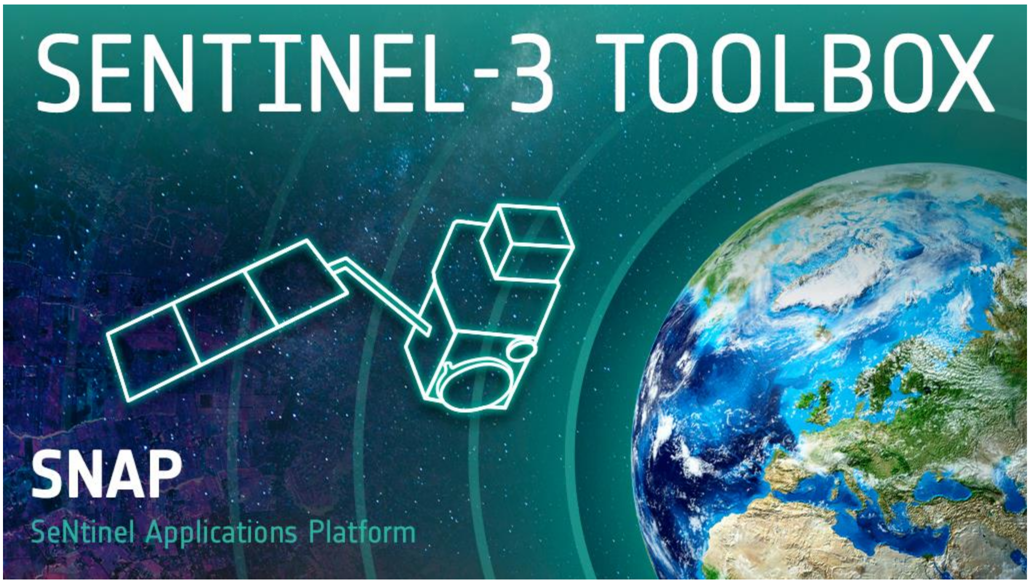
SNAP – S3TBX Collocation Tutorial



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1 INTRODUCTION

Collocations between two satellite sensors are occasions where both sensors observe the same place, in many cases at roughly the same time as shown in Figure 1. Usually, satellite data from different sensors are provided in distinct data products, at different spatial resolutions and different Coordinate Reference Systems (CRS)[1].

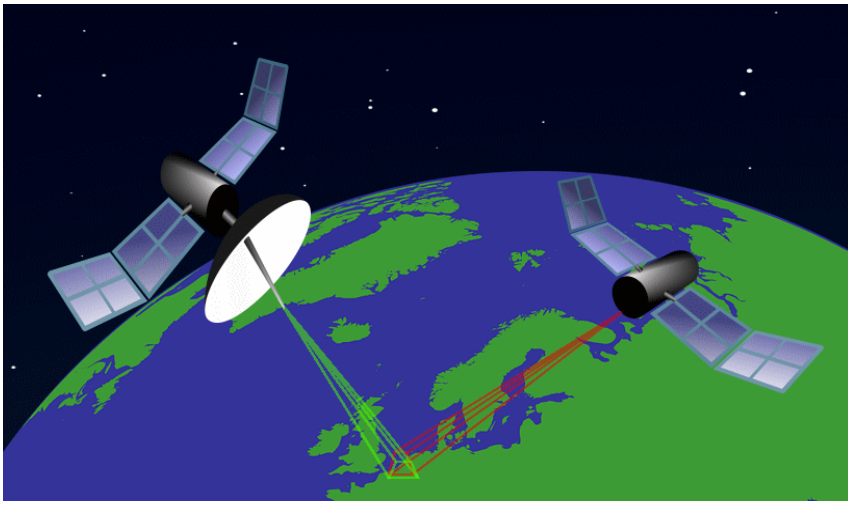


Figure 1 Two satellites observing the same area on earth

These differences make it necessary for the data to be collocated in before any analysis at multiple resolutions In this document we will provide background information and discuss what needs to be considered when doing a collocation. In the end we will provide real world examples to demonstrate the collocation process. These examples will make use of different sensors of the three Sentinel platforms: Sentinel-1, -2 and -3.
Collocating different remote sensing data products has the purpose to make synergistic use of the data. This can have multiple reasons. For example, bands of the visible spectrum from one sensor can be combined with near infrared bands of another. Classification results, which are generated with one sensor, can be collocated with observation data from another sensor. Also, long-term maps, like climatology or land classification maps, can be combined with current observations. The collocation process allows combinations where we can benefit from high temporal resolution, with high spatial resolution and/or with different frequency domains (optical, thermal, PMW, radar).By combining different data sources new applications become possible.

[1] https://docs.qgis.org/2.18/en/docs/gentle_gis_introduction/coordinate_reference_systems.html

2 THEORETICAL BACKGROUND

2.1 GENERAL CONSIDERATIONS

2.1.1 Geo-location accuracy

The collocation result can only be as good as the geographical location of the input products, as the method uses the geo-location information to find matching pixels. This is especially relevant when collocating low resolution secondary data to high resolution reference data.

2.1.2 Pixel Spacing / Spatial Resolution

The term spatial resolution is often used when in fact one is talking about pixel spacing. The pixel spacing refers to the distance in metres on earth between two adjacent pixels. Spatial resolution in contrast refers to the ability to distinguish adjacent objects on Earth. In many cases, these values are approximately the same. In other cases, the value for spatial resolution may be greater than the value for pixel spacing. This means that the objects are more difficult to distinguish. This can happen if the data has already been resampled. When resampling data from 300m to 10m the pixel spacing will afterwards be 10m, but the spatial resolution is still 300m.

The difference in pixel spacing should not be too big between the reference and the secondary product(s). The greater the difference the greater the introduced error in the collocated product due to the values considered by the interpolation which are far away from the actual target location. The allowed difference in pixel spacing must be judged for each application separately.

2.1.3 Time Difference

When merging observations, the time difference between those observations should be minimised. This ensures that the measurements of the sensors are taken under the same (or at least similar) conditions. Of course, when creating time series or when the intention is to compare values with historical a minimal time difference is not the goal. But in those scenarios often the creation of a L3 product is more appropriate. Unfortunately, this L3 creation is out of the scope of this document.

2.1.4 Pre-Processing

Depending on the sensor different pre-processing steps might need to be applied before the collocation. In many cases the pre-processing operations cannot handle the collocated data. This occurs either because of the change in naming of the bands or those operations have been designed for the original data and they do not expect the additional data generated by the collocation. The data to be collocated should have undergone as many processing steps as needed in the end. Only those steps where the data is used in conjunction are performed afterwards.

In addition to these technical limitations, scientific considerations must also be considered. For example, bands and tie-points grids which contain values about the sun and viewing geometry need to be included in the collocation. The geometric angles of the reference data could be very different and should not be used for the data of the secondary products. Cloud shadow detection is a good example of such a case.

2.1.5 Input selection

An appropriate consideration of the impact of collocation on the data is needed before processing. For example, data that come with the tie-point grids in the source product do not consume much disk space but when resampled to the target scene the amount of disk space needed can become significant. If the input is selected by creating a subset before the collocation, a considerable amount of processing time and disk memory can be saved.

2.2 COLLOCATION PROCESS

The essential part of collocation is to bring data from one raster to another. A resampling is always needed if the rasters do not match in pixel-spacing and/or orientation. Different variations of the mismatches are presented in Figure 2. Starting from two rasters with different pixel spacing, the mismatch can vary from only the different pixel spacing (Overlap 1) to a slight shift (Overlap 2) and different orientation (Overlap 3), or all together. Further, if a raster is still in satellite coordinates - not mapped to a regular raster - it may be alternately stretched or compressed like a rubber sheet.

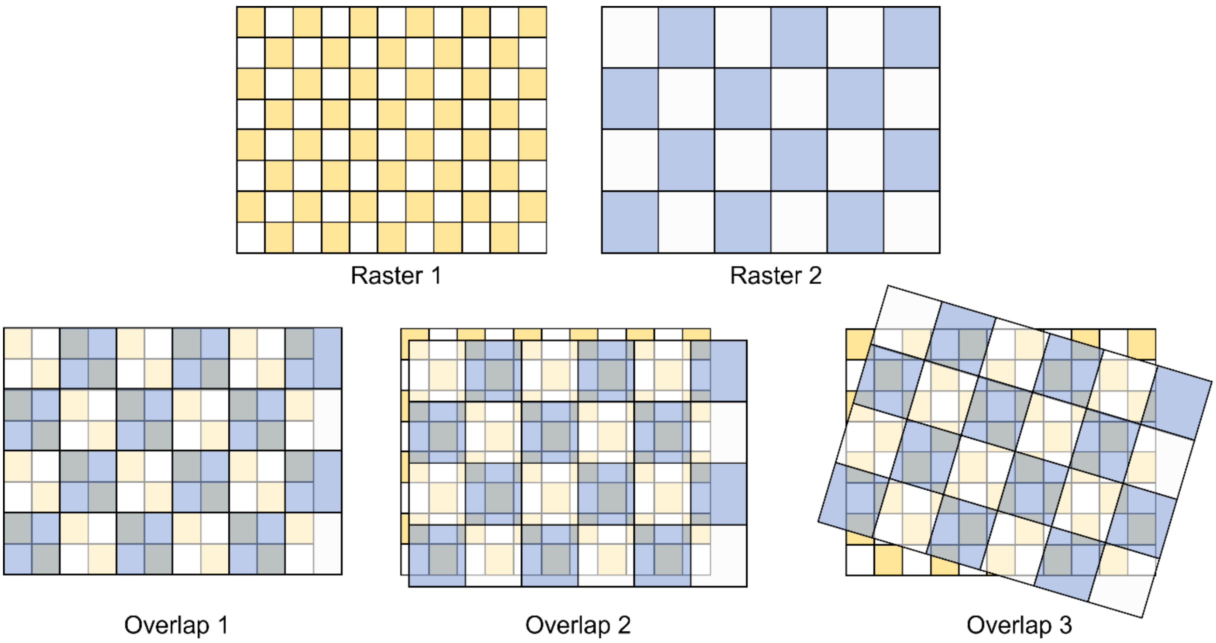


Figure 2 Three types of overlap of 2 rasters with different pixel-spacing

Different resampling methods are available to bring one raster to the other. Resampling methods help to get the best representative pixel from the source data into the new raster. The resampling methods important for the collocation are explained in the following sub-chapters.

2.2.1 Nearest Neighbour Resampling

The nearest neighbour interpolation[2] is the simplest resampling approach. The target value pixel is filled with the spatially closest pixel within the source raster.

[2] https://en.wikipedia.org/wiki/Nearest-neighbor_interpolation

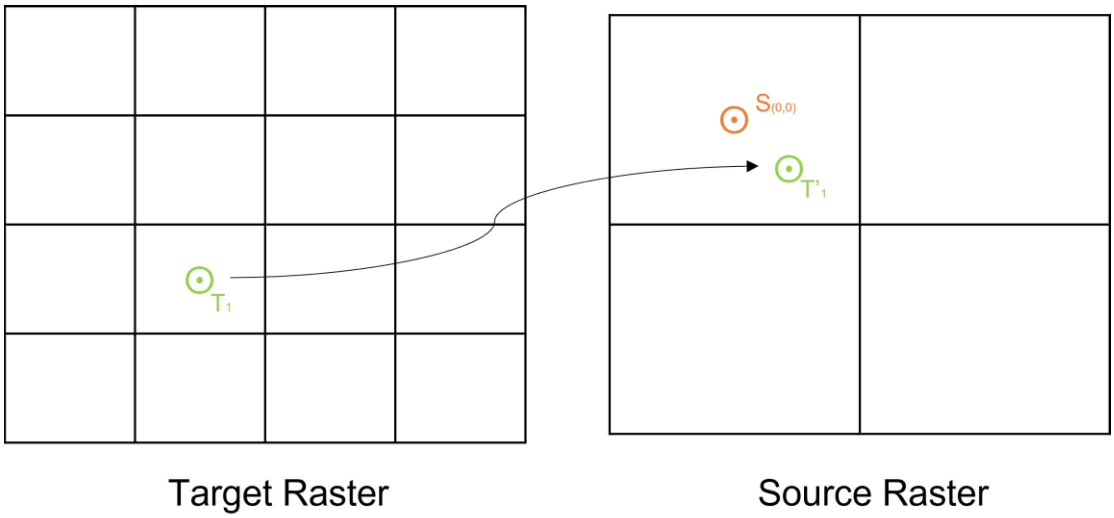


Figure 3 Calculation of the target value by the nearest neighbour resampling

Pros:
The benefits of the nearest neighbour resampling are that it is very simple and fast compared to other interpolation methods. No new values are introduced which did not exist in the source raster because no interpolation is applied. The contrast in the resulting image is higher compared to the results of the interpolation methods.
Cons:
Depending on how the source and target rasters overlap and are aligned, some pixels are lost, and others are duplicated. The image loses sharpness by the resampling process compared to the other interpolation methods.
Use:
This type of resampling should be used when the exact same values are needed in the collocated data as in the source data. For example, for comparison with other data. Nearest neighbour resampling must be used in cases where interpolation would lead to wrong or illegal values. This is the case for data containing discrete values, like classification results or flag data. Figure 4 shows such an example. The blue pixel indicates water with a value of 210, grey (60) indicates an urban area, the orange (130) pixel indicates grass and green (190) forest.

