SIX YEARS OF SENTINEL-2 ARCHIVE OF SLOVENIA

ŠEST LET ARHIVA PODATKOV SENTINEL-2 ZA SLOVENIJO

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IZVLEČEK

Sentinel-2 je visokoločljivostni optični satelitski sistem, ki ga je za Evropsko komisijo razvila Evropska vesoljska agencija (ESA). Trenutno sta v tirnici dva satelita tega sistema: Sentinel-2A od 23. junija 2015, od 7. marca 2017 pa še Sentinel-2B. Par Sentinel-2A in Sentinel-2B vsakih pet dni posname isto območje iz iste tirnice. Z izjemo prvih šestih obratovalnih mesecev (tj. druga polovica 2015) zagotavlja Sentinel-2, še posebej dvojna konstelacija, zelo stabilen vir podatkov.

Že od samega začetka satelitske misije na Znanstveno-raziskovalnem centru Slovenske akademije znanosti in umetnosti (ZRC SAZU) vzdržujemo arhiv podatkov Sentinel-2 za območje Slovenije. Podatke shranjujemo v originalni obliki (tako imenovani produkti L1C) ter v štirih stopnjah nadaljnje obdelave. Arhiv zdaj deluje šest polnih let, kar je zadostno obdobje za statistični pregled. Arhiv podatkov Sentinel-2 smo proučili z različnih vidikov in na ravni vse države. Največ pozornosti smo namenili deležu oblačnosti. S tem, ko pridobimo vpogled v časovno-prostorsko razporeditev oblačnosti, najbolje ocenimo, koliko so optični podatki dejansko uporabni.

ABSTRACT

The Sentinel-2 is a high resolution optical satellite mission, developed by the European Space Agency (ESA) for the European Commission. Currently the mission has two satellites in orbit: Sentinel-2A from 23rd June 2015, and Sentinel-2B from 7th March 2017. Revisit time for this twin constellation is five days. The twin satellites represent a very stable data source, but for the first six operational months (i.e. the second half of the 2015).

From the very start of the mission, the Research Centre of the Slovenian Academy of Sciences and Arts (ZRC SAZU) is collecting its own archive of Sentinel-2 data for the extent of the Republic of Slovenia. The data is saved in its original processing state (Level-1C) and in four levels of processing. The archive has now been operating for six full years, which is a good milestone for a statistical overview. We analyse the archive of Sentinel-2 data of Slovenia from several aspects at the country level. A special focus is placed on cloud cover, as only cloud-free data can give an impression of the actual spatial and temporal usability of optical data.

KLJUČNE BESEDE

Sentinel-2, arhiv, satelitski podatki, časovna vrsta satelitskih posnetkov, stopnja oblačnosti, Slovenija

KEY WORDS

Sentinel-2, archive, satellite data, satellite image time series, cloud cover, Slovenia

1 INTRODUCTION

The Sentinel-2 is an optical satellite mission, developed by the European Space Agency (ESA) for the European Commission as a part of the Copernicus Earth Observation Programme. Copernicus programme aims to observe Earth systematically and to provide accurate, timely and easily accessible information of the environment over a long period.

What makes the Copernicus Sentinel mission so important is its policy of free and open access to data. The Sentinel-2 mission is revolutionizing high-resolution optical Earth observation thanks to its pioneering policy of open access, systematic and frequent acquisition, global coverage, and, above all, data quality (Drusch et al., 2012). According to the Copernicus Open Access Hub last published annual report the use of Sentinel data significantly jumped in 2019 and has been growing ever since (ESA Copernicus Statistic, 2021).

The Sentinel-2 mission has now two satellites in orbit: Sentinel-2A (S-2A) from 23rd June 2015, and Sentinel-2B (S-2B) from 7th March 2017, each having a 7.25-year lifetime with consumables sized for 12 years. The next generation satellites, the Sentinel-2C and Sentinel-2D, are being built by Airbus Defence and Space, and are planned to be launched in 2024 and 2025, respectively, when S-2A and S-2B will reach their end of life.

Sentinel-2 satellites carry a high-resolution optical multispectral instrument with 13 spectral bands and acquire data with a 290 km wide swath and at three resolutions: 10 m (4 bands), 20 m (6 bands) and 60 m (3 bands), thus ranging somewhere between high and medium resolution (Drusch et al., 2012). Revisit time – repetition of acquisition from the same relative orbit – is ten days for each individual satellite. Because S-2A and S-2B are positioned in the same sun-synchronous[1] nearly polar-orbit, phased at 180° to each other, the revisit time for this twin constellation is five days. Despite nominally frequent observations, the utility of optical satellite data can be limited because cloud cover prevents the collection of surface information below the clouds.

Sentinel data is accessible, depending on the mission and type of data, through the Conventional Data Access Points (CDAP) of ESA and EUMETSAT[2], as well as through the Copernicus Data and Information Access Services (DIAS) platforms, which provide (partial) mirrors of the data[3], Thematic Exploitation Platforms (TEPs)[4], regional Copernicus Collaborative Ground Segment data services[5] and other well-known gateways[6] or platforms for the rapid display, query and retrieval of satellite data from these data centres (among these, we would like to highlight in particular the Sentinel Hub platform, which is very successfully operated by the Slovenian company Sinergise) (ESA Sentinel Data Access, 2021; ESA Earth Online, 2021). The DIAS nodes and other gateways commercially provide advanced computing services in addition to access to their mirrors.

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[1] *Time of satellite pass is synchronised with the Sun, so the satellite observes any given point of the Earth's surface at the same local time. Thus, the acquisition time of Slovenia is always around 10:00 UTC (Coordinated Universal Time). In local time this is around 11:00 CET (Central European Time), and in daylight saving time period around 12:00 CEST (Central European Summer Time). Exact acquisition times of Slovenia vary from 09:50 UTC to 10:15 UTC.*

[2] *Examples of ESA and EUMETSAT access points: ESA Copernicus Open Access Hub, Copernicus Space Component Data Access – CSCDA, EUMETSAT EUMETCast, EUMETSAT Copernicus Online Data Access – CODA.*

[3] *Examples of DIAS: ONDA, Sobloo, CreoDIAS, Mundi Web Services.*

[4] *Examples of TEPs: TEP for Forestry, for Food Security, for Urban, for Hydrology.*

[5] *E.g.: TerraScope, SARA – Sentinel Australasia Regional Access.*

[6] *Examples of well-known gateways: Amazon Web Services, USGS Earth Explorer, Google Earth Engine, Open Data Cube, PROBA-V MEP, RUS, NoR, CNES PEPS, Alaska Satellite Facilities.*

While cloud platforms and network infrastructures/hubs are predominant in Europe today, some countries have developed their own data infrastructure in the last decade and established national data cubes or data centres where satellite data are linked and archived with other open government geospatial data[7]. Major initiatives are currently underway by combining space agencies, government and commercial entities to develop targeted data cube environments on a continental scale[8], with the overall aim of enabling a mapping environment with satellite data for government, research and commercial needs.

Interagency Committee on Earth Observation Satellites (CEOS) is advancing the production and distribution of Analysis Ready Data (ARD) to foster rapid, robust, and automated use of Sentinel data, and to enable interoperability both over time and with other datasets, e.g. with Landsat (CEOS, 2020). Data producers, e.g., space agencies (NASA, ESA, JAXA etc.) and major data delivery and access centres (cloud platform providers, regional data hubs) are now accelerating this challenging task to achieve the integration and combination of consistent and comparable data.

From the start of Sentinel-2 mission, the Research Centre of the Slovenian Academy of Sciences and Arts (ZRC SAZU) is collecting its own archive of Sentinel-2 data for the extent of the Republic of Slovenia. We choose to keep the Sentinel-2 data in house for several reasons:

- continuation of many years of experience and algorithm development for geometric and radiometric pre-processing of satellite data,
- enabling data processing on demand for experienced users and researchers,
- enabling durable, and stable service provision and data access for the territory of Slovenia for interested users (research, government).
- The archive is not available on-line however it may be collected for research purposes upon request. We collect data in the original processing state (as downloaded; the standard Sentinel-2 Level-1C products) and provide products in different levels processing:
- geometric transformation (reprojection),
- atmospheric correction with cloud screening,
- topographic correction,
- spatial mosaicking and temporal compositing, and
- bio-physical products (ranging from vegetation, water and soil indices).

The archive has now been operating for six full years, which is a good milestone for short-term statistical overview.

Analytical studies of satellite data archives are not very common. In this paragraph we present few existing approaches found in literature. A statistical study of an archive was done by Wulder et al. (2016) for the global Landsat archive, that has the longest history of all satellite data, lasting for 50 years. The authors give a comprehensive analysis of the archive, providing mostly information on the number of acquired images per area. They do not, however, deal with cloud cover in particular, but show the differences in global record coverage, backed by Landsat program operation. Sudmanns et al. (2020) did similar thorough statistical analyses from metadata of all Sentinel-2 images acquired in 2017. They state that

[7] *Examples of national data centres: Austrian Data Cube Archive (ACube) hosted by EODC; German Satellite Data Archive (D-SDA); French Theia Land Data Centre; Belgian Centre for image processing (CVB), hosted by VITO; Australian CSIRO Centre for Earth Observation, supporting Australian Open Data Cube.*

[8] E.g.: *Digital Earth Australia, Digital Earth Africa.*

data coverage and quality are far from homogeneous, therefore higher acquisition frequencies do not necessarily yield more cloud-free scenes. They also expose some quality issues, e.g., systematically incorrect cloud cover estimation (over-detection) in high non-vegetated altitudes (e.g., Himalayas, Andes). Li and Roy (2017) reflected on one part of the capabilities of existing Sentinel-2 data archive, that is the revisit time of S-2A and S-2B in combination with Landsat 8. Corbane et al. (2020) examined the Sentinel-2 records for the composition of the global cloud free pixel-based Sentinel-2 composite.

Our paper discusses another possible aspect of archive overviewing: a user-oriented view and focus to the practical usability of Sentinel-2 imagery to analyse the given study area, for example, a country. This perspective is partly dictated by the small size of Slovenia (20.271 km^2) and expected needs from different domains (e.g., agriculture, nature preservation, hazards) to systematically monitor natural gradual processes or those abruptly induced on Earth surface on a country level.

2 MATERIALS AND METHODS

2.1 Study area and data accessing

Slovenia is a Central European country, characterised by a very diverse topography and climatic regime, combining four major macro-regions – the high Alps with the pre-Alpine hills, the rugged Dinaric Alps, the flat land of the Pannonian Plain with its hilly edge, and the Mediterranean hills with the moderating effect of the Adriatic Sea (Perko, Ciglič, and Zorn, 2020). The great topographic diversity of mountains, hills and plains, coupled with the historically fragmented nature of agricultural land and a range of contemporary land-use practices, makes Slovenia an excellent test bed for the full range of Earth observation data processing and monitoring development.

Our operational workflow for processing Sentinel-2 data of Slovenia consists of regular downloading of Sentinel-2 imagery from the Copernicus Open Access Hub and systematic processing (Figure 1). This includes adaptation of Earth observation data for use with national geoinformation data sources, where reprojection to the national reference system (Slovene national grid D96, EPSG 3794) is a baseline for most users.

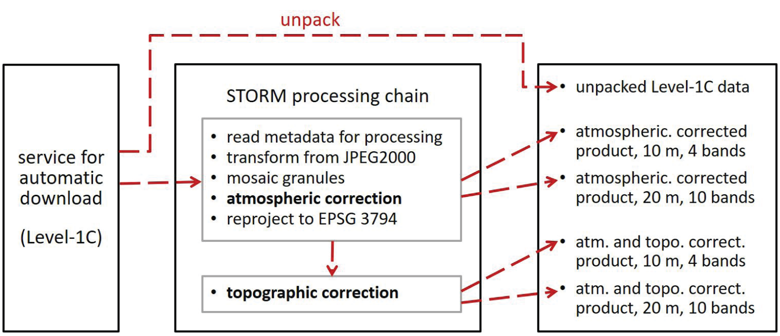

Figure 1: Implemented workflow for processing Sentinel-2 data of Slovenia.

The lowest processing level of Sentinel-2 data that is available to the general public is orthorectified top -of-the-atmosphere (TOA) reflectance product, denoted as Level-1C (Thales Alenia Space, 2021). The reference system used for the Level-1C data is the Universal Transverse Mercator (UTM) on the WGS84 ellipsoid. Based on the fixed UTM grid, each image acquisition[9] is split into several tiles (*granules*) of approximate size 110 × 110 km², having 10 km overlap on all four sides. Products are delivered in the Standard Archive Format for Europe (SAFE). Up to September 26 2016, each SAFE-format product was a *multi-tile* product, including up to 14 tiles and covering a fixed area of approximately 290 km (across-track) by 325 km (along-track). On September 27 2016 ESA moved to a *single-tile* format where each SAFE product includes one tile only.

Slovenia is covered by seven S-2 tiles (Figure 2) (ESA Tiling Grid, 2017). All tiles are in the same UTM zone (UTM 33 North), thus no additional problems with zone mixing arise (Roy at al., 2016).They are acquired from three acquisition orbits[10]: 022, 122 and 079. Because Slovenia is located at mid-latitudes (centre-point roughly around 45°N, 15°E), the overlap of swaths of neighbouring orbits is already substantial, exceeding 100 km (Li and Roy, 2017) (Figure 3).

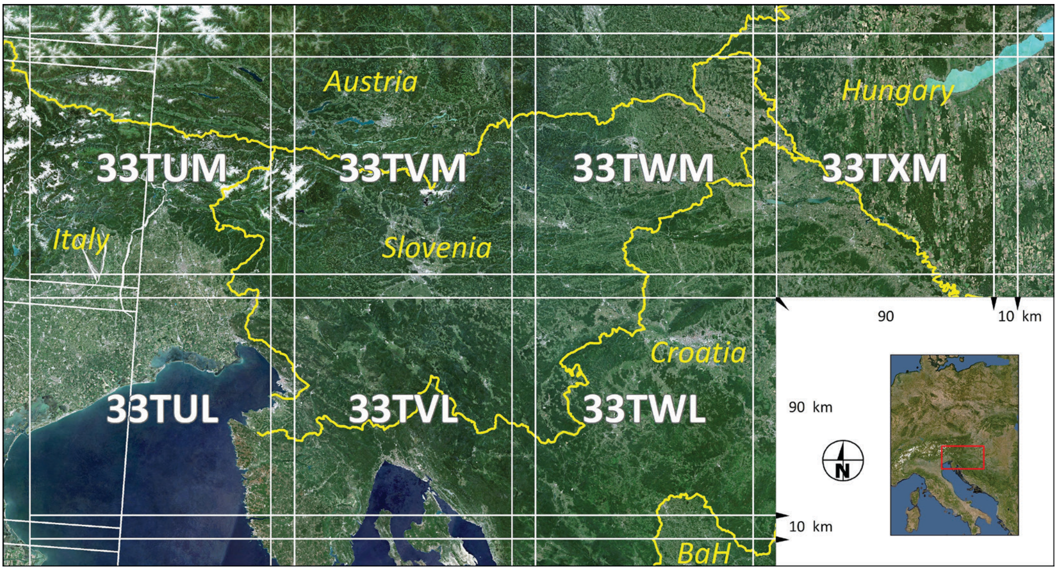

Figure 2: In ESA Sentinel-2 tiling grid Slovenia is covered by seven 110 x 110 km2 tiles in UTM 33 North zone (33TUM to 33TWL). Background image for small overview image is taken from European Environment Agency (EEA).

The ESA Copernicus Open Access Hub (formerly known as Sentinels Scientific Data Hub) provides free and open access to the user products Sentinel-1, Sentinel-2, Sentinel-3 and Sentinel-5P. We have built our archive on top of the API Hub of the Copernicus Open Access Hub portal (https://scihub.copernicus.eu/), because it enables a scripting interface for automatic bulk downloads of Sentinel-2 imagery.

