

MTG-FCI: ATBD for Cloud Mask and Cloud Analysis Product

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1 INTRODUCTION

1.1 Purpose of this Document

This document describes the algorithm theoretical basis for the Cloud Mask (Scenes Analysis) and Cloud Analysis product (SCE/CLA), as it shall be derived from the Meteosat Third Generation Flexible Combined Imager (MTG-FCI).

1.2 Structure of this Document

Section 2 of this document provides a short overview over the MTG imaging instrument characteristics and the derived meteorological products, which will be referenced later in the text. This is followed by a detailed description of the SCE/CLA algorithms. Section 4 describes possible future developments of the SCE/CLA algorithms.

A full list of acronyms is provided in section 1.4, literature references are listed in the following section.

1.3 Applicable and Reference Documents

The following documents have been used to establish this document:

Doc ID	Title	Reference
[AD-1]	MTG End Users Requirements Document	EUM/MTG/SPE/07/0036
[AD-2]	MTG Products in the Level-2 Processing Facility	EUM/C/70/10/DOC/08
[AD-3]	MTG-FCI: ATBD for Radiative Transfer Model	EUM/MTG/DOC/10/0382
[AD-4]	MTG-FCI: ATBD for Clear Sky Reflectance Map Product	EUM/MTG/DOC/10/0559
[RD-1]	ATBD for Cloud Products	SAF/NWC/CDOP/MFL/S CI/ATBD/01, Issue 3

1.4 Acronyms and Definitions

The following table lists definitions for all acronyms used in this document.

Acronym	Full Name
AER	Aerosol Product
AMV	Atmospheric Motion Vectors
ASR	All Sky Radiance
ATBD	Algorithm Theoretical Basis Document
CDOP	Continuous Development and Operations Phase
CLA	Cloud Analysis
CMA	Cloud Mask
CRM	Clear Sky Reflectance Map
CT	Cloud Type
CTTH	Cloud Top Temperature and Height
FCI	Flexible Combined Imager
FCI-FDSS	FCI Full Disc Scanning Service
FCI-RSS	FCI Rapid Scanning Service
FDHSI	Full Disc High Spectral Resolution Imagery
FoR	Field-of-Regard
GII	Global Instability Indices
HRFI	High Spatial Resolution Fast Imagery
HRV	High Resolution Visible Channel of SEVIRI
IR	Infrared
LUT	Lookup Table
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
NIR	Near Infrared
NWC	Nowcasting and Very Short Range Forecasting
NWP	Numerical Weather Prediction
OCA	Cloud Product (Optimal Cloud Analysis)
OLR	Outgoing Longwave Radiation
RTM	Radiative Transfer Model
RTTOV	Radiative Transfer for TOVS
SCE	Scene Identification
SAF	Satellite Application Facility
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SSD	Spatial Sampling Distance
TIROS	Television and Infrared Observation Satellite
TOVS	TIROS Operational Vertical Sounder
TOZ	Total Column Ozone
VIS	Visible (solar)

2 OVERVIEW

2.1 Relevant Instrument Characteristics

The mission of the Meteosat Third Generation (MTG) System is to provide continuous high spatial, spectral and temporal resolution observations and geophysical parameters of the Earth / Atmosphere System derived from direct measurements of its emitted and reflected radiation using satellite based sensors from the geo-stationary orbit to continue and enhance the services offered by the Second Generation of the Meteosat System (MSG) and its main instrument SEVIRI.

The meteorological products described in this document will be extracted from the data of the Flexible Combined Imager (FCI) mission. The FCI is able to scan either the full disc in 16 channels every 10 minutes with a spatial sampling distance in the range 1 – 2 km (Full Disc High Spectral Resolution Imagery (FDHSI) in support of the Full Disc Scanning Service (FCI-FDSS)) or a quarter of the earth in 4 channels every 2.5 minutes with doubled resolution (High spatial Resolution Fast Imagery (HRFI) in support of the Rapid Scanning Service (FCI-RSS)).

FDHSI and HRFI scanning can be interleaved on a single satellite (e.g. when only one imaging satellite is operational in orbit) or conducted in parallel when 2 satellites are available in orbit. Table 1 provides an overview over the FCI spectral channels and their respective spatial resolution.

The FCI acquires the spectral channels simultaneously by scanning a detector array per spectral channel in an east/west direction to form a swath. The swaths are collected moving from south to north to form an image per spectral channel covering either the full disc coverage or the local area coverage within the respective repeat cycle duration. Radiance samples are created from the detector elements at specific spatial sample locations and are then rectified to a reference grid, before dissemination to the End Users as Level 1 datasets. Spectral channels may be sampled at more than one spatial sampling distance or radiometric resolution, where the spectral channel has to fulfil FDHSI and HRFI missions or present data over an extended radiometric measurement range for fire detection applications.

Table 1: Channel specification for the Flexible Combined Imager (FCI)

<i>Spectral Channel</i>	<i>Central Wavelength, λ_0</i>	<i>Spectral Width, $\Delta\lambda_0$</i>	<i>Spatial Sampling Distance (SSD)</i>
VIS 0.4	0.444 μm	0.060 μm	1.0 km
VIS 0.5	0.510 μm	0.040 μm	1.0 km
VIS 0.6	0.640 μm	0.050 μm	1.0 km 0.5 km ^{#1}
VIS 0.8	0.865 μm	0.050 μm	1.0 km
VIS 0.9	0.914 μm	0.020 μm	1.0 km
NIR 1.3	1.380 μm	0.030 μm	1.0 km
NIR 1.6	1.610 μm	0.050 μm	1.0 km
NIR 2.2	2.250 μm	0.050 μm	1.0 km 0.5 km ^{#1}
IR 3.8 (TIR)	3.800 μm	0.400 μm	2.0 km 1.0 km ^{#1}
WV 6.3	6.300 μm	1.000 μm	2.0 km
WV 7.3	7.350 μm	0.500 μm	2.0 km
IR 8.7 (TIR)	8.700 μm	0.400 μm	2.0 km
IR 9.7 (O ₃)	9.660 μm	0.300 μm	2.0 km
IR 10.5 (TIR)	10.500 μm	0.700 μm	2.0 km 1.0 km ^{#1}
IR 12.3 (TIR)	12.300 μm	0.500 μm	2.0 km
IR 13.3 (CO ₂)	13.300 μm	0.600 μm	2.0 km

^{#1}: The spectral channels VIS 0.6, NIR 2.2, IR 3.8 and IR 10.5 are delivered in both FDHSI sampling and a HRFI sampling configurations.

2.2 Generated Products

The agreed list of MTG-FCI Level 2 products is detailed in [AD-2] and is repeated here for easy reference:

1. **SCE-CLA:**
Scene Identification (cloudy, cloud free, dust, volcanic ash, fire) and a number of cloud products (cloud top height, phase)
2. **OCA:**
Cloud Product (cloud top pressure and temperature, cloud top phase, cloud top effective particle size, cloud optical depth, cloud sub-pixel fraction)
3. **ASR:**
All Sky Radiance (mean IR radiance on an $n \times n$ pixel grid, together with other statistical information, for different scenes)
4. **CRM:**
Clear Sky Reflectance Map (VIS reflectance for all non-absorbing channels, accumulated over time)
5. **GII:**
Global Instability Indices (a number of atmospheric instability indices and layer precipitable water contents)
6. **TOZ:**
Total Column Ozone (technically retrieved within the GII product)
7. **AER:**
Aerosol Product (asymmetry parameter, total column aerosol optical depth, refractive index, single scattering albedo, size distribution)
8. **AMV:**
Atmospheric Motion Vectors (vector describing the displacement of clouds or water vapour features over three consecutive images, together with a vector height)
9. **OLR:**
Outgoing Longwave Radiation (thermal radiation flux at the top of the atmosphere leaving the earth-atmosphere system)

The products will be derived from the spectral channel information provided by the FDHSI mission, on the resolution detailed in [AD-2].

An important tool for product extraction is a radiative transfer model (RTM), as described in [AD-3]. The IR model choice for the Level 2 product extraction is RTTOV, which is developed and maintained by the Satellite Application Facility on Numerical Weather Prediction (NWP-SAF). An RTM for solar channels is likely to be product specific and is yet to be fully determined.

This ATBD describes the algorithm of the Scenes and Cloud Analysis Product (SCE/CLA) algorithm. The product will be derived over a certain processing area, defined as pixels lying within a great circle arc of pre-defined size around the subsatellite point (typically 70°). The algorithm presented here is very close to the one developed and maintained by the Satellite Application Facility in Support to Nowcasting and Very Short Range Forecasting (NWC-SAF) and is documented in [RD-1] for the NWC-SAF modules PGE01, PGE02 and PGE03.

3 NWC-SAF PRODUCTS CMA, CT AND CTTH OVERVIEW

3.1 Physical Basis Overview

The basic cloud processing generates three main products:

- cloud mask (CMA, in module PGE01)
- cloud type (CT, in module PGE02)
- cloud top temperature and height (CTTH, in module PGE03)

The cloud mask (CMA) allows identifying cloud free areas where other products (e.g. total or layer precipitable water, land or sea surface temperatures, snow/ice cover delineation) may be computed. It also allows identifying cloudy areas where other products (cloud types and cloud top temperature/height) may be derived. The central aim of the CMA is therefore to delineate all cloud-free pixels in a satellite scene with a high confidence. In addition, the product provides information on the presence of snow/sea ice, dust clouds and volcanic plumes. Brightness temperatures and reflectances of a cloud free area depend on its type, on the atmospheric conditions, on the sun and satellite respective positions. They are more or less modified by clouds, aerosols or snow/sea ice. Indeed, cloudy pixels can be often identified, because they appear colder (at 10.5 μm) and/or brighter (at 0.6 or 0.8 μm) than cloud free areas. A fine analysis of their respective spectral behaviour is nevertheless needed to perform a full cloud detection. For example, low clouds identification at night-time relies on their low emissivities at 3.8 μm , whereas thin cirrus clouds can be identified, due to their different emissivities at 10.5 μm and 12 μm . Cloud free areas covered by snow or ice are identified at daytime with their very low reflectivity at 3.7 μm and high reflectivity at 0.6 μm , whereas oceanic cloud free areas affected by sun glint are identified with their very high reflectivity at 3.8 μm . The CMA identifies pixels that are contaminated by either clouds, dust or snow/sea ice. The problem to be solved is to automatically predict, with sufficient accuracy, brightness temperatures and reflectance of cloud free areas, so that any discrepancy between the measured and predicted values can be used to detect contaminated pixels.

The main objective of the cloud type (CT) product is to provide a detailed cloud analysis. The CT product is essential for the generation of the cloud top temperature and height product and may be useful for the generation of other products. The CT product contains information on major cloud classes: fractional clouds, semi-transparent clouds, separation of high/medium/low clouds, cloud phase. Brightness temperatures and reflectance of clouds very much depend on their characteristics: - height (low, medium or high level clouds); - amount (semi-transparent or opaque; sub-pixel or filling the pixel) and texture; - phase (water or ice clouds). They are also affected by the atmospheric conditions and by the sun and satellite respective positions. The pixels contaminated by clouds are supposed to have been identified by the CMA product. The problem to be solved is then, to determine the adequate combinations of channels that will allow the separation of clouds presenting different characteristics, and how these combinations of channels will be affected by atmospheric conditions and sun/satellite geometry.

The cloud top temperature and height (CTTH) product provides an important contribution to the following areas:

- analysis and early warning of thunderstorm development
- cloud top height assignment for aviation forecast activities
- input to mesoscale models
- input to other product generation elements such as AMV

The CTTH product contains information on the cloud top temperature and height for all pixels identified as cloudy in the satellite scene. Temperatures of the top of opaque clouds may be deduced from the IR brightness temperatures measured in window channels, by accounting for the atmosphere effect above the cloud. Their height can then be retrieved from temperature profiles forecast by NWP. This does not apply to semi-transparent clouds or sub-pixel (fractional) clouds for two reasons:

1. the IR brightness temperatures in window channels are contaminated by the underlying surface.
2. at least two parameters (the effective cloudiness (cloudiness x emissivity) and the top temperature) contribute to the measured brightness temperatures, and must be retrieved simultaneously.

A multi-spectral approach with relevant assumptions (such as cloud emissivities' dependence on wavelength) is therefore needed.

3.2 Assumptions and Limitations

3.2.1 Cloud Mask (CMa)

The following problems may be encountered:

- Low clouds may be not detected in case low solar elevation, over both sea and land.
- It may happen that large areas of low clouds are not detected in night-time conditions over land. This can be the case in “warm sectors”, but also in areas viewed with high satellite zenith angles or if the low clouds are surmounted by very thin cirrus.
- Snow covered grounds are not detected at night-time and are therefore confused either with low clouds or cloud free surface.
- Over land, dust cloud detection is performed only at daytime. Over land, dust clouds are not well detected when the sun is low or if they are too thin. Over sea, some dust areas may not be detected (especially the thinnest parts). Moreover, some wrong detection may be observed in oceanic regions, especially at night-time near Namibie coast and occasionally over the South Atlantic (at latitude larger than 50 degrees).

The CMa product may be used to identify cloud-free surfaces for oceanic or continental surface parameters retrieval. Nevertheless, as some clouds remains undetected and to account for artefacts such as shadows or aerosols, the user should apply a post-processing which could include:

- the spreading of the cloud mask that should allow to detect cloud edges and mask shadows or moist areas near cloud edges

- the use of the cloud mask quality flag not to compute surface parameters in bad quality cloud free areas
- the implementation of an additional filtering based on the temporal variation around the current slot

3.2.2 Cloud Type (CT)

The following problems may be encountered (for wrong cloud detection, please refer to section 3.2.1):

- Very thin cirrus are often classified as fractional clouds.
- Very low clouds may be classified as medium clouds in case strong thermal inversion.
- Low clouds surmounted by thin cirrus may be classified as medium clouds.

3.2.3 Cloud Top Temperature and Height (CTTH)

The following problems may be encountered:

- CTTH will be wrong if the cloud is wrongly classified:
 - Underestimation of cloud top height/pressure for semi-transparent clouds classified as low/medium
 - Over estimation of cloud top height/pressure for low/medium clouds classified as semi-transparent
- No CTTH is available for clouds classified as fractional.
- CTTH may be not computed for thin cirrus clouds.
- Retrieved low cloud top height may be overestimated.

3.3 Algorithm Basis Overview

3.3.1 Cloud Mask (CMa)

The cloud mask (CMa), developed within the NWC-SAF context, allows identifying cloudy and cloud free areas where other products (either also related to clouds or to cloud free areas) may be computed. The cloud mask information is thus important for almost all other meteorological products.

The central aim of the CMa is therefore to delineate all cloud-free pixels in a satellite scene with a high confidence. In addition, the product provides information on the presence of snow/sea ice, dust clouds and volcanic ash plumes. The algorithm is based on multispectral threshold technique applied to each pixel of the image. A first process allows the identification of pixels contaminated by clouds or snow/ice. It consists in a series of threshold tests applied to various channels combination for each pixel of the current image. This is complemented by an analysis of the temporal variation (between individual image repeat cycles) of some spectral combination of channels (to detect rapidly moving clouds) and a specific treatment combining temporal coherency analysis and region growing technique (to improve the detection of low clouds). This first set of tests has the following characteristics:

- The tests, applied to land or sea pixels, depend on the solar illumination and on the viewing angles (daytime, night-time, twilight, sun glint).
- Most thresholds are determined from satellite-dependent look-up tables using as input the viewing geometry (sun and satellite viewing angles), NWP forecast fields (surface temperature and total atmospheric water vapour content) and ancillary data (elevation and climatological data). Some thresholds are empirical, constant or satellite-dependent values.
- The quality of the cloud detection process is assessed by comparing the actual measurement to the threshold values.

This first process allows to determine the cloud cover category of each pixel (cloud-free, cloud contaminated, cloud filled, snow/ice contaminated or undefined/non processed) and compute a quality flag on the processing itself. Moreover, the tests used for the cloud detection are stored.

A second process, allowing the identification of dust clouds and volcanic ash clouds, is applied to all pixels (even already classified as cloud-free or contaminated by clouds). The result is stored in the dust cloud and volcanic ash cloud flags. Also here, certain threshold tests on individual channels and channel combinations are used.

3.3.2 Cloud Type (CT)

The cloud type (CT), developed within the SAF NWC context, provides some more detailed cloud information: fractional clouds, semitransparent clouds, classification into high, medium and low clouds for all the pixels identified as cloudy in a scene.

The CT product is essential for the generation of the cloud top temperature and height product.

