Sentinel-2 MSI
IdePix
Identification of Pixel features

Algorithm Theoretical Basis Document

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Version history

Version	Date	Comment
1.0	14.12.2021	Initial version

List of Abbreviations

CDI	Cloud Displacement Index
CRS	Coordinate Reference System
CTH	Cloud Top Height
DEM	Digital Elevation Model
GPT	Graph Processing Tool
HLS	High Latitude Snow/Ice
L1C	Level 1C
LLS	Low Latitude Snow/Ice
MERIS	MEdium Resolution Imaging Spectrometer
MSI	Multi-Spectral Imager
NIR	Near-infrared
NDSI	Normalized Difference Snow Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
OLCI	Ocean and Land Colour Instrument
OCL	Opaque Cloud Land
OCW	Opaque Cloud Water
Proba-V	Project for On-Board Autonomy - Vegetation
S2	Sentinel-2

SAA	Sun Azimuth Angle
SZA	Sun Zenith Angle
SNAP	SeNtinel Application Platform
SRTM	Shuttle Radar Topography Mission
TOA	Top Of Atmosphere
TC	Tasseled Cap
UTM	Universal Transverse Mercator
VIIRS	Visible/Infrared Imager Radiometer Suite

1 Introduction

Approximately 66% of all global surfaces are constantly covered by clouds. Figure 1 illustrates the average cloud occurrence between 2000 and 2014. While some areas are very rarely covered by clouds some areas have cloud occurrences above 75%, giving even satellites with high repetition times only a slight chance to make a non-obstructed measurement of the earth's surface.

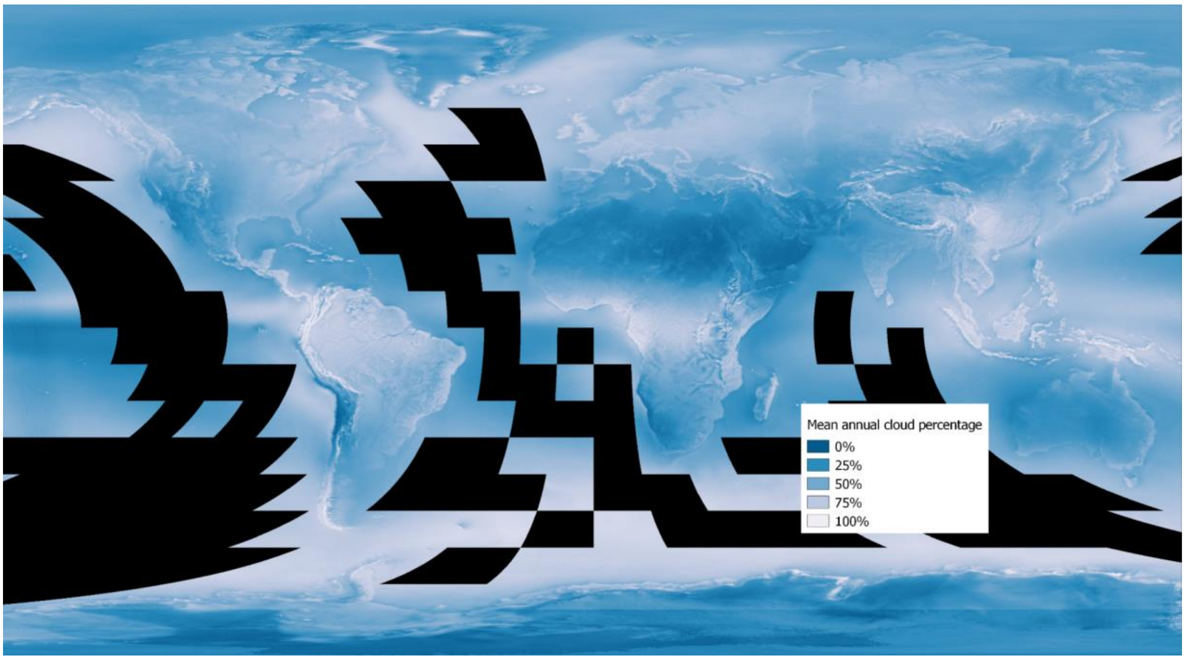

Figure 1: Global mean annual cloud occurrence map 2000-2014 (Wilson, A. M., Jetz, W [2016])

Clouds are multifarious and very dynamic entities, which form and change spontaneously but also constantly, depending on conditions of Earth's atmosphere and surface. Instruments in space simply measure radiance, usually within different spectral wavebands. They are not able to discern whether the measured radiance originated from Earth's surface, a cloud, or a mixture thereof. Operational algorithms to derive Earth surface properties from measured spectral radiance usually yield wrong results when applied to a land or ocean surface that is obscured by undetected clouds. On the other hand, algorithms deriving cloud properties yield invalid outcomes when applied to the cloud free parts of a satellite image. Besides reliable identification of clouds, the detection of thick layers of aerosols is a special concern. The interplay between aerosols and clouds and their effect on Earth's radiation budget is one of the key problems to understand and predict Global Warming. Thus, detecting clouds is like "separating the wheat from the chaff". But what is the "wheat" and what is the "chaff" depends on specific aims and needs. In fact, one user's noise is another user's data. Reliable cloud detection is a prerequisite for the operational interpretation of satellite images in terms of Earth system state variables and their subsequent processing into Climate Data records and other forms of analysis-ready data.

2 Identification of Pixel properties – the design/overview

The term "pixel identification" refers to a classification of a measurement made by a space borne radiometer. Before processing land or water pixels, or exempting them from further processing, it is necessary to sort them into the observation types like clouds, clear sky over land, or clear sky over water. Depending on the downstream processing steps some additional pixel properties like cloud shadow or mountain shadow, snow cover or aerosol contamination are needed.