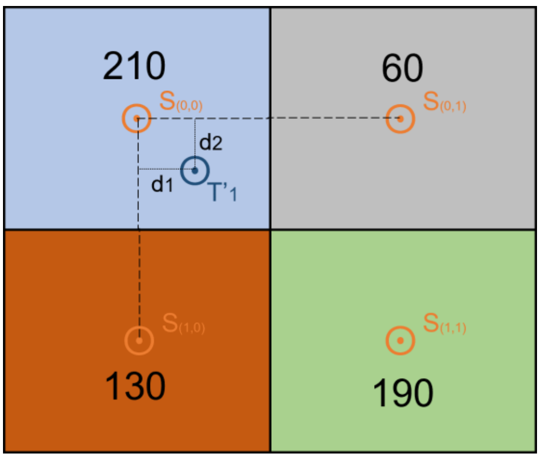


Figure 4 Bilinear Interpolation of discrete values

If a bilinear interpolation of these classes is performed the result is a value of 169.1. The exact value depends on the point T'_1 and the resulting values for d1 and d2. Please see the next chapter 2.2.2 for the equation. Which value shall be used in the target? If in the classification scheme 160 indicates snow and 170 ice and the values in between are not defined, then the impact is a change to an inappropriate class. This example shows that interpolating between discrete values can lead to wrong results. In this case the best selection for the target pixel (green circle) is the blue pixel with a value of 210 which is the result of the nearest neighbour resampling.

2.2.2 Bilinear Interpolation

The bilinear interpolation[3] involves applying a 1D-linear interpolation[4] to 2D data by performing the interpolation first in one direction, and then again in the other direction. The interpolation as a whole is not linear but approaches a quadratic form.

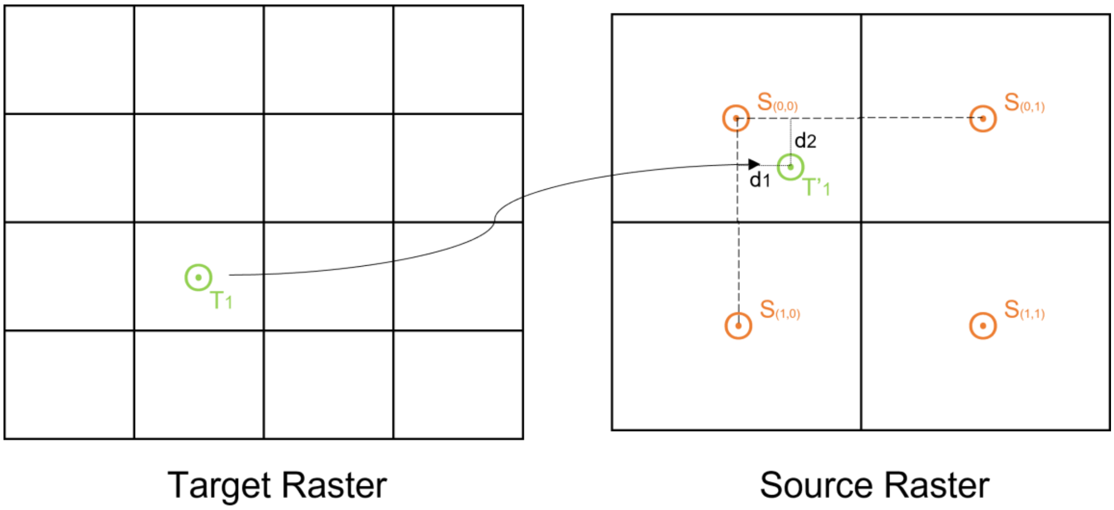


Figure 5 Calculation of the target value by the bilinear interpolation

For calculating the target value T_1 as shown in Figure 5 the following equation is used:

$$T_1 = S_{(0,0)} \times (1 - d_1) \times (1 - d_2) + S_{(0,1)} \times d_1 \times (1 - d_2) + S_{(1,0)} \times (1 - d_1) \times d_2 + S_{(1,1)} \times d_1 \times d_2$$

Pros:
Compared to nearest neighbour resampling the extremes are balanced, and the result is sharper.
Cons:
The processing of the data is slower, and the image has less contrast. Additionally, new values are calculated which are not present in the source data.
Usage:
The bilinear interpolation is applicable for continuous data, like reflectances or air pressure values.

2.2.3 Bicubic Interpolation

The cubic interpolation[5] is intended for one-dimensional data but can be applied to 2D-data if first each row is interpolated separately and then the column resulting from the row-interpolation. The bicubic interpolation[6] is an extension of the cubic interpolation. The interpolation is directly applied in the 2D-space. Both interpolations give almost the same result.

[3] https://en.wikipedia.org/wiki/Bilinear_interpolation
[4] https://en.wikipedia.org/wiki/Linear_interpolation
[5] https://en.wikipedia.org/wiki/Cubic_Hermite_spline
[6] https://en.wikipedia.org/wiki/Bicubic_interpolation

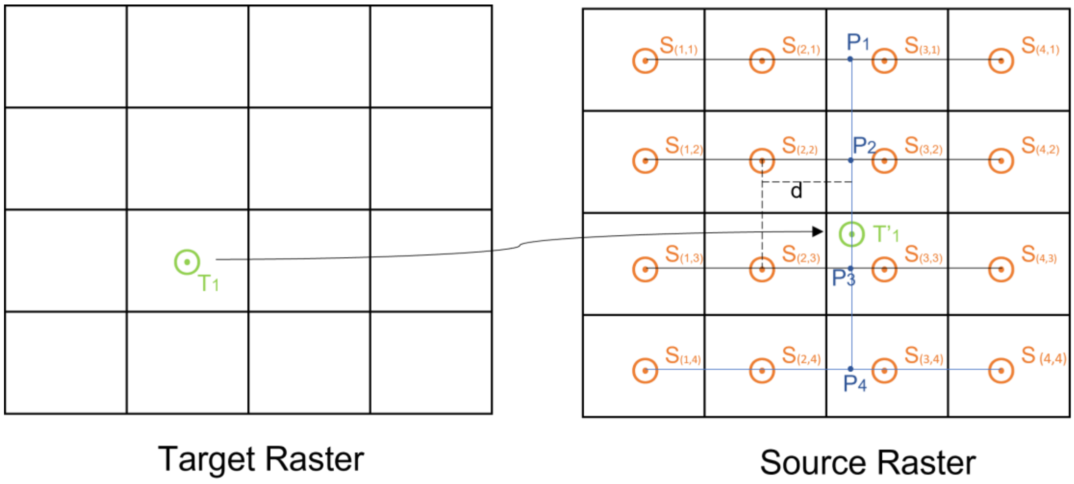


Figure 6 Calculation of the target value by the cubic interpolation approach

The calculation of the 2D cubic interpolation is performed using the following equation:

$$P_k = S_{(k,1)} \times (4 - 8(1-d) + 5(1+d)^2 - (1+d)^3) +$$
$$S_{(k,2)} \times (1 - 2d^2 + d^3) +$$
$$S_{(k,3)} \times (1 - 2(1-d)^2 + (1-d)^3) +$$
$$S_{(k,4)} \times (4 - 8(2-d) + 5(2-d)^2 - (2-d)^3$$

For details of the bicubic interpolation please consult the documentation referenced above

Pros:

By using the (bi)cubic interpolation the extremes are also more balanced, and the image is even more sharpened compared to the bilinear interpolation.

Cons:

The contrast is less than with nearest neighbour resampling and the calculation takes even longer than the bilinear interpolation. The result contains values which are not present in the source data.

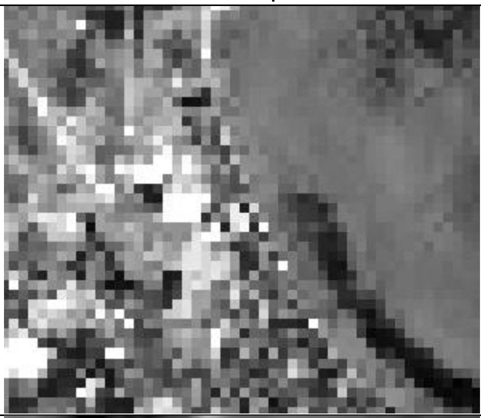
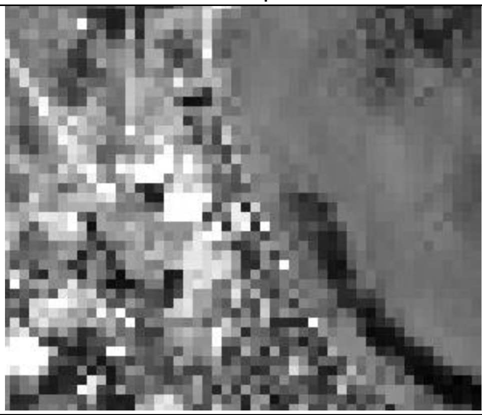
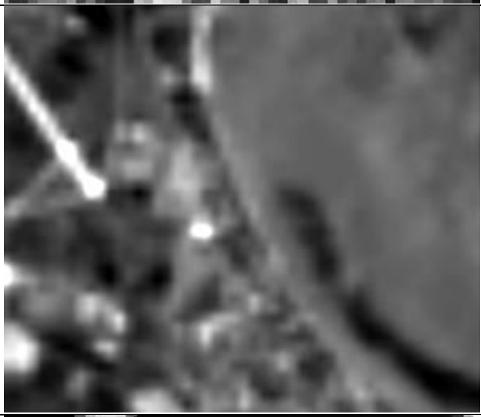
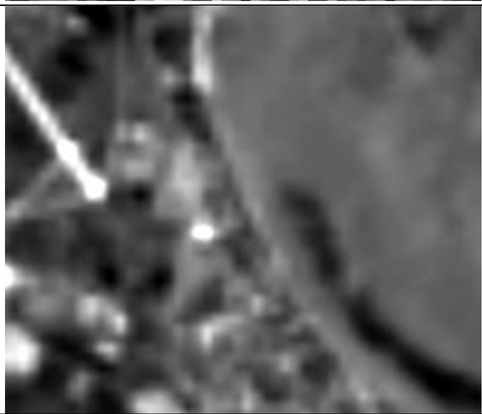
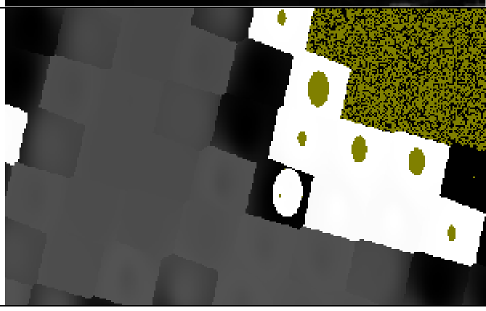
Usage:

Bicubic interpolation can be used for the same data as bilinear interpolation, and it improves the visual appearance. The bicubic interpolation can yield better results for data from a digital elevation model (DEM), for details see Rees, 2000.

2.2.4 Bisinc Interpolation

The bisinc interpolation is the derivative of the sinc[7] interpolation, like bicubic is the derivative of cubic interpolation. Describing this type of interpolation would exceed this documentation. Bisinc interpolation is used for interferometry to do phase preserving interpolation of radar data and should be applied during the pre-processing. Bisinc interpolation does not have any major benefit compared to bicubic interpolation during the collocation process. To underline this, the following table shows the bicubic and bisinc results of section 2.2.5 separately. Thus, the bisinc results are omitted in this section. The dark yellow colour in the last bicubic-bisinc comparison indicates no-data. Those pixels are located over water and have therefore no LST value.