The CT algorithm is a threshold algorithm applied at the pixel scale, based on the use of the Cloud Mask (PGE01) together with spectral and textural features computed from the multispectral satellite images and compared with a set of thresholds.

The set of thresholds to be applied depends mainly on the illumination conditions, whereas the values of the thresholds themselves may depend on the illumination, the viewing geometry, the geographical location and NWP data the vertical structure of the atmosphere.

The CT classification algorithm is based on the following approach:

- Main cloud types are separable within two sets: the fractional and high semitransparent clouds, from the low/medium/high clouds. These two systems are distinguished using certain spectral differences
- Within the first set, the fractional and high semitransparent are separated by further spectral differences and visible reflectance values
- The remaining categories are distinguished through the comparison of infrared brightness temperatures of a number of channels to simulated brightness temperatures derived from NWP forecast fields.

3.3.3 Cloud Top Temperature and Height (CTTH)

The CTTH product contains information on the cloud top temperature and height (expressed as both geometric height and pressure) for all pixels identified as cloudy in the satellite scene.

Depending on the results of the Cloud Type (CT) product, a certain height assignment strategy is adopted. Main input to the height assignment are results of radiative transfer calculations, using the NWP vertical profiles on their native grid as input. Different height assignment schemes are adopted depending on whether the cloud is opaque, semi-transparent or fractional.

3.4 Algorithm Input

3.4.1 Primary Sensor Data

For a given nominal image time, all three cloud processing modules need as input the MTG-FCI image data for all channels in their native resolution, as brightness temperatures and radiances for the infrared channels and as reflectances for the solar channels. (Note: although the 2010 NWC-SAF software does not account for the presence of the MTG-FCI channels VIS0.4, VIS0.5, VIS0.9, NIR1.3 and NIR2.2, it can be anticipated that these may be used somewhere within the cloud processing).

In addition, the image data (as specified above) and the CMA and CT product of the previous repeat cycles must be available (covering at least the previous hour): This helps in the initial cloud identification (rapid change of the conditions of a single pixel) and in twilight conditions.

3.4.2 Ancillary Dynamic Data

Ancillary dynamic datasets are needed, i.e. IR radiative transfer processing results [AD-3] to generate the dynamic thresholds for the processing and the corresponding NWP forecast fields. In addition, the three modules build upon each other: The CT processing needs the output of CMA, and the CTTH processing needs both the CMA and CT output.

3.4.3 Ancillary Static Data

The following ancillary static datasets are needed:

- land/sea mask
- surface type
- surface elevation
- distance to coastline
- surface emissivity information
- climatological data

All these files are available in the NWC-SAF software package.

3.5 Detailed Description

3.5.1 Cloud Mask (CMA) Algorithm Description

3.5.1.1 Algorithm Outline

The algorithm is based on multispectral threshold technique applied to each pixel of the image. A first process allows the identification of cloudy pixels. It consists in a first set of multispectral threshold tests (summed up below) which is complemented by an analysis of the temporal variation (on a short period of time: 10 minutes) of some spectral combination of channels (to detect rapidly moving clouds), a specific treatment combining temporal coherency analysis and region growing technique (to improve the detection of low clouds) and a temporal analysis of the higher resolution solar channels channel (to detect sub-pixel clouds).

The first series of tests allows the identification of pixels contaminated by clouds or snow/ice; this process is stopped if one test is really successful (i.e., if the threshold is not too close to the measured value). The characteristics of this set of tests are summed up below:

- The tests, applied to land or sea pixels, depend on the solar illumination and on the viewing angles (daytime, night-time, twilight, sunlint, as defined in *Table 2*) and are presented in *Table 3* and *Table 4*.
- Most thresholds are determined from satellite-dependent look-up tables (available in coefficients' files) using as input the viewing geometry (sun and satellite viewing angles), NWP forecast fields (surface temperature and total atmospheric water vapour content) and ancillary data (elevation and climatological data). The thresholds are computed at a spatial resolution (called "segment size") defined by the user as a number of infra-red pixels. Some thresholds are empirical constant or satellite-dependent values (available in coefficients' files).
- The quality of the cloud detection process is assessed.
- A spatial filtering is applied, allowing to reclassify pixels having a class type different from their neighbours and to reduce known defaults as cloud false alarms in coastal area and in edges of snowy areas.
- A test is applied to cloud contaminated pixels to check whether the cloud cover is opaque and completely fills the FOV.

This first series of tests allows to determine the cloud cover category of each pixel (cloud-free, cloud contaminated, cloud filled, snow/ice contaminated or undefined/non processed) and compute a quality flag on the processing itself. Moreover, the tests that have allowed the cloud detection (more than one test are possible, if some tests were not really successful) are stored.

A second process, allowing the identification of dust clouds, is applied to all pixels (even already classified as cloud-free or contaminated by clouds). The result is stored in the dust cloud flags.

Table 2: Definition of night-time, twilight, daytime and sunglint

Night-time	Twilight	Daytime	Sunglint
Solar elevation < -3	-3<Solar elevation<10	10 < Solar elevation	Cox-Munk > 10% Solar elevation > 15

Table 3: Test sequence over land

Daytime	Twilight	Night-time
Snow detection	Snow detection	-
T10.5 μ m	T10.5 μ m	T10.5 μ m
R0.6 μ m	R0.6 μ m	-
T10.5 μ m-T12.3 μ m	T10.5 μ m-T12.3 μ m	T10.5 μ m-T12.3 μ m
T8.7 μ m-T10.5 μ m	T8.7 μ m-T10.5 μ m	T8.7 μ m-T10.5 μ m
-	T10.5 μ m-T8.7 μ m	T10.5 μ m-T8.7 μ m
T10.5 μ m-T3.8 μ m	T10.5 μ m-T3.8 μ m	T10.5 μ m-T3.8 μ m
T3.8 μ m-T10.5 μ m	T3.8 μ m-T10.5 μ m	T3.8 μ m-T10.5 μ m
Local Spatial Texture	Local Spatial Texture	Local Spatial Texture
-	T8.7 μ m-T3.8 μ m	T8.7 μ m-T3.8 μ m

Table 4: Test sequence over sea

Daytime	Sunglint	Twilight	Night-time
Ice detection	Ice detection	Ice detection	-
SST	SST	SST	SST
T10.5 μ m	T10.5 μ m	T10.5 μ m	T10.5 μ m
R0.8 μ m (R0.6 μ m)	R0.8 μ m (R0.6 μ m)	R0.8 μ m (R0.6 μ m)	-
R1.6 μ m	-	R1.6 μ m	-
T10.5 μ m-T12.3 μ m	T10.5 μ m-T12.3 μ m	T10.5 μ m-T12.3 μ m	T10.5 μ m-T12.3 μ m
T8.7 μ m-T10.5 μ m	T8.7 μ m-T10.5 μ m	T8.7 μ m-T10.5 μ m	T8.7 μ m-T10.5 μ m
T10.5 μ m-T3.8 μ m	T10.5 μ m-T3.8 μ m	T10.5 μ m-T3.8 μ m	T10.5 μ m-T3.8 μ m
-	-	T12.3 μ m-T3.8 μ m	T12.3 μ m-T3.8 μ m
T3.8 μ m-T10.5 μ m	-	T3.8 μ m-T10.5 μ m	T3.8 μ m-T10.5 μ m
Local Spatial Texture	Local Spatial Texture	Local Spatial Texture	Local Spatial Texture
-	Low Clouds in Sunglint	-	-

[T3.8 μ m, T8.7 μ m, T10.5 μ m and T12.3 μ m stand for brightness temperatures at 3.8, 8.7, 10.5 and 12.3 micrometer ; R0.6 μ m, R0.8 μ m and R1.6 μ m stand for VIS/NIR bi-directional top of atmosphere reflectances at 0.6, 0.8 and 1.6 micrometer normalised for solar illumination ; SST is the split-window (used for SST calculation) computed from T10.5 μ m and T12.3 μ m measurements. Low Clouds in Sunglint is a specific module for low clouds identification in sunglint areas.]

It should be noted that there will be two different methods to generate the thresholds for most of the following tests. Therefore the algorithm must provide the flexibility to change between these two methods.

3.5.1.2 Test on SST

Over sea, a pixel is classified as cloud contaminated if :

- $SST(T_{10.5\mu m}, T_{12.3\mu m}) < SST_{threshold}$ and
- $sst_{clim} > SST_{clim_threshold}$

where (for MSG1/SEVIRI)

$$SST(T_{10.5\mu m}, T_{12.3\mu m}) = a_0 + a_1 * (T_{10.5} - 273.15) + (a_2 * (sst_{clim} - 273.15) + a_3 * (\sec \zeta_{sat} - 1)) * (T_{10.5} - T_{12.3})$$

$\sec \zeta_{sat}$ is the secant of the satellite zenith angle ζ_{sat} ,

sst_{clim} is the climatological SST (in K)

a_0 , a_1 , a_3 are setup parameters.

This test allows to detect most of the clouds over the ocean for any solar illumination. This test is not applied if the climatological SST is too low, which indicates that the ocean could be frozen. A split window algorithm, using $T_{10.5\mu m}$ and $T_{12.3\mu m}$ brightness temperatures to compute Sea Surface Temperature, is applied to all pixels over the ocean. A pixel is then classified as cloudy if its split window value is lower than the estimated Sea Surface Temperature. The threshold is computed from a monthly climatological minimum SST by subtracting an offset (linear function of the secant of the satellite zenith, an additional value being added in coastal areas). This offset is needed to account for the imperfections of the climatology, especially in areas with persistent cloudiness, and in areas where the oceanic SST varies rapidly in space and time. If $T_{12.3\mu m}$ is missing, the test is replaced by $T_{10.5\mu m} < sst_{clim} - b$, where b is a setup parameter.

3.5.1.3 Test on $T_{10.5\mu m}$

A pixel is classified as cloud contaminated if :

- $T_{10.5\mu m} < T_{10.5threshold}$.

The test is applied over land and sea and at all illumination conditions.

Two alternatives exist to calculate the $T_{10.5threshold}$.

Alternative 1:

The thresholds are derived by using forecast data, converted into clear sky brightness temperatures with the help of a radiative transfer model (RTTOV). The clear sky brightness temperatures given on the forecast grid are interpolated to the pixel location (depending on land/sea location) and interpolated in time from the forecast times to the scan time of the

image. With this, the predicted clear sky brightness temperature (T10.5cs) for each pixel is derived.

A correction term (a_2) is subtracted to correct for inhomogeneous areas, in particular:

- Coastal regions and other land/sea mixture situations
- High elevation / mountains
- Cold surfaces (snow/ ice covered)

The final threshold

$$T10.5_{\text{threshold}} = a_0 * T10.5_{\text{cs}} - a_1 - a_2$$

where T10.5cs is the clear sky brightness temperature of channel 10.5 μm derived and interpolated from the RTTOV output. The a_i are setup parameters.

Alternative 2:

The T10.5 μm threshold is computed from surface temperatures forecast by NWP model, by accounting for atmospheric absorption and small scale height effects (over land only) as described below [the different physical meaning of brightness temperature and NWP surface temperature (dependent on the NWP model) is not accounted for] :

- The surface temperature for a given slot is then interpolated from the two nearest NWP fields (spatially interpolated at the segment's spatial resolution) according to rules related to the relative position of the scene and the two NWP terms in a diurnal cycle assumed to be driven by sun rise and sun set local times.
- The atmospheric absorption is accounted for through an offset computed as a function of satellite zenith angle, integrated atmospheric water vapour content and solar zenith angle. Two tables (for night-time and daytime conditions) have been pre-computed by applying RTTOV to radio-soundings from a data set provided by ECMWF (F.Chevalier, 1999). The satellite zenith angle and the water vapour content are used to interpolate in these tables, whereas the solar zenith angle is used to interpolate between the night-time and the daytime values.
- A dry adiabatic law is used to account for the height difference between the elevation of the NWP grid and of the pixel; this simple process, only applied over land, allows to roughly simulate small scale height effects in mountainous regions.

An offset (a_{Africa}) is added in night-time conditions over Africa to limit the confusion of cloud free areas with clouds.

A pixel is diagnosed favourable to extreme cooling over land in night-time and twilight conditions when:

- altitude < T10.5altitude and (FSKT < T10.5skin1 or FSKT < T10.5skin2 and SNOC > T10.5snoc)

where FSKT is the forecasted skin temperature and SNOC is the snow occurrence in any pixel of the segment box surrounding the considered pixel (counted during any of the four

previous or the current day for any daytime duration). A box size of 16 pixels has been used when prototyping. When these conditions are met T10.5threshold is modified as follows:

- If $T10.5threshold \geq T10.5limit$
- $T10.5threshold = T10.5threshold - b_0$
- If $T10.5threshold < T10.5limit$
- $T10.5threshold = T10.5threshold - b_0 - b_1 * (T10.5limit - T10.5threshold)$

The b_i are setup parameters.

The algorithm must provide the flexibility to change between these two threshold alternatives.

3.5.1.4 Test on T10.5 μ m-T12.3 μ m

A pixel is classified as cloud contaminated if :

- $T10.5\mu m - T12.3\mu m > T10.5T12.3threshold$ and
- (over land only) $T10.5\mu m < T10.5T12.3limit$

This test, which can be applied over all surfaces in any solar illumination, allows the detection of thin cirrus clouds and cloud edges characterised by a higher T10.5 μ m-T12.3 μ m than cloud-free surfaces.

The difficulty is to estimate the cloud free surfaces T10.5 μ m-T12.3 μ m difference which depends on the difference of atmospheric absorption (mainly due to water vapour) and surface emissivity in the two infrared wavelengths. This test will be useless if the estimated clear-sky T10.5 μ m-T12.3 μ m difference is too high, which may be the case at daytime. The rough check applied over land to T10.5 μ m allows to minimize the confusion of very warm moist areas with clouds.

The test is applied over land and sea and at all illumination conditions.

Two alternatives exist to calculate the threshold.

Alternative 1:

T10.5T12.3threshold is calculated as follows:

$$T10.5T12.3threshold = a_0 + a_1 * T10.5cs - a_2 * T12.3cs$$

where T10.5cs, T12.3cs are the clear sky brightness temperatures of channels 10.5 μ m and 12.3 μ m derived and interpolated from the RTTOV output. The a_i are setup parameters.

Alternative 2:

Over sea, two look-up tables (for cold and warm seas) have been elaborated by applying RTTOV to radio-soundings from an ECMWF dataset, using Masuda emissivities [RD-1].

The threshold is interpolated into these two tables using satellite zenith angle and water vapour content, and between these tables using the climatological SST.

Over land, two look-up tables (for night-time and daytime conditions) have been calculated by applying RTTOV to radio-soundings from an ECMWF dataset, using a constant emissivity in both channels [RD-1]. The threshold is interpolated into these two tables using satellite zenith angle and water vapour content, and between these two tables using the solar zenith angle. An offset of has been added over Africa to limit the confusion of very moist cloud free areas with clouds.

The algorithm must provide the flexibility to change between these two threshold alternatives.

3.5.1.5 Test on T8.7 μ m-T10.5 μ m

A pixel is classified as cloud contaminated if :

- T8.7 μ m -T10.5 μ m > T8.7T10.5threshold.

This test aims to detect thin cirrus clouds over all surfaces in any solar illumination. It is based on the fact that high semi-transparent clouds are characterised by relatively high T8.7 μ m-T10.5 μ m difference as compared to surface values. The difficulty is to estimate the cloud free surfaces T8.7 μ m-T10.5 μ m difference which depends on the difference of atmospheric absorption (mainly due to water vapour) and surface emissivity in the two infrared wavelengths.

The test is applied over land and sea and at all illumination conditions.

Two alternatives exist to calculate the threshold.

Alternative 1:

The T8.7T10.5threshold is calculated as follows:

$$T8.7T10.5threshold = a_0 + a_1 * T8.7cs - a_2 * T10.5cs$$

where T10.5cs, T8.7cs are the clear sky brightness temperatures of channels 10.5 μ m and 8.7 μ m derived and interpolated from the RTTOV output. The a_i are setup parameters.

Alternative 2:

Over sea, one look-up table has been elaborated by applying RTTOV to radio-soundings from an ECMWF dataset. The threshold is interpolated into this table using satellite zenith angle and water vapour content.

Over land, two look-up tables (in daytime and night-time conditions) have been established by applying RTTOV to radio-soundings from an ECMWF dataset. Only one set of emissivities (Salisbury et al., 1992) has been used, corresponding to vegetated areas (0.98 in

both channel). The threshold is interpolated into these two tables using satellite zenith angle and water vapour content, and between these two tables using the solar zenith angle.