IdePix (Identification of Pixel properties) is a multi-sensor pixel identification tool available as a SNAP (Sentinel Application Platform) plugin. It provides pixel identification algorithms for a wide variety of sensors like Sentinel-2 MSI, Sentinel-3 OLCI, MERIS, Landsat-8, MODIS, VIIRS, Proba-V or SPOT VGT. It is therefore a one-stop pixel identification tool if you are working with multiple sensors. As a SNAP plugin, it can be used in combination with other algorithms available from S2 & S3 toolboxes, to create powerful processing chains with SNAP or GPT (Graph Processing Tool).

IdePix classifies pixels into a series of categories (flags) for further processing using a mono-temporal approach and background information. Its uniqueness consists of a certain set of flags, which are calculated for all instruments (common flags), complemented by instrument specific flags (instrument flags). The technical design of all IdePix is instrument specific and can include decision trees, probabilistic combination of calculated features or neural networks. The Sentinel-2 IdePix, is mainly based on a decision tree technique for cloud calculation as well as geometric calculations for cloud and mountain shadows.

In contrast to many other pixel identification tools, the final IdePix classification is non-exclusive and therefore allows multiple classes to be set for a single pixel. This means a single pixel can have multiple properties like land and cloud (semi-transparent cloud over land), land and snow (land covered with snow), or land, snow and cloud (semi-transparent cloud over snow covered land). This type of implementation allows the most versatile usage of the flagging and combinations according to users' needs compared to a standard integer flag allowing a single status per pixel.

Sentinel-2 IdePix derives water cloud flags and cirrus cloud flags on multiple confidence levels, as well as cloud shadow, mountain shadow, snow/ice and water flags. IdePix can be used as a stand-alone tool. The pixel identification (IdePix) for Sentinel-2 is only working at single resolution (i.e. 10m, 20m, 60m). It is important to note that the Sentinel-2 resampling operator is needed to pre-process the input data to the desired resolution. This specific resampling is needed to preserve the correct geometric (sun & sensor) information required for the two shadow algorithms. Cloud boundary pixels are flagged using a dilation filter. In principle, cloud boundaries are regarded as neighbor pixels of a cloud as identified before by the processor; thus a buffer is set around the cloud. The width of this boundary (in number of pixels) can be set by the user.

3 IdePix algorithm

The Sentinel-2 IdePix algorithm consists of multiple modules. While most of the classification is based on spectral tests and is done in the main classification module, some classification like mountain and cloud shadow are done in post processing, since they rely on prior process flags or auxiliary data.

3.1 Adding elevation data to the product

In a first processing step a new DEM (elevation) band is added to the selected Sentinel-2 MSI L1C product. The band is computed by looking up each pixel in a selected high-resolution DEM. We recommend using the new Copernicus DEM as input, current default is SRTM 3 arc seconds.

3.2 Single pixel based processing

The main part of the IdePix classification algorithm for Sentinel-2 MSI is based on several spectral tests. The Sentinel-2 L1C TOA reflectance is used to calculate a set of features. Some of these features are used to directly derive flags using a threshold (see section 3.2.2 Single test classifications), while others are used in a decision tree (see section 3.2.3) to derive cloud and snow flags. The decision tree is illustrated in Figure 2. The used thresholds are shown in Table 3. A detailed description of the features and tests is given in following sections.

Compared to processing done in the subsequent chapters, single pixel processing means that no information about surrounding pixels is required. Making this processing step quite inexpensive.

In preparation for the processing, the multiresolution Sentinel-2-MSI L1C product must be resampled to the same raster size for all bands (10, 20 or 60m resolution). It is important to note that the Sentinel-2 resampling operator (Sentinel-2 Toolbox in SNAP) is needed to pre-process the input data to the desired resolution. This specific resampling is needed to preserve the correct geometric (sun & sensor) information.

3.2.1 Spectral features

The following features (Table 1) are calculated for Sentinel-2 MSI.

Table 1: Sentinel-2 IdePix – features

Feature	Explanation/ Calculation
NDSI	*NDSI = (B3-B11)/(B3+B11)*
NDVI	*NDVI = (B8-B4)/(B8+B4)*
NDWI	*NDWI = (B8A-B11)/(B8A+B11)*
B3B11	*B3B11 = B3/B11*
VisBright	*VisBright = (B2+B3+B4)/3*
TC1	*TC1 = 0.3029 B2 + 0.2786 B3 + 0.4733 B4 + 0.5599 B8A + 0.508 B11 + 0.1872 B12*
TC4	*TC4 = -0.8239 B2 + 0.0849 B3+ 0.4396 B4- 0.058 B8A + 0.2013 B11 – 0.2773 B12*
TC4Cirrus	*$TC4_{Cirrus}$ = -0.8239 B2+ 0.0849 B3+ 0.4396 B4- 0.058 B8A + 0.2013 B11 – 0.2773 B12 – B10*
Bright	$brightValue = B1/(6 \cdot t_{brr442})$

White	if $brightValue > 0.8$:
	$white\_value = spectral\_flatness$
	else:
	$white\_value = 0$

Spectral flatness	$slope_1 = (B2 - B1)/(490nm - 442nm)$ $slope_2 = (B3 - B4)/(560nm - 665nm)$ $slope_3 = (B5 - B7)/(705nm - 783nm)$ $spectral\_flatness = 1 - \lvert 1000 \cdot (slope_1 + slope_2 + slope_3)/3 \rvert$

Radiometric land	if $B8 \geq B4$:
	$radiometric\_land\_value = 1$
	else:
	$radiometric\_land\_value = 0.5$

Feature	Explanation/ Calculation

RADIOMETRIC WATER	if $B8 < B4$:
	 $radiometric\_water\_value = 1$
	 else:
	 $radiometric\_water\_value = 0.5$

In the sections below all used spectral features are described in detail.

3.2.1.1.1 NDSI

The Normalized Difference Snow Index (NDSI) snow cover is an index that correlates with the presence of snow in a pixel. Snow is highly reflective in the visible (NIR) part of the S2 MSI spectrum and highly absorptive in the short-wave infrared (SWIR) part of the spectrum.