In the implemented workflow, each Level-1C product is downloaded as a single packed ZIP file. Each ZIP file contains multiple tiles in multi-tile format, or only one tile in single-tile format. Each tile contains

[9] *In ESA terminology image acquisition is called datatake (meaning: continuous acquisition of an image during the same pass), and tile is called granule.*

[10] *In ESA nomenclature the numbers denoting the acquisition orbits are called relative orbit numbers; they are fixed, ranging from 1 to 143. On the other hand, the term absolute orbit number refers to current pass, so it increases with each pass.*

13 raster files – one per spectral band – in JPEG2000 format and over 100 supplementary metadata files in XML and GML formats, starting from the main metadata file manifest.SAFE, as defined in the specifications for the SAFE-format.

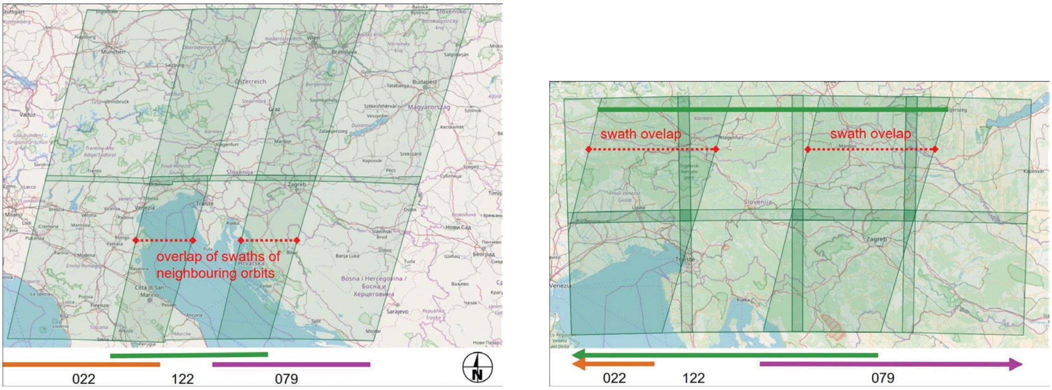

Figure 3: Acquisition of Sentinel-2 images over Slovenia from three orbits: 022 (west part; at the bottom of the figures marked by orange line), 122 (whole Slovenia; note: only these images contain central part of Slovenia; green line) and 079 (east part; violet line), as seen on both screen-shots from Copernicus Open Access Hub. The roughly 100 km overlap between the images acquired from neighbouring orbits can be seen (red dotted line). Right figure: In the old format two adjacent multi-tile SAFE products had to be downloaded per each acquisition, summing up to 28 tiles. On this figure the footprints of six whole SAFE products are shown (however, areas covered by individual tiles are not shown). Left figure: In the currently valid single-tile format 4 to 7 SAFE products – each containing one tile –, have to be downloaded per acquisition to cover Slovenia.

2.2 Data processing

The images are first renamed from vendor-oriented sensor-priority names S2A/B_* to more user-friendly analysis-oriented date-priority names YYYYMMDD*, and they are then processed with our standard pre-processing workflow, implemented with STORM processing chain (Zakšek et al., 2015; Pehani et al., 2016). The STORM delivers atmospherically and topographically corrected Sentinel-2 products for the extent of Slovenia, reprojected into national projection D96TM, EPSG 3794 (EPSG.IO, 2021). Images undergo the following processes:

- for each tile the corresponding metadata is read and all 13 bands are converted from JPEG2000 to GeoTIFF and stacked into a single 13-band file;
- the tiles of the same acquisition are mosaicked into a uniform satellite image in its source projection (UTM 33 North);
- the mosaic image is atmospherically corrected using ATCOR-2 (ReSe Applications, 2021) and an enhanced mask is computed that includes clouds and cirrus classes as well as classes haze, snow, water and shadows;
- the image is reprojected into the Slovene national projection D96TM and cropped to Slovenia.
- The topographic correction is performed in a separate execution, only for images with cloud cover of less than 75%.

To sum up: In addition to original Level-1C product four products are calculated by the described workflow, i.e. two levels of processing in two resolutions (Table 1). For the 4-band 10 m products, the processing workflow is executed only with four 10 m-resolution bands (blue, green, red, near-infrared). For the 10-band 20 m product the processing workflow is executed with all 13 bands, however the three 60 m bands are removed after the completion of atmospheric correction. After the pre-processing the products are equipped with the enhanced mask of anomalies, ready for use with other national geoinformation data sources, and available also for calculation of different vegetation, water or soil indices, temporal composites (e.g., monthly cloud free mosaics), satellite image time series and similar.

Table 1: Quantities of Sentinel-2 archive data of Slovenia of original Level-1C imagery and four types of processed products. Quantities in the last column are calculated for the Sentinel-2 twin constellation, so they are valid from 2018 onwards.

product abbreviation	product description	approx. number of products per year	approx. data storage demand per year [TB]
Level-1C	orthorectified UTM33N TOA reflectance ESA product, 13 bands, resolutions 10, 20, 60 m	217	0.7
atm_10m	atmospherically corrected product, 10 m, 4 bands, D96TM projection	217	2.2
atm_20m	atmospherically corrected product, 20 m, 10 bands, D96TM projection	217	1.5
atm_topo_10m	atmospherically and topographically corrected product, 10 m, 4 bands, D96TM	155*	0.8
atm_topo_20m	atmospherically and topographically corrected product, 20 m, 10 bands, D96TM	155*	0.5

** Topographically corrected products are calculated only for images with cloud cover of less than 75%.*

3 RESULTS AND DISCUSSION

In this chapter, we describe and discuss the statistics on the Sentinel-2 data of Slovenia for the six and a half year period, i.e. from the second half of 2015 to the end of 2021. Because usability of optical data strongly depends on the presence/absence of clouds, the most attention is focused to quantification of cloud cover. We discuss archive statistics from different perspectives, ranging from the total number of acquisitions per area and per time period, detailed cloud cover data by year and by season, to the possibility of creating cloud-free mosaics or dense satellite image time series. We also stress the importance of knowing the basics of the ESA image processing. We conclude this chapter with some examples of use of Sentinel-2 data.

3.1 The archive in numbers

3.1.1 Number of acquisitions per month

The first scene of Slovenia was taken on 28 June 2015. Data collection was not very systematic in 2015, i.e., the first operational half-year of the mission (see Figure 4). From the perspective of a user who needs largely stable and dense satellite image time series, a better dataset starts in 2016. Full availability of the mission data starts with July 2017 when both satellites became operational. The number of monthly acquisitions for the twin constellation is 17 to 19 (variations are due to variable fitting of orbital passes into the yearly calendar, and naturally also due to different months' lengths).

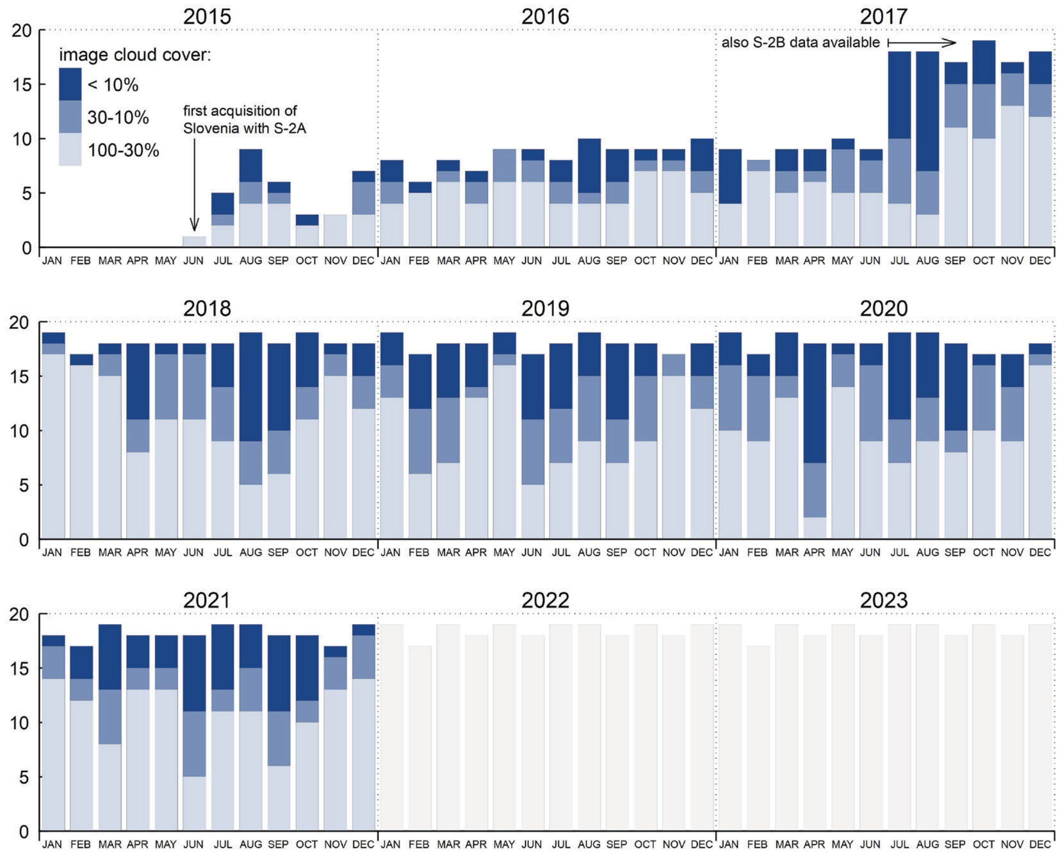

Figure 4: Number of acquisitions of Slovenia per month and image cloud cover. When the S-2B became operational in July 2017, the number of acquisitions doubled. In some months there are no cloud-free images (e.g., May 2016, Feb. 2017, Nov. 2019). In general, most images with less than 10% cloud cover are acquired in summer months (July, August, September), with some notable exceptions (e.g., April 2020). For details see also Figure 8.

3.1.2 Number of acquisitions in swath overlapping areas

From the perspective of spatial coverage, the S-2A and S-2B constellation acquires the central part of Slovenia with revisit time of five days (thus t_0, t_0+5d, …), while – due to considerable swath overlaps – the eastern and western parts of Slovenia are acquired twice in five days (the date sequence is t_0, t_0+2d, t_0+5d, t_0+7d, … on the east side, while on the west side it is t_0, t_0+3d, t_0+5d, t_0+8d, …, where t_0 is the date of arbitrary acquisition of the central part of Slovenia) (Figure 5). For the twin constellation, this results in 73 acquisitions in the central part of Slovenia, and in 146 (exactly double number) acquisitions per year in overlapping areas on the east and west. This yields at maximum 219 acquisitions per year – theoretically; in practice one or two images per year are missing due to maintenance operations –, which demand a 5.7 TB of storage for the original Level-1C and all processed variations of products (Table 1).

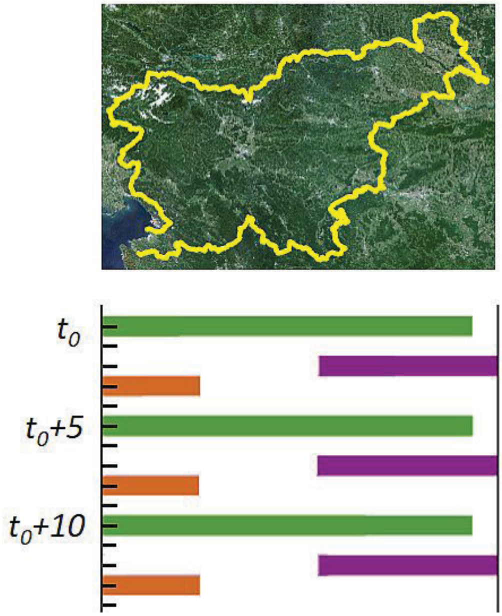

Figure 5: The graphic schematically shows sequence of acquisitions on the y-axis, and coverage of Slovenia on x-axis. Whole Slovenia including central part is acquired only from orbit 122 (green bar), while the east and west part are acquired also from the orbits 079 (violet bar) or 022 (orange bar). Revisit time for the central part is five days. On the other hand, east and west Slovenia is acquired twice in five days.

3.1.3 ESA processing baseline versions

This section gives short insight how in parallel with the ever-growing number of Sentinel-2 images worldwide, the ESA processing environment has also been gradually upgraded. The common user of the Sentinel-2 data is not very familiar with the ESA versioning of the processing and products (and there is no need for that), however some general awareness should be kept in mind in the background that ESA versioning of processing chain exists and that this information can become important when using and processing Sentinel-2 data.

ESA systematically processes Sentinel-2 data into the Level-1C products utilizing – at the moment of processing – the latest valid version of its processing environment. Since the latter was matter of several changes with time, it is obvious, that the products are not homogeneously processed. The processing environment version that ESA uses for product generation is thus important, however, it is e.g., not available in the image search forms on Copernicus Open Access Hub and other popular access points; this information is hidden in the metadata file.

An ESA term *processing baseline* code includes versions of three processing support packages (Thales Alenia Space, 2021):

- the processing chain version;
- the version of its configuration parameters;
- the version of supplementary data (both static, such as digital elevation model used, and dynamic, such as atmospheric data or precise orbital data).

For the first five and a half operational years, ESA used subversions of the processing baseline of version 02 (ESA Processing Baseline, 2021). The initial operational processing baseline 02.00, released on 23rd November 2015, needed several updates and consolidations before the first stable subversion 02.04 was released on 15th June 2016. ESA therefore performed several re-processing campaigns of the Level-1C data.

Table 2 shows processing baseline versions of images of Slovenia in our archive. The table data reveal that ESA did not yet manage to reprocess all its oldest images data with the processing baseline 02.04 or higher. The remaining images processed with less favourable subversions 02.01 or 02.02 are all from the second half of 2015 and the first half of 2016.

The first major upgrade of the processing baseline to version 03 was on 30th March 2021. It introduced geometric refinement along with the use of the new Copernicus Digital Elevation Model (COP-DEM) of 90 m resolution (ESA Processing Baseline, 2021). This greatly improved the geometric accuracy of the Sentinel-2 images. According to ESA Data Quality Report (ESA Data Quality Report, 2021), the long-term geometric performance for products processed with processing baseline of version 02 is 11 m (i.e., 1.10 pixels) at 95.0% confidence level for both satellites. On the other hand, preliminary results for products processed with processing baseline of version 03.00 show much better results, with an absolute geolocation error of 5.5 m and 5.0 m (i.e., 0.55 and 0.50 pixel) at 95.5% confidence for S-2A and S-2B, respectively, suggesting the expected and desired geometric half-pixel accuracy of satellite products.

Table 2: Archive images of Slovenia sorted by the ESA processing baseline sub-version. In general, newer images are processed with newer processing baselines. Images marked with red need to be reprocessed by ESA. Images marked with green are processed with the substantially improved versions 03.+.

sub-version of the ESA processing baseline	02.01	02.02	02.04	02.05	02.06	02.07	02.08	02.09	03.00	03.01
number of acquisitions	34	15	120	87	226	145	125	249	55	110

3.2 Cloud cover

3.2.1 Cloud cover per year and per season

General requirements for the quality of optical satellite data for most applications include precise geometric accuracy (orthorectification) and steps for cloud detection and atmospheric correction (obtaining cloud-free surface reflectance). The presence of clouds causes spatial and temporal data gaps in the time series of observed phenomena. In addition, monitoring of large areas is often not possible in a single satellite overpass, and users must rely on data collected on different days with different cloud cover. The presence of clouds is a natural disturbance; their occurrence is partly related to the season and geographical location. In this context, we have observed the occurrence of clouds in the Sentinel-2 data collected so far for Slovenia.

Table 3 shows the statistics of cloud cover per year and per cloud percentage class as calculated in our STORM workflow for atmospherically corrected 10-band products with a resolution of 20 m (see Table 1, row atm_20m). In the combined class »clouds« we gather all thick layers detected during the atmospheric correction that are impenetrable, so that observation the of Earth's surface is not possible. This represents a collection of ten atmospheric correction classes (clouds, medium and thick cirrus clouds and medium to thick haze over land or over water). We distinguish them from the »snow« class, which is also impenetrable, and from the penetrable »thin layer« classes (this is a collection of four classes: thin to medium haze and thin cirrus over land or over water), which still allow the assumption of actual pixel reflectance.

The mean cloud cover of all processed images is 42.2%. This data alone suggests that the expected cloud cover for an arbitrary image is quite high. The share of images that are generally considered cloud-free and that are having cloud cover less than 10% is 22.2%, while the share of images that are generally considered unusable for Earth observation (except for cloud studies) because they have cloud cover greater than 90% is 10.9%. The distribution of cloud cover between years is quite stable, with the yearly mean cloud cover for six inspected years being only 3% higher and lower (i.e. less and more favourable) in extreme years 2018 and 2020 than the 2016-2021 average (Figure 6).