A pixel is diagnosed favourable to extreme cooling over land in night-time and twilight conditions when:

- altitude < alt_limit and (FSKT < fskt1 or FSKT < fskt2 and SNOC > snoc5)

where FSKT is the forecasted skin temperature and SNOC is the snow occurrence in any pixel of the segment box surrounding the considered pixel (counted during any of the four previous or the current day for any daytime duration). A box size of 16 pixels has been used when prototyping.

When these conditions are met T8.7T10.5threshold is modified as follows:

- if T105threshold < T105limit, T8.7T10.5threshold = T8.7T10.5threshold + T87T105_offset

The algorithm must provide the flexibility to change between these two threshold alternatives.

3.5.1.6 Test on T3.8 μ m-T10.5 μ m

3.5.1.6.1 Test on T3.8 μ m-T10.5 μ m in Night-Time Conditions

A pixel is classified as cloud contaminated if :

- T3.8 μ m - T10.5 μ m > T3.8T10.5threshold_night and
- T10.5 μ m > T10.5_night_limit

This test allows the detection of high semi-transparent clouds only in night-time conditions. It is based on the fact that the contribution of the relatively warm grounds to the brightness temperature is higher at 3.8 μ m than at 10.5 μ m, due to a lower ice cloud transmittance (Hunt, 1973), and to the high non-linearity of the Planck function at 3.8 μ m. This test is usable only at night-time, when solar irradiance does not act upon the 3.8 μ m channel radiance. The cloud free surfaces T10.5 μ m-T3.8 μ m difference (depending on the difference of atmospheric absorption (mainly due to water vapour) and surface emissivity in the two infrared wavelengths) has to be accurately estimated to allow this test to detect most semi-transparent clouds. An additional difficulty is the high radiometric noise (enhanced for low temperatures) that affects the 3.8 μ m channel: this is the reason why the use of this test is limited to pixels warmer than 240K. The non linearity effect makes this test much more efficient than the T10.5 μ m-T12.3 μ m test to detect high semi-transparent clouds over rather warm grounds at night-time.

Two alternatives exist to calculate the threshold.

Alternative 1:

The T3.8T10.5threshold_night is calculated as follows:

$$T3.8T10.5threshold = a_0 + a_1 * T3.8cs - a_2 * T10.5cs$$

where T10.5cs, T3.8cs are the clear sky brightness temperatures of channels 10.5 μm and 3.8 μm derived and interpolated from the RTTOV output. The a_i are setup parameters

Alternative 2:

Two look-up tables (for cold and warm seas) and four look-up tables (for cold and warm vegetated or arid surfaces) have been elaborated by applying RTTOV to radio-soundings from an ECMWF dataset, using Masuda emissivities for oceanic conditions and using a constant emissivity in both channels [RD-1] for vegetation (an offset of is added to simulate arid conditions). The threshold is interpolated into these tables using satellite zenith angle and water vapour content, together with the climatological SST (sea) or forecast surface temperature and climatological visible reflectance (land).

A pixel is diagnosed favourable to extreme cooling over land in night-time condition when:

- altitude < alt_limit and (FSKT < fskt1 or FSKT < fskt2 and SNOC > snoc5)

where FSKT is the forecasted skin temperature and SNOC is the snow occurrence in any pixel of the segment box surrounding the considered pixel (counted during any of the four previous or the current day for any daytime duration). A box size of 16 pixels has been used when prototyping.

When these conditions are met T3.8T10.5threshold_night is modified as follows:

- If T105_night_limit1 <= T105threshold <= T105_night_limit2:
T38T10.5threshold = MAX(T38T10.5threshold, a_1 T105threshold + a_0)
- If T105threshold < T105_night_limit1:
T38T10.5threshold = b_1 T105threshold + b_0

where FSKT is the forecasted skin temperature, SNOC is the snow occurrence in any pixel of the segment box surrounding the considered pixel (counted during any of the four previous or the current day), T105threshold is the primary threshold on T10.5 as computed for the considered vegetated surface, and a_i , b_i are setup parameters.

The algorithm must provide the flexibility to change between these two threshold alternatives.

3.5.1.6.2 Test on T3.8 μm -T10.5 μm in Daytime or Twilight Conditions

The following test is applied in daytime or twilight conditions (except in sunglint areas):

A pixel is classified as cloud contaminated if :

- T3.8 μm - T10.5 μm > T3.8T10.5threshold_day and
- T10.5 μm > T105_day_limit and
- (over Africa only) T8.7 μm - T10.5 μm > ($a_0 - a_1 * (1./\cos(\zeta_{\text{sat}})-1)$) (in K)

where ζ_{sat} is the satellite zenith angle.

This test allows the detection of low clouds at day-time (except sunglint areas over the ocean) and twilight conditions.

It is based on the fact that solar reflection at $3.8\mu\text{m}$ may be high for clouds (especially low clouds), which is not the case for cloud free areas (except sunglint). The rough check applied to $T_{8.7\mu\text{m}}-T_{10.5\mu\text{m}}$ allows to minimize the confusion of sandy arid areas with low clouds.

Two alternatives exist to calculate the threshold.

Alternative 1:

The $T_{3.8T10.5}\text{threshold_day}$ is calculated as follows:

$$T_{3.8T10.5}\text{threshold_day} = a_0 + a_1 * T_{3.8\text{cs}} - a_2 * T_{10.5\text{cs}}$$

where $T_{10.5\text{cs}}$, $T_{3.8\text{cs}}$ are the clear sky brightness temperatures of channels $10.5\mu\text{m}$ and $3.8\mu\text{m}$ derived and interpolated from the RTTOV output. The a_i are setup parameters.

Alternative 2:

The threshold $T_{3.8T10.5}\text{threshold_day}$ is computed from $T_{3.8T10.5}\text{threshold_night}$ (see section 3.5.1.6.1) by adding the solar contribution:

Over ocean:

$$T_{3.8T10.5}\text{threshold_day} = T_{3.8T10.5}\text{threshold_night} + a_1 * \text{cox_munk} * \cos(\zeta_{\text{sun}}) + a_0$$

Over land:

$$T_{3.8T10.5}\text{threshold_day (in K)} = T_{3.8T10.5}\text{threshold_night} + b_1 * \text{Clim_alb} * \cos(\zeta_{\text{sun}}) + b_0 + \text{corrective_factor}$$

ζ_{sun} is the solar zenith angle.

$T_{3.8T10.5}\text{threshold_night}$ is computed as explained in section 3.5.1.6.1, Cox_munk is the maximum ocean surface reflectance computed using Cox-Munk theory [RD-1], Clim_alb is the continental climatological visible reflectance, corrective_factor , added to account for contribution of the solar illumination in backward and forward scattering direction, is defined as:

$$\text{Corrective_factor} = c_1 * \cos(\zeta_{\text{sun}}) * (\cos(\text{scattering angle}) - c_0)^2$$

ζ_{sun} is the solar zenith angle and scattering_angle is the scattering angle ($[0, \pi]$ from backward to forward direction). a_i , b_i , c_i are setup parameters.

The algorithm must provide the flexibility to change between these two threshold alternatives.

3.5.1.7 Test on T10.5 μ m-T3.8 μ m

A pixel is classified as cloud contaminated if:

- T10.5 μ m - T3.8 μ m > T10.5T3.8threshold and
- T10.5 μ m > T105_limit and
- (over land only) T8.7 μ m - T10.5 μ m > (a0 - a1 *(1./cos(ζ_{sat})-1)) (in K)

where ζ_{sat} is the satellite zenith angle.

This test allows the detection of low water clouds at night-time, but also low clouds shadowed by higher clouds. It is based on the fact that the water cloud emissivity is lower at 3.8 μ m than at 10.5 μ m [RD-1], which is not the case for cloud free surfaces (except sandy desert areas). A basic assumption is that the 3.8 μ m channel is not affected by the solar irradiance, which is the case at night-time and in shadows. The cloud free surfaces T10.5 μ m-T3.8 μ m difference (depending on the difference of atmospheric absorption (mainly due to water vapour) and surface emissivity in the two infrared wavelengths) has to be accurately estimated to allow this test to detect most low water clouds. An additional difficulty is the high radiometric noise (enhanced for low temperatures) that affects the 3.8 μ m channel: this is the reason why the use of this test is limited to pixels warmer than 240K. The rough check applied to T8.7 μ m-T10.5 μ m allows to minimize the confusion of sandy arid areas with low clouds.

The test is applied over land and sea.

Two alternatives exist to calculate the threshold.

Alternative 1:

The T10.5T3.8threshold is calculated as follows:

$$\text{T10.5T3.8threshold} = a_0 + a_1 * \text{T10.5cs} - a_2 * \text{T3.8cs}$$

where T10.5cs, T3.8cs are the clear sky brightness temperatures of channels 10.5 μ m and 3.8 μ m derived and interpolated from the RTTOV output. The a_i are setup parameters.

Alternative 2:

Over sea, one look-up table has been elaborated by applying RTTOV to radio-soundings from an ECMWF dataset, using Masuda emissivities [RD-1]. The satellite zenith angle and the water vapour content are used to interpolate in this table.

Over land, two look-up tables (for vegetated and arid surfaces) have been established by applying RTTOV to radio-soundings from an ECMWF dataset. A set of emissivities [RD-1] corresponding to vegetated areas (0.98 in both channels) has been used, the table corresponding to arid areas being obtained from the one for vegetated areas by adding an

offset. The threshold is interpolated into these two tables using satellite zenith angle and water vapour content, and between these two tables using the climatological visible reflectance.

To increase the T10.5 μ m-T3.8 μ m test efficiency over Europe, two correction factors, empirically developed from measurements to better account for satellite zenith angle effect and CO₂ absorption, are added to the threshold computed from RTTOV simulations only over European regions (defined by their latitude between 36 and 90 degrees north, and their longitude between 30 degrees west and 60 degrees east):

The correction factor to account for satellite zenith angle effect is a function of satellite secant $1/\cos(\zeta_{\text{sat}})$ [RD-1]. The correction factor to better account for CO₂ absorption is a function of (T10.5 μ m-T13.4 μ m) brightness temperatures difference [RD-1].

Finally, an offset has been added to the threshold over Africa to decrease the confusion of arid areas with low clouds. It should be noted that all latitude/longitude boundaries and all correction factors need to be defined for MTG-FCI.

The algorithm must provide the flexibility to change between these two threshold alternatives.

3.5.1.8 Test on T12.3 μ m-T3.8 μ m over Ocean

A pixel is classified as cloud contaminated if :

- T12.3 μ m - T3.8 μ m > T12.3T3.8threshold and
- T10.5 μ m > T105_limit

This test intends to detect low water clouds over the ocean in night-time conditions. This test is very similar to the one applied to the T10.5 μ m - T3.8 μ m (see section 3.5.1.7), but is usually more efficient over ocean due to a higher contrast between cloud free and low clouds T10.5 μ m-T3.8 μ m values.

The test is applied over sea and at night-time only.

Two alternatives exist to calculate the threshold.

Alternative 1:

The T12.3T3.8threshold is calculated as follows:

$$\text{T12.3T3.8threshold} = a_0 + a_1 * \text{T12.3cs} - a_2 * \text{T3.8cs}$$

where T12.3cs, T3.8cs are the clear sky brightness temperatures of channels 12.3 μ m and 3.8 μ m derived and interpolated from the RTTOV output. The a_i are setup parameters.

Alternative 2:

Over sea, a look-up table has been elaborated by applying RTTOV to radio-soundings from an ECMWF dataset, using Masuda emissivities [RD-1]. The satellite zenith angle and the water vapour content are used to interpolate in this table.

The algorithm must provide the flexibility to change between these two threshold alternatives.

3.5.1.9 Test on T8.7 μ m-T3.8 μ m over Desert

A pixel is classified as cloud contaminated if :

- T8.7 μ m - T3.8 μ m > T8.7T3.8threshold and
- T10.5 μ m - T3.8 μ m > T10.5T3.8veget_threshold and
- T10.5 μ m > T105_limit

where T10.5T3.8veget_threshold is computed assuming vegetated surface

This test allows the detection over the desert of low water clouds at night-time. It is only applied over Africa.

Low clouds are usually detected at night-time thanks to their T10.5 μ m-T3.8 μ m brightness temperatures differences as explained in section 3.5.1.7. This is practically never the case over desert because there is no contrast in this feature between low clouds and desert.

The T8.7 μ m-T3.8 μ m test is based on the fact that desert areas have low emissivities at 3.8 μ m and 8.7 μ m, whereas low water clouds have low emissivities at 3.8 μ m, but not at 8.7 μ m. A consequence is that low clouds are characterized by higher T8.7 μ m-T3.8 μ m differences as compared to values over desert. This test is limited to pixels warmer than 240K to insure that the 3.8 μ m channel is not too much affected by radiometric noise (enhanced for low temperatures) and to pixels having not too low T10.5 μ m-T3.8 μ m brightness temperature differences to limit confusion of savannah with low clouds.

Two alternatives exist to calculate the threshold.

Alternative 1:

The T8.7T3.8threshold is calculated as follows:

$$T8.7T3.8threshold = a_0 + a_1 * T8.7cs - a_2 * T3.8cs$$

where T8.7cs, T3.8cs are the clear sky brightness temperatures of channels 8.7 μ m and 3.8 μ m derived and interpolated from the RTTOV output. The a_i are setup parameters.

The T10.5T3.8veget_threshold is calculated as follows:

$$T10.5T3.8veget_threshold = b_0 + b_1 * T10.5cs - b_2 * T3.8cs$$

where $T_{10.5cs}$, $T_{3.8cs}$ are the clear sky brightness temperatures of channels $10.5 \mu\text{m}$ and $3.8 \mu\text{m}$ derived and interpolated from the RTTOV output. The b_i are setup parameters.

Alternative 2:

A look-up table has been established by applying RTTOV to radio-soundings from an ECMWF dataset. A set of emissivities (0.98 in both channels) has been used. The threshold is interpolated into this tables using satellite zenith angle and water vapour content as derived from the NWP-data.

The algorithm must provide the flexibility to change between these two threshold alternatives.

3.5.1.10 Test on $T_{10.5\mu\text{m}}$ - $T_{8.7\mu\text{m}}$ over Land

A pixel is classified as cloud contaminated if :

- $T_{10.5\mu\text{m}} - T_{8.7\mu\text{m}} > T_{10.5T_{8.7}}\text{threshold}$ and
- Climatological albedo $< \text{clim_alb_limit}$ and
- $1/\cos(\zeta_{\text{sat}}) > \text{Sat_view_limit}$

where ζ_{sat} is the satellite zenith angle

This test intends to detect low clouds over vegetated areas at high satellite zenith angle at night-time or at low solar elevation. It is only applied over European areas (defined by their latitude between 36 and 90 degrees north, and their longitude between 30 degrees west and 60 degrees east).

Usually, low clouds are characterized at night-time by high $T_{10.5\mu\text{m}}$ - $T_{3.8\mu\text{m}}$ brightness temperatures differences, which allow their identification over land (see section 3.5.1.7). This detection may be less efficient at large viewing angles as cloud free $T_{10.5\mu\text{m}}$ - $T_{3.8\mu\text{m}}$ values may become rather high. To increase low clouds detection efficiency in night-time conditions at high satellite zenith angle, an empirical test has been developed, based on the observation that the decrease of $T_{8.7\mu\text{m}}$ - $T_{10.5\mu\text{m}}$ with satellite zenith angle is much stronger for low clouds than for vegetated areas. This empirical test is also very useful in case low solar elevation to detect low clouds (at large viewing angles only).

The test is applied over land.

Two alternatives exist to calculate the threshold.

Alternative 1:

The $T_{10.5T_{8.7}}\text{threshold}$ is calculated as follows:

$$T_{10.5T_{8.7}}\text{threshold} = a_0 + a_1 * T_{10.5cs} - a_2 * T_{8.7cs}$$

where $T_{10.5cs}$, $T_{8.7cs}$ are the clear sky brightness temperatures of channels $10.5 \mu\text{m}$ and $8.7 \mu\text{m}$ derived and interpolated from the RTTOV output. The a_i are setup parameters.

Alternative 2:

The T10.5T8.7threshold has been empirically derived from measurements as a function of the satellite secant:

$$T10.5T8.7\text{threshold (in K)} = b_0 + b_1 * (1/\cos(\zeta_{\text{sat}}))$$

where b_i are setup parameters.

The algorithm must provide the flexibility to change between these two threshold alternatives.

3.5.1.11 Test on R0.6 μm , R0.8 μm or R1.6 μm

Before these tests are applied, the 1 km resolution data of the solar channels have to be converted to the IR 2km resolution. The 2x2 pixels corresponding to the 2km IR data resolution are converted as follows:

The mean reflectance the standard deviation, the maximum value and the minimum value are derived for each of the channels on the 2x2 pixel array.