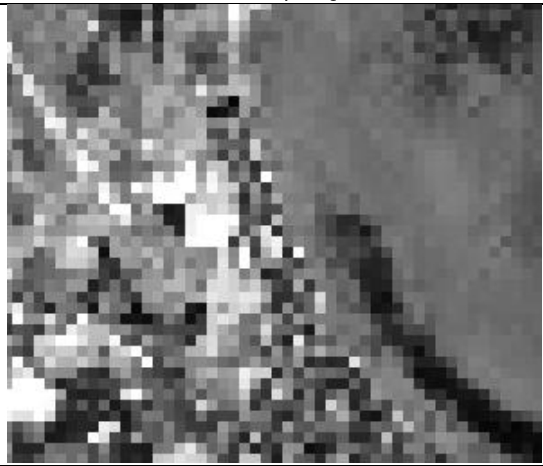
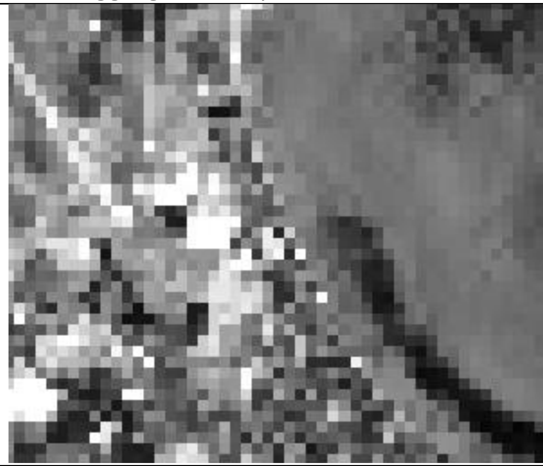
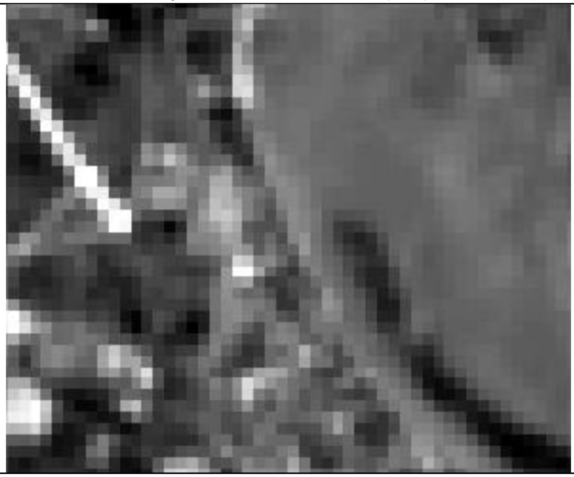
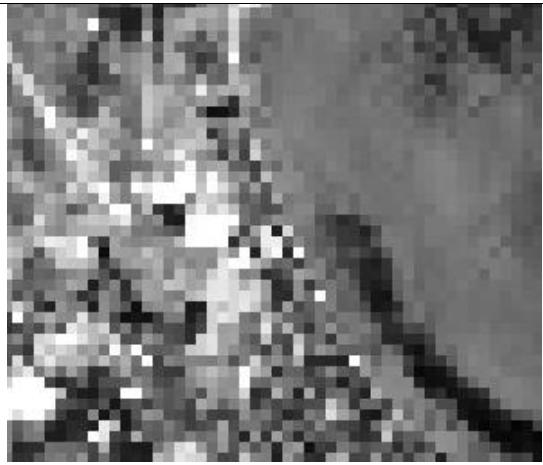
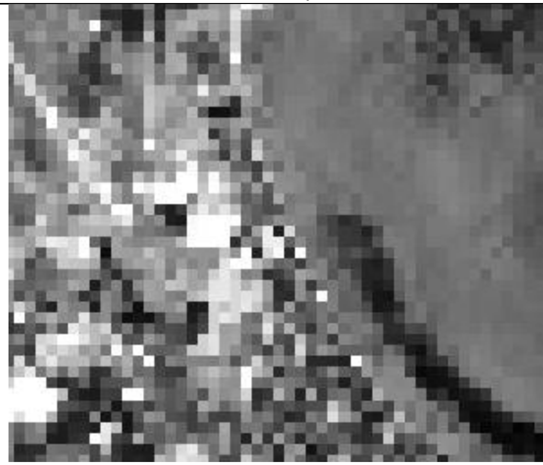
[7] https://en.wikipedia.org/wiki/Sinc_function

	Bicubic interpolation	Bisinc interpolation
From 10m to 60m		
From 60m to 10m		
From 300m to 333m		
From 1000m to 10m		

2.2.5 Resampling Results

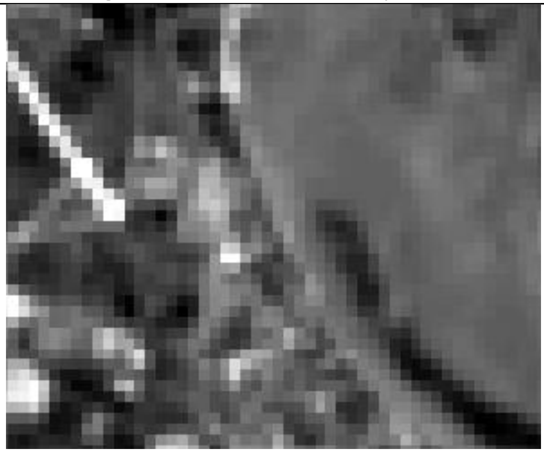
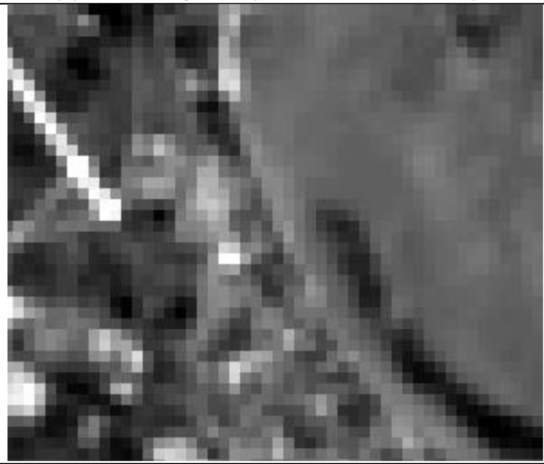
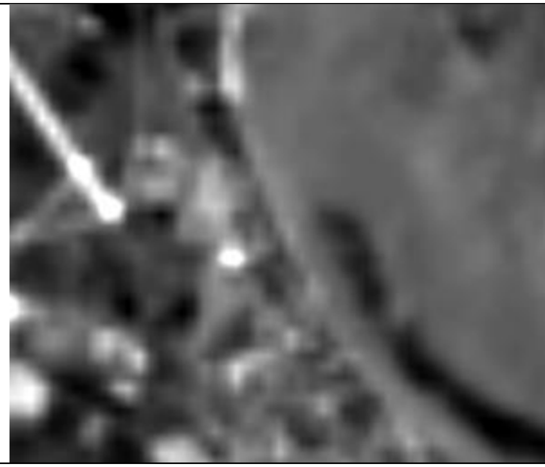
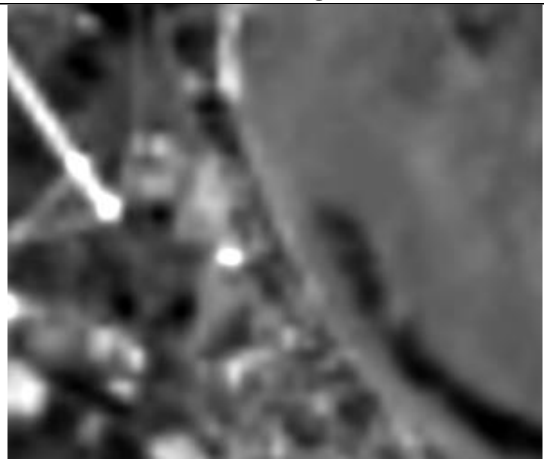
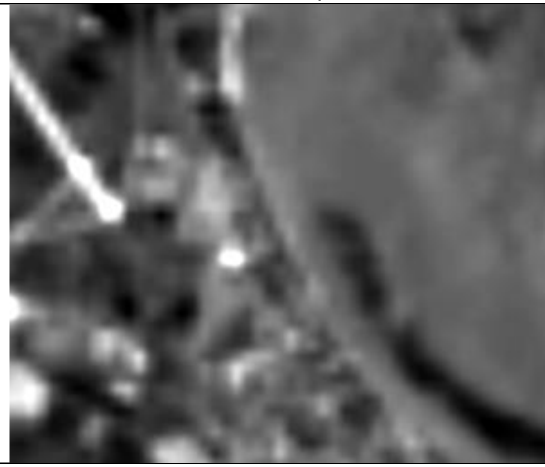
2.2.5.1 From 10m to 60m

Here the results of a collocation of a Sentinel-2 band at 10m to the equivalent at 60m are shown where the reference pixel spacing is 60m and the pixel spacing of the input is 10m. All results look quite similar, and the chosen resampling method is not decisive for the aggregation of pixels.

		
Input scene at 10m (B4)	Nearest neighbour	Bilinear interpolation
		
Reference scene at 60m (B1)	Cubic interpolation	Bicubic interpolation

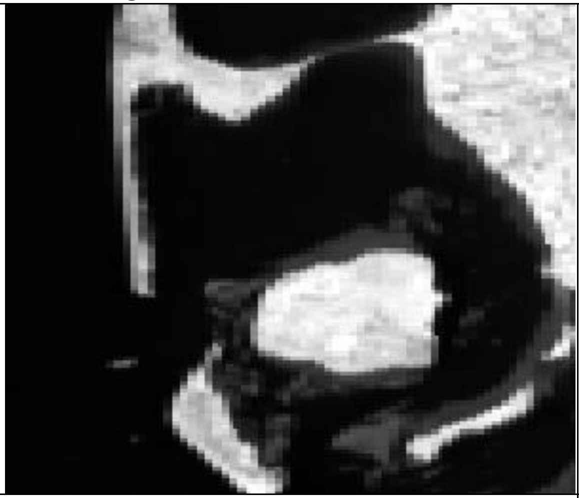
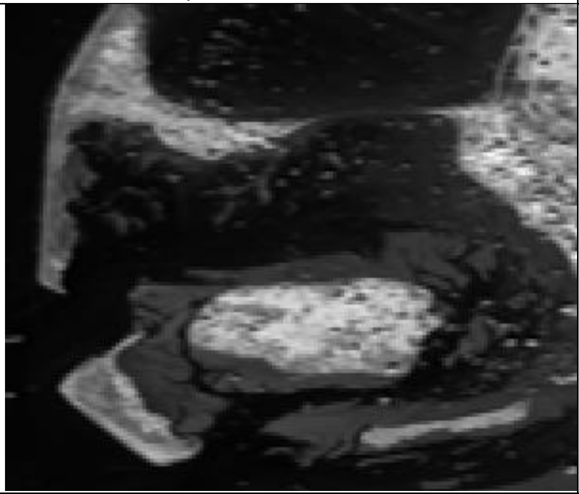
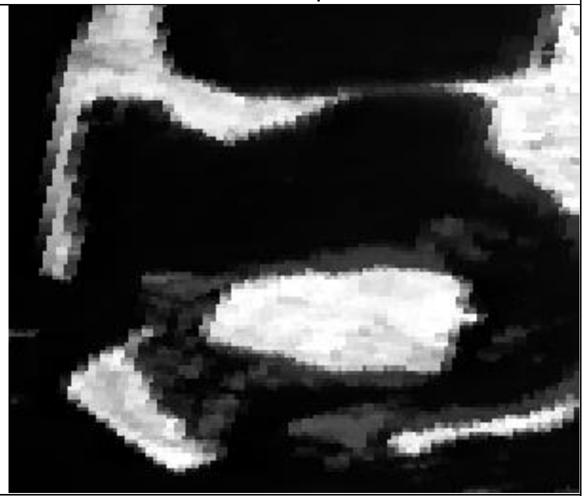
2.2.5.2 *From 60m to 10m*

In this example 60m Sentinel-2 data has been resampled to the 10m resolution. The nearest neighbour approach reproduces the input that is most faithful to the original values, while interpolation results have an apparent higher spatial resolution by introducing new values.

		
Input scene at 60m (B1)	Nearest neighbour	Bilinear interpolation
		
Reference scene at 10m (B4)	Cubic interpolation	Bicubic interpolation

2.2.5.3 *From 300m to 333m*

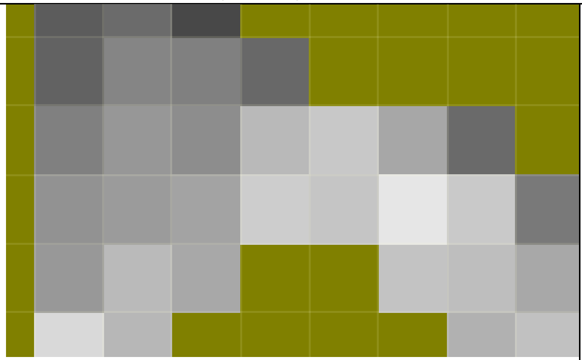
For this example, 300m Sentinel-3 OLCI radiances, converted to TOA reflectances in the pre-processing, have been collocated with TOA reflectances of PROBA-V. This example shows how you can use different but similar sensors to create long time series. The results show how the data needs to be distorted to fit into the target raster.

		
Input scene at 300m	Nearest neighbour	Bilinear interpolation
		
Reference scene at 333m	Cubic interpolation	Bicubic interpolation

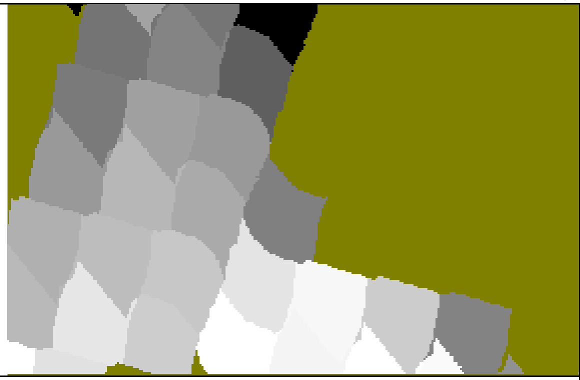
2.2.5.4 *From 1000m to 10m*

In this example 1km Sentinel-3 SLSTR Level-2 Land Surface Temperature (LST) data have been collocated with 10m Sentinel-2 MSI data. The dark yellow colour indicates no-data. Those pixels are located over water and have therefore no LST value.

The results underline very well the difference between pixel spacing and spatial resolution. In the result the pixel spacing is 10m, but the spatial resolution is still 1km. It becomes also visible in the results that the pixels are distorted, especially for the nearest neighbour case. The reason for this the reference scene is a regular reference system (UTM) and the secondary data is on an irregular geographic grid. The calculated geographic distance does not coincidence with the distance in the pixel space. The wholes and the noise for cubic and the bicubic cases are caused by the phenomena of overshooting and undershooting[8].