A general definition of the NDSI is given as:

$$\mathrm{NDSI} = \frac{(\mathrm{Green} - \mathrm{SWIR})}{(\mathrm{Green} + \mathrm{SWIR})}$$

For Sentinel-2 MSI this translates to:

$$\mathrm{NDSI} = \frac{(\mathrm{B3} - \mathrm{B11})}{(\mathrm{B3} + \mathrm{B11})}$$

3.2.1.1.2 NDVI

The Normalized Difference Vegetation Index (NDVI) is sensitive to the chlorophyll content of vegetation. High NDVI values show a high chlorophyll content of the vegetation and thus are linked to healthy vegetation.

A general definition of the NDVI is given as:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}$$

For Sentinel-2 this translates to:

$$\mathrm{NDVI} = \frac{(\mathrm{B8} - \mathrm{B4})}{(\mathrm{B8} + \mathrm{B4})}$$

3.2.1.1.3 NDWI

The Normalized Difference Water Index (NDWI) is sensitive to the water content of vegetation. High NDWI values show a high water content of the vegetation [Gao 1996].

A general definition of the NDWI is given as:

$$\mathrm{NDWI} = \frac{(\mathrm{NIR} - \mathrm{SWIR})}{(\mathrm{NIR} + \mathrm{SWIR})}$$

For Sentinel-2 this translates to:

$$\mathrm{NDWI} = \frac{(\mathrm{B8A} - \mathrm{B11})}{(\mathrm{B8A} + \mathrm{B11})}$$

3.2.1.1.4 B3B11

The ratio of Sentinel-2 Band B3 and B11 is used to separate water and non-water. Even though the bands are used in the NDWI to detect snow, empirical tests had shown that using a threshold of zero on this ratio (B3/B11), leads to quite a good land/water separation after snow detection. The ratio was superior to a threshold on the NDVI or NDWI, both struggling with the land/water transition zone, especially at vegetated shorelines.

3.2.1.1.5 VisBright

The visible brightness (VisBright) is calculated as the mean of the three RGB channels of Sentinel-2.

VisBright is defined as:

$$\mathrm{VisBright} = \frac{(\mathrm{B2} + \mathrm{B3} + \mathrm{B4})}{3}$$

3.2.1.1.6 TC1

The tasseled cap (TC) transformation is a method to transform the spectral information of satellite data into spectral indicators with defined interpretations that are useful for vegetation mapping. A tasseled-cap transform is performed by taking “linear combinations” of the spectral bands - similar in concept to principal components analysis. The coefficients used to create the tasseled-cap bands are derived statistically from products and empirical observations and are specific to each satellite sensor.

The first tasseled cap (TC1) is related to the brightness of a pixel.

At the time of the Sentinel-2 IdePix development no TC1 coefficients have been available. Due to the strong correlation between Landsat 8 and Sentinel-2 bands, the Landsat 8 coefficients have been used, as derived by Baig et al 2014.

TC1 is defined as:

$$\mathrm{TC1} = 0.3029 * \mathrm{B2} + 0.2786 * \mathrm{B3} + 0.4733 * \mathrm{B4} + 0.5599 * \mathrm{B8A} + 0.508 * \mathrm{B11} + 0.1872 * \mathrm{B12}$$

TC1 is used in IdePix to support the NDSI.

3.2.1.1.7 TC4

The fourth tasseled cap (TC4) is related to neither brightness, nor greenness, nor yellowness and therefore was called “non-such”.

TC4 is defined as:

$$\mathrm{TC4} = -0.8239 * \mathrm{B2} + 0.0849 * \mathrm{B3} + 0.4396 * \mathrm{B4} - 0.058 * \mathrm{B8A} + 0.2013 * \mathrm{B11} - 0.2773 * \mathrm{B12}$$

TC4 had proven to be very valuable for the detection of clouds since it is related to the physical state of the atmosphere [Kauth, R.J., & Thomas, G.S. 1976]. The derived values help lowering all surface reflectances compared to clouds.

3.2.1.1.8 TC4Cirrus

The TC4Cirrus component was invented by adding the cirrus band to the TC4 equation. Additionally subtracting the cirrus band helps to boost the separation between clouds and non-cloud pixels. The development was made based on empirical test.

The TC4Cirrus test is defined as:

$$TC4Cirrus\ = TC4 - B10$$

3.2.1.1.9 Bright value

$$brightValue = B1/(6 \cdot t_{brr442})$$

3.2.1.1.10 Spectral flatness

For the spectral flatness value the spectral slopes between six bands are evaluated:

$$slope_1 = (B2 - B1)/(490nm - 442nm)$$
$$slope_2 = (B3 - B4)/(560nm - 665nm)$$
$$slope_3 = (B5 - B7)/(705nm - 783nm)$$

$$spectral\_flatness = 1 - |1000 \cdot (slope_1 + slope_2 + slope_3)/3\ |$$

3.2.1.1.11 White value

The white value is defined as:

if $brightValue > 0.8$:

$$white\_value\ = spectral\_flatness$$

else:

$$white\_value\ = 0$$

3.2.1.1.12 Radiometric land

if $B8 \geq B4$:

$$radiometric\_land\_value\ = 1$$

else:

$$radiometric\_land\_value\ =\ 0.5$$

3.2.1.1.13 Radiometric water

if $B8 < B4$:

$$radiometric\_water\_value = 1$$

else:

$$radiometric\_water\_value = 0.5$$

3.2.2 Single test classifications

In this section all single spectral tests are presented, which are not part of the cloud flagging decision tree approach. Table 2 lists all used thresholds

Table 2: IdePix thresholds for Sentinel 2

Name	Value
t_{brr442}	$0.03 + 0.03 \cdot \cos^2(scattering\ angle)$ [1]
t_{white}	0.9
$t_{brightwhite}$	1.5
t_{water}	0.9
t_{land}	0.9
t_{NDVI}	0.5

3.2.2.1 Invalid test

The valid pixel expression for a L1C product states, that all reflectance bands in a spectrum have to be greater than 0. (all Bx.raw>0). If any of the reflectance measurements is below 0, the pixel is flagged as invalid.