The mean reflectance is used for the following tests:

Over land and over sea (only if R0.8 μm unavailable), a pixel is classified as cloud contaminated if :

- R0.6 μm > R0.6threshold

Over sea, a pixel is classified as cloud contaminated if :

- R0.8 μm > R0.8threshold

Over sea, a pixel is classified as cloud contaminated if :

- R1.6 μm > R1.6threshold

These tests, applied to the visible (0.6 μm) or near-infrared (0.8 μm and 1.6 μm) TOA reflectances, aim to detect at daytime clouds having a reflectance higher than the underlying surfaces.

The visible or near-infrared reflectance measured over the cloud-free oceans mainly corresponds to Rayleigh and aerosol scattering (weaker in the near-infrared band) and to the solar reflection over the ocean, which is very low apart from sunglint conditions, and in turbid areas (for the visible channel only). Therefore near-infrared bands (0.8 μm and 1.6 μm) are used over the ocean, the visible band (0.6 μm) being used only in case 0.8 μm is not available.

As the cloud-free land reflectance is usually much higher in the near-infrared wavelengths than in the visible (due to the vegetation spectral radiative behaviour at these wavelengths), the test is therefore only applied to the visible channel.

The test is applied over land.

Two alternatives exist to calculate the thresholds.

Alternative 1:

The R0.6threshold, R0.8threshold, and R1.6threshold is derived from the clear sky TOA reflectance map, which is described in the MTG-FCI ATBD for Clear Sky Reflectance Map Product [AD-4]. In addition the thresholds are corrected for bi-directional reflectance distribution effects as follows:

$$R0.6threshold = CSRM_{06} * BRF_{06_c} / BRF_{06_m}$$

$$R0.8threshold = CSRM_{08} * BRF_{08_c} / BRF_{08_m}$$

$$R1.6threshold = CSRM_{16} * BRF_{16_c} / BRF_{16_m}$$

Where:

BRF_{nn_c} and BRF_{nn_m} : are the bi-directional reflectance function LUTs for channel nn for the current image c and current CSRM map m respectively. The relevant BRF pixel values are obtained by interpolating based on the pixel's ζ_{sat} , ζ_{sun} , ϕ_{sun_sat} and surface_type_map values.

CSRM_{nn}: is the clear sky reflectance in channel nn from the Clear Sky Reflectance Map. If multiple CRM per day are available, then the correct CSRM_{nn} to be used is the one whose time stamp is equal to:

$$CrmHourLow + \left[\text{Int} \left(\frac{t_c - CrmHourLow - 1/4}{CrmUpdateStep} \right) + 1 \right] \times CrmUpdateStep \quad \text{if } t_c = CrmNoon$$

or

$$CrmHourHigh - \left[\text{Int} \left(\frac{CrmHourHigh - t_c - 1/4}{CrmUpdateStep} \right) + 1 \right] \times CrmUpdateStep \quad \text{if } t_c > CrmNoon$$

where t_c is the time of the current image in hours. So, for example, for a time step of 2 hours, at 09:30 UTC the 10:00 UTC CSRM is used, whereas at 17:00 UTC the 16:00 UTC CSRM is used. In the case that a given CSRM is not available, the CSRM at noon is used instead

In case that no CSRM is available, the secondary threshold derivation is automatically used.

Alternative 2:

The thresholds are computed from the simulation of the surface (ocean or land) TOA reflectance by adding an offset:

- The TOA reflectance is simulated as:
TOA Reflectance = $(a_0 + a_1 * \text{surface} / (1 - a_2 * \max(\text{surface}, \text{max_refl}))) + \text{offset} + \text{corrective_factor}$

where :

a_i are coefficients computed from satellite and solar angles, water vapour and ozone content using look-up tables. These look-up tables have been pre-computed for a great variety of angles and water vapour and ozone content using a very fast model based on 6S [RD-1], using a maritime or continental aerosol of 30km or 70km horizontal visibility for sea and land respectively.

surface is the land or ocean surface reflectance. The Ocean surface reflectance is given by the maximum reflectance computed by the Cox - Munk model [RD-1], for the satellite and solar angles and for wind speed between 0 and 20 m/s: this approach overestimates the reflectance in sunglint conditions. The Land surface reflectance is computed from a monthly climatological visible reflectance atlas, bi-directional effects being simulated using a model developed by Roujean [RD-1] with 2 sets of coefficients empirically derived [($k_0=1.4$, $k_1=0.15*k_0$, $k_2=1.0*k_0$) for low reflectance and ($k_0=1.3$, $k_1=0.05*k_0$, $k_2=0.5*k_0$) for highly reflective areas].

- Offsets (7% over sea (9% for R0.6 μ m), 8% over land) are added; an additional offset (3%) is added over sea in coastal areas to account for possible misregistration.
- The following corrective factor is added over land to allow high reflectance in the forward scattering direction: $\text{corrective_factor (in \%)} = 4.0 + 29 * (\cos(\text{scattering_angle}) - 0.68)^2$ where *scattering_angle* is the scattering angle ($[0, \pi]$ from backward to forward direction).

In addition the following tests are applied to detect sub-pixel clouds, where sub-pixel is related to a nominal IR channel pixel.

3.5.1.11.1 R0.6 Reflectance Test over Land

The assumption is that any low cloud exhibits higher R0.6 reflectance than underlying clear-sky surface. This test is designed to catch static small scale low clouds that are not detected by change detection technique. A pixel is classified as cloud contaminated if not already classified as cloud by previous tests and if:

- $\text{solar_elevation} > \text{sun_elev1}$ and $\text{Max}(\text{R0.6_2x2}) > \text{R0.6threshold}$

where $\text{Max}(\text{R0.6_2x2})$ is the maximum R0.6 normalized reflectance in the 2x2 R0.6 array covered by the corresponding IR low resolution pixel.

The R0.6threshold is derived from the clear sky reflectance maps and corrected for bi-directional reflectance effects.

3.5.1.11.2 Local Spatial R0.8 Texture Test over Sea

A pixel is classified as cloud contaminated if:

- solar elevation > sun_elev2 and
SD(R0.8_2x2)/Mean(R0.8_2x2) > R08_threshold_SD1 or
SD(R0.8_2x2) > R08_threshold_SD2
- solar elevation < sun_elev2 and solar elevation > sun_elev1 and
SD(R0.8_2x2)/Mean(R0.8_2x2) > R08_threshold_SD3 or
SD(R0.8_2x2) > R08_threshold_SD4

Mean(R0.8_2x2) and SD(R0.8_2x2) stand respectively for the mean and standard deviation computed using the 4 reflectances of R0.8 pixels covered by the IR low resolution pixel

3.5.1.11.3 Local Spatial Texture and Temporal Test over Land

This test is a mixture of texture tests, change detection tests and image processing technique.

Change detection test over land:

A pixel is classified as cloud contaminated if:

clear (and not snow covered) and
SD(R0.6_2x2) > R06_threshold_SD1 and
MIN(RN0.6_2x2)_{cur} > R06_threshold_MIN1 and
ABS(1.0- MAX_{cur}(RN0.6_2x2)/ MAX_{prev}(RN0.6_2x2)) > R06_threshold_RAT1
and
ABS(1.0- MIN_{cur}(RN0.6_2x2)/ MIN_{prev}(RN0.6_2x2)) > R06_threshold_RAT2

or

SD(R0.6_2x2) > R06_threshold_SD2 and
MIN(RN0.6_2x2)_{cur} > R06_threshold_MIN2 and
SD_{cur}(R0.6_2x2)/MEAN_{cur}(R0.6_2x2) - SD_{prev}(R0.6_2x2)/MEAN_{prev}(R0.6_2x2) >
R06_threshold_DIF1 and
MAX_{cur}(RN0.6_2x2) > a₁ * MAX_{prev}(RN0.6_2x2)

where

SD MIN MAX MEAN stand respectively for the spatial standard deviation, minimum value, maximum value and mean of the feature.

R0.6 is the reflectance in channel 0.6 μm

RN0.6 is the R0.6 reflectance normalized by the analytical formulation of solar pathlength valid for a standard atmosphere.

subscripts cur and prev stand for pixels from the current image or the one 10 minutes sooner.

The assumption behind this test is that a mobile or evolving bright target inside a 2x2 R0.6 array is a cloud. False alarms that have been problematic are clear sides of cloud shadow limits moving over bright grounds. This is why the pixels detected by this test are further processed by a neighbourhood analysis described below.

3.5.1.12 Low Cloud Test in Sunlint

The following test is applied if the sun elevation is higher than 15 degrees:

A pixel is classified as cloud contaminated if:

$$\begin{aligned}
 &T_{3.8\mu\text{m}} < T_{38_saturation} \text{ (to make sure } 3.8\mu\text{m is not saturated)} && \text{and} \\
 &R_{0.6\mu\text{m}} > R_{06_threshold1} && \text{and} \\
 &(T_{3.8\mu\text{m}} - T_{10.5\mu\text{m}}) / \cos(\zeta_{\text{sun}}) > T_{38T105_threshold_sunlint} && \text{and} \\
 &R_{0.6\mu\text{m}} > a_1 * (T_{3.8\mu\text{m}} - T_{10.5\mu\text{m}}) / \cos(\zeta_{\text{sun}})
 \end{aligned}$$

where ζ_{sun} is the solar zenith angle

This test aims to detect low clouds in sunlint conditions. Low clouds can easily be detected at daytime over the ocean by their high visible or near-infrared reflectances. This is not possible in case of sunlint, because the sea reflectance at these wavelengths may then be higher than that of clouds. The use of both 0.6 μm and 3.8 μm channels allows to detect low clouds even in areas affected by sunlint. Indeed, oceanic areas with high 0.6 μm reflectances have also very high 3.8 μm reflectances, which is usually not the case for low clouds. The solar contribution in the 3.8 μm channel in case of sunlint is approximated by $(T_{3.8\mu\text{m}} - T_{10.5\mu\text{m}}) / \cos(\zeta_{\text{sun}})$. The rapid saturation of the 3.8 μm radiance limits the use of this test in case of strong sunlint.

3.5.1.13 Snow or Ice Detection Test

The following snow and ice detection test is applied if the sun elevation is larger than 5 degrees:

A pixel is classified as contaminated by snow if:

$$\begin{aligned}
 &(R_{1.6\mu\text{m}}) < R_{1.6_threshold} && \text{and} \\
 &(R_{0.6\mu\text{m}} - R_{1.6\mu\text{m}}) / (R_{0.6\mu\text{m}} + R_{1.6\mu\text{m}}) > (a_0 + a_1 * (\cos(\text{scattering angle}) - 1)^2) && \text{and} \\
 &(T_{3.8\mu\text{m}} - T_{10.5\mu\text{m}}) / \cos(\zeta_{\text{sun}}) < T_{38T105_threshold_snow} && \text{and} \\
 &(T_{10.5\text{threshold}} - b_0) < T_{10.5\mu\text{m}} < T_{105_threshold_snow} && \text{and} \\
 &T_{10.5\mu\text{m}} - T_{12.3\mu\text{m}} < T_{105T123_threshold_snow} && \text{and} \\
 &R_{0.6\mu\text{m}} > \text{Min}(R_{0.6\text{threshold}}, (a_0 + a_1 * (\cos(\text{scattering angle}) - a_2)^2)) && \text{and} \\
 &R_{0.8\mu\text{m}} > R_{08_threshold_snow}
 \end{aligned}$$

where

R1.6threshold depends on the solar zenith and the satellite viewing angle (TBD)

T10.5threshold and R0.6threshold are thresholds used in cloud masking with infrared and visible channels

ζ_{sun} is the solar zenith angle,

scattering angle is the scattering angle ($[0,\pi]$ from backward to forward direction).

Ice and snow appear rather cold and bright, and may therefore be confused with clouds (especially with low clouds) during the cloud detection process. Ice and snow must therefore be identified first, prior to the application of any cloud detection test. This test aims to detect pixels contaminated by snow or ice: if this test is satisfied, the pixel is classified as snow or ice and no further cloud detection is attempted. The basis of this test, restricted to daytime conditions, is the following :

- Snow & ice are separated from water clouds by their low reflectance at 1.6 μm or at 3.8 μm .
- Snow & ice are separated from cloud free oceanic or continental surfaces by their higher R0.6 μm visible reflectance and slightly colder T10.5 μm brightness temperature.
- T10.5 μm -T12.3 μm brightness temperature difference helps to discern cirrus from snow & ice.
- R0.8 μm is useful to separate shadows from snow & ice.

Surface snow reflectances have been tabulated for various viewing geometries and for hexagonal particle shape (3 different sizes) with the radiative transfer model developed by C.Le Roux [RD-1]. Top of Atmosphere snow reflectance at 1.6 μm are then computed using these look-up tables (both 250 μm and 70 μm hexagonal particles have been retained) together with a module (based on 6S [RD-1]) to simulate the atmospheric effects. The R1.6threshold threshold applied to the 1.6 μm channel is derived from these simulated snow reflectances by adding an offset (10%).

3.5.1.14 Local Spatial Texture Tests

The following tests are applied:

Over Sea, a pixel is classified as cloudy if :

$$\begin{aligned}
 & [\text{SD}(\text{T}10.5\mu\text{m}) > \text{T}105_threshold_SD1 && \text{and} \\
 & \text{SD}(\text{T}10.5\mu\text{m}-\text{T}3.8\mu\text{m}) > \text{T}105\text{T}38_threshold_SD1 && \text{and} \\
 & \text{T}10.5\mu\text{m} < \text{MAX}(\text{T}10.5\mu\text{m}) - a_1 * \text{noise}(\text{T}10.5\mu\text{m})] \\
 & \text{or} \\
 & [\text{SD}(\text{R}0.8\mu\text{m}) > (b_0 + b_1 * \text{R}0.8\text{threshold}) && \text{and} \\
 & \text{R}0.8\mu\text{m} > \text{MIN}(\text{R}0.8\mu\text{m}) + c_1 / \text{SNR}(\text{R}0.8\mu\text{m})]
 \end{aligned}$$

Over Land, a pixel is classified as cloudy if :

$$\begin{aligned}
 & [\text{SD}(\text{T}10.5\mu\text{m}) > \text{T}105_threshold_SD2 && \text{and} \\
 & \text{SD}(\text{T}10.5\mu\text{m}-\text{T}3.8\mu\text{m}) > \text{T}105\text{T}38_threshold_SD2 \\
 & \text{or} \\
 & [\text{DR}0.6\mu\text{m} > f(\text{DT}10.5\mu\text{m}) / (\text{DR}0.6\mu\text{m})]
 \end{aligned}$$

where:

SD, MIN, MAX, stand for local standard deviation, minimum, maximum, computed using the 8 surrounding pixels (i.e. a 3x3 pixel array), provided they correspond to the same surface type (i.e., sea or land)

R0.8threshold is the visible threshold (in %) defined previously

DR0.6 μ m stands for the maximum difference between the visible reflectance of a pixel and its eight neighbours; DT10.5 μ m is the corresponding brightness temperature difference and $R = DT10.5\mu\text{m} / DR0.6\mu\text{m}$ is the ratio.

Noise stands for the instrumental noise in Kelvin of the feature at the given brightness temperature. SNR stands for the signal to noise ratio of the feature for the given visible band. The $f(R)$ function is described in [RD-1].

These tests detect small broken clouds, thin cirrus or cloud edges, by using their high spatial variations in the visible, near infrared or infrared channels. The difficulty comes from the natural heterogeneity of the surface background. Oceanic areas are rather homogeneous, with the exception of strong thermal fronts (large T10.5 μ m variation), turbid coastal areas (large R0.6 μ m variation), sunglint areas (large R0.6 μ m and R0.8 μ m variation); Land surfaces are generally much more inhomogeneous, especially in mountainous or desertic regions. The simultaneous analysis of spatial coherency in two spectral bands allows to overcome the difficulty:

- Over Ocean, the combined use of T10.5 μ m & T10.5 μ m-T3.8 μ m for all illumination conditions is efficient for detecting clouds, and avoids misclassification of thermal front.
- Over land, the combined use of T10.5 μ m & T10.5 μ m-T3.8 μ m for all illumination conditions allows to minimise misclassification, except in very mountainous or in arid areas.
- Continental areas at daytime may present as large R0.6 μ m, R0.8 μ m and T10.5 μ m horizontal differences as clouds do. But, a cloud-free surface having higher R0.6 μ m than the neighbourhood is less vegetated and therefore warmer, whereas a pixel contaminated by clouds and having higher R0.6 μ m than its neighbours should be more cloud contaminated, and therefore colder. This property, not observed in arid areas, is used at daytime over land in the Local Spatial Texture Test.