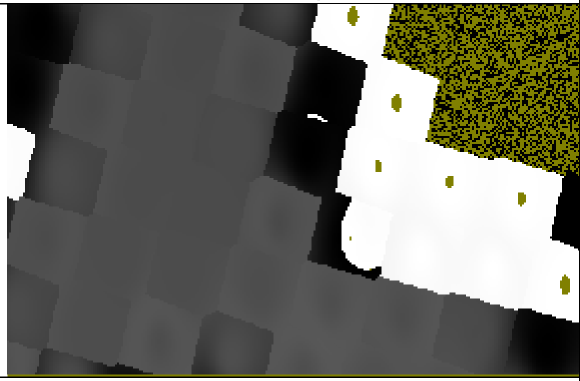
Input scene at 1km



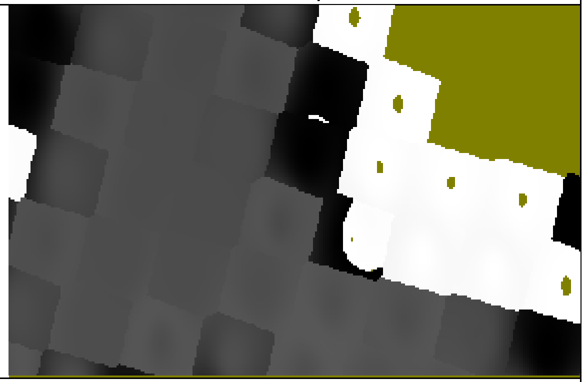
Nearest neighbour

Bilinear interpolation

Reference scene at 10m



Cubic interpolation



Bicubic interpolation

[8] https://en.wikipedia.org/wiki/Overshoot_(signal)

2.3 SUMMARY

In most cases the nearest neighbour resampling or the Bilinear interpolation have the best balance between accurate results and processing time. The different interpolation results shown above underline the higher-degree polynomial interpolations do not provide much benefit in many cases but slow down the processing. Choosing one of these higher polynomial interpolation methods can even introduce errors in extreme cases, as seen above. The selection of the interpolation method depends on the specific use-case.

3 THE COLLOCATION IN SNAP

The *Collocation Tool* allows collocation of spatially overlapping products. Collocating products implies that the pixel values of secondary (slave) products are resampled into the geographical raster of the reference (master) product.

To avoid naming conflicts, the Collocation Tool allows renaming of both reference and secondary components such as bands, flag codes and bitmask definitions according to a user defined specification.

3.1 ALGORITHM

When products are collocated, a new product is created containing a copy of all components of the reference product, i.e., band data, tie-point grids, flag codes, bitmask definitions, and metadata. The components of the secondary products are transferred in the following manner:

Geophysical Data
Each band of the secondary products is resampled independently into the geographical raster of the reference product. The user may choose between five different resampling methods: nearest neighbour, bilinear interpolation, cubic convolution, bicubic and bisinc Interpolation.
If an uncertainty band is associated with a band containing geophysical values both are treated independently. This still gives meaningful uncertainty values if those are continuous. However, a dedicated uncertainty propagation is not performed, and the additional error introduced by the collocation resampling is also not considered.

Flag/Index Data
For flag bands, like the quality flags in OLCI L1C products, or index bands resulting from a classification process the data is always resampled using the nearest neighbour method. Those bands contain discrete integer values and must not be interpolated. This has been discussed already in 2.2.1.

For bands where a valid-pixel expression is defined, as it is for Sentinel-2 MSI data (e.g., B2.raw > 0) or in results of a processing step, always the nearest neighbour resampling is also used. This should actually be not the case. This limitation is scheduled for investigation. Please see the related entry [SNAP-1546][9] in our issue database.

To establish a mapping between the samples in the reference and the secondary raster data, the geographical position of a reference sample is used to find the corresponding sample in the secondary raster. If there is no sample for a requested geographical position, the reference sample is set to the no-data value. This can happen if parts of the secondary product are outside of the region of the reference product. The collocation algorithm requires accurate geo-positioning information for both reference and secondary products. When necessary, accurate geo-positioning information may be provided by ground control points, as a pre-processing step.

It is also important to note that the collocation processor does not support multi-resolution products as reference. Data like those from Sentinel-2, which consist of bands of three different resolutions, need to be resampled beforehand. It is possible to use multi-resolution data as secondary input. See also the section 3.2.2.

[9] https://senbox.atlassian.net/browse/SNAP-1546

3.2 Sensor Specific Considerations

This document focuses on data taken by sensors of the Sentinel-1, -2 and -3 family. More on the satellites, the sensors and the available data can be found at the Sentinel Online website[10]. The considerations and guidelines are in general also applicable to other sensors. This document does not handle all available sensors and or cases therefore you will need to either adapt the suggestions provided in this guide to your needs and/or consult further sensor specific documentation.

3.2.1 Sentinel-1

As for any other sensor necessary pre-processing steps should be performed before the collocation, as already explained in section 2.1.4. What needs to be done has already been discussed in the tutorial *Synergetic use of radar and optical data*[11]. The specific steps depend on the given case, but most important is the terrain correction. If you are doing interferometry with the Sentinel-1 data, you should consider doing the bisinc interpolation in the pre-processing steps. More on bisinc interpolation can be found in the section 9.22 in the *Sentinel-1 Level 1 Detailed Algorithm Definition* document which can be found in the *Sentinel-1 SAR Document Library*[12].

3.2.2 Sentinel-2

Due to a current limitation in the SNAP collocation tool, bands having a valid-pixel expression assigned, like the reflectance bands of S2 MSI, are resamped using the nearest neighbour. Removing the valid-pixel expression let the tool use the selected interpolaton method. But this can only be used if no invalid pixels are marked in the scene. Alternatively, the data can be preprocessed and each invalid pixel can be replaced by a no-data value, e.g. NaN. This can be done by using the Band Maths tool.

If Sentinel-2 data are used as the reference product they need to be resampled to a common resolution using the S2 Resampling operator. This is necessary due to the multi-resolution nature of the MSI data, and the fact that the collocation requires one common grid as target.

3.2.3 Sentinel-3

For best collocation results the fractional accuracy should be enabled for pixel-based geo-coding. Pixel-based geo-coding means that for each pixel certain latitude/longitude values are provided. The fractional accuracy means that when looking up a location in the source scene it does not always fall on the pixel centre, e.g., [X: 1053.5, Y: 214.5], but fractional values are possible, like [X: 1053.73, Y: 214.321]. For Sentinel-3 data the pixel-based geo-coding is the default setting since version 9 of the Sentinel-3 Toolbox. The settings for the fractional accuracy and the geo-coding can be found in SNAP in the Options dialog.

This fractional accuracy computation is costly and slows down the processing but has an impact on the collocation results, when using any of the interpolating methods. In fact, the interpolation is disabled when no fractional positions are computed because the interpolation weights are either zero or one. This is equal to a nearest neighbour resampling.

You need to decide if this is important for your results. Depending on the resolution of your collocation source and target the difference between nearest neighbour and interpolation might be negligible. For decision making please have a look at section 2.2.5, or even better start a comparison for your specific use-case and decide on an interpolation.

Sentinel SLSTR L1b data is provided as a multi-resolution (500m and 1km) product. Before this data can be used as reference data it is either necessary to resample the data or to open the product in the 500m or 1km mode within SNAP by selecting the respective reader. As SLSTR L1B is also

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[10] https://sentinel.esa.int

[11] http://step.esa.int/docs/tutorials/S1TBX%20Synergetic%20use%20of%20S1%20(SAR)%20and%20S2%20(optical)%20data%20Tutorial.pdf

[12] https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/document-library

observing the Earth at night, data is provided from the ascending orbit. The scenes are flipped upside down (north pointing down). This can be corrected by applying a reprojection during the pre-processing, if wanted.

If performance is most important for your processing, you can switch to a tie-point based geocoding in the Sentinel-3 Toolbox settings. This is faster than the pixel-based geo-coding, even if no fractional accuracy is enabled, because less data needs to be read. This performance improvement comes with a penalty in the geo-location accuracy because tie-point based geo coding cannot be as accurate as the pixel-based one. For OLCI data a geo-location point is provided only for every 16 pixels in RR and every 64 pixels for FR scene, in between the values are interpolated. The tie-point based geo-coding, however, provides fractional locations which are needed when selecting one of the interpolating resampling methods.

Sentinel-3 data is provided with uncertainties. Those uncertainty data are collocated independently from the actual geo-physical data. This means that neither an uncertainty propagation is performed nor is the error which is introduced by the resampling considered.

3.3 User Interfaces

The Collocation Tool can be invoked from the menu in SNAP by selecting **Processing->Geometric Operations->Collocation...**, or in batch mode by using the command line tool *gpt* (Graph Processing Tool) which is in the *bin* directory. For the latter type 'gpt Collocate -h' for further information. There is also a wiki page *Bulk Processing with GPT*[13] available, which explains in general how processing can be done from the command line. When selecting the **Collocation...** command from the SNAP menu the following dialogue pops up, shown in Figure 7. The configuration components for the processing are explained below.

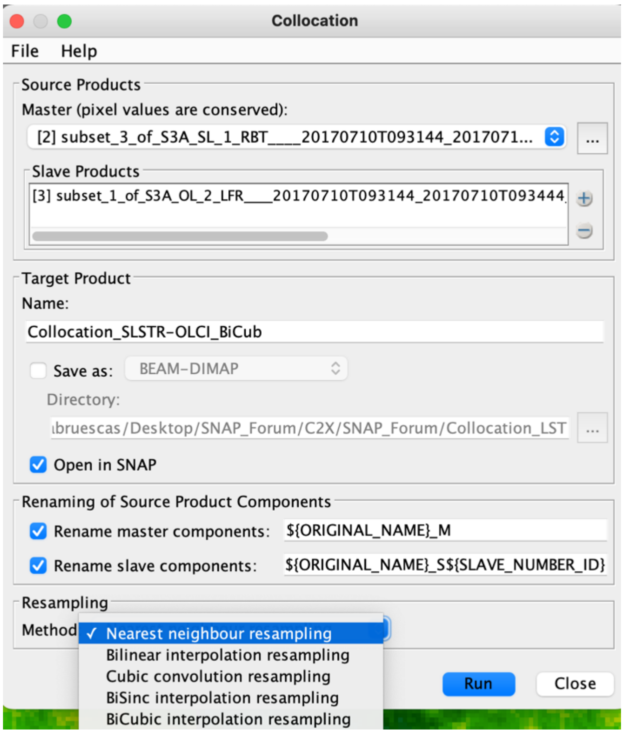

Figure 7 Example of the GUI window of the Collocation Tool

[13] https://senbox.atlassian.net/wiki/spaces/SNAP/pages/70503475/Bulk+Processing+with+GPT

3.3.1 Source Product Group

Master (Reference): Here the user specifies the reference product. The selection box presents a list of all products opened in SNAP. The user may select one of these or, by clicking on the button next to the combo box, choose a product from the file system.

Slave (Secondary): Here the user specifies the secondary products, the products to be collocated with the reference product. The user may select one or more products opened in SNAP or products from the file system.

3.3.2 Target Product Group

Name: Used to specify the name of the output or 'target' product.

Save as: Used to specify whether the target product should be saved to the file system. The combo box presents a list of file formats.

Open in SNAP: Used to specify whether the target product should be opened in the Sentinel Toolbox. When the target product is not saved, it is opened in the Sentinel Toolbox automatically.

3.3.3 Component Renaming Group

Each product consists of different components, such as bands, flag codes and bitmask definitions. To avoid naming conflicts between reference and secondary product components, the user can specify a renaming pattern.

Rename master (reference) **components**: By checking or unchecking this option the automatic renaming of reference product components can be activated or deactivated, respectively. If activated, all components of the reference product are renamed according to the pattern given in the text field next to the check box. The expression *${ORIGINAL_NAME}* can be used to refer to the original name of the component.
Rename slave (secondary) **components**: By checking or unchecking this option the automatic renaming of secondary product components can be activated or deactivated, respectively. If activated, all components of the secondary products are renamed according to the pattern given in the text field next to the check box.
The expression *${ORIGINAL_NAME}* or *${SLAVE_NUMBER_ID}* can be used to refer to the original name of the component or the id of the secondary (0,1,2...) respectively.

3.3.4 Resampling Group

The methods available are *Nearest Neighbour*, *Bilinear Interpolation*, *Cubic Convolution*, *BiCubic* and *BiSinc Interpolation (most useful for insar interferometry but not here for the collocation process)*. The resampling methods and how they work are explained in section 2.2.

3.4 COLLOCATION RESULTS

When collocating multiple data sources to one reference, not only the bands of the reference and the secondary products are merged but special bands are also generated. These collocation flag bands indicate where the source provided input to the target. The bands start with the prefix 'collocationFlags' and end with the name of the secondary source product.