Table 3: Number of acquisitions of Slovenia per cloud coverage classes and per year.

cloud cover [%]	< 1	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-99	> 99	total
2015	2	6	5	2	2	5	2	4	3	2	0	1	34
2016	4	17	11	8	7	15	7	7	6	9	6	5	102
2017	7	33	20	16	12	14	6	13	11	16	4	9	161
2018	12	31	22	17	19	19	20	18	20	15	14	11	218
2019	14	34	32	17	11	15	20	19	15	16	11	12	216
2020	14	36	28	23	21	20	10	17	13	12	18	5	217
2021	12	36	17	23	30	23	13	13	9	11	22	9	218
total	**65**	**193**	**135**	**106**	**102**	**111**	**78**	**91**	**77**	**81**	**75**	**52**	**1166**
share [%]	5.6	16.6	11.6	9.1	8.7	9.5	6.7	7.8	6.6	6.9	6.4	4.5	100.0

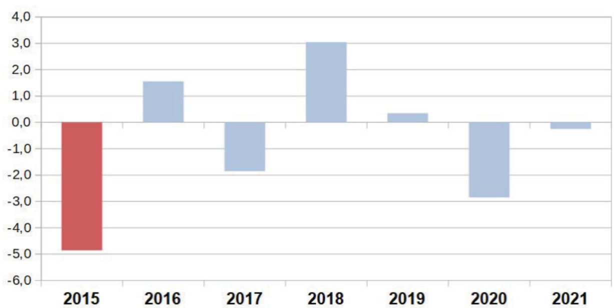

Figure 6: Difference between the yearly mean cloud cover for years 2015 to 2021 and the 2016-2021 average. The value given for 2015 should be taken with caution due to small number of acquisitions.

More detailed data per season (with thresholds of 21 March, 21 June, 23 September and 21 December) and per region (presented by acquisition orbit) can be found in Table 4. The calculated data are completely in tune with expectations. They confirm known climatology facts that in our mixed Alpine-Mediterranean country summer is the driest and least cloudy season and that the autumn and winter months are the wettest and cloudiest. Some examples of Sentinel-2 mosaics over the seasons and the different cloud cover conditions are shown in Figure 7 and summarised in Table 5.

Table 4: Variability of mean cloud cover per season and per area (i.e., acquisition orbit). Extremes are marked with green and red colour.

mean cloud cover [%]	Winter total (022/122/079)	Spring total (022/122/079)	Summer total (022/122/079)	Autumn total (022/122/079)	mean per whole year
2015	-	-	34.3 (30.4/24.2/52.3)	49.6 (41.1/46.7/63.9)	37.6
2016	46.1 (49.2/36.5/51.7)	47.0 (56.6/37.3/45.0)	35.6 (39.7/29.7/36.7)	46.5 (39.0/45.1/54.4)	44.0
2017	48.1 (51.5/43.3/48.9)	39.0 (36.7/33.6/47.2)	29.1 (34.4/29.0/23.8)	47.4 (41.6/52.9/47.3)	40.6
2018	65.9 (69.0/61.0/67.6)	37.6 (47.6/35.0/30.0)	29.6 (25.9/26.5/36.4)	49.6 (52.2/53.5/43.2)	45.4
2019	42.2 (35.4/46.9/44.2)	48.4 (52.7/44.8/48.1)	28.5 (34.5/26.3/24.5)	54.1 (48.4/65.6/49.6)	42.8
2020	37.1 (35.3/41.9/34.1)	38.4 (37.7/50.9/25.9)	29.0 (24.9/37.4/24.7)	51.4 (41.4/59.4/53.1)	39.6
2021	49.9 (55.6/47.6/46.5)	42.4 (36.5/31.9/59.4)	30.2 (32.4/34.4/23.7)	47.6 (44.8/59.2/38.4)	42.2

Table 5: Descriptive parameters of images A to K, displayed on Figure 7.

Image	Date of acquisition	Satellite	Orbit	Part of Slovenia acquired	Cloud cover [%]	Thin layers [%]	Snow cover [%]	Short description of image properties (cloud cover, snow cover, other specifics)
A	16th Mar. 2020	S-2A	122	whole	0.3	0.5	2.1	clear-sky image; snow in mountains
B	13th Aug. 2021	S-2B	122	whole	53.7	13.5	0.0	very thick cirrus may be mismatched with clouds
C	6th Mar. 2020	S-2A	122	whole	67.9	10.9	14.2	unusable image due to clouds and snow
D	12th Dec. 2018	S-2A	122	whole	43.7	29.0	1.0	although image is very cloudy, it is usable in some south-west areas
E	14th Jan. 2019	S-2A	022	west	7.9	2.3	5.7	image is usable everywhere except in mountainous areas
F	29th Mar. 2017	S-2A	079	east	0.0	0.0	0.0	clear-sky image
G	29th Jan. 2018	S-2A	022	west	36.0	0.1	11.1	partly usable, partly unusable image
H	16th Aug. 2017	S-2A	079	east	5.9	6.2	0.0	very tiny cirrus may not be detected
I	3rd Sep. 2017	S-2B	122	whole	61.3	12.0	0.2	missing one tile (large part of image)

Image	Date of acquisition	Satellite	Orbit	Part of Slovenia acquired	Cloud cover [%]	Thin layers [%]	Snow cover [%]	Short description of image properties (cloud cover, snow cover, other specifics)
J	11th Dec. 2015	S-2A	022	west	12.3	6.0	0.1	missing one tile (tiny part of image)
K	3rd Feb. 2016	S-2A	079	east	99.7	0.0	0.3	unusable image, totally covered with clouds

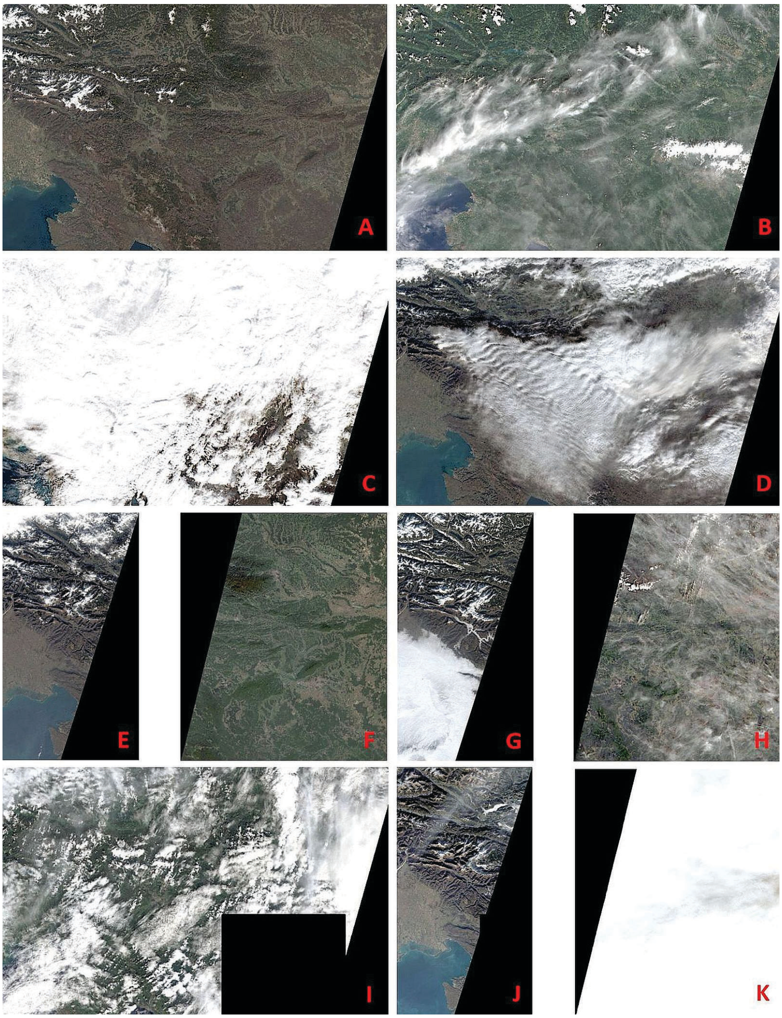

Figure 7: Examples of satellite image mosaics, acquired at different seasons, in different years, from various orbits, in variable cloud conditions (see also Table 4). Two opposite extremes are on one hand clear sky on images A and F; and on the other hand, unusable images C and K due to large cloud cover. Images B and H show that also tiny cirrus or tiny haze may hinder their usability, and that the differentiation between cloud, cirrus and haze may represent great challenge. Images D, E and G show the situation where image is partly usable, however partly not usable (areas covered with clouds or snow). Anomalies in ESA databases are shown on images I and J (image is not complete due to missing tile).

3.2.2 Cloud cover of Sentinel-2 time series

The number of images with a given cloud percentage alone does not indicate their usefulness for most applications (e.g., systematic site monitoring of natural or urban environment, change detection, land cover classification studies, development of satellite image time series, etc.). In common remote sensing practise, one is interested in analysing stable cloud-free satellite image time series over a given region of interest over a longer period of time. Thus, we are not only interested in the temporal distribution (i.e., a sequence) of all images acquired, but in a sequence of useful images (i.e., those with low cloud content) over a given region. In this respect, Figure 8 shows the sequence of all archived images with their cloud cover (percentage of cloud cover) and snow cover. This gives an insight into the density of usable time series we can expect over the whole Slovenian area. More analysis-friendly intervals are visible as continuous dark blue colour clusters.

3.2.3 Cloud-free composites in growing season

The focus of research studies is often limited to a specific region and/or to time period. For applications dealing with phenology, such as forestry, agriculture and biology, the time period in which the entire vegetation growing season may be of particular interest.

Growing season in Slovenia lasts from as early as beginning of March (at the coastal area) to the end of October. The most suitable date interval, that fits to this timespan, that is compatible with revisit time of the twins (5 days) and is dividable by 15, 30 and 60 (half a month, a month, two months; these are intervals that are close to common human comprehension of time) is the 240-day period from 2 March to 27 October. This period covers most vegetation types in Slovenia. If one considers calculating in 15-day intervals, this period is covered by sixteen 15-day intervals. In each 15 days, nine Sentinel-2 images are acquired, three from each orbit, meaning that the overlapping areas in the east and west are acquired six times, while the central Slovenia is acquired three times. These nine images are used to compose 15-day composites.

On the time series of the 20 m spatial resolution we have checked how many cloud-free (no cloud cover) pixels are available for each 15-day interval within given growing season period for years 2015 to 2021. The results show that a 15-day composite dense cloud-free time series with 12 to 16 cloud-free pixels can be obtained for most pixels in years 2018, 2019 and 2021, except for the high mountainous regions in the north (Julian Alps, Karavanke and Kamnik-Savinja Alps) (the proportion of pixels with at least 12 cloud-free pixels is 97%, 98% and 97% for 2018, 2019 and 2021, respectively) (Figure 9). For 2017 and 2020 this is only true where the swaths overlap (73% and 83% of pixels with at least 12 cloud-free pixels for 2017 and 2020, respectively), while for the central part of Slovenia the time series would not be complete. This is particularly evident in the mountainous regions – Kamnik-Savinja Alps and Karavanke in the north. For 2015 no usable 15-day time series can be produced for the vegetation-growing season, while for 2016 this is only possible for east and some western parts of Slovenia, where the swaths overlap (0% and 50% of pixels with at least 12 cloud-free pixels for 2015 and 2016, respectively).

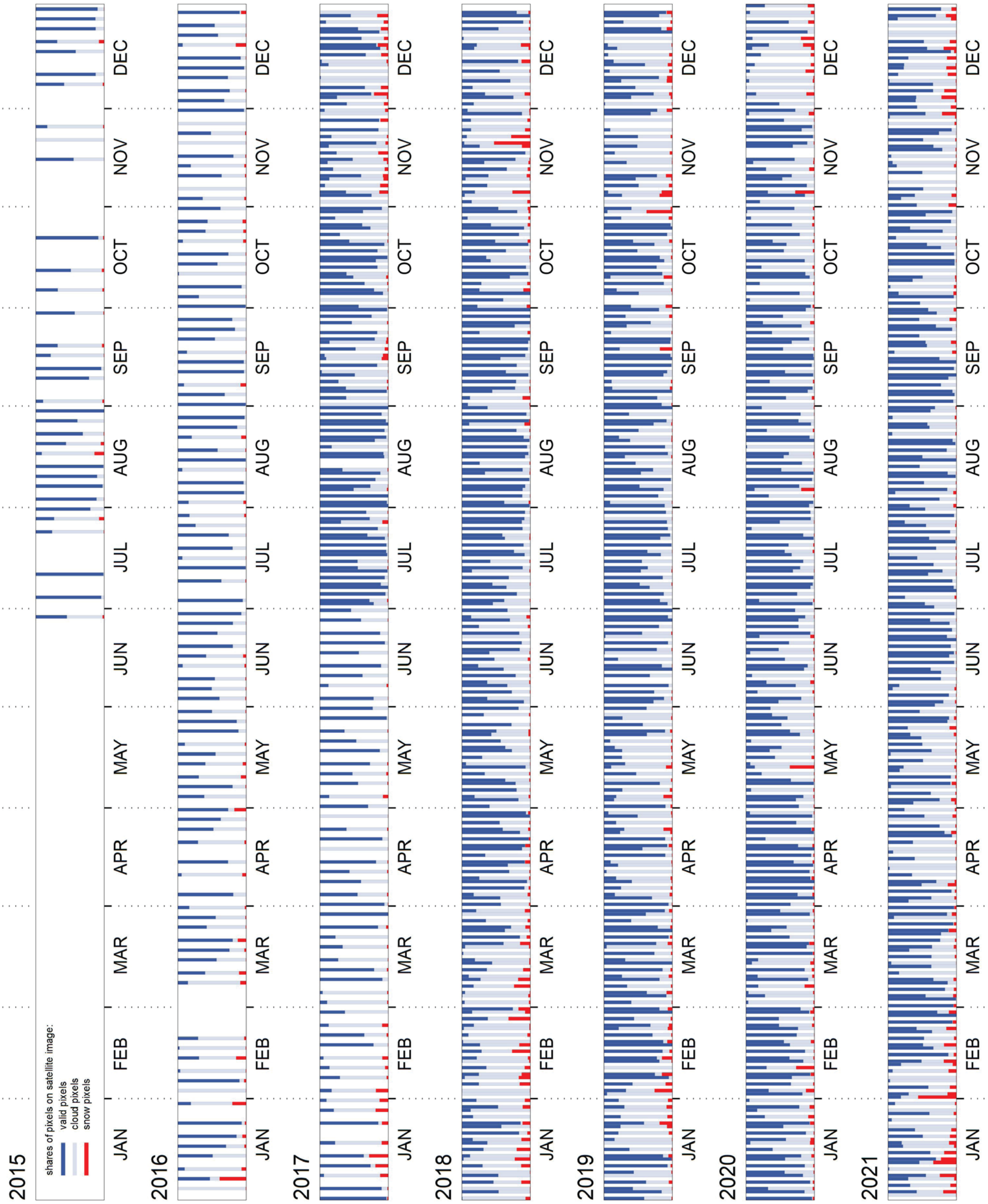

Figure 8: Graphical representation of cloud and snow cover of all acquisitions in archive of Sentinel-2 images for Slovenia up to the end of 2021; data are taken from 10-band atmospherically corrected product of resolution 20 m. The dates progress in upward direction. Each image is represented by a tiny box, plotted on the date of acquisition, where dark blue colour represents non-cloudy (i.e., usable) percentage of the image, while light blue and red colours represent the percentage of clouds and snow, respectively. The orbit from which the image was acquired (122, 079 or 022) – and consequently the area that was captured (whole, east or west Slovenia) –, is not considered in this graphical representation.