This process is not applied in very mountainous regions, moreover T10.5 μ m-T3.8 μ m is not used in too cold areas (due to noise effects).

It should also be noted that the thresholds T105T38_threshold_SD1 and T105T38_threshold_SD2 may vary for day/night/twilight.

3.5.1.15 Temporal Test to Detect Rapidly Moving or Developing Clouds

This time-differencing test is applied to the whole image. It is designed to catch high thin clouds moving rapidly and appearing colder than their underlying surface that are not

detected by spectral or textural tests. It is similar to the technique described by d'Entremont and Gustafson [RD-1]. A time-interval of 10 minutes is used.

- Over sea a pixel whose $\Delta_{10mn}(T10.5)$ is lower than DT10.5_sea is declared as cloudy
- Over land a pixel whose $\Delta_{10mn}(T10.5)$ is lower than DT10.5_land is declared as cloudy

DT10.5_land varies from $-3.0K$ to $-0.6K$ according to time related to local sunset and sunrise. For deserts near sunset DT10.5_land has been set to $-4K$. This temporal test is also applied to snow contaminated pixels. The threshold DT10.5_land used over land is computed so that a maximum cooling in the diurnal cycle near the sunset does not generate a false alarm. Therefore the test may be more efficient over arid surfaces around sunset than at noon during the warming period before the observed maximum temperature. The derivation of the threshold is illustrated in the following figure

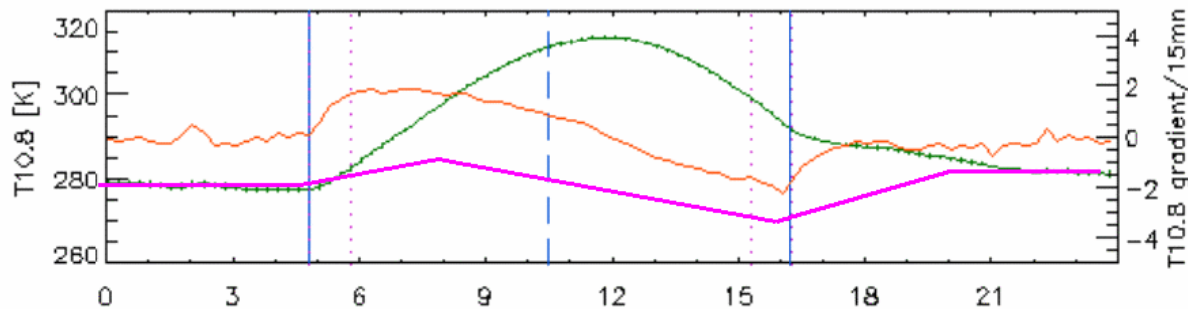


Figure 1: graphical illustration of DT10.8 threshold over land (pink) for a 24h period labelled in UTC time, sunrise and sunset are vertical solid blue line, compared with a real T10.8 cycle (green) and its gradient (orange) for a 10 minute interval

3.5.1.16 Temporal Test to Restore Stationary Low or Mid-Level Clouds in Twilight Conditions

The day-night terminator separates sunlit from dark regions and its line is apparent near local sunrise and sunset. It crosses the earth's disk with a speed about 1600 km/h in equatorial regions. Its orientation varies with the season, showing a larger sunlit area in the higher latitudes during summer. If defining the day-night transition as the area where sun zenith angle ζ_{sun} is between 80° and 93° , about one hour is necessary to get separated zones near the equator, for high latitude regions it may be longer. Therefore a one-hour time interval between images is a minimum if one wants to get a given "twilight" pixel previously analysed by the day or night algorithm.

In the current image the day-night transition portion is delimited according to sun zenith angle, and temporal differences of features that are known to be nearly insensitive to solar illumination change for a low cloud target are computed:

- $|\Delta_{1h}(T10.5)|$,
- $|\Delta_{1h}(T10.5-T12.3)|$,

- $|\Delta_{1h}(T10.5-T8.7)|$

where $|\Delta_{1h}|$ is the absolute value of temporal difference with a time interval of one hour. The CMA_{1h} and CT_{1h} of the previous image are used to identify pixels of the current image that were previously classified as low or mid-level clouds one hour earlier and detected by a high confidence test. Those pixels are restored as cloudy in the current transition area if the absolute values of temporal features, noted Δ_{1h} , satisfy the following conditions:

- over land
 $|\Delta_{1h}(T10.5)| < DT10.5_1h_land$ and
 $|\Delta_{1h}(T10.5-T8.7)| < DT105T87_1h_land$
- over water
 $|\Delta_{1h}(T10.5)| < DT10.5_1h_sea$ and
 $|\Delta_{1h}(T10.5-T12.3)| < DT105T123_1h_sea$

With this, cloud parts still remain undetected, but discernible in enhanced VIS image. In general the inner part of low cloud decks were caught while their optically thinner part or new portions appearing with the cloud development or its forward motion may have passed through the temporal differencing procedure and kept as clear. Moreover pixels that are not detected one hour sooner can't be restored by this technique.

3.5.1.17 Spatial Expansion of Stationary Clouds in Twilight Conditions

To improve the detection of the outer part of the cloud the radiometric statistical attributes of the newly detected pixels is used. A region-growing technique applied to the initial stationary cloudy pixels identified is done by the first step. The goal of this second step is to spatially extend the initial cloud "seeds" to their connected pixels presenting similar characteristics.

The normalization used when handling VIS values is an inverse cosine function of satellite zenith angle ζ_{sat} . In the day-night terminator area two effects become important: curvature of atmosphere and refraction. When sun zenith angle approaches 90° , because of curvature of atmosphere the solar beam pathlength is significantly shorter than the plane parallel one. This explains why for VIS pictures normalized using this inverse cosine function, values displayed near day-night terminator appear too high.

Twilight whose exact definition is the diffused light in the sky when the sun is just below the horizon, just after sunset or just before sunrise, is an effect of atmospheric refraction. The refractive index of air decreases when wavelength increases, in other words, blue light, which comprises the shortest wavelength region in visible light, is refracted at significantly greater angles than is red light. Refraction may be neglected even for $\zeta_{sun} < 85^\circ$.

For these two reasons the inverse cosine BRF normalization function is replaced by an analytical formulation valid for a standard atmosphere. The parameterization accounts for spherical atmosphere and refraction. This parameterization should be adapted to the narrowband spectral characteristics of each VIS band of MTG-FCI and to the current state of

atmosphere, and kept as a first order correction for a better handling of VIS BRF in twilight area.

Because BRF of pixels in day-night terminator portion becomes very sensitive to noise when approaching the terminator line, a region-growing for $75^\circ < \zeta_{\text{sun}} < 89^\circ$ is allowed. Groups of connected pixels restored by the first temporal-differencing method form initial seeds for the region-growing are identified. Any group comprising more than eight elements is taken into account. For each significant group two mean values are computed: normalized BRF0.6 (AVG0.6) and T105 (AVG10.5). A group is expanded while a 8-connectivity neighbour pixel x belonging to the day-night transition area satisfies simultaneously the following conditions:

$$\begin{aligned} \text{SCAT}_x &< \text{scat_angle_limit} \\ \text{BRF0.6}_x &> \text{MAX}(a_1 * \text{AVG0.6}, \text{THR}_{\text{exp}}) \\ \text{AVG10.5} + b_0 &< \text{T10.5}_x < \text{AVG10.5} - b_1 \end{aligned}$$

where:

THR_{exp} is 40% over Africa to avoid false alarms over arid areas and 30% elsewhere

SCAT_x is the scattering angle $[0^\circ, 180^\circ]$, 0° for backward scattering

BRF0.6_x is the normalized BRF in channel $0.6\mu\text{m}$ at location x

T10.5_x is the brightness temperature of $10.5\mu\text{m}$ at location x

The main risk of the method is to add cloud false alarms and it is maximal when the radiometer is looking in the sun direction because measured clear-sky BRF0.6 increase dramatically. That is why region growing at locations where scattering angle is greater than 150° is not performed. Moreover region-growing restoring more than 10000 elements for the same seed is rejected assuming that a too wide region-growing is suspect. The strategy employed in the region-growing technique may produce small differences in presence of blurry low cloud edges resulting in small jumps in cloud features animations.

3.5.1.18 Restoral Tests

3.5.1.18.1 Clear Restoral Test over Land

This test is designed to remove some false alarms passing through the previous test, and is applied only to pixels detected by the previous test. A pixel at low resolution scale is restored as clear if:

Its $\text{MEAN}(\text{R0.6}_{2x2})$ is minimum among other land pixels in its low resolution neighbourhood

3.5.1.18.2 Cloud Restoral Test over Land

Obviously during visual inspection of the results some clouds remained missed after the change detection test. Brighter pixels in the neighbourhood of pixels detected as clouds by the R0.6 change detection algorithm described in section 3.5.1.11.3 should also be detected as cloudy. This test is designed to this purpose.

A pixel on land at low resolution scale in the 11x11 neighbourhood of a R0.6 change detection is restored as cloud if at least 5 pixels inside 11x11 neighbourhood are detected by R0.6 change detection tests

$$\text{MIN}(R0.6_2x2)_{\text{cur}} > R06_restoral_MIN \quad \text{and}$$

$$\text{MAX}(R0.6_2x2) > \text{MEAN}_{11x11}(\text{Max}(R0.6_2x2)) \quad \text{and}$$

$$\text{SD}(R0.6_2x2) > R06_restoral_SD$$

or

$$\text{MAX}(R0.6_2x2) - \text{MIN}(R0.6_2x2) > \text{MEAN}_{11x11}(\text{MAX}(R0.6_2x2) - \text{MIN}(R0.6_2x2))$$

3.5.1.19 Clear Restoral Test for Cold Scenes

This test is designed to remove some remaining false alarms in the coldest scenes. It exploits the fact that for some extremely cold ground surfaces, in presence of strong nocturnal clear-sky inversion, the T7.3 brightness temperature, sensitive to atmosphere temperature is warmer than the one observed in the 10.5 μ m atmospheric window. A pixel is restored as clear when detected by T105thr test at any illumination, or Visible test or T38T105thr test at daytime or twilight under the following conditions:

$$T10.5 < T105_restoral \quad \text{and}$$

$$T7.3 - T10.5 > T73T105_restoral$$

3.5.1.20 Spatial Filtering

The spatial filtering is applied at the final stage of cloud detection after the sequence of all tests. The use of local spatial texture test, even relaxed, in the vicinity of coast line may induce false alarms in the sea side of the coastal zone. This spatial filtering dedicated only to coastal pixels is designed to reduce this default. It is not applied around a water group smaller than 50 elements

The coastal seaside pixels are identified by subtracting the result of 2 morphological dilatations of land pixels eroded twice by a 3x3 structuring element.

The following filtering is applied to coastal pixels:

- Over sea a pixel detected cloudy by a local spatial texture test is restored clear when belonging to a 3x3 box clear at 10% and to a 7x7 box clear at 50%.
- Over land a pixel detected as cloudy is restored clear when belonging to a 3x3 box clear at 10% and to a 7x7 box clear at 50%.

In CT pictures it is very frequent to observe snowy areas surrounded by a band of low clouds. In general such pixels are in fact partially covered by snow and wrongly detected as cloud because insufficiently covered by snow. Such pixels are in general detected cloudy by a local spatial texture test.

The outer limits of snowy areas are identified by subtracting the result of 2 morphological dilatations of snowy pixels by a 3x3 structuring element eroded twice by the same structuring element. The following filtering is applied to outer edge band of a snowy area:

- A pixel detected cloudy by local spatial texture test is restored clear if belonging to a 3x3 box with at least a clear pixel and without cloudy pixels detected by another test

The following spatial filtering process is finally applied:

- all the isolated cloudy pixels that have been detected by a test using the 3.8 μ m are reclassified as cloud-free.
- all the isolated cloud free pixels are reclassified as cloudy.

All the reclassified pixel are flagged as of very low confidence.

3.5.1.21 Opaque Cloud Detection Test

This test has been implemented to identify opaque clouds :
 A cloud contaminated pixel is classified as opaque cloud if :

- $T_{10.5\mu m} - T_{12.3\mu m} < T_{105T123_opaque}$

The aim is to identify pixels fully covered by a single cloud layer whose infrared emissivity is close to unity, and are therefore not contaminated in the infrared wavelength by the surface. The calculation of the cloud top temperature and height of these pixels would then have only required a correction for atmospheric attenuation above the cloud.

The opaque cloud identification is applied to pixels previously detected as cloud contaminated. It relies on the analysis of the T10.5 μ m -T12.3 μ m brightness temperature difference : this difference is higher for semi-transparent ice clouds (due to their higher transmittivity at 10.5 μ m) and broken clouds, than for opaque clouds.

3.5.1.22 Dust Cloud Identification

The following algorithm has been empirically derived to detect and classify dust clouds at daytime and also at night-time over sea:

Over the sea at daytime, a pixel is classified as contaminated by dust cloud if :

- Separation from cloud free surfaces:

$[(R_{1.6\mu m} / R_{0.6\mu m}) > R_{16R06_ratio1}$	and
$(R_{1.6\mu m} > R_{1.6threshold} - R_{16_dust1})$	and
$(T_{12.3\mu m} - T_{10.5\mu m}) > T_{120T105threshold}$]	
or	
$[(R_{1.6\mu m} / R_{0.6\mu m}) > R_{16R06_ratio2}$	and
$(R_{1.6\mu m} > R_{1.6threshold} - R_{16_dust2})$]	
or	
$[(R_{1.6\mu m} / R_{0.6\mu m}) > R_{16R06_ratio3}$	and
$(R_{1.6\mu m} > R_{1.6threshold} - R_{16_dust3})$	and
$SD(T_{10.5\mu m} - T_{3.8\mu m}) < T_{105T38_dust_SD1}$	and
$(T_{12.3\mu m} - T_{10.5\mu m}) > T_{123T105_dust1}$]	
or	
$[R_{0.6\mu m} > R_{0.6threshold} - R_{06_dust1}$	and

$$(T12.3\mu\text{m}-T10.5\mu\text{m}) > T123T105\text{threshold}]$$

- Separation from clouds:

$$\begin{aligned}
 & a_0 - a_1 * (1/\cos(\zeta_{\text{sat}}) - 1) < T10.5\mu\text{m} - \text{SSTclim} && \text{and} \\
 & (T8.7\mu\text{m}-T10.5\mu\text{m}) > -(b_0 - b_1 * (1-1/\cos(\zeta_{\text{sat}}))) && \text{and} \\
 & \text{SD}(T10.5\mu\text{m}) < T105_dust_SD1 && \text{and} \\
 & [R0.6\mu\text{m} < R0.6\text{threshold} + R06_dust1 && \text{and} \\
 & \text{SD}(R0.6\mu\text{m}) < R06_dust_SD1 && \text{and} \\
 & \text{SD}(R0.8\mu\text{m}) < R08_dust_SD1 && \text{and} \\
 & [\text{SD}(R1.6\mu\text{m}) < R16_dust_SD1 + c_1 * R0.6\mu\text{m} \\
 & \text{or} \\
 & \text{SD}(R0.6\mu\text{m}) < R06_dust_SD2] && \text{and} \\
 & \text{SD}(T10.5\mu\text{m}-T3.8\mu\text{m}) < T105T38_dust_SD2] \\
 & \text{or} \\
 & R0.6\mu\text{m} > R0.6\text{threshold} + R06_dust2 && \text{and} \\
 & (T8.7\mu\text{m}-T10.5\mu\text{m}) > T87T105_dust1 && \text{and} \\
 & \text{SD}(R0.6\mu\text{m}) < R06_dust_SD3 \\
 & \text{or} \\
 & [R0.6\text{threshold} + R06_dust3 < R0.6\mu\text{m} < R0.6\text{threshold} + R06_dust4 && \text{and} \\
 & (T8.7\mu\text{m}-T10.5\mu\text{m}) > T87T105_dust2 && \text{and} \\
 & \text{SD}(R0.6\mu\text{m}) < R06_dust_SD4 && \text{and} \\
 & \text{SD}(R0.8\mu\text{m}) < R08_dust_SD1 && \text{and} \\
 & \text{SD}(T10.5\mu\text{m}-T3.8\mu\text{m}) < T105T38_dust_SD1] \}
 \end{aligned}$$

where

R0.6threshold and R1.6threshold are the same as used in the cloud masking scheme

ζ_{sat} is the satellite zenith angle,

T120T105threshold is the same as used in the cloud masking scheme

SD is the standard deviation

Over the ocean at nighttime, a pixel is classified as contaminated by dust cloud if :

$$\begin{aligned}
 & [(\text{Saharan_dust_index} > \text{SDI_threshold1} && \text{and} \\
 & a_0 - a_1 * (1/\cos(\zeta_{\text{sat}}) - 1) < T10.5\mu\text{m} - \text{SSTclim}) \\
 & \text{or} \\
 & (\text{Saharan_dust_index} > \text{SDI_threshold2} && \text{and} \\
 & b_0 - b_1 * (1/\cos(\zeta_{\text{sat}}) - 1) < T10.5\mu\text{m} - \text{SSTclim})] \\
 & \text{and} \\
 & \text{SD}(T10.5\mu\text{m}) < T105_dust_SD2 && \text{and} \\
 & \text{SD}(T10.5\mu\text{m}-T3.8\mu\text{m}) < T105T87_dust_SD2 && \text{and} \\
 & (T105\mu\text{m}-T123\mu\text{m}) < T105T123_dust2 && \text{and} \\
 & (T87\mu\text{m}-T105\mu\text{m}) > -(c_0 - c_1 * (1-1/\cos(\zeta_{\text{sat}}))) \}
 \end{aligned}$$

where:

ζ_{sat} is the satellite zenith angle and

SD is the standard deviation and

Saharan Dust Index (SDI) = $d_1 * (T38\mu\text{m}-T87\mu\text{m}) - d_2 * (T105\mu\text{m}-T120\mu\text{m}) + d_0$

Over continental surfaces at daytime, a pixel is classified as contaminated by dust if :

```

Sun elevation larger than 20 degrees           and
T105_dust1 < T10.5µm < T105_dust2           and
R0.6µm < R0.6threshold + R06_dust3           and
SD(T10.5µm) < T105_dust_SD                   and
SD(R0.6µm) < R06_dust_SD
and
[[ ( (T3.8µm - T10.5µm) > T38T105_dust3 and (T12.3µm-T10.5µm) > T123T105_dust3
or
  ( (T3.8µm - T10.5µm) > T38T105_dust4 and (T12.3µm-T10.5µm) > T123T105_dust4)
or
  [ (T12.3µm-T10.5µm) > T123T105_dust5           and
    { (T8.7µm-T10.5µm) > T87T105_dust3 and R0.6µm /R1.6µm < R06R16_ratio3 }
or
  (T8.7µm-T10.5µm) > min(a0 , b0 - b1*R0.6µm) and R0.6µm/R1.6µm < R06R16_ratio4}]]
    
```

where R0.6threshold is as used in cloud masking

The aim is to identify dust that is transported out of deserts over both continental and oceanic surfaces. These events are rather frequent over North Africa and adjacent seas (Atlantic Ocean and Mediterranean sea). The difficulty is to separate dust clouds from cloud free areas without confusing them with water clouds. Techniques proposed in literature are based on brightness temperature differences [10.5 and 3.8µm, or 10.5 and 12.3µm (used by NOAA to map dust clouds); a thermal contrast between the ground and the dust cloud is needed to make these techniques efficient], or on visible reflectances spatial homogeneity. The result of this detection process is stored in a separate flag. The threshold applied over the ocean to the T12.3µm-T10.5µm brightness temperature difference is, as most IR thresholds, calculated from pre-computed tables defined by applying RTTOV to an atmospheric profiles database provided by ECMWF. The night time detection of dust over sea is based on the thresholding of the Saharn Dust Index (SDI, see [RD-1]) computed from T3.8µm, T8.7µm, T10.5µm and T12.3µm.

3.5.1.23 Quality Assessment

A quality flag is appended to the CMA. It allows the identification of cloud-free, cloudy and snowy pixels that may have been misclassified:

- a pixel classified as cloudy is flagged as of low confidence if no cloud detection test has been really successful. A threshold test is said really successful if the difference between the threshold and the measurement is larger than a security margin depending on the test itself.
- a pixel classified as cloud free is flagged as of low confidence if the difference between the threshold and the measurement is lower than an security margin for at least one cloud detection test.
- a pixel classified as snow/ice is flagged as of low confidence if the difference between its observed R1.6µm and the corresponding threshold of this feature used in the snow/ice detection test is lower than 0.2*threshold.

Such a quality flag should allow to identify high confidence cloud free areas for surface parameters computation. On the other hand, the identification of extended cloudy or cloud free area flagged as low confidence should help in identifying areas where the algorithm may be not accurate enough. Cloud edges or cloud free areas bordering clouds are flagged as of low confidence.

3.5.2 Cloud Type (CT) Algorithm Description

3.5.2.1 Algorithm Outline

The CT algorithm is a threshold algorithm applied at the pixel scale, based on the use of CMA and spectral & textural features computed from the multispectral satellite images and compared with a set of thresholds.

The set of thresholds to be applied depends mainly on the illumination conditions (defined in *Table 2*), whereas the values of the thresholds themselves may depend on the illumination, the viewing geometry, the geographical location and NWP data describing the water vapour content and a coarse vertical structure of the atmosphere.

The CT classification algorithm is based on a sequence of thresholds tests which are detailed in the following sections. A separate processing described in section 3.5.2.6 is applied to compute the cloud phase. In addition, it should be noted that in the current version of CT, no separation between cumuliform and stratiform clouds is performed.

3.5.2.2 Fractional and High Semitransparent Cloud Identification at Night-Time

The high semitransparent clouds are distinguished from opaque clouds using the T10.5 μ m-T12.3 μ m, T8.7 μ m-T10.5 μ m or T3.8 μ m-T10.5 μ m features.

- T10.5 μ m-T12.3 μ m is usually higher for cirrus clouds than for thick clouds, especially in case of large thermal contrast between the cloud top and the surface. This brightness temperature difference decreases if the semitransparent cloud is too thick or too thin.
- T8.7 μ m-T10.5 μ m is usually higher for cirrus clouds than for thick clouds, especially in case of large thermal contrast between the cloud top and the surface.
- The T3.8 μ m-T10.5 μ m feature is also very efficient to distinguish high semitransparent clouds from the opaque clouds. It is based on the fact that the contribution of the relatively warm grounds to the brightness temperature of semitransparent cloud is higher at 3.8 μ m than at 10.5 μ m, due to a lower ice cloud transmittance, and to the high non-linearity of the Planck function at 3.8 μ m. This feature is more efficient if the thermal contrast between cloud top and surface is large. Due to noise problem, this feature cannot be used in case of too cold T3.8 μ m.

The fractional low clouds have also T10.5 μ m-T12.3 μ m and T3.8 μ m-T10.5 μ m higher than opaque clouds, which therefore may lead to confusion with very thin cirrus. But usually cirrus clouds have larger T8.7 μ m-T10.5 μ m than fractional low clouds. The presence of a lower level under the cirrus cloud leads to reduce T10.5 μ m-T10.2 μ m and T3.8 μ m-T10.5 μ m when compared to those of single level cirrus. T10.5 μ m-T12.3 μ m is more reduced than T3.8 μ m-T10.5 μ m, making this last feature more efficient to detect cirrus overlaying low water clouds. But it seems impossible to detect overlapping clouds with only spectral features

such as T10.5 μ m-T12.3 μ m or T3.8 μ m-T10.5 μ m at the pixel resolution, neither with local textural features; the CT algorithm therefore does not separate cirrus overlaying low clouds from fractional cover or mid-level clouds at night-time. The scheme used at night-time is the following:

Table 5 High semi-transparent clouds (night-time)

high semitransparent thick clouds:	T10.5 μ m < maxT105hi	T10.5 μ m-T12.3 μ m > T105T120thick
high semitransparent meanly thick clouds:	maxT105hi < T10.5 μ m < T105interthr	[T3.8 μ m -T10.5 μ m > T38T105thin_high or T10.5 μ m -T12.3 μ m > T105T120thick]
	T105interthr < T10.5 μ m < maxT105med	[T3.8 μ m -T10.5 μ m > T38T105thin_low or T10.5 μ m -T12.3 μ m > T105T120thick]
high semitransparent thin clouds:	maxT105med < T10.5 μ m < maxT105low	[T3.8 μ m -T10.5 μ m > T38T105t_low or T10.5 μ m -T12.3 μ m > T105T120thick] and [T8.7 μ m-T10.5 μ m > T87T105opaque or T3.8 μ m -T10.5 μ m > T38T105thin_low]
	maxT105low<T10.5 μ m<maxT105low+delt a	[T3.8 μ m -T10.5 μ m > T38T105_vlow or T10.5 μ m -T12.3 μ m > T105T120thick] and [T8.7 μ m -T10.5 μ m > T87T105opaque or T3.8 μ m -T10.5 μ m > T38T105thin_low]

Table 6 Fractional low clouds (Night-time)

Fractional clouds:	maxT105med < T10.5 μ m < maxT105low	[T3.8 μ m -T10.5 μ m > T38T105_low or T10.5 μ m -T12.3 μ m > T105T120thick] and [T8.7 μ m -T10.5 μ m < T87T105opaque] and [T3.8 μ m -T10.5 μ m < T38T105thin_low]
	maxT105low<T10.5 μ m<maxT105low+delta	[T10.5 μ m -T12.3 μ m > T105T120thick or T3.8 μ m -T10.5 μ m > T38T105_vlow] and [T8.7 μ m -T10.5 μ m < T87T105opaque] and [T3.8 μ m -T10.5 μ m < T38T105thin_low]
	maxT105low+delta < T10.5 μ m	[T10.5 μ m -T12.3 μ m > T105T120thick or T3.8 μ m -T10.5 μ m > T38T105_vlow]

The thresholds used in this scheme are the following:

- MaxT105low, maxT105med, maxT105hi and maxT105vh thresholds are explained in section 3.5.2.5.
- An intermediate T10.5 μ m threshold has been defined:
T105interthr = maxT105low+(maxT105hi- maxT105low)/2

If $T_{105interthr} > \max T_{105med}$ $T_{105interthr} = \max T_{105med} + (\max T_{105hi} - \max T_{105med}) / 2$.

- $T_{105T120opaque}$, $T_{38T105opaque}$, $T_{87T105opaque}$ and Delta are computed by interpolating in look-up tables using satellite zenith angle and total integrated atmospheric water vapour content. These look-up tables have been elaborated by applying RTTOV to radiosoundings from an ECMWF dataset for surface having an emissivity of one.
- New T_{38T105} thresholds according to observed $T_{10.5\mu m}$ have been defined as:
 $T_{38T105thin_high} = T_{38T105opaque} + a_1 * (\max T_{105low} - T_{105}) / (\max T_{105low} - \max T_{105hi})$
 $T_{38T105thin_low} = T_{38T105opaque} + b_1 * (\max T_{105low} - T_{105}) / (\max T_{105low} - \max T_{105hi})$
 $T_{38T105_low} = T_{38T105opaque} + c_1$
 $T_{38T105_vlow} = T_{38T105opaque} - d_1$
- $T_{105T120thick}$ has been defined as : $\text{MAX} (T_{105T120opaque} - a, b)$

3.5.2.3 Fractional and Semitransparent Cloud Identification in Twilight Conditions

$T_{3.8\mu m}$ cannot be used in twilight conditions as in night-time conditions, due to solar contamination. High semitransparent or fractional low clouds can still be separated from opaque clouds by their relatively high $T_{10.5\mu m} - T_{12.3\mu m}$ value. As in nighttime conditions, cirrus clouds have much higher $T_{8.7\mu m} - T_{10.5\mu m}$ values than fractional low clouds.

The scheme used in twilight conditions is the following:

Table 7 High semi-transparent clouds (twilight)

high semitransparent thick clouds:	$T_{10.5\mu m} < \max T_{105hi}$	$T_{10.5\mu m} - T_{12.3\mu m} > T_{105T120opaque}$
high semitransparent meanly thick clouds:	$\max T_{105hi} < T_{10.5\mu m} < \max T_{105med}$	$T_{10.5\mu m} - T_{12.3\mu m} > T_{105T120opaque}$
high semitransparent thin clouds:	$\max T_{105med} < T_{10.5\mu m} < \max T_{105low} + \delta$ ta	$T_{10.5\mu m} - T_{12.3\mu m} > T_{105T120opaque}$ and $T_{8.7\mu m} - T_{10.5\mu m} > T_{87T105opaque}$

Table 8 Fractional low clouds (twilight)

Fractional clouds:	$\max T_{105med} < T_{10.5\mu m} < \max T_{105low} + \delta$ a	$T_{10.5\mu m} - T_{12.3\mu m} > T_{105T120opaque}$ and $T_{8.7\mu m} - T_{10.5\mu m} < T_{87T105opaque}$
	$\max T_{105low} + \delta < T_{10.5\mu m}$	$T_{10.5\mu m} - T_{12.3\mu m} > T_{105T120opaque}$

The meaning of the thresholds is the same as in the night-time scheme.

3.5.2.4 Fractional and High Semitransparent Cloud Identification at Daytime

The high semitransparent clouds are distinguished from opaque clouds using spectral features ($T_{10.5\mu m} - T_{12.3\mu m}$, $T_{8.7\mu m} - T_{10.5\mu m}$, $R_{0.6\mu m}$) and textural features (variance $T_{10.5\mu m}$ coupled to variance $R_{0.6\mu m}$ in daytime conditions):

- T10.5 μ m-T12.3 μ m is usually higher for cirrus clouds than for thick clouds, especially in case of large thermal contrast between the cloud top and the surface. This brightness temperature difference decreases if the cloud is too thick or too thin.
- T8.7 μ m-T10.5 μ m is usually higher for cirrus clouds than for thick clouds, especially in case of large thermal contrast between the cloud top and the surface.
- Cirrus clouds present lower R0.6 μ m reflectances than opaque clouds having the same radiative temperature.
- Cirrus clouds are much more spatially variable in temperature than in visible reflectance.

The fractional low clouds have also T10.5 μ m-T12.3 μ m higher than opaque clouds, but usually lower than thin cirrus. Fractional low clouds usually appears warmer and brighter than thin cirrus clouds; moreover cirrus clouds have larger T8.7 μ m-T10.5 μ m than fractional low clouds

High semitransparent over low or medium clouds appear rather bright and cold, but are characterised by rather high T10.5 μ m-T12.3 μ m and T8.7 μ m-T10.5 μ m (if the thermal contrast between cirrus and lower cloud layer top temperature is large enough).

The scheme used at daytime is the following:

Table 9 High semi-transparent clouds (daytime)

high semitransparent thick clouds:	$T_{10.5\mu m} < \max T_{105hi}$	$T_{10.5\mu m} - T_{12.3\mu m} > T_{105T120opaque}$
high semitransparent meanly thick clouds:	$\max T_{105hi} < T_{10.5\mu m} < \max T_{105med}$	$R_{0.6\mu m} < \max CiR_{06}$ and $T_{10.5\mu m} - T_{12.3\mu m} > T_{105T120opaque}$
high semitransparent above low or medium clouds:		$R_{0.6\mu m} > \max CiR_{06}$ and $T_{10.5\mu m} - T_{12.3\mu m} > T_{105T120opaque}$
high semitransparent thin clouds:	$\max T_{105med} < T_{10.5\mu m} < \max T_{105low}$	[$R_{0.6\mu m} > \max CiR_{06}$ and $T_{10.5\mu m} - T_{12.3\mu m} > T_{105T120opaque}$ and $\text{varilog}T_{10.5}/\text{varilog}R_{06} > \text{varilogthr}$] or [$R_{0.6\mu m} < \max CiR_{06}$ and $T_{8.7\mu m} - T_{10.5\mu m} > T_{87T105opaque}$]
	$\max T_{105low} < T_{10.5\mu m} < \max T_{105low} + \delta$	[$R_{0.6\mu m} < \max CiR_{06}$ and $T_{8.7\mu m} - T_{10.5\mu m} > T_{87T105opaque}$] or [$R_{0.6\mu m} > \max CiR_{06}$ and $T_{10.5\mu m} - T_{12.3\mu m} > (T_{105T120Threshold} + T_{105T120opaque})/2$ and $T_{8.7\mu m} - T_{10.5\mu m} > T_{87T105opaque}$]

Table 10 Fractional low clouds (daytime)

Fractional clouds:	$\max T_{105\text{med}} < T_{10.5\mu\text{m}} < \max T_{105\text{low}}$	$R_{0.6\mu\text{m}} < \max \text{CiR}_{06}$ and $T_{8.7\mu\text{m}} - T_{10.5\mu\text{m}} < T_{87T105\text{opaque}}$
	$\max T_{105\text{low}} < T_{10.5\mu\text{m}} < \max T_{105\text{low}+\text{delta}}$	[$R_{0.6\mu\text{m}} > \max \text{CiR}_{06}$ and $T_{10.5\mu\text{m}} - T_{12.3\mu\text{m}} >$ $(T_{105T120\text{threshold}} + T_{105T120\text{opaque}})/2$ and $T_{8.7\mu\text{m}} - T_{10.5\mu\text{m}} < T_{87T105\text{opaque}}$] or [$R_{0.6\mu\text{m}} < \max \text{CiR}_{06}$ and $T_{8.7\mu\text{m}} - T_{10.5\mu\text{m}} < T_{87T105\text{opaque}}$]
	$\max T_{105\text{low}+\text{delta}} < T_{10.5\mu\text{m}}$	[$R_{0.6\mu\text{m}} > \min \text{LowR}_{06}$ and $T_{10.5\mu\text{m}} - T_{12.3\mu\text{m}} >$ $(T_{105T120\text{threshold}} + T_{105T120\text{opaque}})/2$] or [$R_{0.6\mu\text{m}} < \min \text{LowR}_{06}$]

The IR thresholds used in this scheme are the following:

- $\max T_{11\text{low}}$, $\max T_{11\text{med}}$, $\max T_{11\text{hi}}$ and $\max T_{11\text{vh}}$ thresholds are explained in section 3.5.2.5
- $T_{105T120\text{Threshold}}$ is the threshold used to separate cloudy from cloud-free pixels (see section 3.5.1.4).
- $T_{87T120\text{opaque}}$, $T_{105T120\text{opaque}}$ and Δ have already been defined in the night-time scheme.