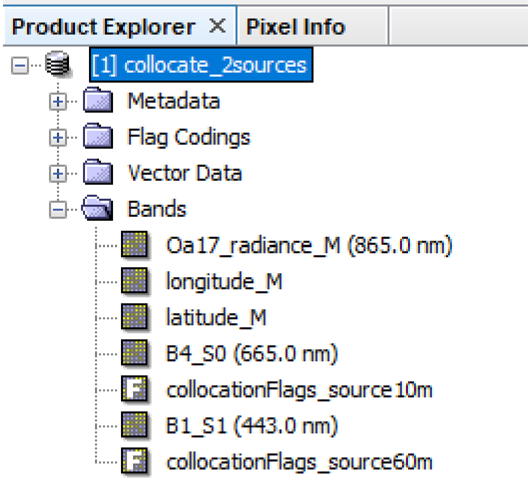

Figure 8 Collocated product in SNAP Product Explorer

In Figure 9 only a small part (white box) of the reference data was covered by the source data while in Figure 10 the part is much bigger.

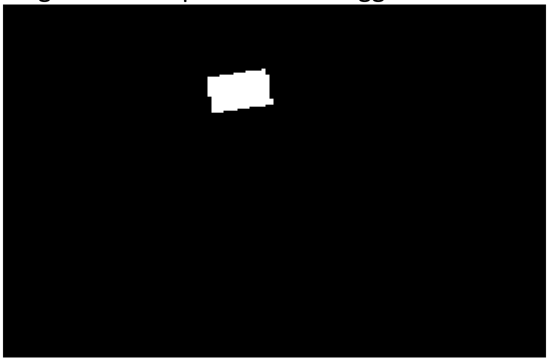

Figure 9 Example 1 of a collocation flag band

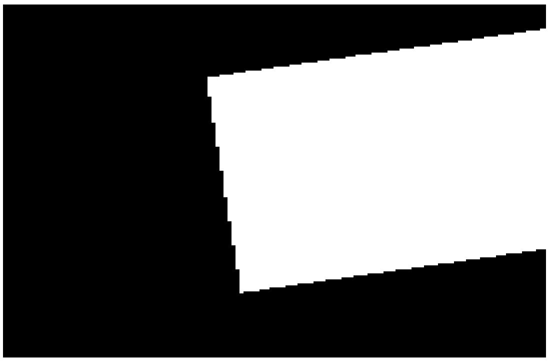

Figure 10 Example 2 of a collocation flag band

4 COLLOCATION EXAMPLES

4.1 LST EXTRACTION USING OLCI AND SLSTR: DOWN-SAMPLING THE DATA

4.1.1 Introduction

Land surface temperature (LST) is one of the key parameters in the physics of land-surface processes on regional and global scales, combining the results of all surface-atmosphere interactions and energy fluxes. In this exercise we will explore the synergistic use of OLCI/SLSTR instruments on board Sentinel-3 platform to retrieve LST products using the Sentinel-3 Toolbox implemented in SNAP. For this purpose, the high spatial resolution data from OLCI (OL_2_LFR) will be used for a good characterization of the land surface sub- pixel heterogeneity, in particular, for a precise parameterization of surface emissivity using the Normalized Difference Vegetation Index (NDVI) and the threshold method (THM) (Sobrino et al., 2008, Yang et al., 2020). Effective emissivity and water vapour extractions allow accurate LST retrievals using the SLSTR thermal bands by developing a synergistic split-window algorithm (Sobrino et al., 2016).

The processing chain consists of the following steps:

1. Calculation of the NDVI using RC681 and RC865 within the OLCI L2 LFR product, which stores the atmospheric correction bands that are needed for the NDVI estimation. To simplify the process the OGVI, which is stored in the L2 product, could be used instead.
2. Emissivity calculation based on NDVI thresholds method using band math on OLCI L2. The processing chain, coefficients and details are explained in the **Annex II.**
3. Water vapour band selection from OLCI L2 LFR
4. Collocation of SLSTR (reference) / OLCI (secondary) to 1000 m: down-sampling using *Nearest Neighbour, or Bicubic interpolation* methods.
5. Apply the LST split window algorithm (Equation 1) with the band math tool only on valid pixels (non-cloudy, land pixels). The definition of "valid pixel" can be modified using different flag/mask combinations.

$$= T_i + c_1(T_i - T_j) + c_2(T_i - T_j)^2 + c_0$$

$$+(c_3 + c_4 W)(1 - \varepsilon) + (c_5 + c_6 W)\Delta\varepsilon \qquad (1)$$

where Ts is the LST (in K), $T_{i,j}$ are at-sensor brightness temperatures (in K), W is the atmospheric water vapour content (in g·cm^{-2} or cm), ε is the mean LSE 0.5·(ε_i+ ε_j), and Δε is the LSE difference ε_i- ε_j). Subindices 'i' and 'j' refer to two different TIR bands, thus leading to the SW algorithm, or to one TIR band but two different view angles (e.g., nadir 'n' and oblique 'o' views), thus leading to the DA algorithm. Coefficients c_0 to c_6 are obtained from statistical regressions performed over simulated data.

Comparison of the LST product using different interpolation algorithms in the collocation result.

A video which shows the processing is available on YouTube (https://youtu.be/dLtCLjqRABI). A simplified version of the process is shown in Figure 11.

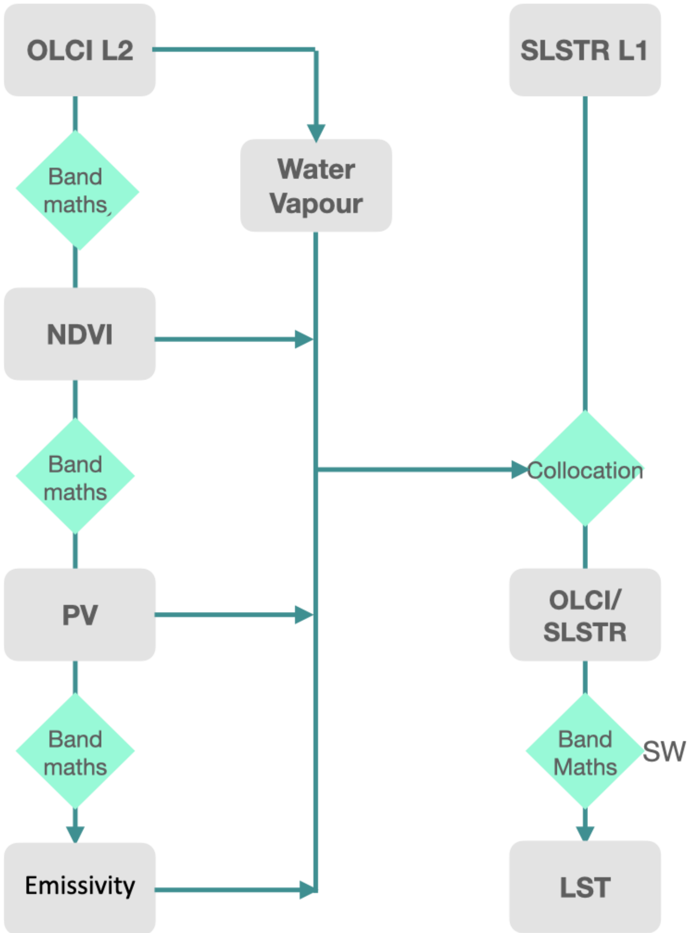

Figure 11 Processing chain of LST estimation using OLCI and SLSTR in synergy

Format details of the Sentinel-3 data types can be found in the ANNEX I: Data Formats.

We will use some of the bands stored in the OL_2_LFR product. Each product provides as measurement data files described in the Table 1. All products have error estimates. In addition to the geophysical products, other data comprise:

- The classification, quality, and science flags (LQSF) provide information about validity, suspicious quality, cosmetic filling, environment, and input quality.
- Common data such as the ortho-geolocation of land pixels, solar and satellite angles, atmospheric and meteorological data, time stamp or instrument information. These variables are inherited from Level-1B products.

Variables	Description	Units	Input Bands
OLCI Global Vegetation Index (OGVI)	Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) in the plant canopy	dimensionless	Oa03, Oa10, Oa17
OLCI Terrestrial Chlorophyll Index (OTCI)	Estimates of the Chlorophyll content in terrestrial vegetation, aims at monitoring vegetation condition and health	dimensionless	Oa10, Oa11, Oa12
Integrated Water Vapour (IWV)	Total amount of water vapour integrated over an atmosphere column	$kg.m^{-2}$	Oa18, Oa19
RC681 and RC865	By-products of the OGVI, the so-called red and NIR rectified reflectances are virtual reflectance largely decontaminated from atmospheric and angular effects, and good proxy to Top of Canopy reflectances.	dimensionless	Oa10, Oa17

Table 1. Description of land geophysical products in OL_2_LFR. Source: Sentinel Online

The two images used in this example, SLSTR and OLCI, are:

- S3A_SL_1_RBT____20170710T093144_20170710T093444_20170711T141258_0179_019_364_2159_LN2_O_NT_002 (Sentinel-3 SLSTR Product Data Format Specification - Level 1)
- S3A_OL_2_LFR____20170710T093144_20170710T093444_20170711T140642_0179_019_364_2159_LN1_O_NT_002 (Sentinel-3 OLCI Product Data Format Specification - Level 2 Land)

It is important to open the SLSTR image using the "Import" option: **`File/Import/Optical Sensors/Sentinel 3/Sentinel3 SLSTR L1B (1km).`** In this example we open it in 1km resolution.
Both images can also be subset to the same area, using the one with the best resolution (smaller area) as reference (**`Raster/Subset`**). It is important that the same area is covered in the two images.

4.1.2 Step-by-Step Processing

1. **NDVI calculation with OLCI bands**[14]: within the OLCI L2 LFR product we can find the RC681 and the RC865 that can be used for the NDVI estimation. RC681 is in the red part of the spectrum (623-750nm), while RC865 is part of the near infrared (NIR). The NDVI can be calculated using the

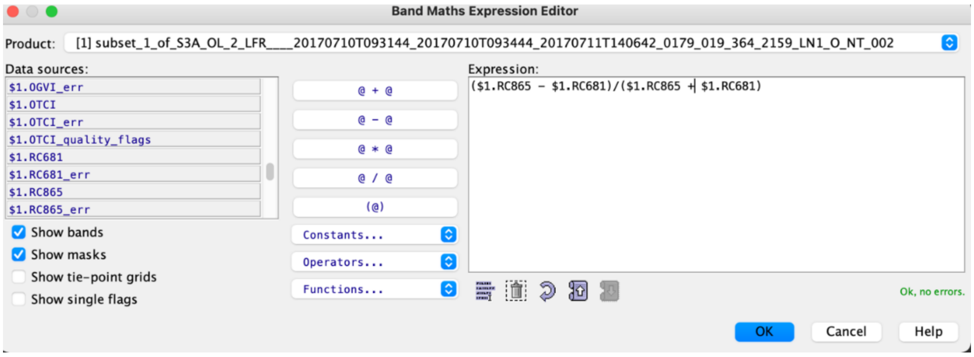

Figure 12 NDVI expression with Band Maths

processor in **`Optical/Thematic Land Processing/Vegetation Radiometric Indices/NDVI processor`** or can be done manually with **`Raster/Band Maths`** (see Figure 12).

[14] To simplify the exercise, this step can be skipped and use the OGVI stored in the S2_OLCI LFR image.

2. **Emissivity calculation**: this is an 8-step procedure that uses information from the atmospherically corrected red band (RC681) and the NDVI from OLCI. The emissivity (ε) at a given wavelength (λ) and temperature (T) is defined as the ratio of the radiance (R_{λ}) emitted by a body at temperature (T) and the radiance emitted (B_{λ}) by a black body at the same temperature (T).
    a. **Calculation of the percentage of vegetation (Pv):** the Pv is a coefficient based on the NDVI that considers the surface as a mix of bare soil plus vegetation and that differs depending on the vegetation cover.

$$Pv=\frac{NDVI-0.15}{0.9-0.15}$$

    b. Effective emissivity[15], ε, is calculated following different steps (see ANNEX II: Code in Band Maths)
3. **Water vapour band** selection: take the IWV (Integrated Water Vapour) band of OLCI L2 and pass from Kg/m^2 to g/cm^2 using Band Maths: IWV/10

4. Collocation of SLSTR and OLCI: use Raster/Geometric/Collocation

    a. Before the Collocation, it is possible to subset the SLSTR scene to match the OLCI extension. It is also a good idea to reduce the number of bands, to reduce the amount of data and processing time, for instance, by selecting only the thermal bands of interest (S*_BT_in) together with the location bands and related flags/masks (*_in). The other bands are not needed in this example.
    b. Collocation is done using the *Nearest Neighbour*, the *Cubic Convolution* and the *BiCubic interpolation* functions for comparison

5. Apply the **LST split window** algorithm (Figure 13):
S8_BT_in_M + (1.084 * (S8_BT_in_M – S9_BT_in_M)) + (0.2771*((S8_BT_in_M – S9_BT_in_M) ^ 2)) + (-0.268) + ((45.1 + (-0.73 * IWV_g_S))*(1 – emis_effect_S)) + (((-125 + (16.7*IWV_g_S)))* (emis_diff_S))

[15] The step-by-step procedure and the code for Band Maths is in Annex II

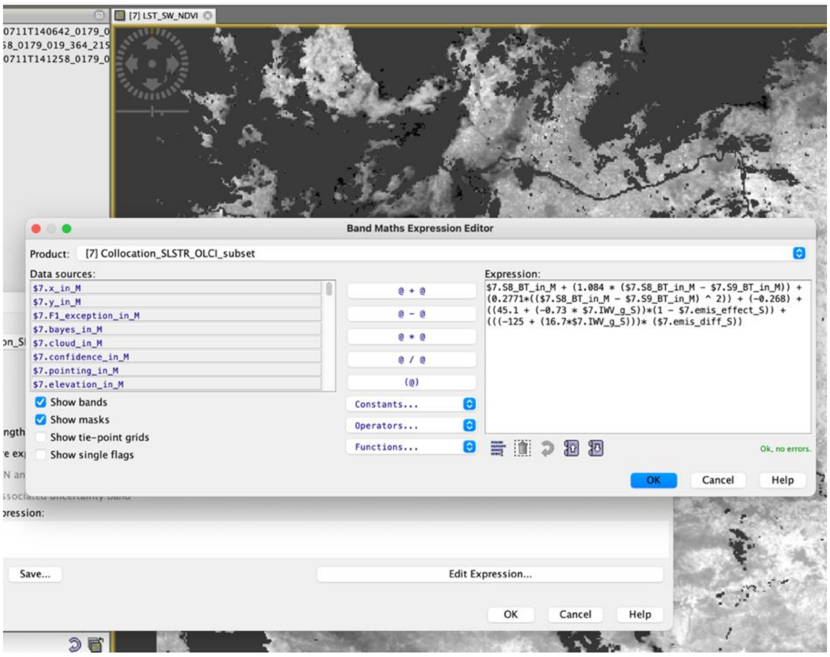

Figure 13 LST Split window algorithm in Band Maths

Results of the application of the algorithm are shown in Figure 14. The Cloud mask extracted from the SLSTR reference product is highlighted in white and the Adriatic Sea in blue.