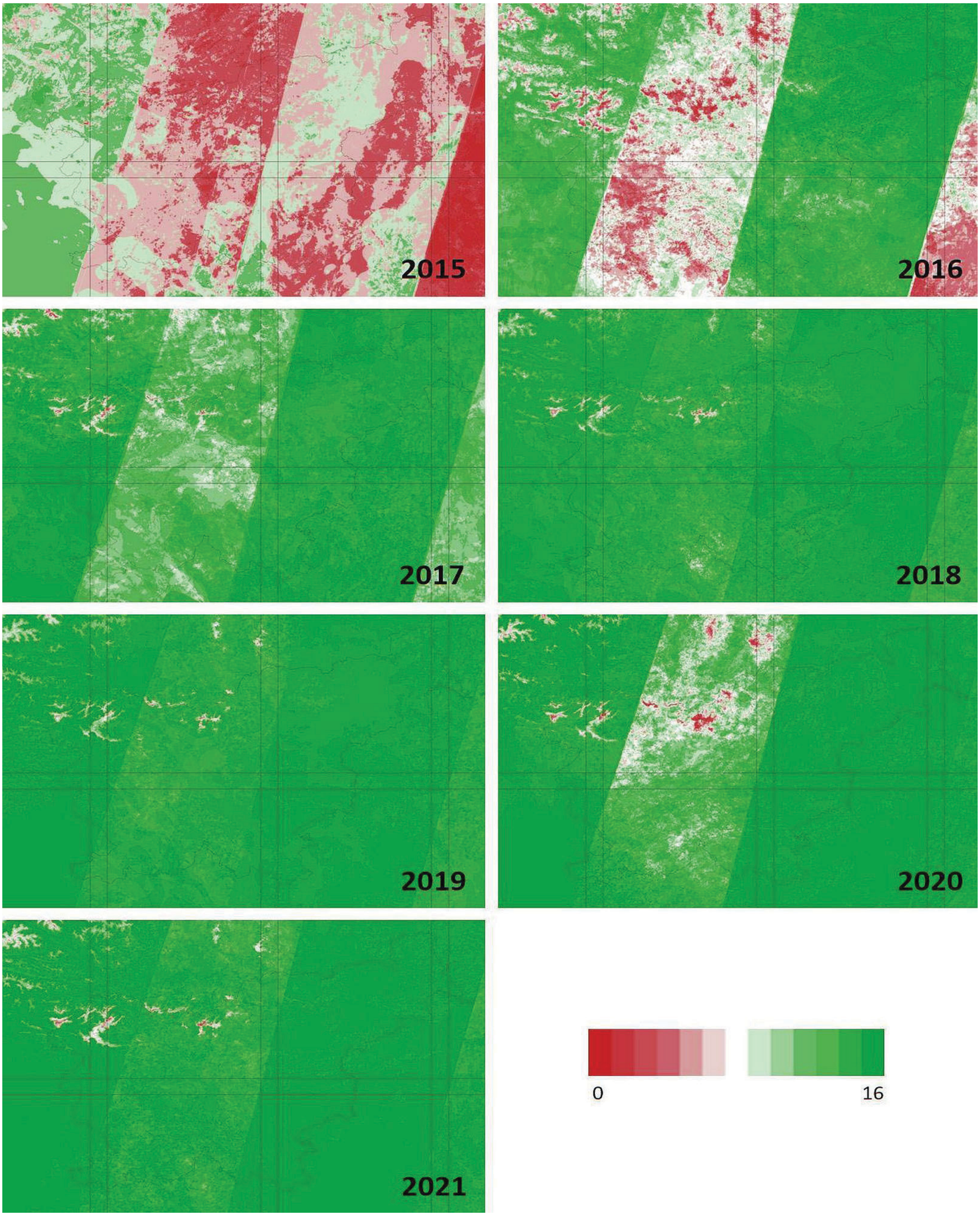

Figure 9: Cloud free pixels on a 15-day, 20 m composite times series of the growing season, i.e. from 2nd March to 27th October (16 intervals), per year. Twelve or more cloud free pixels in a time series can be found for most parts of the Slovenia – with exception of high mountainous areas – in 2018, 2019 and 2021. The time series is much sparser for some areas in north and central Slovenia in 2017 and 2020 and even more sparse for many larger regions of the country in 2015 and 2016 (when only Sentinel-2A was orbiting).

3.2.4 Use cases

The described archive was already used in several research cases. Studies completed so far include the Sentinel-2 based temporal detection of agricultural land use anomalies in support of common agricultural policy monitoring (Kanjir et al., 2018), the bark beetle damage detection study (Kobler and Ogris, 2021) and the study on mapping grassland intensity use (intensive, extensive grassland) for the area of the whole of Slovenia for the Institute of the Republic of Slovenia for Nature Conservation (Potočnik Buhvald et al., in publishing process).

The first study analysed the short-term Sentinel-2 time series (three years available: 2016–2018) and the feasibility of monitoring anomalies in grassland and cropland management in three selected test areas. The study highlighted the need for sufficient density of satellite data (e.g. bi-weekly) to provide relevant information to support common agricultural policy management. All test areas are located where the swaths overlap, however only 30–40 usable, cloud free observations per year (out of theoretically possible 146) formed a seasonal time series. The second study gave a realistic insight into the usability of the Sentinel-2 time series on a small area of interest. In the four years studied, only 31 patches of images were available that covered the area of interest and had cloud cover of less than 10% (5, 5, 14 and 7 images in 2015, 2016, 2017 and 2018, respectively). Nevertheless, this scarce time series was sufficient to monitor the slow destruction of trees by the bark beetle. In the third study, an attempt was made to determine the number of times each grassland was mowed. For this study, the Sentinel-2 time series alone was not sufficient, so it was supplemented by the Sentinel-1 radar time series, which is not weather dependent.

The Sentinel-2 data were also studied to develop spatio-temporal composites (Čož et al., 2020). The study found that for the growing season monthly composites of Slovenia can be generated, while composites for shorter periods cannot be systematically guaranteed. This means that with the standard compositing method proposed for Sentinel-2 data, monthly information could be calculated for the territory of Slovenia, if the weather conditions are not extremely bad.

Theoretically, the temporal density of the Sentinel-2 time series seems to be sufficient for monitoring relatively fast-changing events, e.g. those that occur weekly. However, the described practical use cases have shown that the presence of clouds can significantly reduce the density of useful images within the time series. In practice, the Sentinel-2 time series have been shown to be sufficient to detect only slower – i.e. annual, seasonal or monthly – changes, e.g. detailed mapping of agricultural drought (HD-Drought, 2021). In contrast, for successful monitoring of more frequent – i.e. weekly – events, the Sentinel-2 time series has to be combined with the Sentinel-1 time series which is unaffected by weather conditions. Two more comprehensive studies, covering also this topic, are currently underway: time series studies to monitor agricultural land (SURS GEOS, 2021) and forest environment, grasslands and wetlands (ROVI, 2021) of the whole Slovenia. In both these studies Sentinel-2 time series are complemented with Sentinel-1 time series.

4 CONCLUSIONS

The two Sentinel-2 satellites are a very reliable source of high-resolution optical satellite data. We have studied these data from the point of view of their usability. The first six years (2016–2021) of the operational Sentinel-2 data archive of Slovenia, which is maintained at ZRC SAZU, are analysed statistically. Data from the second half of 2015 are also shown, however they should be taken as uncertain due to small number of acquisitions.

For researchers an important aspect of the Sentinel-2 images is their geometric accuracy. We have not addressed this issue in detail in this article, as ensuring the general positional accuracy of satellite images is largely a task of ESA processing. ESA claims for the whole world, on average geometric accuracy is 1.1 pixels by the end of February 2021. A significant improvement to 0.5 pixels will be possible when the entire archive will be reprocessed by ESA with a new processing baseline version 03, introduced in March 2021.

Beside the geometric quality, the number of acquisitions (observations) is also a very important aspect for the use of satellite data. With twin constellation of Sentinel-2 central part of Slovenia is acquired 73-times per year, while number of acquisitions of eastern and western parts of Slovenia is – due to extensive 100 km wide swath overlap – exactly double, i.e. 146-times per year.

The critical aspect for the usefulness of the optical satellite data is presence/absence of clouds on an image. For Slovenia, an average image over the inspected years has a cloud cover of 42% (with an expected huge standard deviation of 32%). In total, 22.2% of the images have a cloud cover of less than 10%, and 10.9% are unusable because they are mostly cloudy (cloud cover of more than 90%). The calculated cloud masks allow the identification of individual usable (valid) pixels and thus the search for find usable data (dates) and the creation of time series over selected, even very small, regions of interest. Knowledge of the pattern of cloud cover over the years is also important for assessing the quality and expected density of satellite image time series, and for further planning of satellite data gap fillers, and thus for assessing the applicability of monitoring over selected areas and phenomena.

In practice, Sentinel-2 time series showed to be sufficient for detecting slower changes (monthly, seasonal, yearly). On the other hand, for successful monitoring of frequent, e.g. weekly events the time series of Sentinel-2 is to be combined with the weather-independent time series of radar system Sentinel-1.

The complete archival data at all processed levels are available for further analysis and use cases. We have already produced several time series of cloud-free mosaics and of indices that are most used (e.g., NDVI – normalized difference vegetation index, NDWI – normalized difference water index, EVI – enhanced vegetation index). The archive, that is not available on-line however it may be collected for research purposes, is used also by researchers of other research and academic institutions (e.g., Slovenian Forestry Institute, University of Ljubljana). Its usefulness grows with each additional week that the Sentinel-2 twins are in operation.

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ŠEST LET ARHIVA PODATKOV SENTINEL-2 ZA SLOVENIJO

OSNOVNE INFORMACIJE O ČLANKU:

GLEJ STRAN 220

1 UVOD

Sentinel-2 je optični satelitski sistem, ki ga je za Evropsko komisijo razvila Evropska vesoljska agencija (ESA) v okviru programa Kopernik. Cilj programa Kopernik je sistematično opazovanje Zemlje ter zagotavljanje natančnih, pravočasnih in lahko dostopnih informacij o okolju v daljšem časovnem obdobju.

Pomembna značilnost Kopernikovega programa in s tem tudi vseh misij Sentinel je politika prostega in odprtega dostopa do vseh podatkov. To pomeni, da so vsi podatki brezplačno in neomejeno na voljo vsem zainteresiranim uporabnikom. Misija Sentinel-2 s svojo pionirsko politiko odprtega dostopa, sistematičnim in pogostim zajemom podatkov, svetovno pokritostjo z opazovanji ter zagotavljanjem kakovosti podatkov revolucionarno spreminja optično opazovanje Zemlje v opazovanje v visoki ločljivosti (Drusch et al., 2012). Glede na zadnje letno poročilo portala Copernicus Open Access Hub je uporaba podatkov Sentinel precej poskočila leta 2019 in od takrat stalno narašča (ESA Copernicus Statistic, 2021).

Misija Sentinel-2 ima v tirnici dva satelita: Sentinel-2A (S-2A) od 23. junija 2015, Sentinel-2B (S-2B) pa od 7. marca 2017. Predvidena življenjska doba vsakega je 7,25 leta, zalog goriva pa imata za 12 let. Satelita naslednje generacije, Sentinel-2C in Sentinel-2D, že izdeluje podjetje Airbus Defence and Space, njuna izstrelitev pa je načrtovana za leti 2024 oziroma 2025, ko se bo predvidena življenjska doba satelitov S-2A in S-2B iztekla.

Satelita Sentinel-2 nosita večspektralni optični senzor visoke ločljivosti, ki podatke zajema v 290 kilometrov širokem pasu, v trinajstih spektralnih kanalih ter v treh ločljivostih: 10 metrov (štirje kanali), 20 metrov (šest kanalov) in 60 metrov (trije kanali), torej tako v visoki kot v srednji ločljivosti (Drusch et al., 2012). Čas ponovnega obiska – ponovitev zajema iz iste tirnice – je za vsak posamezen satelit deset dni. Ker sta satelita S-2A in S-2B nameščena v isti sončno-sinhroni[1] skoraj polarni tirnici s faznim zamikom 180°, je čas ponovnega obiska za to dvojno konstelacijo pet dni. Kljub nominalno pogostim opazovanjem je uporabnost optičnih satelitskih podatkov omejena predvsem zaradi oblačnosti, ki preprečuje opazovanje površja pod oblaki.

Do podatkov Sentinel je, odvisno od misije in vrste podatkov, mogoče dostopati prek običajnih dostopnih točk ESE in EUMETSAT-a[2] ali prek platform DIAS[3] (*Data and Information Access Services*), ki

[1] Prehod satelita je usklajen s Soncem, zato satelit preleti poljubno točko na Zemljini površini vedno v približno istem lokalnem času. Slovenijo Sentinel-2 zajame vedno okoli 10:00 po univerzalnem koordiniranem času (Coordinated Universal Time, UTC). Po lokalnem času je to okoli 11:00 po tako imenovanem sončnem/zimskem času, oziroma okoli 12:00 po tako imenovanem poletnem času. Točen čas zajema, izražen v univerzalnem koordiniranem času, variiria med 09:50 in 10:15.

[2] Primeri dostopnih točk ESE in EUMETSAT-a: Copernicus Open Access Hub, Copernicus Space Component Data Access – CSCDA, EUMETSAT EUMETCast, EUMETSAT Copernicus Online Data Access – CODA.

[3] Primeri platform DIAS: ONDA, Sobloo, CreoDIAS, Mundi Web Services.

zagotavljajo (delno) zrcaljenje podatkov, tematskih platform TEP[4] (*Thematic Exploitation Platforms*) ali regionalnih podatkovnih storitev[5] (*Copernicus Collaborative Ground Segment*), kot tudi drugih uveljavljenih podatkovnih centrov[6] ali spletišč za hitro prikazovanje in iskanje satelitskih podatkov po obširnih bazah podatkov teh centrov (med temi želimo posebej izpostaviti platformo Sentinel Hub, ki jo zelo uspešno upravlja slovensko podjetje Sinergise) (ESA Sentinel Data Access, 2021; ESA Earth Online, 2021). Platforme DIAS in drugi podatkovni centri poleg dostopa do svojih podatkov ponujajo plačljive napredne računalniške storitve.

Medtem ko v Evropi danes prevladujejo platforme v oblaku in omrežne infrastrukture/vozlišča, so nekatere države v zadnjem desetletju razvile lastno podatkovno infrastrukturo ter vzpostavile nacionalne podatkovne kocke (angl. *data cubes*) ali podatkovne centre, kjer so satelitski podatki povezani in arhivirani z drugimi prosto dostopnimi državnimi geoprostorskimi podatki[7]. V razvoju je mnogo pobud, ki povezujejo vesoljske agencije ter vladne in komercialne subjekte pri razvoju namenskih podatkovnih kock na ravni celin[8], s splošnim ciljem omogočiti geopodatkovno okolje, ki vključuje tudi satelitske podatke, za vladne, raziskovalne in komercialne potrebe.

Medagencijski Odbor za satelite za opazovanje Zemlje (*Committee on Earth Observation Satellites*, CEOS) spodbuja pripravo in distribucijo tako imenovanih ‚podatkov, pripravljenih za analizo' (*Analysis Ready Data*, ARD), s čimer želi podpreti hitro, zanesljivo in avtomatizirano uporabo podatkov Sentinel ter omogočiti interoperabilnost tako med različnimi obdobji zajema satelitskih podatkov kot z drugimi zbirkami satelitskih podatkov, na primer s podatki Landsat (CEOS, 2020). Doseganje ustrezne primerljivosti in boljše konsistentnosti satelitskih podatkov ter s tem boljše povezljivosti in združljivosti podatkov je zahtevna naloga, zato pri njej sodelujejo vsi pomembnejši proizvajalci podatkov, tj. vesoljske agencije (NASA, ESA, JAXA itd.) ter glavni centri za dostavo in dostop do podatkov (ponudniki storitev v oblaku, regionalna podatkovna vozlišča).

Raziskovalni center Slovenske akademije znanosti in umetnosti (ZRC SAZU) od začetka misije Sentinel-2 vodi lasten arhiv posnetkov Sentinel-2 za območje Republike Slovenije. Za lastno hrambo podatkov Sentinel-2 smo se odločili iz več razlogov:

– nadaljevanje razvoja algoritmov za geometrično in radiometrično predobdelavo satelitskih podatkov, kjer imamo dolgoletne izkušnje;
– možnost obdelave podatkov na zahtevo za zahtevnejše uporabnike in raziskovalce;
– možnost trajnega in stabilnega zagotavljanja storitev in dostopa do podatkov, ki pokrivajo Slovenijo, zainteresiranim uporabnikom (raziskovalni sektor, državna uprava).