The textural features used are defined as:

- $\text{Varilog}T_{10.5} = \log(1 + \text{var}(T_{10.5\mu\text{m}}))$ and
- $\text{Varilog}R_{0.6} = \log(1 + \text{var}(R_{0.6\mu\text{m}})/a_1)$

where

var stands for the standard deviation in a bin of 9 pixels centred on the pixel to classify.

a_1 is a setup parameter

The threshold applied to the ratio $\text{varilog}T_{10.5}/\text{varilog}R_{0.6}$ (varilogthr) is a constant value.

$\max \text{CiR}_{06}$ mainly aims to separate opaque from semi-transparent clouds. Its computation is based on the assumption that semitransparent and opaque clouds can be roughly separated in the $R_{0.6\mu\text{m}}/T_{10.5\mu\text{m}}$ space by a straight line defined by two reference points:

- The coldest and brighter one is determined by: ($T_{10.5\mu\text{m}}=223.15\text{K}$, $R_{0.6\mu\text{m}}=35\%$).

- The warmest and darker one is depending surface effects and atmospheric effects :
 - Its reflectance depends on the surface reflectance, for which there is an indication from a sea reflectance when over sea or the monthly mean 0.6 μ m value from climatology when over ground.
 - Its temperature is estimated from the SST climatology file over sea or from NWP surface forecast temperature over land.

Two sets (sea and land) of thresholds (slope and intercept of the straight line) are then computed by accounting for cloud bidirectional effects, for the visible calibration variation with time, and for the variation of earth-sun distance.

MinLowR06 is aimed to put a minimum value to an acceptable reflectance of a low cloud, mainly to separate fractional and low clouds. It is derived from a constant value (different over sea and over land) accounted for bidirectional effects.

3.5.2.5 Low/Medium/High Cloud Separation

Once the semitransparent or fractional clouds have been identified, the classification of the remaining cloudy pixels between low, mid-level and high clouds is performed through a simple thresholding on the T10.5 μ m brightness temperature which is related to their height. In order to account for atmospheric variability, NWP forecast temperatures at several pressure levels are used to compute the thresholds that allows to separate very low from low clouds (maxT11low), low from medium clouds (maxT11med), medium from high clouds (maxT11hi), and high from very high clouds (maxT11vh).

To decrease the wrong classification of low clouds as medium clouds (in case strong atmospheric thermal inversion), medium clouds are not allowed to present too large T10.5 μ m-T7.3 μ m brightness temperature differences. In fact, for a field of view obstructed by a low or mean opaque cloud, T7.3 μ m is sensitive to water vapour content above the cloud and to cloud top temperature. Therefore for a same atmospheric profile and identical microphysical properties of opaque clouds, T10.5 μ m-T7.3 μ m decreases with cloud top pressure.

The separation between cumuliform and stratiform clouds is not performed in the current version of CT. Hence, the clouds are labelled as stratiform and a flag indicates that the separation between stratiform and cumuliform clouds has not been attempted.

Table 11 Opaque clouds

Very high opaque and stratiform clouds:	$T_{10.5\mu m} < \max T_{105vh}$	Not semitransparent or fractional
high opaque and stratiform clouds:	$\max T_{105vh} < T_{10.5\mu m} < \max T_{105hi}$	Not semitransparent or fractional
Medium and stratiform clouds:	$\max T_{105hi} < T_{10.5\mu m} < \max T_{105me}$ and $T_{10.5\mu m} - T_{7.3\mu m} < T_{105T73thrlo}$	Not semitransparent or fractional
Low and stratiform clouds:	$\max T_{105me} < T_{10.5\mu m} < \max T_{105low}$ or [$\max T_{105hi} < T_{10.5\mu m} < \max T_{105me}$ and $T_{10.5\mu m} - T_{7.3\mu m} > T_{105T73thrlo}$]	Not semitransparent or fractional

Very low and stratiform clouds:	$\max T_{105\text{low}} < T_{10.5\mu\text{m}}$	Not semitransparent or fractional
---------------------------------	--	-----------------------------------

These five thresholds are the following :

- $\max T_{10.5\text{vh}} = a_1 * T_{500\text{hPa}} + a_2 * T_{\text{tropo}} - a_0$
- $\max T_{10.5\text{h}} = b_1 * T_{500\text{hPa}} - b_2 * T_{700\text{hPa}} + b_0$
- $\max T_{10.5\text{me}} = c_1 * 0.8 * T_{850\text{hPa}} + c_2 * T_{700\text{hPa}} - c_0$
- $\max T_{10.5\text{low}} = d_1 * T_{850\text{hPa}} - d_2 * T_{700\text{hPa}} - d_0$
- $T_{105T73\text{thrlow}} = e_1 * \sec \zeta_{\text{sat}} + e_0$ ($\sec \zeta_{\text{sat}}$ is the secant of the satellite zenith angle ζ_{sat})

If the air temperature at tropopause level is not available:

$$\max T_{10.5\text{vh}} = \max T_{10.5\text{h}} - T_{105_offset}.$$

In case a thermal inversion has been detected in the NWP fields input by the user, an additional process is applied that allows to reclassify medium clouds as low clouds if their $T_{8.7\mu\text{m}} - T_{10.5\mu\text{m}}$ is lower than a specific thresholds depending of the satellite viewing secant and if their $T_{10.5\mu\text{m}}$ is warmer than $\max T_{11\text{med}}$ minus an offset (up to 10°K depending on the $T_{8.7\mu\text{m}} - T_{10.5\mu\text{m}}$ value). The basis of this test is that low $T_{8.7\mu\text{m}} - T_{10.5\mu\text{m}}$ values characterizes low clouds rather than medium clouds. The test on $T_{10.5\mu\text{m}}$ is a security to avoid too cold clouds to be classified as low clouds. This “reclassification test” is applied only in case of the presence of a thermal inversion which is characterized by NWP air temperature differences between two vertical levels (950/925hPa and surface, 850hPa and surface, 850hPa and 950/925hPa) larger than 3°K . This test is not applied over arid areas. To summarize, a mid-level clouds is therefore reclassified as low level clouds if:

- A thermal inversion is present in the NWP fields input by the user
- $\text{Visclim} < \text{VIS_desert}$ (to exclude arid areas)
- $T_{8.7\mu\text{m}} - T_{10.5\mu\text{m}} < -a_0 - (1./\cos(\zeta_{\text{sat}}) - 1)$ and
 $T_{10.5\mu\text{m}} > \max T_{105\text{me}} - a_1$
or
 $T_{8.7\mu\text{m}} - T_{10.5\mu\text{m}} < b_0 - (1./\cos(\zeta_{\text{sat}}) - 1)$ and
 $T_{10.5\mu\text{m}} > \max T_{105\text{me}} - b_1$
or
 $T_{8.7\mu\text{m}} - T_{10.5\mu\text{m}} < -c_0 - (1./\cos(\zeta_{\text{sat}}) - 1)$ and
 $T_{10.5\mu\text{m}} > \max T_{105\text{me}} - c_1$

where

visclim is the climatological $0.6\mu\text{m}$ reflectance value,

$\max T_{105\text{me}}$ is the threshold normally applied to $T_{10.5\mu\text{m}}$ to distinguish low from mid-level clouds,

ζ_{sat} is the satellite zenith angle

A rough insight of the range of low/medium/high clouds top pressures has been obtained by analysing statistics of retrieved cloud top pressure for each of these cloud types. The following rough top pressure ranges have been obtained (no dependency with latitude or season was observed):

- Very low opaque cloud pressure larger than 800hPa
- Low opaque cloud pressure between 650hPa and 800hPa
- Medium opaque clouds pressure between 450hPa and 650hPa
- High opaque clouds pressure between 300hPa and 450hPa
- Very high opaque clouds pressure lower than 300hPa

3.5.2.6 Cloud Phase Flag Computation

The cloud phase retrieval algorithm makes a pragmatic use of T8.7 μ m-T10.5 μ m, T10.5 μ m and the CT cloud type itself to complement a fine analysis of the measured and simulated 0.6 μ m and 1.6 μ m reflectances, as summarized below:

- Ice clouds are usually characterized by stronger absorption at 1.6 μ m than water clouds and should therefore have lower 1.6 μ m reflectances for given 0.6 μ m reflectances. Radiative transfer calculations nevertheless shows that it may be difficult to distinguish clouds made
- of small ice crystal from those made of large water particles. During the phase retrieval, the observed 0.6 μ m and 1.6 μ m reflectances for cloudy pixels are compared to the appropriate pre-calculated cloud reflectances (available in LUT (Look Up table)), ambiguous situations are identified.
- Warm (respectively cold) opaque clouds are supposed to be constituted of water (respectively ice) particles, whereas the temperature range between 0°C and -40°C may correspond to both (or a mixture) of water or ice clouds.
- Cloud classified as semi-transparent in CT cloud type are supposed be constituted of ice particles. Cloud classified as fractional may correspond to thin cirrus or sub-pixel low clouds; their retrieved cloud phase is therefore set “undefined”.
- Water clouds usually have low T8.7 μ m-T10.5 μ m and ice clouds rather high values. Simple viewing angle-dependant thresholds subjectively defined from observations is used to identify obviously water or ice clouds.

Some details on the content of the LUTs and on the origin of the 0.6 μ m/1.6 μ m surface reflectances climatologies used during the process are first given. The algorithm logic is then detailed together with the thresholds computation. The content of the cloud phase flag is also recalled.

LUT computation:

A radiative transfer model is used to perform a set of radiative transfer calculations for four water cloud models (characterized by their droplet size) and four ice cloud models (characterized by their crystal size diameter), as described in Table 12 , to prepare the LUTs.

Table 12 Properties of the cloudy atmosphere used for the radiative transfer calculations to generate the LUTs

<u>Wavelengths</u>	VIS0.6 and NIR1.6 (MSG filters)
<u>Illumination and Viewing Angles</u>	
Cosine Solar Zenith Angle (μ_0):	1.0 to 0.0 in steps of 0.05
Cosine Viewing Zenith Angle (μ):	1.0 to 0.0 in steps of 0.05
Relative Azimuth Angle (ψ):	0, 2.5, 5, 10, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105, 115, 125, 135, 145, 155, 165, 170, 175, 177.5, 180
<u>Cloud Properties</u>	
Water Droplets:	Mie theory $R_e = 4, 8, 16, 30 \mu\text{m}$
Ice Particles:	Obtained from Baum. $D_e = 10.0, 20.0, 30.0, 40.0 \mu\text{m}$
Optical Depths:	0.25, 0.50, 1, 2, 3, 4, 8, 16, 32, 64, 96, 128
Cloud top height:	3 km
<u>Surface Reflectances</u>	
0.64 μm :	0.02, 0.05, 0.1, 0.2, 0.3, 0.5
1.6 μm :	0.02, 0.05, 0.1, 0.2, 0.3, 0.5, 0.7, 1.0
<u>Atmosphere:</u>	Mid-latitude summer

Cloud free 0.6 μm /1.6 μm surface reflectances monthly climatology:

Cloud free surface reflectances are used during the comparison of the simulated and measured 0.6 μm /1.6 μm cloudy reflectances. Over continental areas, they are derived from

MODIS white-sky surface albedo monthly climatologies available from NASA (<http://modis-atmos.gsfc.nasa.gov/ALBEDO/index.html>). These white sky albedos represents bi-hemispheric reflectances without the direct component which is a good approximation of the surface albedo below a cloud. Over sea, constant values are used: 3% (at 0.6 μ m) and 1% (at 1.6 μ m).

The cloud phase flag content is the following:

- Non processed (containing no data or corrupted data) or no cloud
- Water cloud
- Ice cloud
- Undefined (due to known separability problems)

Cloud phase retrieval logic in daytime conditions:

First a cloud phase is retrieved by only comparing measured and simulated 0.6 μ m and 1.6 μ m reflectances as explained below:

- As a first step, the particle size and optical thickness are estimated by a comparison of measured and simulated 0.6 μ m and 1.6 μ m reflectances (assuming a water cloud). Simulated reflectances are obtained by interpolation in LUTs with viewing angles and surface reflectances (known values only dependant on the location and time of the day), and particle size and optical thickness (quantities to be retrieved). This step is straightforward except if the 1.6 μ m reflectances does not regularly decrease with the increasing particle size which may be the case for low cloud optical thickness.
- The ideal case is that for a given 0.6 μ m reflectances the simulated 1.6 μ m reflectances for water clouds are larger than those for ice clouds. The simple comparison of the measured 1.6 μ m reflectance to the simulated one should then give the cloud phase. In practice the cloud phase only using 0.6 μ m and 1.6 μ m is retrieved as follows:
 - A water cloud phase is set if the retrieved particle size is lower than 32 μ m and if the measured 1.6 μ m reflectance is higher than the 1.6 μ m reflectance simulated for all ice cloud model (for the current measured 0.6 reflectance)
 - An ice cloud phase is set:
 - If the retrieved particle size is larger than 32 μ m,
 - or if the retrieved particle size is between 16 and 32 μ m and if the measured 1.6 μ m reflectance is lower than the 1.6 μ m reflectance simulated for at least 3 ice cloud models (for the current measured 0.6 reflectance)
 - or if the retrieved particle size is between 2 and 16 μ m and if the measured 1.6 μ m reflectance is lower than the 1.6 μ m reflectance simulated for all ice cloud model (for the current measured 0.6 reflectance)
 - Otherwise the cloud phase is set “undefined”

The final cloud phase retrieval is based on the cloud phase retrieved from 0.6 μ m and 1.6 μ m reflectances, the CT cloud type, the T8.7 μ m and T10.5 μ m brightness temperatures. The algorithm logic is the following:

- If CT cloud type is fractional : cloud phase is set to undefined

- If CT cloud type is semi-transparent (thin, medium, thick or above) : cloud phase is set to ice
- If CT cloud type is opaque cloud:
 - If $T_{10.5\mu m} > T_{105_watercloud}$: cloud phase is set to water cloud
 - If $T_{10.5\mu m} < T_{105_icecloud}$: cloud phase is set ice clouds
 - If $T_{105_icecloud} < T_{10.5\mu m} < T_{105_watercloud}$:
 - If $T_{8.7\mu m} - T_{10.5\mu m} < a_0 - (1./\cos(\zeta_{sat}) - 1)$: cloud phase is set to water clouds
 - If $T_{8.7\mu m} - T_{10.5\mu m} > b_0 * (1./\cos(\zeta_{sat}) - 1)$ (in K) : cloud phase is set to ice clouds
 - If $a_0 - (1./\cos(\zeta_{sat}) - 1) < T_{8.7\mu m} - T_{10.5\mu m} < b_0 (1./\cos(\zeta_{sat}) - 1)$: cloud phase is the cloud phase retrieved from 0.6 μm and 1.6 μm reflectances (see above)

Cloud phase retrieval logic in night-time or twilight conditions:

The cloud phase retrieval is only based on the use of CT cloud type and on the T8.7 μm and T10.5 μm brightness temperatures. The algorithm logic is the following:

- If CT cloud type is fractional: cloud phase is set to undefined
- If CT cloud type is semi-transparent (thin, medium, thick or above): cloud phase is set to ice
- If CT cloud type is opaque cloud:
 - If $T_{10.5\mu m} > T_{105_watercloud}$: cloud phase is set to water cloud
 - If $T_{10.5\mu m} < T_{105_icecloud}$: cloud phase is set ice clouds
 - If $T_{105_icecloud} < T_{10.5\mu m} < T_{105_watercloud}$:
 - If $T_{8.7\mu m} - T_{10.5\mu m} < a_0 - (1./\cos(\zeta_{sat}) - 1)$: cloud phase is set to water clouds
 - If $T_{8.7\mu m} - T_{10.5\mu m} > b_0 * (1./\cos(\zeta_{sat}) - 1)$ (in K) : cloud phase is set to ice clouds
 - If $a_0 - (1./\cos(\zeta_{sat}) - 1) < T_{8.7\mu m} - T_{10.5\mu m} < b_0 (1./\cos(\zeta_{sat}) - 1)$: cloud phase is set to undefined

3.5.2.7 Quality Assessment

A quality flag is appended to the CT. It allows the identification of pixels that may have been misclassified:

- The quality flag of a cloudless pixel is the same as that of CMA
- A pixel classified as cloudy is flagged as of low confidence:
 - if is flagged as of low confidence in CMA
 - or if, either for spectral (T10.5 μm -T12.3 μm , T3.8 μm -T10.5 μm , R0.6 μm) or for textural features (variance T10.5 μm coupled to variance R0.6 μm), the difference between the threshold and the measurement is lower that a security margin listed in next table:

Table 13 Properties of the cloudy atmosphere used for the radiative transfer

Cloud Test	T10.5μm- T12.3μm	T3.8μm- T10.5μm	T8.7μm- T10.5μm	R0.6	varilogT10.5 /varilogR06
Security margin for quality assessment	A ₁	A ₂	A ₃	A ₄ *threshold	A ₅ *threshold

3.5.3 Cloud Top Temperature and Height (CTTH) Algorithm Description

3.5.3.1 Algorithm Outline

The different steps of the processing, applied to cloud-classified image, are listed below. The exact process applied to each pixel depend on the availability of NWP and MTG-FCI data.