$$INVALID = if\ Min(B1.raw, B2.raw, \dots, Bn.raw) < 0$$

With n = maximum Sentinel-2 band number

3.2.2.2 Bright test

$$BRIGHT = brightValue > 0.25$$

3.2.2.3 White test

$$WHITE = white\_value > t_{white}$$

3.2.2.4 Bright white test

$$BRIGHT\_WHITE = white\_value + bright\_value > t_{brightwhite}$$

[1] $scattering\ angle = -cos(SZA) * cos(VZA) - sin(SZA) * sin(VZA) * cos((VAA - SAA)$

3.2.2.5 Land

LAND

$$\text{if } LATITUDE < 60 \,\&\, LATITUDE > -56 \,\&$$

$$(SRTM\ water\ body\ mask > 0)$$

else:

$$radiometric\_land\_value > t_{land}$$

3.2.2.6 Water

$$WATER\ if\ !LAND$$

3.2.2.7 Clear land

$$CLEAR\_LAND = !INVALID \,\&\, !CLOUD\_SURE \,\&\, !CLOUD\_AMBIGUOUS \,\&$$

$$!CIRRUS\_SURE \,\&\, !CIRRUS\_ABIGUOUS \,\&\, radiometric\_land\_value < t_{land}$$

3.2.2.8 Clear water

$$CLEAR\_WATER = !INVALID \,\&\&\, !CLOUD\_SURE \,\&\, !CLOUD\_AMBIGUOUS \,\&$$

$$!CIRRUS\_SURE \,\&\, !CIRRUS\_ABIGUOUS \,\&\, radiometric\_water\_value < t_{water}$$

3.2.2.9 Vegetation risk

The vegetation risk test is based on the NDVI and identifies pixels that are likely to be vegetated.

The test is defined as:

$$VEG\_RISK = NDVI > t_{NDVI}$$

3.2.3 Decision tree classification for cloud and snow

Cloud and snow classification is achieved using a decision tree approach, shown in Figure 2

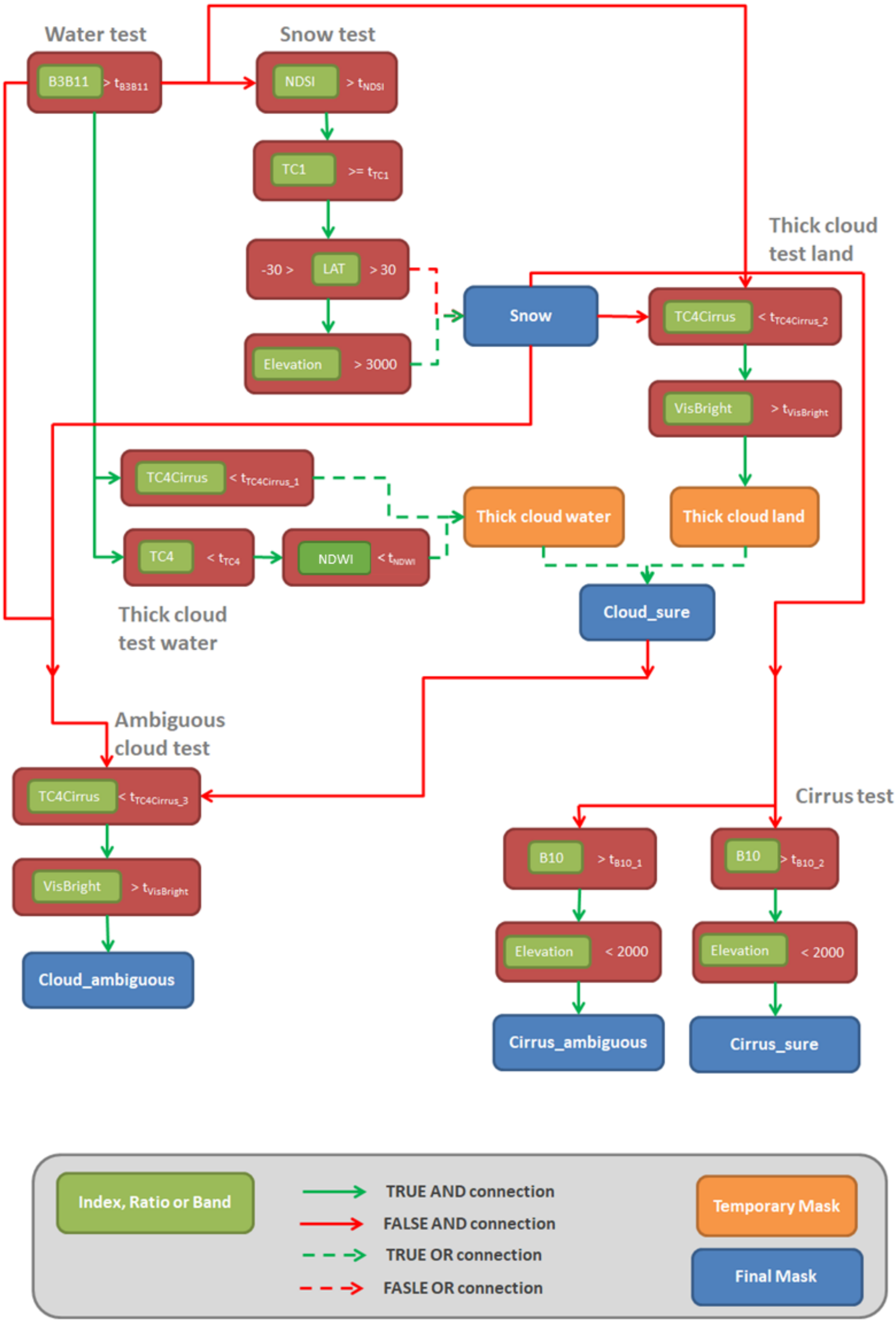

Figure 2: IdePix – Decision tree for Sentinel 2

Table 3: IdePix thresholds for Sentinel 2

Name	**Value**
t_{B3B11}	1.0
t_{NDSI}	0.6
t_{TC1}	0.36
$t_{TC4Cirrrus\_1}$	-0.1
$t_{TC4Cirrrus\_2}$	-0.11
$t_{TC4Cirrrus\_3}$	-0.085
t_{TC4}	-0.08
t_{NDWI}	0.04
$t_{VisBright}$	0.12
t_{B10_1}	0.0035
t_{B10_2}	0.01