Arhiv ni javno objavljen na spletu, ga je pa mogoče pridobiti za raziskovalne namene. Podatke Sentinel-2 hranimo v izvornem stanju (standardni produkt L1C, angl. *Level-1C*; v tej ravni obdelave jih pridobimo), nato pa izdelamo produkte z različnimi stopnjami obdelave. Te so:

– geometrična transformacija (preprojekcija),

4 Primeri platform TEP: za gozdarstvo, za varnost preskrbe s hrano, za urbanizem, za hidrologijo itd.

5 Na primer: TerraScope, SARA – Sentinel Australasia Regional Access.

6 Primeri znanih podatkovnih spletišč: Amazon Web Services, USGS Earth Explorer, Google Earth Engine, Open Data Cube, PROBA-V MEP, RUS, NoR, CNES PEPS, Alaska Satellite Facilities.

7 Primeri nacionalnih podatkovnih centrov: Austrian Data Cube (ACube), ki ga gosti EODC; German Satellite Data Archive (D-SDA); francoski Theia Land Data Centre; belgijski Center za obdelavo posnetkov (CVB), ki ga gosti VITO; avstralski Center za opazovanje Zemlje CSIRO z lastno Open Data Cube.

8 Na primer: Digital Earth Australia, Digital Earth Africa.

- atmosferski popravki z maskiranjem oblakov,
- topografski popravki,
- prostorsko mozaičenje in časovni kompoziti ter
- biofizikalni produkti (na primer vegetacijski, vodni in talni indeksi).

Arhiv deluje šest let, kar je dober mejnik za kratkoročen statistični pregled.

Analitične študije arhivov satelitskih podatkov niso prav pogoste, nekaj pristopov pa smo zabeležili in jih podajamo v nadaljevanju. Statistično študijo za globalni arhiv posnetkov Landsat, ki ima med vsemi satelitskimi sistemi najdaljšo zgodovino – deluje že petdeset let –, so opravili Wulder et al. (2016). Avtorji podajo celovito analizo arhiva, pri čemer navajajo podatke o številu zajetih posnetkov po geografskih območjih ter na svetovni ravni prikazujejo razlike v pokritosti s posnetki v celotnem obdobju delovanja programa Landsat. Z oblačnostjo pa se ne ukvarjajo. Sudmanns et al. (2020) so podobno statistično analizo opravili za posnetke Sentinel-2, zajete v letu 2017, in sicer na podlagi metapodatkov. Avtorji navajajo, da pokritost s posnetki ter njihova kakovost nista homogeni, večja pogostost zajema pa da ne prinaša nujno tudi več brezoblačnih posnetkov. Razkrivajo tudi nekatere manj kakovostne metapodatke arhiva, na primer sistematično napačno ocenjeno (prekomerno zaznano) oblačnost na neporaslih visokogorskih območjih (na primer v Himalaji, Andih). Li in Roy (2017) sta proučevala zgolj eno, a specifično prvino obstoječega niza podatkov Sentinel-2, to je čas ponovnega obiska S-2A in S-2B, v kombinaciji z Landsatom 8. Corbane et al. (2020) so preučili ustreznost posnetkov Sentinel-2 za sestavo globalnega brezoblačnega kompozita.

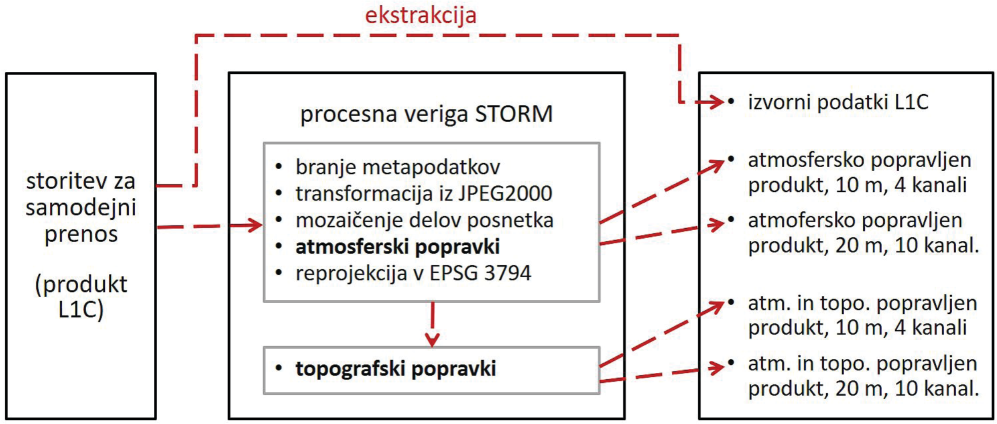
V prispevku obravnavamo še en mogoč vidik pregleda arhiva posnetkov: uporabniško usmerjen pogled, osredotočen na praktično uporabnost posnetkov Sentinel-2 za analizo nekega študijskega območja, na primer države. Po eni strani tak vidik delno narekuje majhnost Slovenije (20.271 km^2), po drugi strani pa je utemeljen tudi zaradi vse večje potrebe različnih strokovnih področij (na primer kmetijstva, varstva narave, naravnih nesreč) po sistematičnem spremljanju naravnih – postopnih ali nenadnih – procesov na zemeljskem površju na ravni cele države.

2 MATERIALI IN METODE

2.1 Študijsko območje in dostop do podatkov

Slovenija je srednjeevropska država, za katero sta značilna zelo raznolik relief in pester podnebni režim, saj združuje štiri večje makroregije – visoke Alpe s predalpskim gričevjem, razgibano Dinarsko gorovje, ravnino Panonske nižine z njenim hribovitim robom ter sredozemsko gričevje z blagim vplivom Jadranskega morja (Perko, Ciglič in Zorn, 2020). Velika topografska raznolikost gora, hribovja in ravnin na eni strani ter zgodovinska razdrobljenost kmetijskih zemljišč in vrsta sodobnih načinov rabe tal na drugi strani pomenita, da je Slovenija odlično testno območje za razvoj celega nabora obdelav in načinov opazovanja Zemlje.

Naš operativni postopek za obdelavo podatkov Sentinel-2 za Slovenijo je sestavljen iz prenosa posnetkov Sentinel-2 s portala Copernicus Open Access Hub ter sistematične obdelave (slika 1). Slednja zajema tudi prilagoditev daljinsko zaznanih podatkov za uporabo z državnimi geoinformacijskimi podatkovnimi viri, tj. preprojekcijo v državni koordinatni sistem D96TM (EPSG 3794).



Slika 1: Implementirani postopek za obdelavo podatkov Sentinel-2 za Slovenijo.

Najnižja raven obdelave podatkov Sentinel-2, ki je na voljo širši javnosti, je tako imenovani produkt L1C. To je ortorektificiran posnetek, vrednosti pikslov pa so odbojnosti na vrhu atmosfere (angl. *Top-of-the-Atmosphere reflectance*, TOA *reflectance*) (Thales Alenia Space, 2021). Referenčni sistem, ki se uporablja za te podatke, je univerzalni prečni Mercatorjev (angl. *Universal Transverse Mercator*, UTM) na elipsoidu WGS84. Na podlagi fiksne mreže v UTM je vsak zajeti posnetek[9] razrezan na več izrezov (angl. *tile*) približne velikosti 110 × 110 km^2, ki se na vseh štirih straneh prekrivajo za 10 kilometrov. Produkti so sestavljeni po pravilih tako imenovanega standardnega arhivskega formata za Evropo (angl. *Standard Archive Format for Europe*, SAFE). Do 26. septembra 2016 so produkti SAFE vsebovali več – do 14 – izrezov (angl. *multi-tile*) in pokrivali fiksno območje približno 290 km (pravokotno na smer gibanja) × 325 km (v smeri gibanja). ESA je 27. septembra 2016 prešla na nov format, pri katerem vsak produkt SAFE vsebuje le en izrez (angl. *single-tile*).

Slovenijo pokriva sedem izrezov S-2 (slika 2) (ESA Tiling Grid, 2017). Vsi izrezi so v isti coni UTM (tj. UTM 33 North), zato ni dodatnih težav, ki nastopijo zaradi mešanja con (Roy et al., 2016). Posnetki so zajeti s treh tirnic[10]: 022, 122 in 079. Ker se Slovenija nahaja na srednjih zemljepisnih širinah (središčna točka približno okoli 45° s. š., 15° v. d.), je prekrivanje posnetkov, zajetih s sosednjih tirnic, že precejšnje in presega 100 kilometrov (Li in Roy, 2017) (slika 3).

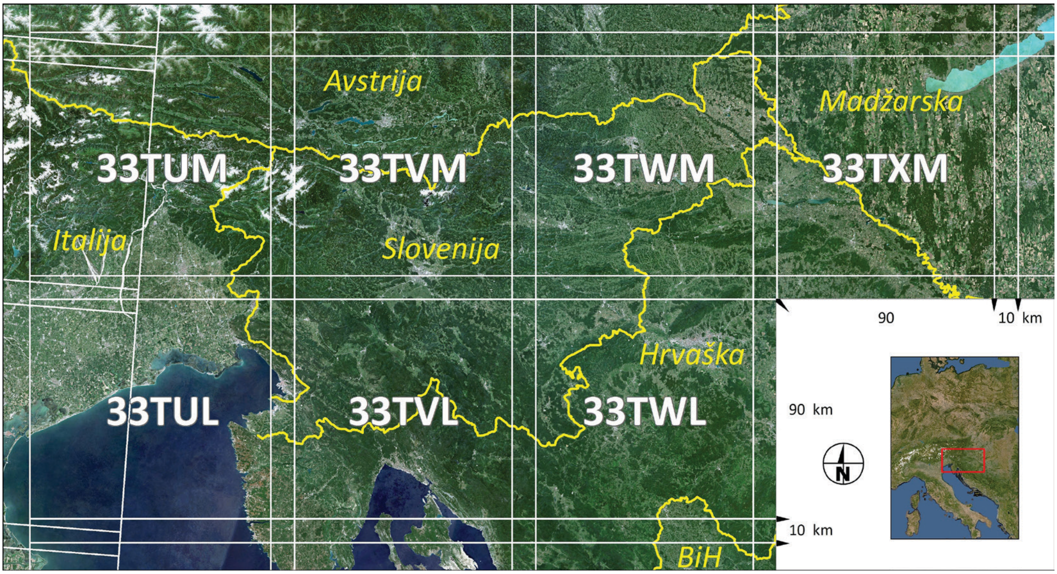
ESIN portal Copernicus Open Access Hub (https://scihub.copernicus.eu/, prej znan kot Sentinels Scientific Data Hub) zagotavlja brezplačen in odprt dostop do uporabniških izdelkov Sentinel-1, Sentinel-2, Sentinel-3 in Sentinel-5P. Prenos posnetkov s tega spletišča v naš arhiv smo realizirali prek vmesnika API Hub, ki vsebuje skriptne ukaze za samodejni prenos večjega števila posnetkov Sentinel-2.

V implementiranem delovnem procesu se vsak produkt L1C prenese kot ena stisnjena datoteka ZIP. Vsaka datoteka ZIP v prvotni različici formata SAFE obsega podatke več izrezov, v sedanji različici pa zgolj podatke enega izreza. Kot je opredeljeno v specifikacijah formata SAFE, podatki za vsak izrez obsegajo

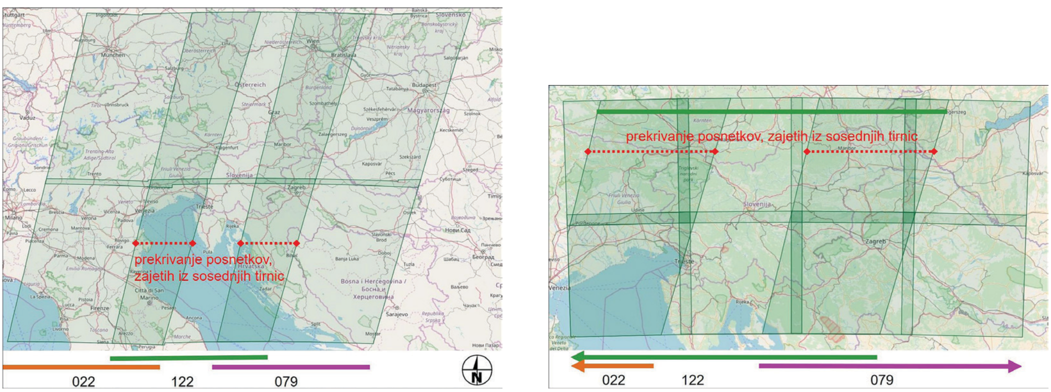
[9] *V ESINI terminologiji se zajem posnetka imenuje datatake (predstavlja neprekinjen zajem posnetka med istim preletom), posamezni izrezi posnetka pa se imenujejo granule.*

[10] *V ESINI terminologiji se številke, ki označujejo tirnice zajema, imenujejo številka relativne tirnice; so fiksne in se gibljejo od 1 do 143. Po drugi strani pa se izraz številka absolutne tirnice nanaša na zaporedno številko tirnice trenutnega preleta, ki se z vsakim preletom poveča.*

13 rastrskih datotek – po eno na spektralni kanal – v formatu JPEG2000, pa tudi več kot 100 metapodatkovnih datotek v formatih XML in GML, začenši z glavno metapodatkovno datoteko manifest.SAFE.



Slika 2: V ESINI mreži za razrez posnetkov Sentinel-2 je Slovenija pokrita s sedmimi izrezi velikosti 110 x 110 km2; vsi so v območju UTM 33 North (oznake od 33TUM do 33TWL). Ozadje za pregledni zemljevid je od Evropske agencije za okolje (EEA).



Slika 3: Zajem posnetkov Slovenije s satelitoma Sentinel-2 poteka iz treh tirnic: 022 (zahodni del; na dnu obeh slik označen z oranžno črto), 122 (cela Slovenija; opomba: osrednji del Slovenije pokrivajo zgolj posnetki iz te tirnice; zelena črta) in 079 (vzhodni del; vijolična črta). Sliki sta pridobljeni z zajemom zaslona s portala Copernicus Open Access Hub. Vidno je približno stokilometrsko prekrivanje posnetkov, zajetih iz sosednjih tirnic (rdeča prekinjena črta). Desna slika: V prvotnem formatu je bilo treba od vsakega zajema prenesti dva zaporedna produkta SAFE. Ker je vsak vseboval do 14 izrezov, je to pomenilo prenos do 28 izrezov. Na sliki so označene meje šestih celih produktov SAFE (meje posameznih izrezov pa niso označene). Leva slika: V sedaj veljavnem formatu je treba za pokritje Slovenije od vsakega zajema prenesti od 4 do 7 produktov SAFE; v vsakem je zgolj en izrez.

2.2 Obdelava podatkov

Posnetke najprej preimenujemo v uporabniku in analizam bolj prilagojena imena; proizvajalčeva imena posnetkov, ki se začnejo z oznako senzorja (tj. S2A/B_*), preimenujemo tako, da se začnejo z datumom (YYYYYMMDD*). Nato jih s procesno verigo STORM obdelamo z našimi standardnimi postopki predobdelave (Zakšek et al., 2015; Pehani et al., 2016). STORM pripravi atmosfersko in topografsko popravljene produkte Sentinel-2 za območje Slovenije, preprojicirane v državni koordinatni sistem D96TM, EPSG 3794 (EPSG.IO, 2021). Vsak posnetek gre torej skozi naslednje korake obdelave:

– za vsak posamezen izrez preberemo ustrezne metapodatke, vseh 13 kanalov pretvorimo iz JPEG2000 v GeoTIFF ter združimo v eno 13-kanalno datoteko;
– izreze istega posnetka mozaičimo v skupni posnetek v izvorni projekciji (UTM 33 North);
– mozaičen posnetek atmosfersko popravimo z ATCOR-2 (ReSe Applications, 2021), pri čemer izračunamo izboljšano masko anomalij, ki vključuje oblake, ciruse, meglice, sneg, vodo in sence;
– posnetek preprojiciramo v državni koordinatni sistem D96TM ter obrežemo na območje Slovenije.

