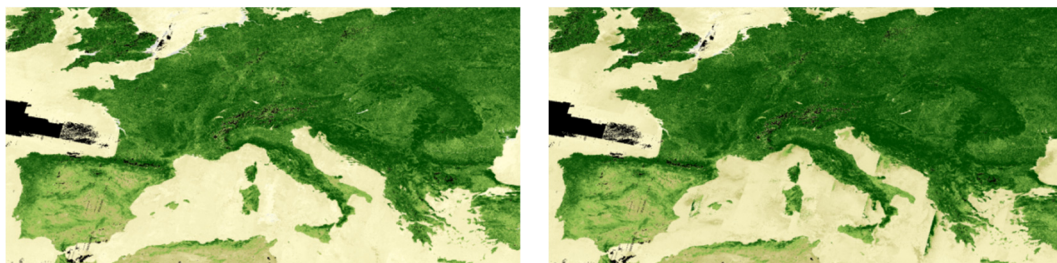


Figure 5. Comparison of outputs of two compositing approaches for the same compositing period over Europe: Median compositing method (left) and max NDVI method as a reference (right) for NDVI values. Identical colour coding is used for NDVI values representation

3.2 Coverage with useful pixels

Numerical parameters describing the image quality were calculated to assess different composites and compare different compositing methods. The main aspects of composite quality and usefulness are the number of observations per pixels that are used in the compositing process and the percentage of atmospherically unproblematic observations. The number of all and cloud free observations were assigned per pixel and status maps were produced for each composite. Status maps served to determine expected probability of cloud cover for observed area in given period of observation (i.e. month).

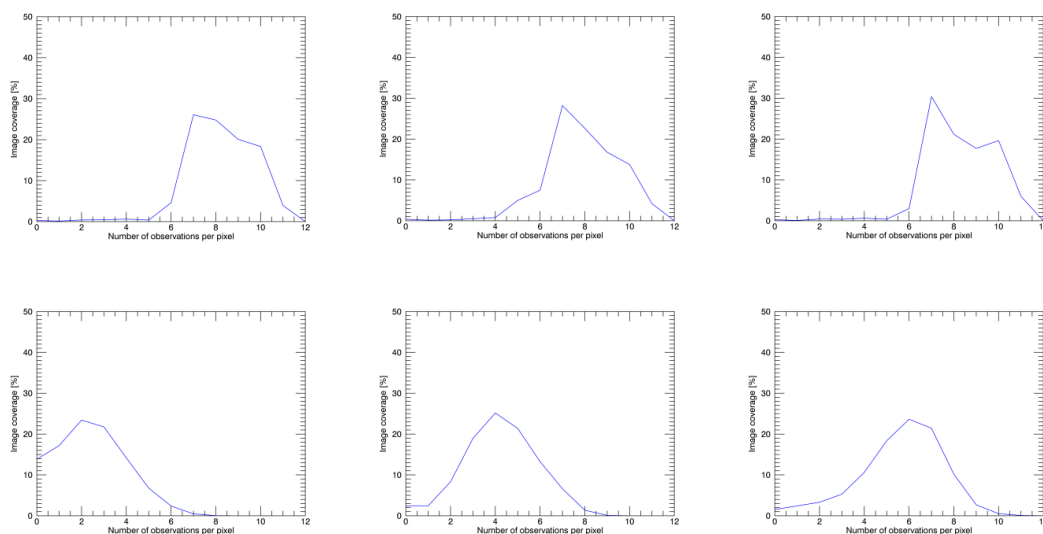


Figure 6. Histograms representing image coverage with observations per pixel (top row) and image coverage with useful observations per pixel (bottom row) for the Europe mosaic in January, April and August 2015 (by columns)

The graphs in Figure 6 represent the coverage of the mosaics with different number of observations per pixel. Graphs in the first row show the number of all available observations per pixel. The shapes of the curves are similar and comparable throughout the year. Graphs in the second row show only the number of observations per pixel that proved useful and were selected for the compositing. As expected, the shape of the observation's distribution stays the same for every month, whereas its mean value changes dramatically: from only two useful observations in winter months to near seven observations per pixel in summer months.

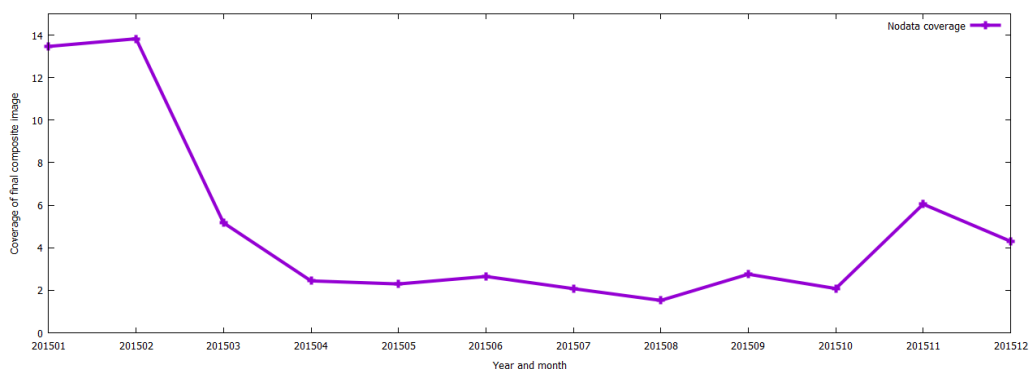


Figure 7. Percentage of nodata values in the final mosaiced composite image of Europe. The graph is similar for all compositing approaches