3.2.3.1 Cloud and snow/ice decision tree

3.2.3.1.1 Land/water test

The first test of the decision tree uses the B3B11 ratio to separate land and water surfaces, in order to perform dedicated cloud test over water and land. This separation is useful, since thin/transparent clouds over water or land require different methodologies and thresholds.

$$B3B11 = \frac{B3}{B11} > t_{B3B11}$$

3.2.3.1.2 Snow/ice test

Snow and ice contradict the most with clouds. Therefore, in a first test, snow and ice pixels are flagged. Different test strategies are used for low and high latitudes to minimize the effect of false snow/ice detection.

Low latitude snow/ice is detected using the following tests:

$$LLS = (latitude < 30° \,\&\, latitude > -30°) \,\&\, Elevation > 3000 \,\&\, NDSI > t_{NDSI} \,\&\, TC1 \geq t_{NDSI}$$

While high latitude snow/ice is detected using the following tests:

$$HLS = (latitude \geq 30° \,\&\, latitude \leq -30°) \,\&\, NDSI > t_{NDSI} \,\&\, TC1 \geq t_{NDSI}$$

Together these tests form the SNOW_ICE flag:

$$SNOW\_ICE = LLS \mid HLS$$

Elevation is used to minimize false snow/ice detections for low latitudes. Currently, the test is limited to all surfaces detected as land by the B3/B11 test. This means there is no snow/ice detection over water implemented.

3.2.3.1.3 Cloud detection

As shown in Figure 2, there are mainly six branches in the decision tree leading to four different kinds of cloud flags. The final cloud flags are called CLOUD_SURE, CLOUD_AMBIGUOUS, CIRRUS_SURE, and CIRRUS_AMBIGUOUS. While the latter two identify ice clouds, the first two identify predominant water droplet-based clouds. The categories SURE and AMBIGUOUS relate to the level of confidence of the identified pixel being either CLOUD or CIRRUS.

3.2.3.1.4 Predominant water droplet-based cloud tests

Water droplet-based clouds are identified by three sets of tests, depending on whether the pixel was identified as water or land by the land/water test. Additionally, these pixels have not been identified as snow/ice by the snow/ice test.

For very opaque clouds the land/water test does not really detect water or land surfaces but helps to separate opaque clouds in a way that different thresholds and test can be used afterwards, to identify clouds with a high probability. Therefore, there are two tests identifying opaque water clouds with a very high probability, together forming the CLOUD_SURE flag.

The first test is the “opaque cloud water” (OCW) test:

$$OCW = TC4Cirrus < t_{TC4Cirrus\_1} \mid (TC4 < t_{TC4} \,\&\, NDWI < t_{NDWI})$$

The second test is the “opaque cloud land” (OCL) test:

$$OCL = TC4Cirrus < t_{TC4Cirrus\_2} \,\&\, VisBright > t_{VisBright}$$

These two tests together are combined to from the CLOUD_SURE flag:

$$CLOUD\_SURE = OCW \mid OCL$$

All remaining pixels, that are neither snow/ice, nor CLOUD_SURE are classified as CLOUD_AMBIGUOUS using the following test:

$$CLOUD\_AMBIGOUS = TC4Cirrus < t_{TC4Cirrus\_3} \,\&\, VisBright > t_{VisBright}$$

The CLOUD_SURE and CLOUD_AMBIGUOUS flags are then combined to form the CLOUD flag for user convenience.

3.2.3.1.5 Predominant ice cloud (cirrus) tests

Predominant ice clouds are identified using the Sentinel-2 band B10 and elevation data. Cirrus clouds are defined on two different probability levels using different thresholds, leading to a CIRRUS_SURE and CIRRUS_AMBIGUOUS flag. The pixels are identified independent from the water cloud tests (CLOUD_SURE and CLOUD AMBIGUOUS), since ice clouds normally form at high altitudes and thus are able to overlay water droplet-based clouds, or tops of very high stretching water-based clouds are formed by ice particles. If users want to use the CIRRUS flag for cirrus correction during atmospheric correction, the CIRRUS flags can simply be subtracted by the CLOUD flags.

The CIRRUS flags are defined as:

$$CIRRUS\_SURE = B10 > t_{B10\_2} \ \& \, Elevation < 2000$$

$$CIRRUS\_AMBIGUOUS = B10 > t_{B10\_1} \ \& \, Elevation < 2000$$

3.3 Spatial cloud refinement

With the decision tree-based cloud detections, the distinction between bright artificial build up areas and especially low altitude clouds often fails. The Cloud Displacement Index (CDI) makes use of the near parallax effect by using the three correlated near infrared bands and their different view angles to detect elevated objects [Frantz et al. 2018]. The difference between B8A and B8 ($R_{8A,8}$) and between B8A and B7 ($R_{8A,7}$) are calculated, and a spatial 7x7 standard deviation filter is applied to both. The CDI Is defined as:

$$CDI = \frac{R_{8A,7}std^2 - R_{8A,8}std^2}{R_{8A,7}std^2 + R_{8A,8}std^2}$$

The threshold for the CDI is set to -0.5. The use of the CDI approach is restricted to land surfaces, non-cirrus pixel (not CIRRUS_SURE and not CIRRUS_AMIGUOUS) and regions without gapless cloud cover. For the gapless cloud cover restriction, a 11x11 filter is used on the predefined Idepix cloud mask (CLOUD_SURE) and the CDI is not applied if this pixel area has only classified cloud pixel. The refinement of the cloud detection is implemented into the CLOUD_SURE flag.