Topografske popravke izvedemo v ločeni obdelavi, in sicer samo za posnetke, ki so manj kot 75-odstotno pokriti z oblaki.

Povzemimo: Iz izvornega produkta L1C z opisanim postopkom izračunamo štiri izdelke, tj. dve ravni obdelave v dveh ločljivostih (preglednica 1). Za štirikanalne izdelke ločljivosti 10 metrov postopek obdelave poteka zgolj na štirih kanalih ločljivosti 10 metrov (modri, zeleni, rdeči ter bližnji infrardeči kanal). Za desetkanalne izdelke ločljivosti 20 metrov postopek obdelave izvedemo na vseh trinajstih kanalih, vendar po končanih atmosferskih popravkih vse tri kanale ločljivosti 60 metrov odstranimo. Po predobdelavi so izdelki opremljeni z izboljšano masko anomalij ter pripravljeni za uporabo z drugimi državnimi viri geoinformacijskih podatkov. Na voljo so tudi za izračun različnih indeksov (na primer vegetacijskih, vodnih in talnih indeksov), časovnih kompozitov (na primer mesečnih brezoblačnih mozaikov), časovnih vrst satelitskih posnetkov in podobno.

Preglednica 1: Količine arhivskih podatkov Sentinel-2 za Slovenijo v izvorni obliki L1C ter štirih stopnjah obdelave. Količine v zadnjem stolpcu so izračunane za konstelacijo dveh Sentinel-2, zato veljajo od leta 2018 dalje.

Oznaka produkta	Opis produkta	Približno število produktov na leto	Približna količina podatkov na leto [TB]
L1C	ESIN ortorektificiran produkt, odbojnost na vrhu atmosfere, projekcija UTM33N, 13 kanalov, ločljivosti 10, 20, 60 m	217	0,7
atm_10m	atmosfersko popravljen produkt, 10 m, 4 kanali, projekcija D96TM	217	2,2
atm_20m	atmosfersko popravljen produkt, 20 m, 10 kanalov, projekcija D96TM	217	1,5
atm_topo_10m	atmosfersko in topografsko popravljen produkt, 10 m, 4 kanali, D96TM	155*	0,8
atm_topo_20m	atmosfersko in topografsko popravljen produkt, 20 m, 10 kanalov, D96TM	155*	0,5

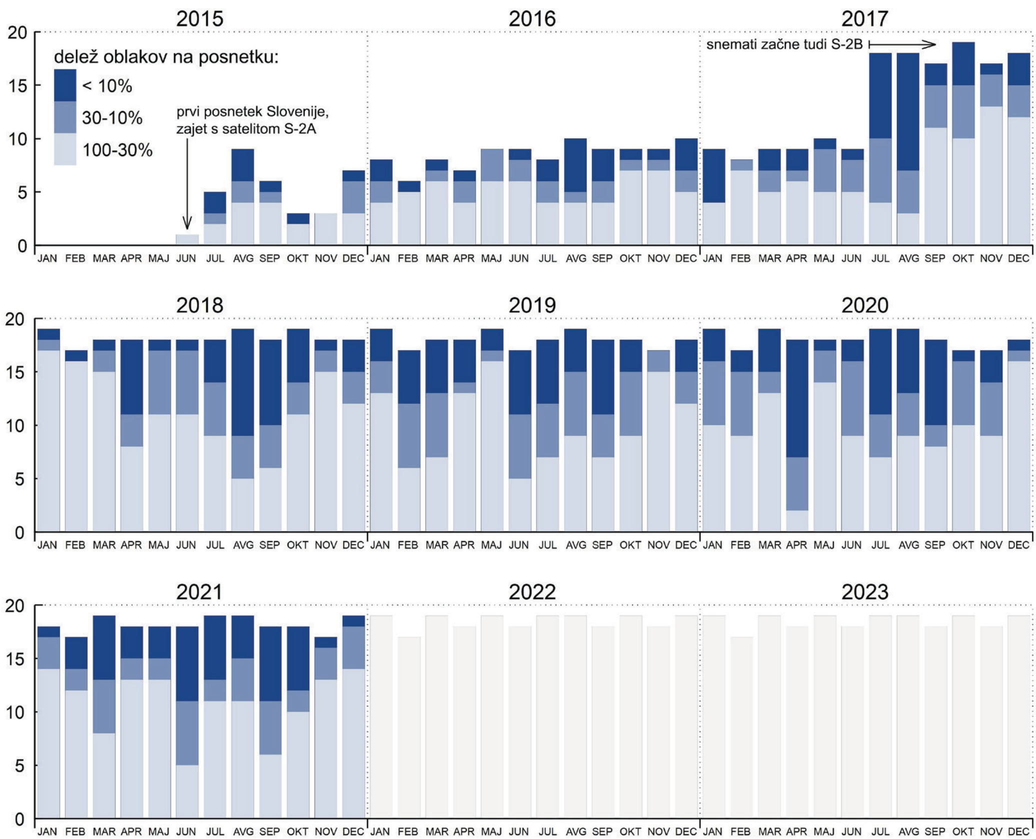
** Topografsko popravljene produkte izračunamo samo za posnetke z manj kot 75-odstotno pokritostjo z oblaki.*

3 REZULTATI IN RAZPRAVA

V tem poglavju z različnih vidikov opisujemo in obravnavamo posnetke Sentinel-2 Slovenije za obdobje šestih let in pol, tj. od druge polovice leta 2015 do konca leta 2021. Ker je uporabnost optičnih podatkov močno odvisna od prisotnosti/odsotnosti oblakov, največ pozornosti namenjamo količinski opredelitvi oblačnosti. Podajamo različne statistike števila posnetkov na obravnavanem območju, skupaj z oceno oblačnosti, skozi celotno časovno obdobje. Oblačnost predstavimo podrobneje tudi po letih in letnih časih ter z vidika možnosti za ustvarjanje brezoblačnih mozaikov ali ustreznih časovnih vrst satelitskih posnetkov. Opišemo tudi pomen poznavanja osnovne obdelave posnetkov, ki jo opravi ESA. Poglavje zaključimo z nekaj primeri uporabe podatkov iz arhiva Sentinel-2.

3.1 Arhiv v številkah

3.1.1 Število zajemov na mesec

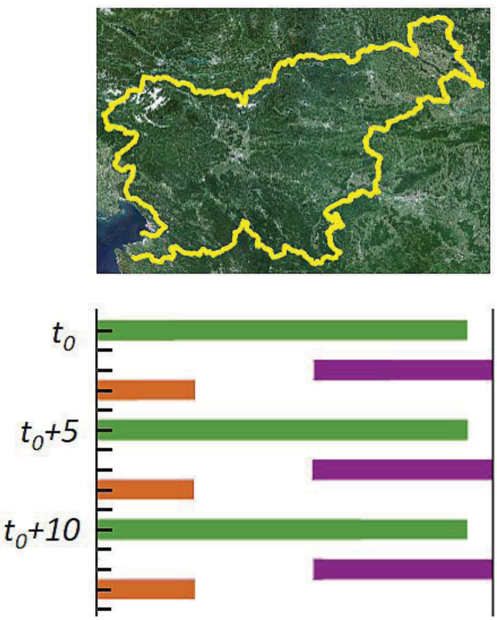


Slika 4: Število posnetkov Slovenije na mesec in njihova pokritost z oblaki. Ko je julija 2017 začel zajemati tudi S-2B, se je število posnetkov podvojilo. V nekaterih mesecih ni brezoblačnih posnetkov (na primer maj 2016, februar 2017, november 2019). Na splošno je večina posnetkov, ki imajo manj kot 10-odstotno pokritost z oblaki, zajeta v poletnih mesecih (julij, avgust, september). Opazimo pa lahko tudi kakšno izstopajočo posebnost (na primer april 2020). Za podrobnosti glej sliko 8.

Prvi posnetek Slovenije je bil zajet 28. junija 2015. V letu 2015, tj. v prvem operativnem polletju misije, zajem posnetkov ni bil prav sistematičen (glej sliko 4). Z vidika uporabnika, ki si želi stabilne in goste časovne vrste satelitskih posnetkov, se boljši nabor satelitskih podatkov začne leta 2016. Polna razpoložljivost podatkov te misije nastopi z julijem 2017, ko začne snemati še drugi satelit. Število mesečnih zajemov za satelitski par je od 17 do 19 (odstopanja so posledica tega, da se preleti satelitov različno umeščajo v letni koledar, in pa različnih dolžin mesecev).

3.1.2 Število zajemov na območjih, kjer se posnetki s sosednjih tirnic prekrivajo

Konstelacija S-2A in S-2B zajame osrednji del Slovenije na vsakih pet dni (torej t_0, t_0 +*5d* ...), vzhodni in zahodni del Slovenije pa – zaradi precejšnjega prekrivanja posnetkov, zajetih iz sosednjih tirnic – zajame dvakrat v petih dneh (zaporedje datumov na vzhodni strani je t_0, t_0 +*2d*, t_0 +*5d*, t_0 +*7d* ..., na zahodni strani pa t_0, t_0 +*3d*, t_0 +*5d*, t_0 +*8d* ..., pri čemer je t_0 datum poljubnega zajema osrednjega dela Slovenije) (slika 5). Na leto dvojna konstelacija izvede 73 zajemov osrednjega dela Slovenije ter 146 (točno dvojno število) zajemov na območjih prekrivajočih se posnetkov na vzhodu in zahodu. Tako dobimo 219 posnetkov na leto – teoretično; v praksi zaradi vzdrževalnih posegov eden ali dva zajema na leto umanjkata. Skupno to pomeni 5,7 TB podatkov letno, kar vključuje izvorne posnetke L1C in vse štiri različice obdelave (preglednica 1).



Slika 5: Grafikon na osi y shematično prikazuje zaporedje zajemov, na osi x pa pokritost Slovenije. Cela Slovenija, vključno z osrednjim delom, je zajeta le iz tirnice 122 (zelena črta), medtem ko sta vzhodni in zahodni del zajeta tudi iz tirnic 079 (vijolična črta) in 022 (oranžna črta). Osrednji del je zajet vsakih pet dni, medtem ko sta vzhodna in zahodna Slovenija zajeta dvakrat v petih dneh.

3.1.3 Različice ESINEGA procesnega okolja

V tem razdelku na kratko predstavljamo, kako je ESA, vzporedno z rastočim številom posnetkov Sentinel-2 z vsega sveta, postopoma nadgrajevala tudi obdelovalno okolje. Običajni uporabnik podatkov Sentinel-2 ni seznanjen z različicami obdelave in izdelkov ESE (in to niti ni potrebno), vendar je koristno vedeti, da različice ESINEGA procesnega okolja obstajajo – ter da lahko tovrstna informacija postane pomembna pri uporabi in obdelavi podatkov Sentinel-2.

ESA sistematično obdeluje posnetke Sentinel-2 v produkte L1C, pri čemer uporablja – v trenutku obdelave – najnovejšo veljavno različico svojega procesnega okolja. Ker se je slednje v teh letih večkrat spremenilo, to pomeni, da produkti niso povsem homogeno izdelani. Različica procesnega okolja, ki ga ESA uporablja za izdelavo izdelkov, je torej pomembna, vendar ni na voljo na primer v obrazcih za iskanje posnetkov na portalu Copernicus Open Access Hub in drugih priljubljenih dostopnih točkah. Ta informacija je zabeležena v metapodatkovni datoteki.

ESIN izraz *procesno okolje* (angl. *processing baseline*) vključuje različice treh procesnih paketov (Thales Alenia Space, 2021):

- različico procesne verige,
- različico njenih konfiguracijskih parametrov,
- različico uporabljenih dodatnih podatkov (ti so lahko statični, na primer digitalni model višin, ali dinamični, na primer atmosferski podatki ali natančni podatki o tirnici).

ESA je v prvih petih letih in pol delovanja uporabljala procesno okolje različice 02 in njenih podrazličic (ESA Processing Baseline, 2021). Od začetne operativne podrazličice 02.00, razširjene 23. novembra 2015, je bilo potrebnih več posodobitev in konsolidacij, preden je bila 15. junija 2016 objavljena prva stabilna podrazličica 02.04. ESA je zato izvedla več kampanj ponovne obdelave podatkov L1C.

Preglednica 2 prikazuje različice ESINEGA procesnega okolja, s katerimi so bili obdelani posnetki Slovenije v našem arhivu. Kot je razvidno iz preglednice, ESI še ni uspelo ponovno obdelati vseh svojih najstarejših posnetkov s procesnim okoljem različice vsaj 02.04. Posnetki, obdelani z manj ugodnimi podrazličicami 02.01 ali 02.02, so vsi iz druge polovice leta 2015 in prve polovice leta 2016.

Pomembna nadgradnja ESINEGA procesnega okolja na različico 03 je nastopila 30. marca 2021. Ta različica je uvedla izboljšave pri geometričnih popravkih ter uporabo novega Kopernikovega digitalnega modela višin (COP-DEM) ločljivosti 90 metrov (ESA Processing Baseline, 2021). S tem se je geometrična točnost posnetkov Sentinel-2 močno izboljšala. V skladu z ESINIM poročilom o kakovosti podatkov (ESA Data Quality Report, 2021) je dolgoročna geometrična točnost za izdelke, obdelane s procesnim okoljem različice 02, za oba satelita 11 metrov (tj. 1,10 piksla) s 95-odstotno stopnjo zaupanja. Preliminarni rezultati za posnetke, obdelane s procesnim okoljem različice 03.00, kažejo veliko boljše rezultate, saj absolutna napaka geolokacije s 95,5-odstotno stopnjo zaupanja znaša 5,5 metra in 5,0 metra (tj. 0,55 in 0,50 piksla) za S-2A oziroma S-2B, kar je blizu pričakovani in želeni geometrični točnosti satelitskih posnetkov te ločljivosti.

Preglednica 2: Arhivski posnetki Slovenije, razvrščeni po podrazličicah ESINEGA procesnega okolja. Na splošno so novejši posnetki obdelani z novejšimi različicami procesnega okolja. Posnetke, označene z rdečo barvo, mora ESA ponovno obdelati. Posnetki, označeni z zeleno, so obdelani z bistveno izboljšanimi različicami 03.+.

Podrazličica ESINEGA procesnega okolja	02.01	02.02	02.04	02.05	02.06	02.07	02.08	02.09	03.00	03.01
Število posnetkov	34	15	120	87	226	145	125	249	55	110

3.2 Oblačnost

3.2.1 Oblačnost po letih in letnih časih

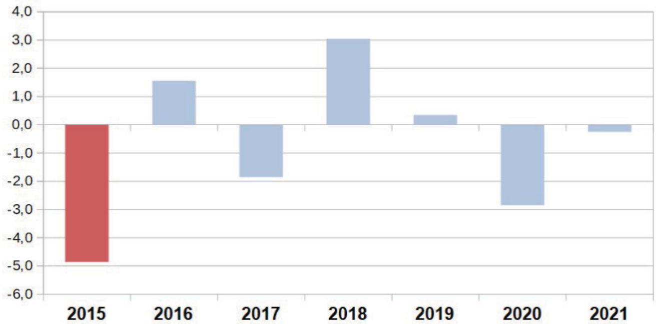
Večina aplikacij ima enake splošne zahteve za kakovost optičnih satelitskih podatkov; te obsegajo visoko geometrično točnost (ortorektifikacija) ter postopke zaznave oblakov in popravljanja atmosferskih vplivov (izračun brezoblačne odbojnosti na površju). Prisotnost oblakov povzroča prostorske in časovne vrzeli v časovnih vrstah opazovanih pojavov. Zajem velikih območij običajno ni mogoč z enim samim satelitskim preletom, zato se moramo uporabniki zanašati na podatke, zbrane v različnih dneh z različno oblačnostjo. Prisotnost oblakov je naravna motnja, njihovo pojavljanje je delno povezano z letnim časom in geografskim položajem. V tem kontekstu smo opazovali pojavljanje oblakov na doslej zajetih posnetkih Sentinel-2 za Slovenijo.