The graph in Figure 7 shows the percentage of nodata values in the mosaic. Pixels with nodata values are those with zero reflectance, are not defined or are extreme outliers in all of the spectral bands. Some areas of the mosaic will always have nodata value as parts of the oceans are not acquired by the PROBA-V satellite Earth observation plan. Otherwise, the pattern is reasonable, expected and informative: most nodata values in the final mosaiced composite image are accounted during winter months. Lack of useful pixels can be attributed to snow cover and enhanced cloud coverage – typical for the winter season in Europe. On the other hand, we also observed that there are other areas, besides oceans, uncovered in the monthly composite image – regardless of the month of satellite images acquisition. This suggests that the five-day frequency of PROBA-V 100 m data acquisition plan might be insufficient for some areas to get one clear (and thus useful) observation per month.

3.3 Invalid data coverage

Invalid data represent unexpected or irregular values for a particular vegetation product under observation. For example, for the NDVI, expected, allowable and useful values are in the value range between $[-1, 1]$. Invalid (vegetation) index values were defined as index pixels whose reflectance is zero (or not defined) in RED or NIR spectral bands and not classified as nodata/background pixel. The graph in Figure 8 shows the percentage of invalid index values in the vegetation index mosaic for two compositing approaches.

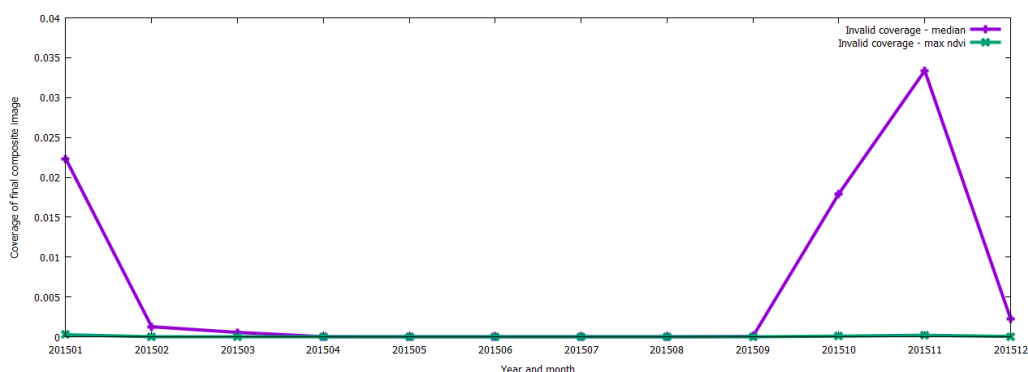


Figure 8. Percentage of invalid values in the mosaiced composite image for median and max NDVI compositing approaches

Indices calculated from the zero-valued reflectances most likely result in unreliable index values, and should be avoided in further processing steps. Recognition and reclassification of invalid index data are considered of utmost importance. Namely, minimum or maximum index compositing methods would select exactly those values as they are located at the extreme minimum or maximum interval of the possible (regular) index values and would be therefore preferred by the selected compositing algorithm.

4 CONCLUSION

In the study, the potential of PROBA-V 100 m imagery for the generation of large-scale vegetation products was successfully demonstrated. This suggests that monitoring on a global scale is becoming accessible in higher (medium) spatial resolutions as an alternative to standard few-hundred meters vegetation products. To assure repeatable and regular time series of composite products it would be beneficiary to have daily observations to work with, as in some areas a five-day observation frequency cannot provide a single valid observation over the entire monthly period.

As the processing of large areas requires huge storage capabilities and computer time, we limited our study to the extent of Europe. Using the equal masking procedure, we created composites with different compositing strategies. To assess the effect of image compositing on vegetation indices, we selected maximum NDVI composite as a standard reference image and compared the results to the median method. It was found out that the default (i.e. standard max NDVI) compositing approach does not always select the best reflectance values if homogeneous composites are sought for. Thus, other compositing approaches should also be considered in large scale studies.

When using a compositing approach, it is important to know the characteristics of specific geographical regions, such as the temporal and spatial presence of clouds, topography, dynamics of landscape processes, phenology, and availability of satellite data. Likewise, the need for specific information (e.g., mapping of disturbances, estimation of biophysical parameters) may dictate a compositing strategy, target periods and other application-specific compositing rules. Generally, it is desirable to create composites that consistently summarize vegetation phenology, where patches without data are minimized, and best represent the observed phenomenon (e.g., land cover classes, forest structural attributes, or specific disturbance events).