3.4 Cloud buffer

For pixels identified as cloudy (CLOUD), a cloud buffer of specified width can be set by the user to finally obtain a more conservative cloud mask. This is done in a post-processing step after the cloud classification has been applied on the full image. The cloud buffer algorithm works on pixel windows of size (2N+1) x (2N+1) with N = cloud buffer width. Note that the cloud buffer is only applied on cloud-free pixels, i.e., cloudy pixels are not flagged as cloud buffer of cloudy neighboring pixels. The cloud buffer is optional and can be omitted.

3.5 Mountain shadow

The algorithm for computing mountain shadow for a Sentinel-2 MSI product is based on a hillshading approach (e.g., Schuckmann 2020, ESRI 2016) and uses slope and aspect. Since Sentinel-2 products are projected in UTM, the true north can deviate from the aspect calculated from the DEM only using pixel directions (up = north). Therefore, the correct orientation is calculated using latitude and longitude to correct for this effect.

Orientation gives the angle between the North direction and the y-direction in a 3x3 macro-pixel (same x-pixel-value in satellite coordinates), which is defined by two points: Point 1 with satellite coordinates (x0, y1) and geographical coordinates (lat1, lon1) and Point 2 (x0, y2) with (lat2, lon2). From these coordinates orientation or bearing (see Upadhyay 2015) can be derived as follows:

$$X = \cos(lat2) * \sin\,(lon2 - lon1)$$

$$Y = \cos(lat1) * \sin(lat2) - \sin(lat1) * X$$

$$orientation = \mathrm{atan}\,(X, Y)$$

Spatial resolution is either calculated from the great circle distance of two points or it relies on the CRS geo-coding.

Because S2-MSI L1C products are orthorectified and projected, all effects of the viewing geometry are already considered and need not be explicitly corrected (as it was necessary for S3-OLCI or any products in satellite coordinates).

From a 3x3 macropixel, the slope is calculated from elevation with corrected spatial resolution:

$$b = (elev[2] + 2 * elev[5] + elev[8] - elev[0] - 2 * elev[3] - elev[6])/8$$

$$c = (elev[0] + 2 * elev[1] + elev[2] - elev[6] - 2 * elev[7] - elev[8])/8$$

$$slope = \mathrm{atan}\,(\sqrt{b^2 + c^2})$$

$$aspect = \mathrm{atan}(-b, -c)$$

A pixel is flagged as mountain shadow, if the following condition is met:

$$\cos\beta = \cos sza * \cos slope + \sin sza * \sin slope * \cos(saa - (aspect + orientation))$$

$$\cos\beta < shadow\_threshold$$

Currently, the shadow_threshold is set to 0.

3.6 Cloud shadow

S2-MSI provides no spectral measurements in the O_2 absorption bands, so that the cloud top height cannot be estimated and used to determine the cloud shadow analytically. Instead, two purely geometrical approaches are designed. Firstly, the cloud mask is shifted in the direction of the illumination until the mean value of covered observed reflectances reaches a local minimum. Secondly, for all continuous cloud areas the darkest cluster of pixels is identified within the potential cloud shadow area separately.

S2-MSI L1C products are projected and orthorectified. All objects, which are represented in the used DEM, are portrayed at the positions they would take up when observed from nadir view. This is not true for elevated objects at unknown heights like clouds. If they are observed at a view zenith angle away from nadir, the clouds are mapped on the ground in the viewing direction away from their actual position. In the projection and orthorectification process the cloud observations are mapped to positions corresponding to those which they originally appeared to be located at on the ground. As shadows are cast by the cloud in its actual position over ground, the angles must be adjusted. For this projected case, this correction has not yet been devised (these effects are not as large as they are in unprojected data).

The potential cloud shadow path is determined as a function of maximum cloud top height (cth_{max}, expressed as a function of latitude, in meter) and sun illumination direction (ΔProjX and ΔProjY), which is taken as a constant at the tile center for the entire tile.

$$cth_{max} = 0.5 * (90 - |lat|)^2 + 25 * (90 - |lat|) + 5000$$

$$\Delta ProjX = (cth_{max} - surfaceAltitude_{min}) * \tan SZA * \cos SAA \,/ spatialResolution$$

$$\Delta ProjY = (cth_{max} - surfaceAltitude_{min}) * \tan SZA * \sin SAA \,/ spatialResolution$$

With a constant direction, the path of potential cloud shadow can be expressed as discrete steps of pixel coordinates between a starting pixel (x_0, y_0) and an end point $(x_0 + \Delta ProjX, y_0 + \Delta ProjY)$

Each cloud pixel becomes then the starting point of such a potential path of cloud shadow, and this intermediary classification is recorded in the flag IDEPIX_POTENTIAL_SHADOW.

3.6.1.1 Algorithm 1: Shifting the cloud mask

The mean reflectance of cloud free pixels covered by the shifted cloud mask in band B3 is calculated for each step along the illumination path (starting from the cloud, away from the sun). The results are three functions of mean reflectance parameterized by the step along the path: two functions of mean reflectance values for land and water pixels separately, and a function of mean reflectance values for all pixels. Because the scene is split internally into smaller subsections (which are called tiles here) to allow parallelized processing, there are three of these mean reflectance functions for each tile.

Each of these functions is evaluated and excluded from further processing, if:

- the minimum reflectance is in position 1 or in the last position of the path. The function is discarded.
- the minimum reflectance is in the second half of the path, which is generous in its extent. This is most likely not a minimum created by cloud shadow.

The remaining mean reflectance functions are scaled (here: divided by their respective maximum value) and added up to a single scaled mean function per class (all, land, water).