Preglednica 3 prikazuje statistične podatke o oblačnosti na leto po razredih odstotkov oblakov. Posnetke smo obdelali s procesno verigo STORM. V preglednici smo prikazali rezultate atmosfersko popravljenih 10-kanalnih produktov z ločljivostjo 20 metrov (glej preglednico 1, vrstica atm_20m). V kombinirani razred »oblaki« smo združili vse debele plasti, ki so tako neprosojne, da opazovanje Zemljinega površja ni mogoče. To je zbir desetih razredov, ki jih dobimo pri izračunu atmosferskih popravkov (oblaki, srednje debeli in debeli cirusi ter srednje gosta do gosta megla nad kopnim ali nad morjem). Razred »sneg« vsebuje zgolj sneg in je prav tako neprepusten. V kombinirani razred »tanka plast« pa smo združili štiri prepustne razrede (redka do srednja gosta meglica ter tanki cirusi nad kopnim ali nad morjem), ki še vedno omogočajo realno oceno dejanske vrednosti odbojnosti na površini.

Povprečna oblačnost vseh obdelanih posnetkov je 42,2 %. Že ta podatek kaže, da je pričakovana pokritost z oblaki za poljuben posnetek precej visoka. Delež brezoblačnih ali skoraj brezoblačnih posnetkov, za katere velja, da imajo pokritost z oblaki manjšo od 10 %, je 22,2 %. Delež posnetkov, ki veljajo za neuporabne za opazovanje Zemlje (razen za študije oblakov), ker imajo pokritost z oblaki večjo od 90 %, pa je 10,9 %. Porazdelitev oblačnosti med leti je precej stabilna, saj je povprečna letna oblačnost v izstopajočih letih 2018 in 2020 le za 3 % večja in manjša (tj. manj in bolj ugodna), kot je povprečje šestih obravnavanih let 2016–2021 (slika 6).

Preglednica 3: Število posnetkov Slovenije po razredih pokritosti z oblaki ter po letih

Oblačnost [%]	< 1	1–10	11–20	21–30	31–40	41–50	51–60	61–70	71–80	81–90	91–99	> 99	skupaj
2015	2	6	5	2	2	5	2	4	3	2	0	1	34
2016	4	17	11	8	7	15	7	7	6	9	6	5	102
2017	7	33	20	16	12	14	6	13	11	16	4	9	161
2018	12	31	22	17	19	19	20	18	20	15	14	11	218
2019	14	34	32	17	11	15	20	19	15	16	11	12	216
2020	14	36	28	23	21	20	10	17	13	12	18	5	217
2021	12	36	17	23	30	23	13	13	9	11	22	9	218
skupaj	**65**	**193**	**135**	**106**	**102**	**111**	**78**	**91**	**77**	**81**	**75**	**52**	**1166**
delež [%]	**5.6**	**16,6**	**11,6**	**9,1**	**8,7**	**9,5**	**6,7**	**7,8**	**6,6**	**6,9**	**6,4**	**4,5**	**100,0**

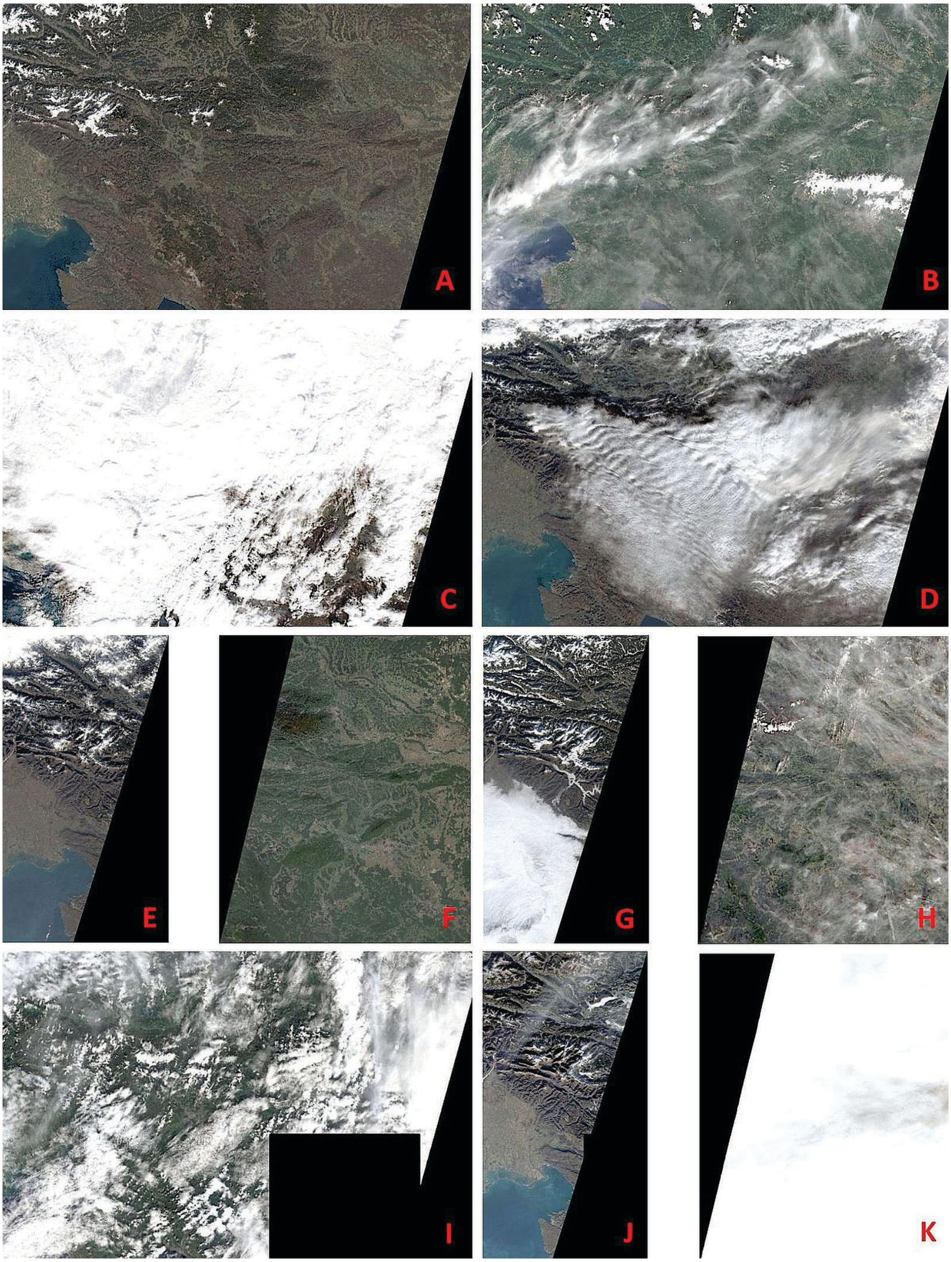


Slika 6: Razlika med letnim povprečjem oblačnosti v letih od 2015 do 2021 in povprečjem za obdobje 2016–2021. Vrednost, podano za leto 2015, je treba zaradi majhnega števila zajemov vzeti z rezervo.

Podrobnejši podatki po letnih časih (z mejnimi vrednostmi 21. marec, 21. junij, 23. september in 21. december) in območjih Slovenije (ta so urjena po tirnicah zajema) so na voljo v preglednici 4. Izračunani podatki so povsem v skladu s pričakovanji. Potrjujejo znana klimatološka dejstva, da je pri nas, v mešani alpsko-sredozemski državi, poletje najbolj suho in najmanj oblačno ter da so jesenski in zimski meseci najbolj mokri in najbolj oblačni. Nekaj primerov mozaikov Sentinel-2 v posameznih letnih časih in različnih razmerah oblačnosti je prikazanih na sliki 7 in povzetih v preglednici 5.

Preglednica 4: Spremenljivost povprečne oblačnosti po letnih časih in območjih (tj. tirnica zajema). Izstopajoče vrednosti so označeni z zeleno in rdečo barvo.

Povprečna oblačnost [%]	Zima skupaj (022/122/079)	Pomlad skupaj (022/122/079)	Poletje skupaj (022/122/079)	Jesen skupaj (022/122/079)	Povprečje na celo leto
2015	-	-	34,3 (30,4/24,2/52,3)	49,6 (41,1/46,7/63,9)	37,6
2016	46,1 (49,2/36,5/51,7)	47,0 (56,6/37,3/45,0)	35,6 (39,7/29,7/36,7)	46,5 (39,0/45,1/54,4)	44,0
2017	48,1 (51,5/43,3/48,9)	39,0 (36,7/33,6/47,2)	29,1 (34,4/29,0/23,8)	47,4 (41,6/52,9/47,3)	40,6
2018	65,9 (69,0/61,0/67,6)	37,6 (47,6/35,0/30,0)	29,6 (25,9/26,5/36,4)	49,6 (52,2/53,5/43,2)	45,4
2019	42,2 (35,4/46,9/44,2)	48,4 (52,7/44,8/48,1)	28,5 (34,5/26,3/24,5)	54,1 (48,4/65,6/49,6)	42,8
2020	37,1 (35,3/41,9/34,1)	38,4 (37,7/50.9/25,9)	29,0 (24,9/37,4/24,7)	51,4 (41,4/59,4/53,1)	39,6
2021	49,9 (55,6/47,6/46,5)	42,4 (36,5/31,9/59,4)	30,2 (32,4/34,4/23,7)	47,6 (44,8/59,2/38,4)	42,2



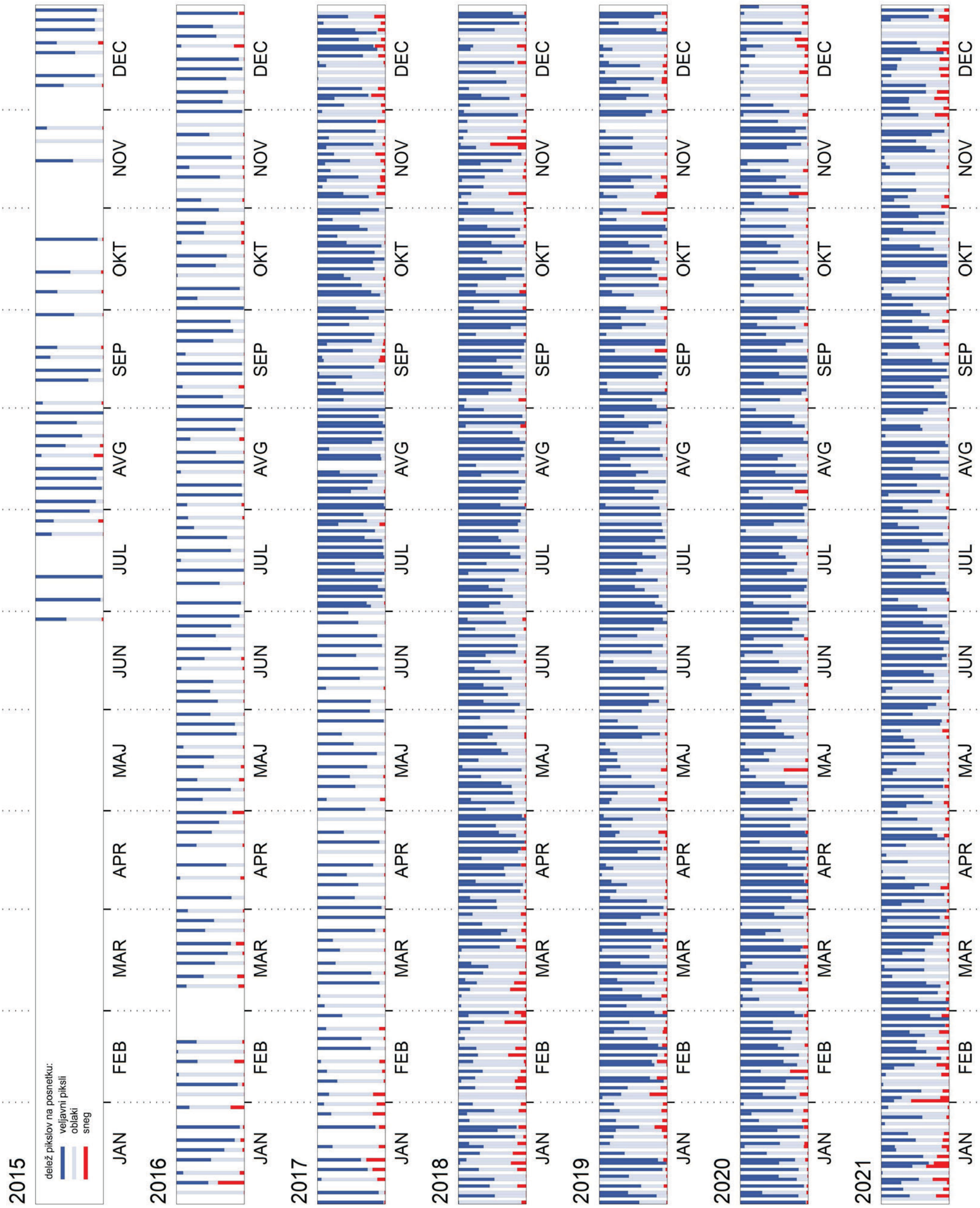
Slika 7: Primeri mozaikov satelitskih posnetkov, zajetih v različnih letnih časih, v različnih letih, z različnih tirnic in v različnih vremenskih razmerah (glej tudi preglednico 4). Dve nasprotni skrajnosti sta na eni strani jasno nebo na posnetkih A in F ter na drugi strani zaradi velike oblačnosti neuporabna posnetka C in K. Posnetka B in H kažeta, da lahko tudi tanek cirus ali meglica ovira njuno uporabnost ter da je razlikovanje med oblakom, cirusom in meglico lahko velik izziv. Posnetki D, E in G kažejo razmere, v katerih je posnetek delno uporaben, delno pa neuporaben (območja, prekrita z oblaki ali snegom). Anomalije v ESINIH podatkovnih zbirkah so prikazane na posnetkih I in J (posnetka nista popolna zaradi manjkajočih izrezov).

Preglednica 5: Opisni parametri posnetkov od A do K, prikazanih na sliki 7.