Composites represent a paradigm in remote sensing that is no longer reliant on scene-based analysis. A time series of these best available pixel image composites fosters novel opportunities to generate information products characterizing land cover, land cover change, and forest structural attributes in a manner that is dynamic, transparent, systematic, repeatable, and spatially exhaustive – in steadily increasing spatial resolutions.

Acknowledgement:

This research was funded by the European Space Agency project, under the ESA's PECS programme (Development of PROBA-V 100 m Vegetation Products). The authors also acknowledge the financial support from the Slovenian Research Agency for the core research funding of Anthropological and Spatial Studies, No. P6-0079 and the core research funding of Astrophysics and Physics of the Atmosphere, No. P1-0188.

This research was also partially funded by the Slovenian Research Agency, under the grant J2-9251 (M3Sat – Methodology of Multitemporal Multisensor Satellite Image Analysis) and grant J6-9395 (High-resolution drought monitoring based on satellite and ground data).

REFERENCES

- Cabral, A., de Vasconcelos, M.J.P, Pereira, J.M.C., Bartholome, E., Mayaux, P. (2014). Multi-temporal compositing approaches for SPOT-4 VEGETATION. *Int. Journal of Remote Sensing*, 24 (16), 3343-3350.
- Cihlar, J., Manak, D., D'Iorio, M. (1994). Evaluation of Compositing Algorithms for AVHRR Data over Land. *IEEE Transactions on Geosciences and Remote Sensing*, 32 (2), 427-437.
- Dennison, P.E., Roberts, D.A., Peterson, S.H. (2007). Spectral shape-based temporal compositing algorithms for MODIS surface reflectance data. *Remote Sens. Environ.*, 109, 510-522.
- Dierckx, W., Sterckx, S., Benhadj, I., Livens, S., Duhoux, G., Van Achteren, T., Francois, M., Mellab, K., Saint, G. (2014). PROBA-V mission for global vegetation monitoring: standard products and image quality. *Int. Journal of Remote sensing*, 35, 2589-2614.
- Franz, D., Röder, A., Stellmes, M., Hill, J. (2017). Phenology-adaptive pixel-based compositing using optical earth observation imagery. *Remote Sensing of Environment*, 190, 331-347.

Fraser, A.D., Massom, R.A., Michael, K.J., (2009). A method for compositing polar MODIS satellite images to remove cloud cover for landfast sea-ice detection. *IEEE Trans. Geosci. Remote Sens.*, 47 (9), 3272–3282.

Griffiths, P., Van der Linden, S., Kuemmerle, T., Hostert, P. (2013). A Pixel-Based Landsat Compositing Algorithm for Large Area Land Cover Mapping. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 6 (5), 2088-2101.

Holben, B.N. (1986). Characteristics of maximum-value composite images from temporal AVHRR data. *Int. Journal of Remote sensing*, 7/11, 1417-1434.

Lück, W., van Niekerk, A. (2016). Evaluation of a rule-based compositing technique for Landsat-5 TM and Landsat-7 ETM + images. *Int. J. Appl. Earth Obs. Geoinf.*, 47, 1-14.

Maisongrande, P., Vandenabeele, J., Malingreau, J.P., Lobo, A., de Fourny, P., Gonthier, E., Mellab, K., Kleihorst, R. (2010). PROBA-V, A Satellite for the Continuity of the SPOT/VEGETATION Mission. *EGU General Assembly Conference Abstracts*, 2010, Vol. 12, p. 14202.

Qi, J., Kerr, Y. (1997). On current compositing algorithms. *Remote Sensing Reviews*, 15, 235–256.

Sterckx, S., Benhadj, I., Duhoux, G., Livens, S., Dierckx, W., Goor, E., Adriaensen, S., Heyns, W., Van Hoof, K., Strackx, G., others (2014). The PROBA-V mission: image processing and calibration. *Int. Journal of Remote sensing*, 35, 2565-2588.

Wang, L., Xiao, P., Feng, X., Li, H., Zhang, W., Lin, J. (2014). Effective Compositing Method to Produce Cloud-Free AVHRR Image. *IEEE Geoscience and Remote Sensing Letters*, 11(1), 328-332.

Authors:

Tatjana Veljanovski, PhD

Scientific Research Centre of the Slovenian Academy of Sciences and Arts
Novi trg 2, SI-1000 Ljubljana
Slovenia
tatjana.veljanovski@zrc-sazu.si

Klemen Čotar, B.Sc

Faculty of Mathematics and Physics, University of Ljubljana
Jadranska 19, SI-1000 Ljubljana
Slovenia
klemen.cotar@fmf.uni-lj.si

Aleš Marsetič, PhD

Scientific Research Centre of the Slovenian Academy of Sciences and Arts
Novi trg 2, SI-1000 Ljubljana
Slovenia
ales.marsetic@zrc-sazu.si