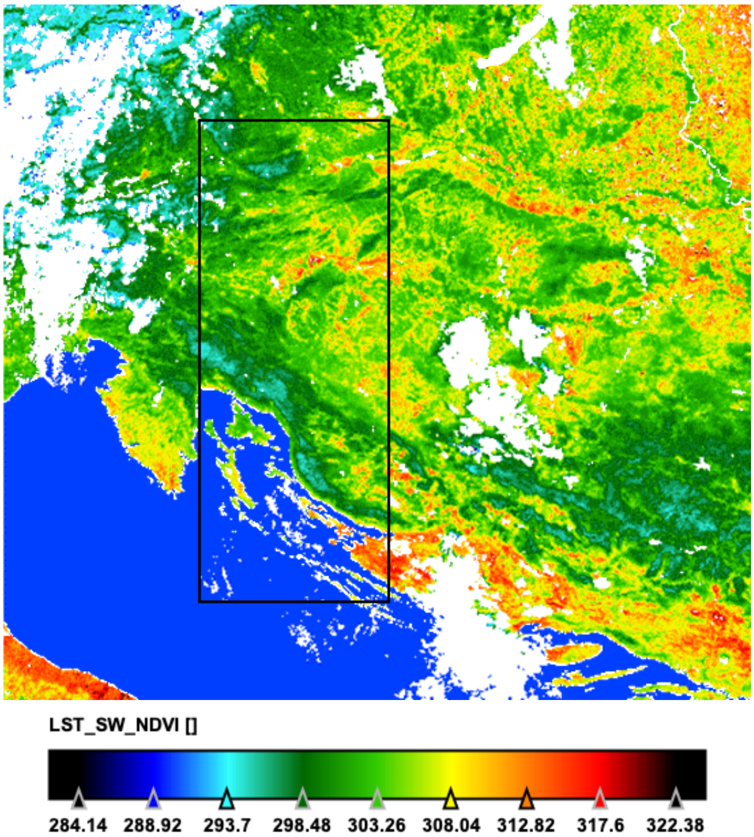

Figure 14 Results of the LST over the AOI using the nearest neighbour interpolation method for the band collocation at 1 km

6. Comparison of LST results using different interpolation approaches (Figure 15). Please note clouds are transparent in this comparison and not white as in Figure 14:

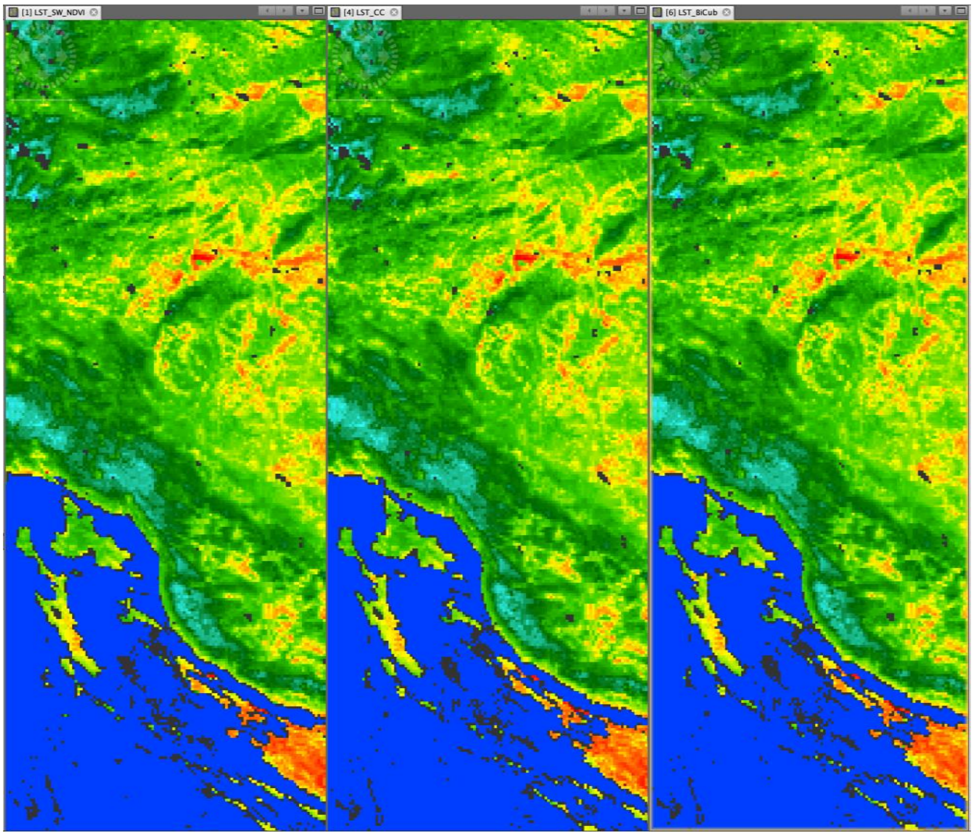

Figure 15 Results of the LST over the AOI using the Nearest Neighbour, the Cubic Convolution and the Bicubic interpolation methods for the band collocation at 1 km

4.2 SYNERGETIC USE OF RADAR AND OPTICAL: SENTINEL-1 AND SENTINEL-2

4.2.1 Introduction

We show here an example of the merging of Sentinel-1 SAR data and Sentinel-2 MSI using the collocation tool. The flow chart in Figure 16 summarizes the steps to merge images from these two sensors:

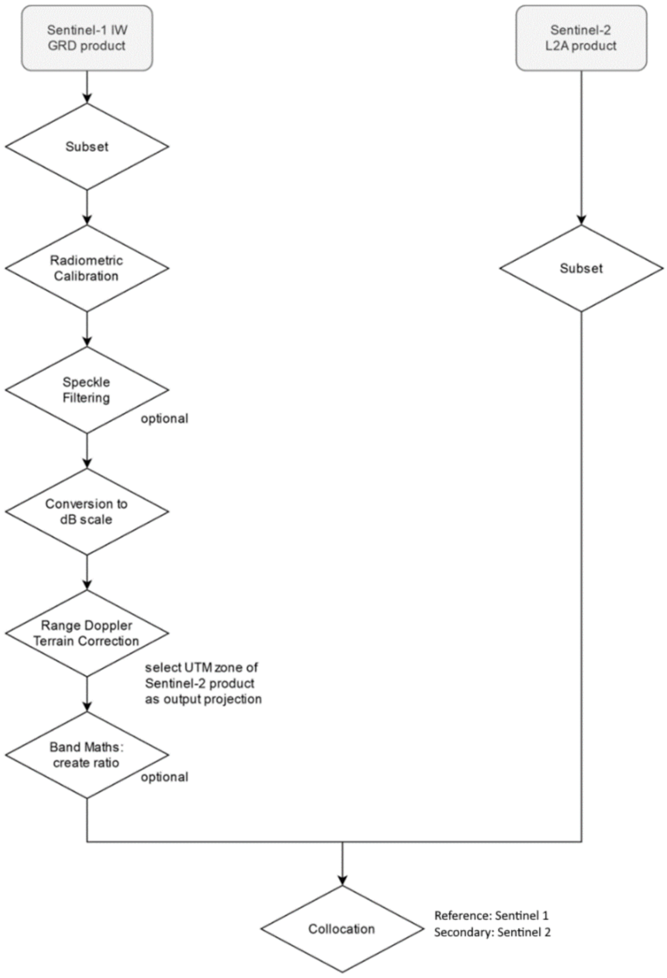

Figure 16 Flow chart for the merge of Sentinel-1 and Sentinel-2 images. Source: Braun, 2021

The Sentinel-1 is used as the reference product for the collocation because its geolocation accuracy is very high after Range Doppler Terrain Correction. While the S1 product needs several pre-processing steps to be usable for the collocation, the S2 MSI L2A product can be used directly. A resampling is not needed because it is used as a source and not as the collocation reference. It is already atmospherically corrected and has a good geo-information accuracy. Only band B8A is excluded in the subset step, as it is not used in the subsequent analysis. For a detailed step by step processing please see Braun (2021).

The graph with the S1-S2 collocation is stored in SNAP in the user directory at ***.snap/graphs/Radar/SAR Optical Graphs/S1-S2 Collocation.xml*** (Figure 18).

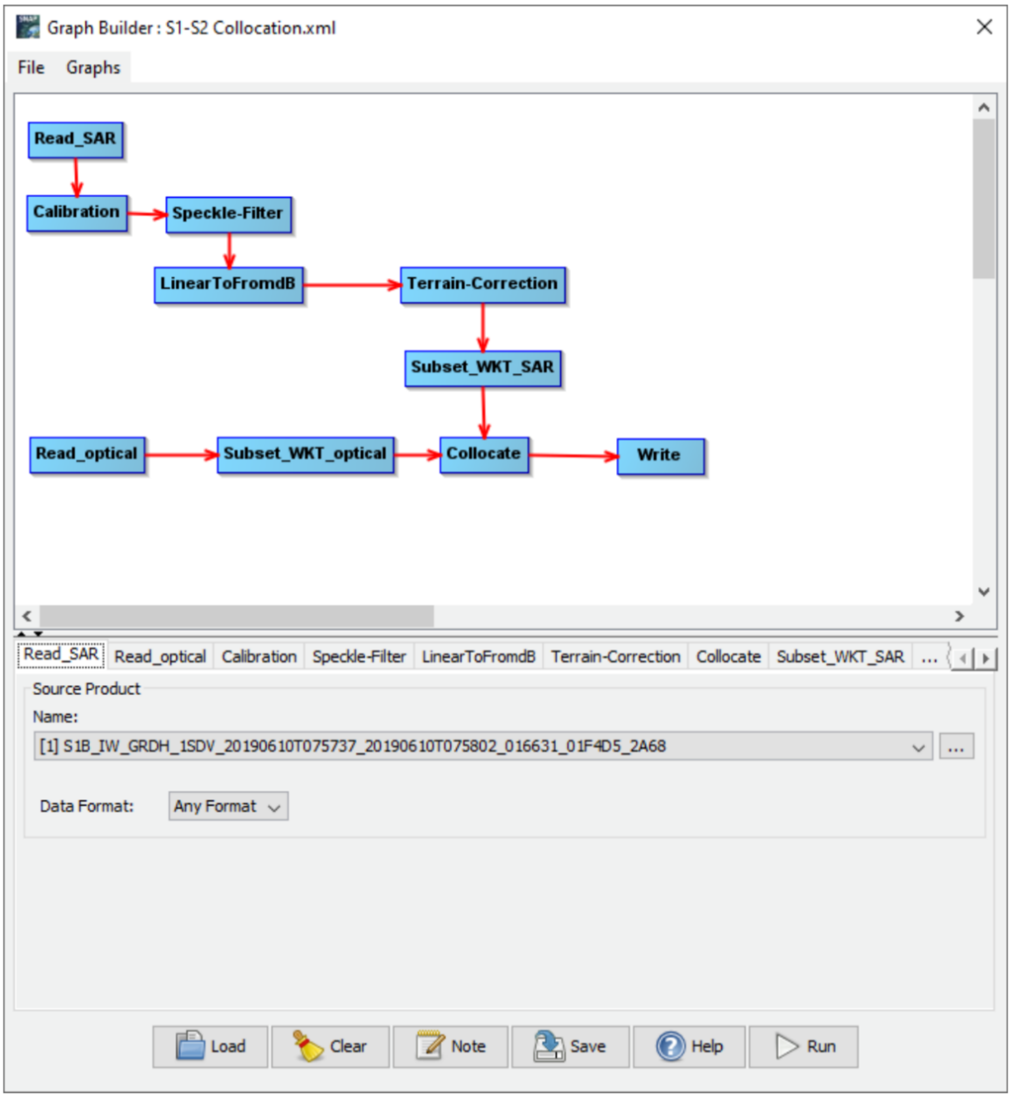

Figure 17 Graph with pre-processing functions and Collocation tool as final step. Source: Braun, 2021

To collocate the products, the pre-processing of the two must be done using the graph shown in Figure 17 or on a step-by-step manual processing. The two datasets can be merged since they have similar spatial extent, and they are projected in the same coordinate system. Sentinel-1 SAR IW GRD data is used as the reference product because its geolocation accuracy is very high after Range Doppler Terrain Correction.