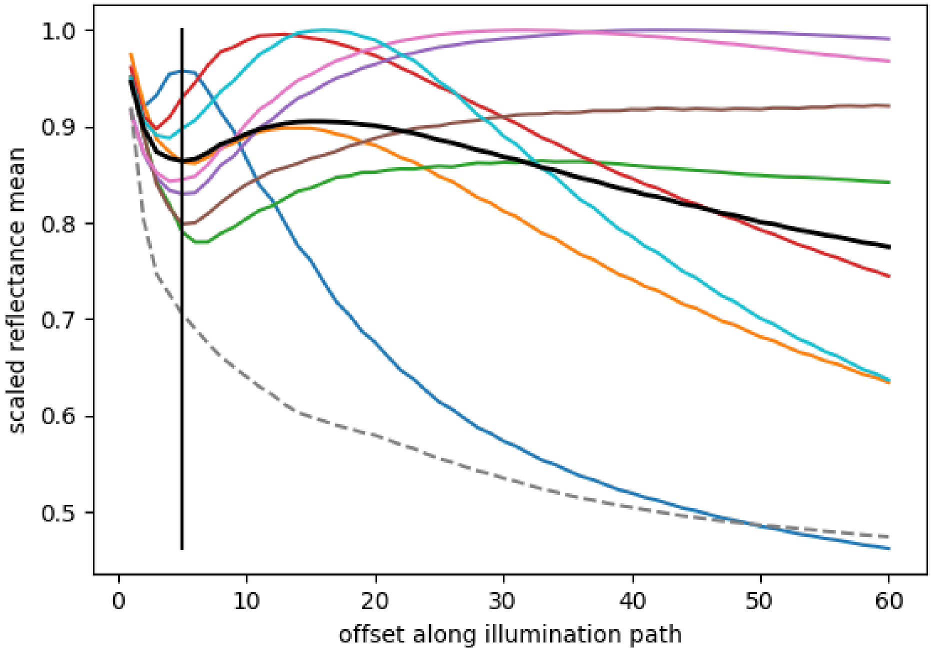

Figure 3: Functions of scaled mean reflectance versus offset along the illumination path per tile (colored lines). The result from one tile is excluded from the analysis (dashed line), because it has no relative minimum but for the absolute one at the maximum offset. The black line represents the mean value of all functions, the vertical line marks the relative minimum, which gives an estimate of the best overall shift of the cloud mask.

Often enough, this algorithm leads to a smooth function with a clear relative minimum (see Figure 3). The first minimum along the path, which is not at step 1 or the last step, is a potential offset for shifting the cloud mask in a scene. From the three offsets the most likely one is determined by the numbers of water and land pixels involved in the data for the mean function:

- if the number of water pixels is larger than two times the number of land pixels (at least 66% water pixels), the decision should be made based on the water pixels. The offset from the water pixel analysis is used.
- Respectively, the land pixel offset is used if most pixels have been land pixels (at least 66% land pixels).
- Otherwise, the offset from the function, which used both land and water pixels, is used.

Within this algorithm, the internal flag SHIFTED_CLOUD_SHADOW_FLAG is raised if conditions are met. The determined offset is stored for adjustments in the clustering algorithm.

3.6.1.2 Algorithm 1b: shifted cloud mask in cloud gaps

By convolution of the cloud mask with a circle shaped kernel of 1000m radius, the gaps within clouds are found. If a gap pixel coincides with the SHIFTED_CLOUD_SHADOW_FLAG, a new internal processing flag is raised (SHIFTED_CLOUD_SHADOW_IN_GAPS).

3.6.1.3 Algorithm 2: Finding a threshold from the clusters of darkest pixels

All continuous cloud mask areas are identified, so that each cloud and its potential shadow can be addressed separately, if they are spatially separated in their pixel-based representation. In this way, different cloud top heights, which are unknown, can be realized. Still, areas of lower and higher drifting clouds might overlap in the cloud mask, and they will be handled as a single entity of cloud. When finding the darkest clusters of pixels in the potential shadow area, which is formed by all the potential shadow paths of one cloud mask entity, the variable cloud top height of a larger conglomeration of clouds is no impediment.

Three analysis modes are implemented, employing different reflectance bands in the clustering:

- "land-water", which uses two bands (B8A for land, B3 for water) separately in the clustering;
- "multiple bands", which uses two bands combined (B8A, B3) in the clustering;
- "single band", which uses just one band (B8A).

For a continuous part of the cloud mask, all (cloud free) potential shadow pixels are collected. The darkest pixel is identified from all these pixels. If the mode of analysis uses more than one band, the minimum is calculated based on the sum of squares over all bands, i.e., the values are either from B8A or B3, or $B8A^2 + B3^2$. The collection of cloud-free pixels is prepared for clustering in the following way: the brightest 6% of all pixels are excluded from the collection and the value of the darkest pixel is added 0.5% times with respect to the total amount of pixels in the potential cloud shadow area. At least one duplicate of the darkest pixel is added.

The best number of clusters is set to 4 (or less, if less pixels are available) and the collection of pixels is clustered with the k-means clustering approach. Clusters are sorted by their darkness ($cluster_i$), the darkest ones first. The darkness threshold is defined by the center value of the darkest cluster ($cluster_0$) added by half the distance between the second darkest to the darkest cluster center.

$$cluster_0 = \min cluster_i$$

$$threshold_{dark} = cluster_0 + (\mathrm{cluster}_1 - \mathrm{cluster}_0)/2$$

In the "multiple bands" mode, the distance and the threshold are calculated from the sum of squares of all bands.

If the value of the band (or sum of squares of bands) is below the threshold, the pixel is possibly a cloud shadow, but it could be a dark, cloud free bare soil patch as well. To avoid some of these misidentifications, the offset which was used to shift the cloud mask in the first approach is considered as a spatial distance threshold: if the dark pixel has a positive offset (counted from the search path's starting point closest to the edge of the cloud (x_0, y_0)), which is three times lower than the cloud-shift offset, and the cloud size (number of pixels in the cloud) is larger than 1, the cloud shadow flag is raised for this pixel:

$$if\ B(x,y) < threshold_{dark}\ \&\ if\ |(x,y) - (x_0,y_0)| < 3 * cloudshiftOffset\ AND\ size_{cloud} > 1\ then\ CLOUD\_SHADOW\_FLAG$$

If the global best offset has not been able to be derived, only the cloud size is tested.