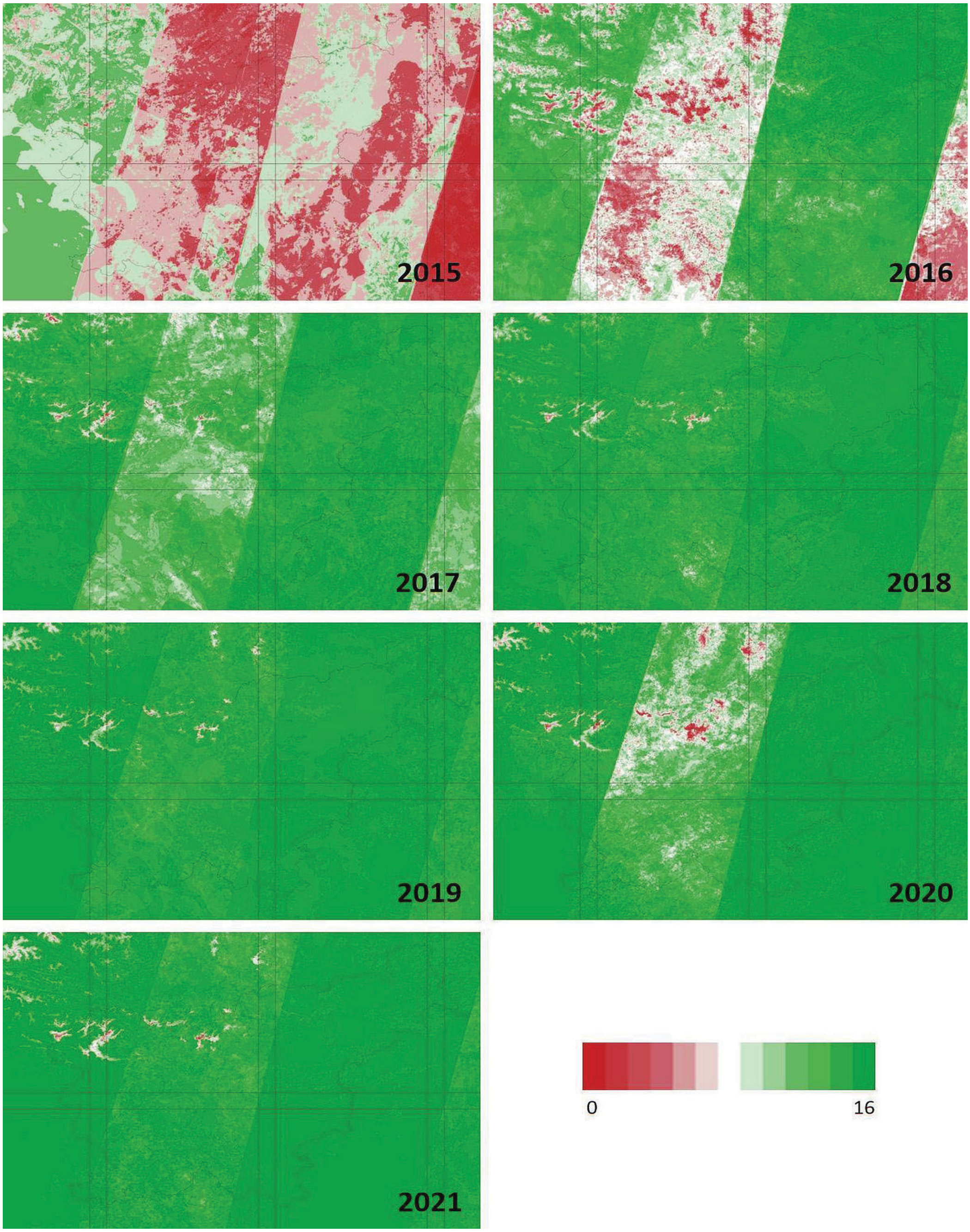
Posnetek	Datum zajema	Satelit	Tirnica	Območje Slovenije	Oblačnost [%]	Tanke plasti [%]	Snežna odeja [%]	Kratek opis lastnosti posnetka (oblačnost, snežna odeja, druge posebnosti)
A	16. marec 2020	S-2A	122	cela	0,3	0,5	2,1	jasno nebo; sneg v gorah
B	13. avgust 2021	S-2B	122	cela	53,7	13,5	0,0	zelo debele ciruse se zlahka zamenja za oblake
C	6. marec 2020	S-2A	122	cela	67,9	10,9	14,2	neuporaben posnetek: oblaki in sneg
D	12. december 2018	S-2A	122	cela	43,7	29,0	1,0	čeprav je posnetek zelo oblačen, je na nekaterih jugozahodnih območjih uporaben
E	14. januar 2019	S-2A	022	zahod	7,9	2,3	5,7	posnetek je uporaben povsod, razen na gorskih območjih
F	29. marec 2017	S-2A	079	vzhod	0,0	0,0	0,0	jasno nebo
G	29. januar 2018	S-2A	022	zahod	36,0	0,1	11,1	delno uporaben, delno neuporaben posnetek
H	16. avgust 2017	S-2A	079	vzhod	5,9	6,2	0,0	zelo tankih cirusov ni mogoče zaznati
I	3. september 2017	S-2B	122	cela	61,3	12,0	0,2	manjka en izrez (velik del posnetka)
J	11. december 2015	S-2A	022	zahod	12,3	6,0	0,1	manjka en izrez (zelo majhen del posnetka)
K	3. februar 2016	S-2A	079	vzhod	99,7	0,0	0,3	neuporaben posnetek, popolnoma prekrit z oblaki

3.2.2 Deleži oblačnosti v časovni vrsti Sentinel-2

Zgolj iz števila posnetkov in deležev njihove pokritosti z oblaki ne moremo enostavno sklepati o njihovi uporabnosti v praksi (na primer za sistematično spremljanje naravnih ali urbanih območij, zaznavanje sprememb, študije klasifikacije pokrovnosti tal, razvoj časovnih vrst satelitskih posnetkov itd.). Pri daljinskem zaznavanju nas običajno zanima analiza stabilnih in primerno gostih časovnih vrst satelitskih posnetkov brez oblakov na določenem območju opazovanja v daljšem časovnem obdobju. Se pravi, zanima nas zaporedje uporabnih posnetkov (tj. tistih z nizko pokritostjo z oblaki) na danem območju. Slika 8 prikazuje zaporedje vseh arhivskih posnetkov, z deležem oblačnosti in deležem snežne odeje. Prikazano zaporedje daje vpogled v gostoto uporabnih časovnih vrst, ki jih lahko pričakujemo na območju vse Slovenije; analizi prijazni so intervali neprekinjenih skupkov temno modre barve.



Slika 8: Grafični prikaz deležev oblačnosti in snežne odeje vseh posnetkov Sentinel-2 Slovenije v arhivu do konca leta 2021. Podatki so prikazani za 10-kanalni atmosfersko popravljen produkt ločljivosti 20 metrov. Datumi rastejo v smeri navzgor. Vsak posnetek je predstavljen z majhnim okvirčkom, ki je zarisan na datum zajema, pri čemer temno modra barva predstavlja brezoblačen (tj. uporaben) delež posnetka, svetlo modra in rdeča barva pa deleže oblakov oziroma snega. Tirnica, iz katere je bil posnetek zajet (122, 079 ali 022), in posledično območje, ki je bilo zajeto (cela, vzhodna ali zahodna Slovenija), v tem grafičnem prikazu nista upoštevana.



Slika 9: Število brezoblačnih pikslov na časovni vrsti 15-dnevnih kompozitov v ločljivosti 20 metrov v rastni sezoni, tj. od 2. marca do 27. oktobra (16 intervalov), na leto. Dvanajst ali več brezoblačnih pikslov v časovni vrsti je mogoče najti v večjem delu Slovenije – z izjemo visokogorskih območij – v letih 2018, 2019 in 2021. V letih 2017 in 2020 je za nekatera območja v severni in osrednji Sloveniji časovna vrsta precej redkejša, še redkejša pa je za številna večja območja države v letih 2015 in 2016 (ko je v površje Zemlje snemal le Sentinel-2A).

3.2.3 Brezoblačni kompoziti v rastni sezoni

Raziskave in študije so pogosto omejene na posamezno regijo in/ali časovno obdobje. Za uporabo satelitskih podatkov na strokovnih področjih, ki proučujejo fenologijo rastlin, na primer v gozdarstvu, kmetijstvu in biologiji, je še posebej zanimivo časovno obdobje, ki zajema rastno sezono vegetacije.

Rastna sezona v Sloveniji traja od začetka marca (na obali) do konca oktobra. Najprimernejši datumski interval, ustrezen temu časovnemu razponu, ki je skladen s časom ponovnega zajema (5 dni za par satelitov) in je deljiv s 15, 30 in 60 (pol meseca, mesec, dva meseca; to so intervali, ki so blizu običajnemu človeškemu pojmovanju časa), je 240-dnevno obdobje od 2. marca do 27. oktobra. To obdobje zajema večino vegetacijskih vrst v Sloveniji. Če račune izvedemo v 15-dnevnih intervalih, to obdobje pokrije šestnajst 15-dnevnih intervalov. Vsakih 15 dni je zajeto devet posnetkov Sentinel-2, po trije iz vsake tirnice, kar pomeni, da so prekrivajoča se območja na vzhodu in zahodu zajeta šestkrat, osrednja Slovenija pa trikrat. Teh devet posnetkov uporabimo za sestavo 15-dnevnih kompozitov.

Na časovni vrsti prostorske ločljivosti 20 metrov smo preverili, koliko brezoblačnih pikslov je na voljo za vsak 15-dnevni interval v obdobju rastne sezone v letih od 2015 do 2021. Rezultati kažejo, da je za večino pikslov v letih 2018, 2019 in 2021 iz 15-dnevnih kompozitov mogoče sestaviti gosto brezoblačno časovno vrsto, ki ima od 12 do 16 brezoblačnih pikslov, po celi Sloveniji, razen v visokogorju na severu (Julijske Alpe, Karavanke in Kamniško-Savinjske Alpe) (delež pikslov z vsaj 12 brezoblačnimi piksli je 97 %, 98 % in 97 % za leta 2018, 2019 in 2021) (slika 9). Za leti 2017 in 2020 to velja le tam, kjer se posnetki prekrivajo (73 % in 83 % pikslov z vsaj 12 brezoblačnimi piksli za leti 2017 oziroma 2020), medtem ko za osrednji del Slovenije časovna vrsta ni gosta. To je še posebej očitno v gorskih območjih na severu – v Kamniško-Savinjskih Alpah in Karavankah. Za leto 2015 v rastni sezoni iz 15-dnevnih kompozitov ni mogoče izdelati uporabne časovne vrste, za leto 2016 pa je to mogoče le za vzhod in nekatere zahodne dele Slovenije, kjer se posnetki prekrivajo (0 % in 50 % pikslov z vsaj 12 brezoblačnimi piksli za leti 2015 in 2016).

3.2.4 Primeri uporabe

Opisani arhiv je bil že uporabljen v več raziskavah. Doslej dokončane študije vključujejo časovno zaznavanje anomalij rabe kmetijskih zemljišč na podlagi posnetkov Sentinel-2 za podporo spremljanja skupne kmetijske politike (Kanjir et al., 2018), študijo zaznavanja škode, ki jo povzroči lubadar (Kobler in Ogris, 2021), ter študijo kartiranja intenzivnosti rabe travnikov (intenzivni, ekstenzivni travniki) za območje cele Slovenije za Zavod RS za varstvo narave (Potočnik Buhvald et al., v postopku objave).

Prva navedena študija analizira kratkoročne časovne vrste Sentinel-2 (tri leta: 2016–2018) in izvedljivost spremljanja anomalij pri upravljanju travnikov in obdelovalnih površin na treh izbranih testnih območjih. Študija je pokazala, da je za zagotavljanje ustreznih informacij v podporo upravljanju skupne kmetijske politike potrebna zadostna gostota satelitskih podatkov (na primer dvotedensko). Čeprav so vsa testna območja ležala v območju prekrivanja posnetkov iz sosednjih tirnic, je sezonsko časovno vrsto sestavljalo le 30–40 uporabnih brezoblačnih opazovanj letno (od teoretično možnih 146). Druga študija je omogočila realen vpogled v uporabnost časovnih vrst Sentinel-2 na majhnem območju opazovanja. V štirih preučevanih letih je bilo na voljo le 31 izsekov posnetkov, ki so pokrivali opazovano območje in so imeli oblačnost manj kot 10 % (5, 5, 14 in 7 posnetkov v letih 2015, 2016, 2017 oziroma 2018). Kljub vsemu je ta skromna časovna serija zadostovala za spremljanje počasnega propada dreves zaradi lubadarja. V tretji navedeni študiji smo izvedli poskus za določitev števila košenj na posameznem travniku. Za to študijo zgolj časovna vrsta Sentinel-2 ni zadostovala, zato je bila dopolnjena s časovno vrsto radarskega sistema Sentinel-1, ki je neodvisna od vremenskih razmer.

Proučevali smo tudi primernost podatkov Sentinel-2 za izdelavo prostorsko-časovnih kompozitov (Čož et al., 2020). Študija je pokazala, da je v rastni sezoni mogoče izdelati mesečne kompozite Slovenije, medtem ko kompozitov za krajša obdobja ni mogoče sistematično zagotoviti. To pomeni, da s standardno metodo za izdelavo kompozitov, predlagano za podatke Sentinel-2, lahko izračunamo mesečne informacije za ozemlje Slovenije, če le vremenske razmere niso ekstremno slabe.

Časovna gostota satelitskih posnetkov Sentinel-2 teoretično zadostuje za spremljanje razmeroma hitro spreminjajočih se pojavov, na primer tudi tedenskih sprememb. Opisani primeri praktične uporabe so pokazali, da se zaradi prisotnosti oblakov znatno zmanjša gostota uporabnih posnetkov v časovni vrsti. Izkazalo se je, da časovne vrste posnetkov Sentinel-2 zadoščajo zgolj za zaznavanje počasnejših – tj. letnih, sezonskih ali mesečnih – sprememb, kot je na primer detajlno kartiranje kmetijske suše (HD-Drought, 2021). Za uspešno spremljanje pogostejših – tj. tedenskih – pojavov pa je treba časovno vrsto Sentinel-2 kombinirati s časovno vrsto Sentinel-1, na katero vremenske razmere ne vplivajo. Trenutno potekata dve obsežnejši študiji tudi na to temo: študija časovnih vrst za spremljanje kmetijskih zemljišč (SURS GEOS, 2021) ter za spremljanje gozdnega okolja, travnikov in mokrišč (ROVI, 2021) na ravni Slovenije. V obeh študijah časovne vrste Sentinel-2 dopolnjujemo s časovnimi vrstami Sentinel-1.

4 ZAKLJUČKI

Satelita Sentinel-2 sta zelo zanesljiv vir optičnih satelitskih podatkov visoke ločljivosti. Podatke smo preučili z vidika njihove uporabnosti. Statistično smo analizirali prvih šest let (2016–2021) operativnega arhiva podatkov Sentinel-2 za Slovenijo, ki ga hrani ZRC SAZU. Prikazani so tudi podatki iz druge polovice leta 2015, ki pa jih je treba zaradi majhnega števila zajemov jemati s pridržkom.

Za raziskovalce je pomemben vidik posnetkov Sentinel-2 njihova geometrična točnost. V tem članku tega vprašanja nismo podrobneje obravnavali, saj je zagotavljanje splošne položajne točnosti satelitskih posnetkov naloga ESE. Na podlagi ESINIH študij je povprečna geometrična točnost posnetkov s celega sveta do konca februarja 2021 znašala 1,1 piksla. Bistveno izboljšanje na 0,5 piksla bo mogoče, ko bo ESA celoten arhiv ponovno obdelala z novim procesnim okoljem različice 03, ki je bilo vpeljano marca 2021.

Poleg geometrične točnosti je za uporabo satelitskih podatkov zelo pomemben vidik število zajemov (opazovanj). Par satelitov Sentinel-2 osrednji del Slovenije zajame 73-krat na leto, medtem ko je število zajemov vzhodnega in zahodnega dela Slovenije – zaradi obsežnega 100-kilometrskega prekrivanja posnetkov, zajetih iz sosednjih tirnic – natančno dvakratno, tj. 146-krat na leto.

Odločujoči vidik za uporabnost optičnih satelitskih podatkov je prisotnost/odsotnost oblakov na posnetkih. Delež oblakov na povprečnem posnetku za Slovenijo v šestih obravnavanih letih je 42 % (s pričakovano velikim standardnim odklonom 32 %). V tem obdobju ima 22,2 % posnetkov manj kot 10 % oblakov, 10,9 % posnetkov pa je neuporabnih, ker so pretežno oblačni (pokritost z oblaki več kot

90 %). Izračunane maske oblakov omogočajo identifikacijo posameznih uporabnih (veljavnih) pikslov in s tem iskanje uporabnih podatkov (datumov) ter pripravo časovnih vrst za izbrana, tudi zelo majhna območja opazovanja. Poznavanje vzorca oblačnosti skozi leta je pomembno za ocenjevanje kakovosti in pričakovane gostote časovnih vrst satelitskih posnetkov. Pomembno pa je tudi za načrtovanje zapolnjevanja vrzeli satelitskih podatkov in s tem za ocenjevanje uspešnosti uporabnosti časovne vrste Sentinel-2 za spremljanje izbranih območij in pojavov.

V praksi se je pokazalo, da časovna vrsta posnetkov Sentinel-2 zadostuje za zaznavanje počasnejših sprememb (mesečnih, sezonskih, letnih). Za uspešno spremljanje pogostejših, na primer tedenskih pojavov pa je treba časovno vrsto Sentinel-2 kombinirati z vremensko neodvisno časovno vrsto radarskega sistema Sentinel-1.

Vsi arhivski podatki v vseh fazah obdelave so na voljo za nadaljnje analize in primere uporabe. Pripravili smo že več časovnih vrst brezoblačnih mozaikov, pa tudi spektralnih indeksov, ki se najpogosteje uporabljajo (na primer NDVI – normiran diferencialni vegetacijski indeks, NDWI – normiran diferencialni vodni indeks, EVI – izboljšan vegetacijski indeks). Arhiv ni javno objavljen, ga je pa mogoče pridobiti za raziskovalne namene. Uporabljajo ga tudi raziskovalci drugih raziskovalnih in akademskih ustanov (na primer Gozdarskega inštituta Slovenije, Univerze v Ljubljani). Uporabnost arhiva narašča z vsakim dodatnim tednom delovanja para satelitov Sentinel-2.

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