4.2.2 Processing Explained

The Collocation operator requires one reference product which determines the extent, pixel size and pixel registration of the output product, and one or more secondary products which will be clipped and resampled accordingly. The Sentinel-1 product is the reference. Use the button to add the Sentinel-2 with Add product(s)... to the list of the secondary products. In this case the Bilinear interpolation is used as the resampling method. According to section 2.2 this gives the best results. After the process has finished, a new product is created which contains three radar bands and 11 multispectral bands. Because the pixel spacing of Sentinel-2 MSI data differs between its bands they are resampled independently (60m→10m, 20m→10m, 10m→10m).
The resampling is the most important step for image fusion, because it allows a range of different methods to utilize the information content of both products in the following. In the output product

all optical bands are marked with _S and their corresponding wavelength (as retrieved from the metadata). This is automatically done to avoid naming conflicts and can be modified (or completely disabled) under Renaming of Source Product Components of the Collocation tool (Figure 18Figure 18).

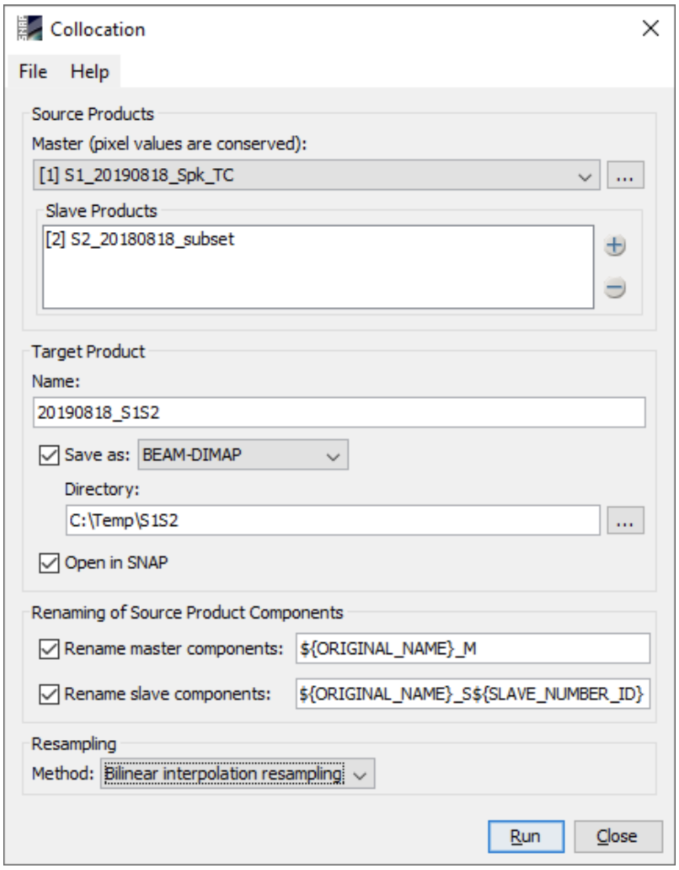

Figure 18 Collocation of Sentinel-1 (reference) and Sentinel-2 (secondary). Naming convention can be changed using the "Renaming of Source product Components" (Source: Braun, 2021)

The collocation flag band is an indicator for the presence of the input products. The value is 1 where both images are present. As the extent of a Sentinel-1 image (250km swath width for IW product types) is usually larger than the extent of a Sentinel-2 image chip (100km squared), the common area could be only a part of the output product (Figure 19). An example of an RGB composite using the bands from the two sensors in shown in Figure 20.

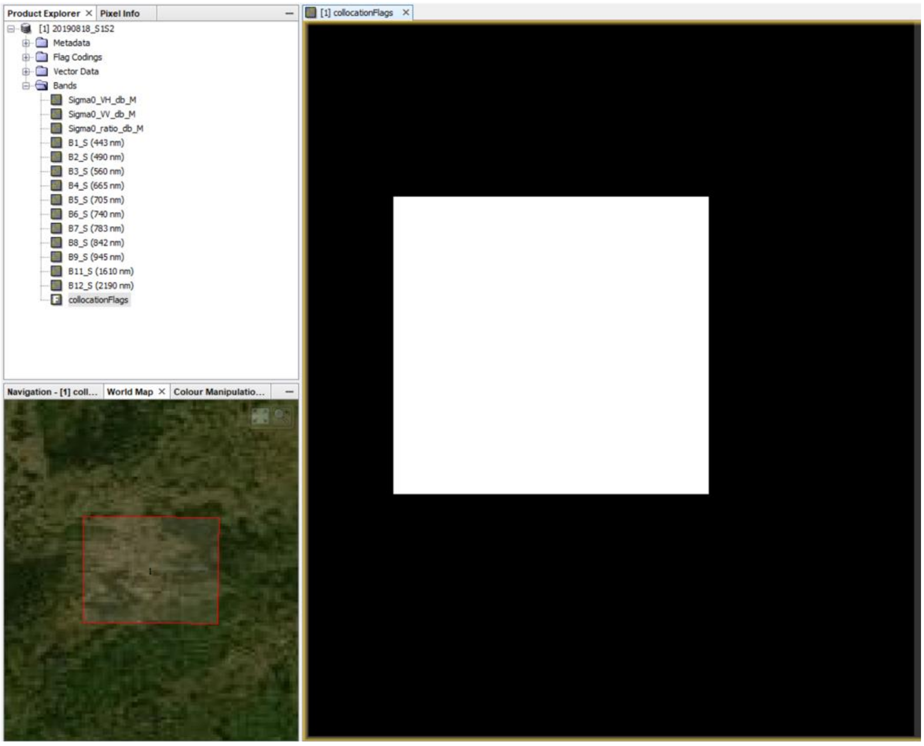

Figure 19 Collocation flags of the merge product. Source: Braun, 2021

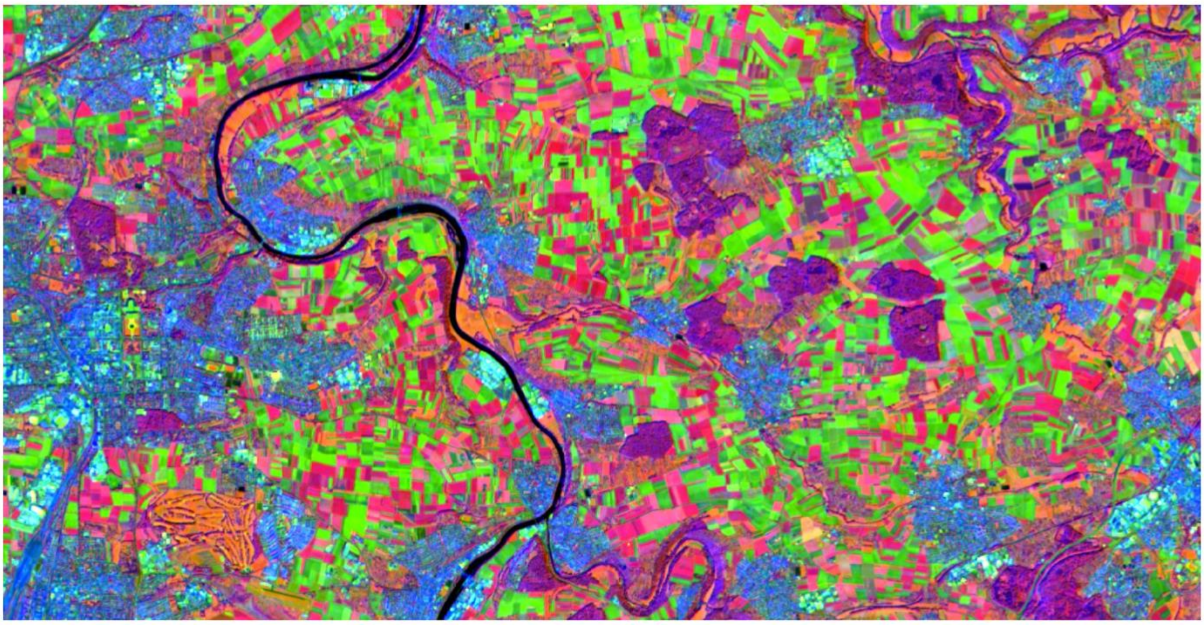

Figure 20 Results of the RGB generated with the merge product: red(S2_B9), green (S2_B5) and blue (S1_VH). Source: Braun, 2021

4.3 Synergetic use of optical: Sentinel-2 and Sentinel-3 (e.g., Evapotranspiration maps

4.3.1 Introduction

In the following section we show how to merge Sentinel-2 MSI with Sentinel-3 SLSTR data to derive evapotranspiration maps. Since the whole process can be done following the SEN-ET tutorial[16], we will not give all the details, but focus on the part when the SLSTR-LST is collocated to the MSI spatial dimensions. The example shown here does not follow the steps of the SEN-ET process but shows how those two products can be collocated together to extract an LST product fitted to the dimensions and spatial resolution of the MSI image. Within the SEN-ET process, the LST product is pansharpened using a cubic spline approach. To do so, information about the Digital Elevation Model and geometries of both sensors are necessary. We simplify the process here to show how to do something similar using the Collocation Tool. This is useful to explain some of the limitations encountered when using these approaches, compared with the pan sharpening process followed in SEN-ET.

4.3.2 Pre-processing of Sentinel-2 MSI L2A and Sentinel-3 SLSTR LST

The Sentinel-2 L2A image is previously resampled to 20 metres, it can be also subset to a ROI (Region Of Interest). For resampling the S2 Resampling Processor is used.

Sentinel-3 SL_2_LST (S3-LST), the LST product derived from the SLSTR sensor, can also be subset to a smaller area using the Subset function in SNAP. The subset can also be done on the bands, for instance to leave only the LST and LST uncertainty. This will help later to reduce processing time on the collocation step. Instead of using the standard Level 2 LST data, the data generated in the first example can be used too.

Figure 21 shows the subsets made on the S3-LST and S2-MSI, with the bands to be included in the collocation product. The white rectangle shows the area of the S3 image, while the red rectangles is the area covered by the S2-MSI image.

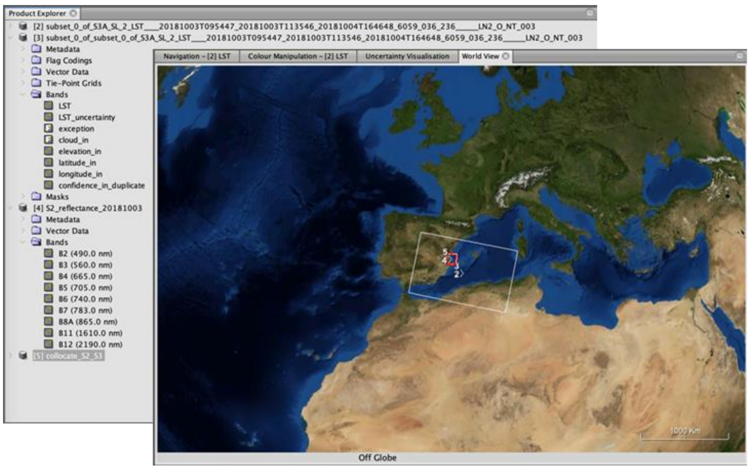

Figure 21 Subsets of the S3-LST and S2-MSI

[16] https://www.esa-sen4et.org/static/media/sen-et-user-manual-v1.1.0.5d1ac526.pdf

4.3.3 Collocation of MSI and S3-LST products

The Collocation processor uses the S2-MSI reflectance image as reference, and the subset of the S3-LST as secondary. In order to use a similar algorithm to the Cubic spline used in the SEN-ET processing chain, the *Bicubic Interpolation* is used as the resampling method.

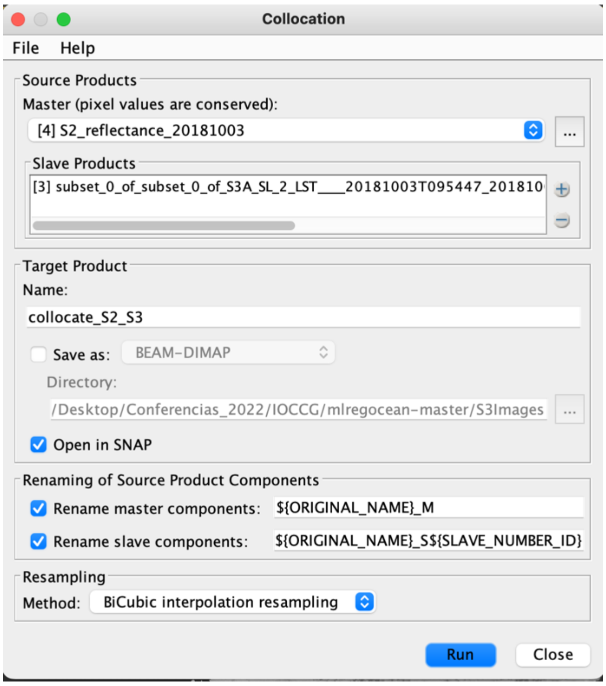

Figure 22 Configuration of the Collocation tool.