For small clouds (defined as: 0 < potential number of shadow pixels < minimum number of members in a cluster (with number of clusters N=4): 2N+1=9) the test is different: no cloud shadow flag can be raised, if the reflectance minimum along the path of illumination has been reached. Only pixels before this minimum can be cloud shadow.

By these criteria, the internal CLOUD_SHADOW_FLAG is raised.

3.6.1.4 Connecting both algorithms

Adjustment 1 – Priority of clustered shadow over globally shifted cloud mask for darkest cluster

A first adjustment and comparison of clustered and shifted cloud shadows is already applied at the end of the clustering algorithm. If the global best offset has been successfully determined in algorithm 1, and if the best offset is larger than zero, the number of pixels, which are below the threshold determined by clustering, is larger than 20 and the cloud size is larger than one pixel, the shadow pixels from the clustering threshold are analyzed spatially and all continuous shadow areas are found:

$$\begin{aligned}&\boldsymbol{if}\ cloudShiftOffset > 0\ \&\ N(B < threshold_{dark}) > 20\ \&\ size_{cloud} > 1\\&\boldsymbol{then}\ analyseContinuousShadowArea\end{aligned}$$

If there is more than one shadow area, the algorithm continues: Mean offset and mean reflectance of the spatially continuous shadow areas from the clustering approach are calculated and the minimum mean reflectance is determined.

The darkest, spatially continuous cluster gets to have an influence on the shifted cloud mask flag. If the minimum mean reflectance determined by the clustering method is darker than the mean reflectance value from pixels covered by the shifted cloud mask (one cloud), the shifted cloud mask is turned off (SHIFTED_CLOUD_SHADOW_FLAG) for this cloud and the clustered shadow mask is set (CLOUD_SHADOW_FLAG).

This test helps with different cloud top heights, which have not been taken into account in the globally shifted cloud mask.

Adjustment 2 – Coincidence of shadow areas from shifted and clustering approach

In the best case, the shifted cloud mask and the darkest cluster both cover the same cloud shadows in a scene. This step checks whether a dark cluster area falls within the shifted cloud mask area based on the shifted cloud mask flag. This test is not restricted to the cloud shadow estimates of one cloud, because the shifted cloud mask flag can be raised by a different neighboring cloud.

If coincidence occurs, these cloud shadows based on the clusters are considered shadows and the internal CLOUD_SHADOW_COMB_FLAG is raised. If there is no coincidence between the clustered dark areas and the shifted cloud mask, the area is probably not a shadow, but a different type of dark surface.

3.6.1.5 Combining all: Recommended Cloud Shadow Flags

If the best offset has been determined successfully in Algorithm 1, the internal RECOMMENDED_CLOUD_SHADOW_FLAG is defined as the combination of internal CLOUD_SHADOW_COMB_FLAG and SHIFTED_CLOUD_SHADOW_GAPS_FLAG.

If no best offset is available, the CLOUD_SHADOW_FLAG is copied to the RECOMMENDED_CLOUD_SHADOW_FLAG.

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- IDEPIX_CLOUD_SHADOW is set with the RECOMMENDED_CLOUD_SHADOW_FLAG (internal)
- IDEPIX_POTENTIAL_SHADOW is set with the POTENTIAL_CLOUD_SHADOW (internal)
- IDEPIX_CLUSTERED_CLOUD_SHADOW is set with the CLOUD_SHADOW (internal)

3.7 Flag definitions

Table 4 list all flags produced by the Sentinel-2 IdePix. The methodological basis for the flags was described in the previous sections. Some of the listed flags in Table 4, like IDEPIX_CLOUD_SURE, are common flags, available for each Satellite sensor processable with IdePix (e.g. Sentinel-3 OLCI, Envisat MERIS, or Proba-V), while other flags are sensor specific and do not exist for all sensors, like IDEPIX_CIRRUS_AMBIGUOUS.

Table 4: IdePix flagging

Bit	Integer value	Flag name	Description
1	1	IDEPIX_INVALID	Invalid pixels
2	2	IDEPIX_CLOUD	Pixels which are either cloud_sure or cloud_ambiguous
3	4	IDEPIX_CLOUD_AMBIGUOUS	Semi transparent clouds, or clouds where the detection level is uncertain
4	8	IDEPIX_CLOUD_SURE	Fully opaque clouds with full confidence of their detection
5	16	IDEPIX_CLOUD_BUFFER	A buffer of n pixels around a cloud. n is a user supplied parameter. Applied to pixels masked as 'cloud'
6	32	IDEPIX_CLOUD_SHADOW	Pixel is affected by a cloud shadow (combination of shifted cloud mask in cloud gaps and dark clusters coinciding with a corrected shifted cloud mask)
7	64	IDEPIX_SNOW_ICE	Clear snow/ice pixels
8	128	IDEPIX_BRIGHT	Bright pixels
9	256	IDEPIX_WHITE	White pixels
10	512	IDEPIX_COASTLINE	Pixels at a coastline (not defined for Sentinel-2)
11	1024	IDEPIX_LAND	Land pixels identified by the used land/water mask (default SRTM)
12	2048	IDEPIX_CIRRUS_SURE	Cirrus clouds with full confidence of their detection
13	4096	IDEPIX_CIRRUS_AMBIGUOUS	Cirrus clouds, or clouds where the detection level is uncertain
14	8192	IDEPIX_CLEAR_LAND	Clear land pixels

15	16384	IDEPIX_CLEAR_WATER	Clear water pixels
16	32768	IDEPIX_WATER	Water pixels identified by the used land/water mask (default SRTM)
17	65536	IDEPIX_BRIGHTWHITE	'Brightwhite' pixels
18	131072	IDEPIX_VEG_RISK	Pixels with vegetation risk
19	262144	IDEPIX_MOUNTAIN_SHADOW	Pixel is affected by mountain shadow
20	524288	IDEPIX_POTENTIAL_SHADOW	Potentially a cloud shadow pixel
21	1048576	IDEPIX_CLUSTERED_CLOUD_SHADOW	Cloud shadow identified by clustering algorithm

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