Cubic spline interpolation is a mathematical method commonly used to construct new points within the boundaries of a set of known points. These new points are function values of an interpolation function (referred to as spline), which itself consists of multiple cubic piecewise polynomials. The difference between cubic interpolation and cubic spline interpolation is that in cubic interpolation 4 data points are used to compute the polynomial. There are no constraints on the derivatives. Cubic spline interpolation computes a third order polynomial only from two data points with the additional constraint that the first and second derivative at the interpolation points are continuous. So, if you have 4 points, then you compute 3 different polynomials (between points 1-2, 2-3, and 3-4), and these polynomials are smoothly connected in the sense that their first and second derivatives are equal at the given data points. Results do not look as smooth as the results with the pan-sharpening method used in the SEN-ET (Figure 23), but the LST covers perfectly the ROI corresponding to the S2-MSI image.

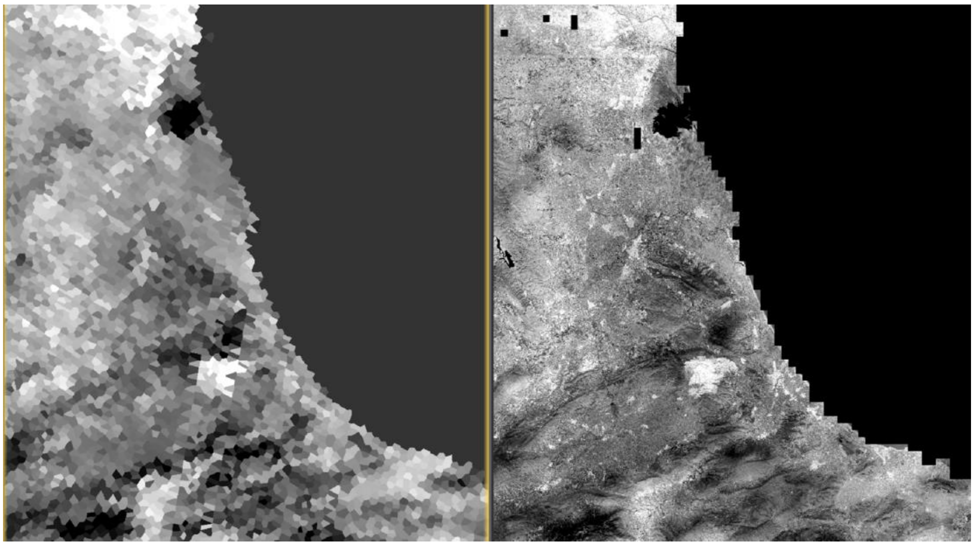

Figure 23 Comparison of the LST at 20 m generated by the Collocation tool, and the LST sharpening generated following the SEN-ET processing chain

The blockiness of the coast in the SEN-ET results is due to the mask used in the SLSTR product (part of the SEN-ET process) to screen clouds from land/ocean areas. The sandy coast and some other bright pixels are flagged as clouds. It is important to highlight the before mentioned limitations of the interpolation when the difference in resolution between the two sensors is high. This leads to effects that look like abstract art, but the results are not wrong. It is just caused by the huge difference in resolution. In the result the pixel spacing is 20m, but the spatial resolution is still 1km.

5 REFERENCES

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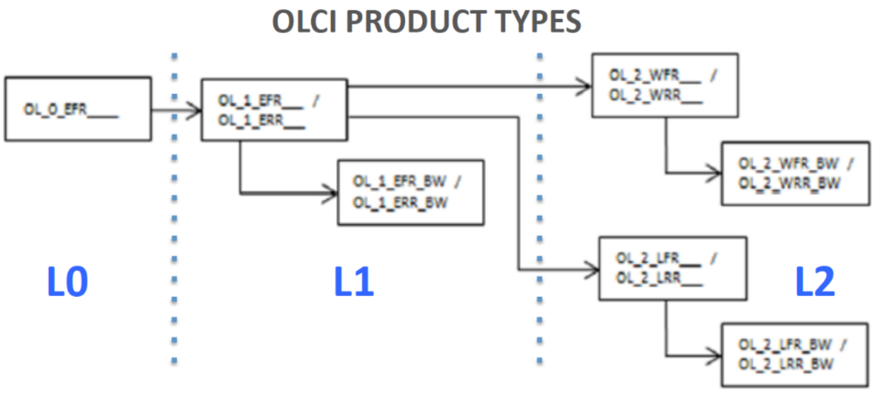
6 ANNEX I: DATA FORMATS

Since we use several products derived by different sensors on board of the Sentinel-1, Sentinel-2, and Sentinel-3 satellites, it is worth providing a reminder of the different products and levels.

Figure 24 shows the OLCI product types:

- Level-0 is the reconstructed and time-sorted Instrument Source Packet (ISP) at full space-time resolution. All communications artefacts (e.g., synchronisation frames, communications headers, and duplicate data) and invalid packets are removed. OLCI data is always sensed in full resolution mode (300 m resolution).



LEVEL 0
EFR *Earth observation Full Resolution*

LEVEL 1
EFR *Earth observation Full Resolution (calibrated)*
ERR *Earth observation Reduced Resolution (cal.)*
EFR_BW *EFR browse product*

LEVEL 2
WFR *Water and atmosphere Full Resolution*
WFR_BW *WFR Browse Product*
WRR *Water and atmosphere Reduced Res.*
LFR *Land Full Resolution*
LRR *Land Reduced Resolution*
Etc.

Figure 24 OLCI product types

- Level-1 includes Top-Of-Atmosphere (TOA) radiometric measurements, radiometrically corrected, calibrated and spectrally characterised. It is quality controlled, ortho-geolocated (latitude and longitude coordinates, altitude) and annotated with satellite position and pointing, landmarks and preliminary pixel classification (e.g., land/water/cloud masks). Products are generated in FR (300 m) and in RR (approx. 1 km) for the whole globe with the same coverage.
- In addition to the Level-1B OLCI product, the SENTINEL-3 SYN product is produced by combining products of OLCI and SLSTR instruments. More information on the SYN product can be found on the Sentinel-3 Synergy User Guide pages.
- Level-2 products consist of geophysical quantities derived from the processing of measurement data provided in the Level-1 product. Level-2 products specifically for marine and land application domains are generated separately, with each containing the parameter relevant for the specific field of application. Level-2 atmospheric information relevant for both application domains, such as water vapour, is reported in both data streams.

Sentinel 3 OLCI products can be associated with different timeliness:

- The Near Real Time (NRT) timeliness implies a delivery in less than 3 hours after data acquisition. This timeliness is mainly used for marine meteorology and ocean-atmosphere gas transfer studies.

- The Non-Time Critical (NTC) timeliness is typically defined for deliveries within 1 month after data acquisition. This additional delay allows consolidation of some auxiliary or ancillary data (e.g., precise orbit data) and the data are mainly used for geophysical studies and operational oceanography.

SLSTR product types are shown in Figure A2. The Level-1 product provides radiances and brightness temperatures for each pixel in the instrument grid, each view and each SLSTR channel, plus annotations data associated with SLSTR pixels. For thermal IR and fire channels (labelled as S7 to S9 for TIR channels and F1, F2 for fire channels), the radiometric measurements are expressed in Top Of Atmosphere (TOA) brightness temperatures. In the case of visible / SWIR channels (labelled as S1 to S6), these measurements are expressed in TOA radiances.

The radiometric measurements are indexed according to the across track and along track direction:

- on a 1 km grid for brightness temperature for channels S7-S9 and F1-F2
- on a 0.5 km grid for radiances. In this case, two stripes are distinguished: stripe A for S1-S6 and stripe B for S4-S6.

There are essentially eight 'grids' due to the TIR 1km infrared 'i' grid, the 'f' grid specific to F1, and the two different 0.5km grids 'a', 'b'. Each of these is represented on the nadir and oblique views, making a total of eight.

The Level-2 products and output of SLSTR Level-2 processing are:

- Level-2 WCT product (not disseminated to users) providing the sea surface temperature for single and dual view, for two or three channels
- Level-2 WST product providing L2P sea surface temperature, following the GHRSST specifications
- Level-2 LST and FRP products providing land surface temperature and fire radiative power (under specification)

The SLSTR Level-2 LST product provides land surface parameters generated on the wide 1 km measurement grid. It contains:

- measurement file with Land Surface Temperature (LST) values computed and provided for each re-gridded or orphan pixel
- associated ancillary parameters

The Measurement Dataset (MD) is indexed by across track and along track dimensions and include:

- The LST values and their estimated total uncertainties
- The exception flags associated to LST

One Annotation DataSet (ADS) is specifically associated with LST MD and provides:

- Normalized Difference Vegetation Index (NDVI)
- GlobCover surface classification code (noted “biome”)
- Fraction of vegetation cover
- Total Column Water Vapour (TCWV)

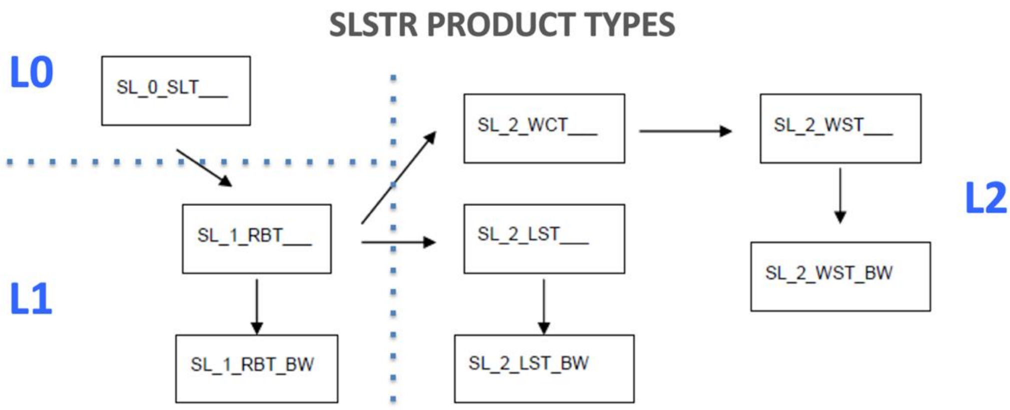


Figure 25 SLSTR product types

7 ANNEX II: CODE IN BAND MATHS

The effective emissivity, ε, is calculated by:

i. With NDVI values higher than 0.99: value 0.99
ii. In areas without vegetation, with NDVI values between 0-0.15 (Pv=0, Ci=0):

$$\varepsilon_{s8s}= (-0{,}051*\rho_{681}) + 0.98$$
$$\varepsilon_{s9s}= (-0{,}031*\rho_{681}) + 0.983$$

iii. Mixed vegetation emissivity (NDVI between 0.15 and 0.99):

$$\varepsilon_{s8m}= 0.969(1-Pv) + 0{,}99*Pv$$
$$\varepsilon_{s9m}= 0.977(1-Pv) + 0{,}99*Pv$$

iv. Total emissivity:

$$\varepsilon_{s8}total= 0.99+\varepsilon_{s8s}+\varepsilon_{s8m}$$
$$\varepsilon_{s9}total=0.99+\varepsilon_{s9s}+\varepsilon_{s9m}$$

v. Effective emissivity:

$$e = (\varepsilon_{s8}total+\varepsilon_{s9}total)/2$$

vi. Differential emissivity:

$$\Delta\varepsilon=(\varepsilon_{s8}total+\varepsilon_{s9}total$$

Band Maths Expressions:

#Pv calculation
Pv = (NDVI -0.15)/(0.9 -0.15)

 # Soil emissivity
emis_s_S8_in = if (NDVI < 0.15) then (-0,051 * RC681) + 0.98 else 0
emis_s_S9_in = if (NDVI < 0.15) then (-0,031 * RC681) + 0.983 else 0

 # Mixed vegetation emissivity
emis_m_S8_in = if (NDVI >= 0.15) and (NDVI <= 0.99) then (0.969 * (1-Pv)) + (0.99 * Pv)) else 0
emis_m_S9_in = if (NDVI >= 0.15) and (NDVI <= 0.99) then (0.977 * (1-Pv)) + (0.99 * Pv)) else 0

 # Vegetation emissivity
emis_v = if (NDVI > 0.99) then 0.99 else 0

 # Total emissivity
emis_t_S8_in = if (emis_s_S8_in !=0) or (emis_m_S8_in !=0) then (emis_s_S8_in + emis_m_S8_in) else NaN
emis_t_S9_in = if (emis_s_S9_in !=0) or (emis_m_S9_in !=0) then (emis_s_S9_in + emis_m_S9_in) else NaN

 # Effective emissivity
emis_effect = (emis_t_S8_in + emis_t_S9_in) / 2

#Differential emissivity
emis_diff = emis_t_S8_in - emis_t_S9_in

 # Water vapour to g*cm2
IWV_g = IWS / 10

#Split window algorithm for LST

S8_BT_in_M + (1.084 * (S8_BT_in_M - S9_BT_in_M)) + (0.2771*((S8_BT_in_M - S9_BT_in_M) ^ 2)) + (-0.268) + ((45.1 + (-0.73 * IWV_g_S))*(1 - emis_effect_S)) + (((-125 + (16.7*IWV_g_S)))*(emis_diff_S))