If all mandatory NWP and MTG-FCI data are available (see list of input for CTTH):

The following process is then applied:

RTTOV radiative transfer model is applied using NWP temperature and humidity vertical profile to simulate 6.2 μ m, 7.3 μ m, 13.4 μ m, 10.5 μ m, and 12.3 μ m cloud free and overcast (clouds successively on each vertical pressure levels) radiances and brightness temperatures. This process is performed in each segment of the image (the size of the segment is defined by the user, the default value being 16*16 IR pixels). The vertical profiles used are temporally interpolated to the exact slot time using the two nearest in time NWP fields input by the user.

The techniques used to retrieve the cloud top pressure depend on the cloud's type (as available in CT product):

For very low, low or medium thick clouds: The cloud top pressure is retrieved on a pixel basis and corresponds to the best fit between the simulated and the measured 10.5 μ m brightness temperatures. The simulated brightness temperature are available at the segment resolution. In case of the presence of a low level thermal inversion in the forecast NWP fields, the very low, low or medium clouds are assumed to be above the thermal inversion only if their brightness temperatures are colder than the air temperature below the thermal inversion minus an offset whose value depends on the nature of thermal inversion (dry air above the inversion level or not).

For high thick clouds: a method called the radiance rationing method (see the next bullet for further explanation of this method) is first applied to remove any remaining semi-transparency that could have been undetected by the cloud type scheme. In case of failure, the method defined for medium opaque clouds is then applied.

For high semi-transparent clouds: The 10.5 μ m infrared brightness temperatures are contaminated by the underlying surfaces and cannot be used as for opaque clouds. A correction of semi-transparency is applied, which requires the use of two infrared channels: a window (10.5 μ m) and a sounder (13.4 μ m, 7.3 μ m or 6.2 μ m) channels. The basis is that clouds have a stronger impact in a window channel than in a sounding channel. The following process is implemented:

The H₂O/IRW intercept method [RD-1] based on a window (10.5 μ m) and sounding (13.4 μ m, 7.3 μ m or 6.2 μ m) radiance bi-dimensional histogram analysis, is applied. The histograms are built in boxes of 32*32 IR pixels centred on each segment of the image (whose size is defined by the user, the default value being 16*16 IR pixels). It therefore allows the retrieval of cloud top pressure at the segment horizontal resolution (i.e., by default 16*16 IR pixels). This method is successively applied using the 7.3 μ m, 6.2 μ m and 13.4 μ m radiances, the final

retrieved cloud pressure being the minimum cloud top pressures obtained using single sounding channels.

- If no result can be obtained with the H₂O/IRW intercept method, the radiance ratioing method, is then applied to the 10.5 μ m and 7.3 μ m radiances to retrieve the cloud top pressure at a pixel basis. If no result can be obtained, the method is applied to 6.2 μ m and finally to 13.4 μ m radiances.
- If the radiance ratioing technique leads to cloud top temperatures warmer than the corresponding 10.5 μ m brightness temperatures, the method for thick clouds is used instead.
- For fractional clouds : No technique is proposed in the current version for low broken clouds. The sounding channels are nearly unaffected by broken low clouds and are therefore useless; the infrared channels at 10.5 μ m and 12.3 μ m are contaminated by the surface and cannot therefore be used as for opaque clouds.
- A gap-filling procedure is applied in semi-transparent cloud top pressure field: in each box of 32x32 SEVIRI IR pixels, a cloud top pressure is computed as the average pressure of all pixels containing semi-transparent clouds inside the current and the eight surrounding boxes. This average cloud top pressure is then assigned to all pixels of the current box containing semi-transparent clouds and having no retrieved cloud top pressure.
- Cloud top temperature and height (above sea level) are then computed from their pressure using general modules. During these processes, the atmospheric vertical profiles are temporally interpolated to the exact slot time using the two nearest in time NWP outputs fields.
- Effective cloudiness (defined as the fraction of the field of view covered by cloud (the cloud amount) multiplied by the cloud emissivity in the 10.5 μ m window channel) is also computed during the processing. It is equal to 1.0 for thick clouds and takes a value between 0. and 1. for semi-transparent clouds.

In case some mandatory NWP or satellite data are missing:

Cloud top temperature of very low, low, medium and high clouds are then computed by applying a climatological atmospheric absorption correction to the 10.5 μ m brightness temperature using look-up tables. The cloud top pressure and height are not retrieved.

3.5.3.2 Opaque Cloud Top Temperature Retrieved from Climatological Atmospheric Absorption Correction

This empirical technique allows to retrieve the cloud top temperature of opaque clouds on a pixel basis, only using T10.5 μ m brightness temperature. This technique is used if NWP temperature and humidity vertical profile or if mandatory SEVIRI channels are missing.

The cloud top temperature is calculated from the 10.5 μ m brightness temperature by adding an offset that accounts for the atmospheric absorption. This offset, which should be higher for low clouds and high viewing angles, is estimated from a pre-computed table with the 10.5 μ m brightness temperature of the pixel (indicating the cloud height) and the viewing angle as input.

This pre-computed table has been elaborated off-line using RTTOV simulations : T10.5 μ m brightness temperatures have been simulated from radio-soundings available in TIGR dataset by assuming opaque clouds at various pressure levels in the troposphere. The values of the pre-computed table have been regressed from these simulations. Pixels processed by this method are flagged as of low confidence.

3.5.3.3 Opaque Cloud Top Pressure Retrieved from Window Channel Brightness Temperature

This technique allows to retrieve the cloud top pressure of opaque clouds on a pixel basis. It is not applied to low or medium clouds if a thermal inversion is detected in forecast NWP fields (see 3.5.3.4). It relies on the support of on-line RTTOV simulations and therefore requires the availability of the atmospheric vertical profile. These atmospheric profiles are forecast by a NWP model and temporally interpolated to the exact slot. The RTTOV simulations are computed on segments whose size is defined by the user (by default, 16*16 IR pixels).

Top of Atmosphere T10.5 μ m brightness temperatures are simulated assuming opaque clouds at the different pressure levels of the atmospheric vertical profile. These simulated T10.5 μ m brightness temperature vertical profiles are then inspected from surface level up to the tropopause level : two consecutive pressure levels having simulated temperatures respectively higher and lower than the T10.5 μ m brightness temperature are looked for; the cloud top pressure is finally obtained by a linear interpolation (logarithm of pressure used) between these two simulated temperatures.

The consistency of the technique is estimated on-line by retrieving the cloud top pressure from both the T10.5 μ m and T12.3 μ m brightness temperatures, the result being ideally equal. The pixel will be flagged as of low confidence if the difference between the results obtained from these two wavelengths is larger than 0.5°C.

3.5.3.4 Low or Medium Opaque Cloud Top Pressure Retrieved from Window Channel Brightness Temperature in Case of Thermal Inversion

This technique allows retrieving the cloud top pressure of low or medium opaque clouds on a pixel basis, in case a thermal inversion has been detected in forecast NWP fields. It relies on the support of on-line RTTOV simulations and therefore requires the availability of the atmospheric vertical profile. These atmospheric profiles are forecast by a NWP model, temporally and spatially interpolated to the exact slot and to the processed pixel. The RTTOV simulations are computed on segments whose size is defined by the user (by default, 16*16 SEVIRI IR pixels).

The cloud is set below the thermal inversion only if its T10.5 μ m brightness temperature is larger than the air temperature below the inversion minus 10K (in case of subsident thermal inversion (see the definition in 3.5.3.7)) or larger than the simulated T10.5 μ m brightness temperature below the inversion minus 5K (in case of non subsident thermal inversion). In that case, the cloud is set below the inversion at a level between the top of the inversion and the colder part below the inversion depending on the strength of the inversion.

Otherwise, the cloud is set above the thermal inversion. The method to retrieve its top pressure is then similar to the one described in 3.5.3.3 if the difference between the T10.5 μ m brightness temperature and the air temperature is larger than 10K. Otherwise, the cloud top is set at a level between the level where simulated and observed brightness temperature fits best and a level between the top of the inversion and the colder level between the inversion. Pixels processed by this method are flagged as of low confidence. Moreover the presence of a thermal inversion in the forecast vertical temperature profile is also flagged.

3.5.3.5 Semitransparent Cloud Top Pressure Retrieved Using Radiance Ratioing Technique

The radiance ratioing technique allows retrieving semitransparent cloud top pressure at a pixel scale from radiances in two infrared channels, one of these channels being a sounding channel. It relies on on-line RTTOV simulations and therefore requires the availability of the atmospheric vertical profile. The basic equation 1 of the method is the following equation:

$$\frac{L_{m1} - L_{clear1}}{L_{m2} - L_{clear2}} = \frac{N\varepsilon_1 (L_{op1} - L_{clear1})}{N\varepsilon_2 (L_{op2} - L_{clear2})} \quad (1)$$

where L_m is the measured radiance, L_{clear} is the clear radiance, L_{op} is the opaque cloud radiance, N is the cloud amount and ε is the cloud emissivity. The terms of denominators on both side come from the same channel (index 2) and the nominators from the other one of the pair (index 1).

Assuming that the ratio of the emissivities is close to one the equation becomes simpler in equation 2:

$$\frac{L_{m1} - L_{clear1}}{L_{m2} - L_{clear2}} = \frac{L_{op1} - L_{clear1}}{L_{op2} - L_{clear2}} \quad (2)$$

Both side of this equation depends on the chosen channels, surface temperature, vertical temperature and absorbing material profiles. The right side of the equation also depends on the cloud pressure due to L_{op} . Consequently if a fixed surface temperature and vertical profiles is used, the right side becomes a function depending on the pressure, the left side being a constant. The retrieved cloud top pressure corresponds to the pressure that satisfies Eq.2. In practice the clear sky radiances L_{clear} are either measured or simulated, the opaque cloud radiances L_{op} are simulated values, while the L_m is the measured data.

It has been implemented using the 10.5 μ m window channel together with the 13.4 μ m CO₂ channels, the 7.3 μ m and 6.2 μ m water vapour channel. It allows to retrieve cloud top pressure for semitransparent ice clouds and high thick clouds on a pixel basis. The process is performed in several steps described below.

Simulation of the radiances

TOA infrared 10.5 μm , 13.4 μm , 7.3 μm and 6.2 μm radiances for clear atmosphere and for opaque clouds at various pressure levels have been previously simulated with RTTOV.

Modification of simulated radiances

The method very much depends on the cloud free and opaque clouds values. As the simulated radiances for the water vapour channels are not reliable enough (mainly due to the inaccuracy of the atmosphere water vapour description by NWP models, as pointed out in Nieman et al., 1993), the following process is applied to modify them:

- modification of cloud free 7.3 μm and 6.2 μm simulated radiances : cloud free 7.3 μm and 6.2 μm radiances are computed over the whole image at the segment spatial resolution from cloud free individual pixels and pixels containing opaque clouds too low to affect these measurements. They are used instead the simulated ones.
- modification of opaque 7.3 μm and 6.2 μm simulated radiances : the cloudy 7.3 μm and 6.2 μm radiances are modified to account for the discrepancy between the simulated and observed cloud free radiances : the radiance for clouds at the tropopause remain unchanged, the radiance for the lowest clouds are replaced by the cloud free observed radiance, whereas the modification for the other clouds is linearly linked to its 10.5 μm radiance. This modification is performed only if it leads to an increase of the simulated radiances.
- modification of cloud free 10.5 μm and 13.4 μm simulated radiances : cloud free 10.5 μm and 13.4 μm radiances are computed over the whole image at the segment spatial resolution from cloud free individual pixels. When available, these observed cloud free values replace the simulated ones.

Calculation of the cloud top pressure

Using the simulated and the measured radiances, the simulated ratio is calculated as a function of the cloud top pressure (right side of Eq.2), and the measured ratios (left side of Eq.2). The retrieved pressure level corresponds to this difference equal to zero.

Calculation of the cloud effective cloudiness

The cloud effective cloudiness (N_{ϵ}) is calculated from the 10.5 μm window radiance, using the retrieved cloud pressure.

Rejection

The retrieved cloud pressure is assumed to be unreliable in the following cases :

- the difference between the measured and the simulated clear sky radiances ($L_m - L_{\text{clear}}$) is within three times the instrument noise level.
- the difference between the retrieved and measured radiances is larger than 30% of the difference between the simulated and measured radiances

Quality flag

The pressure retrieval is flagged as of low confidence if :

- the cloud free cluster is derived from simulation.
- the retrieved radiances are higher than measured ones.

This technique is very much sensitive to the noise (especially for very thin clouds), and to the inaccuracy of the water vapour channel simulated radiances (if 7.3 μ m or 6.2 μ m channels are used), due to bad water vapour forecast.

3.5.3.6 Semi-transparent Cloud Top Pressure Retrieved using H₂O/IRW Intercept Method

The H₂O/IRW intercept method is described in [RD-1]. It is successively applied to the window 10.5 μ m channel and one sounding channel (either 6.2 μ m, 7.3 μ m or 13.4 μ m), the final retrieved cloud pressure being the averaged cloud top pressures obtained using a single sounding channel. This method is based on a radiance histogram analysis. The histograms are built in boxes of 32*32 IR pixels centred on each segment of the image (whose size is defined by the user, the default value being 16*16 IR pixels). It therefore allows the retrieval of semitransparent ice cloud top pressure at the segment horizontal resolution (i.e., by default 16*16 IR pixels). It makes use of on-line RTTOV simulations and therefore requires the availability of the atmospheric vertical profile.

The fundamental assumption of the method is that there is a linear relationship between radiances in the two spectral bands observing a single cloud layer. In particular, all pairs of radiances in the sounding (6.2 μ m, 7.3 μ m or 13.4 μ m) and window (10.5 μ m) channels viewing a cloud layer at pressure p_c will lay along a straight line, the spreading along the line corresponding to changes in cloud amounts. On the other hand, the pairs of radiances in the window (10.5 μ m) and sounding channel (6.2 μ m, 7.3 μ m or 13.4 μ m) for opaque clouds at different pressure levels will lay along a curve that can be calculated from the atmospheric vertical structure using RTTOV radiative transfer model. Therefore, the cloud top pressure for semitransparent ice clouds is retrieved as the intersection between the linear fit to the observations and the simulated opaque cloud curve.

The process is performed in several steps detailed below:

Simulation of the radiances

TOA infrared 10.5 μ m, 13.4 μ m, 7.3 μ m and 6.2 μ m radiances for clear atmosphere and for opaque clouds at various pressure levels have been previously simulated with RTTOV.

Modification of simulated radiances

As the method very much depends on the opaque clouds values, and as these simulations for the water vapour channels are not very reliable (mainly due to the inaccuracy of the atmosphere water vapour description by NWP models), the following process is applied to modify the simulated values :

- modification of cloud free 7.3 μ m and 6.2 μ m simulated radiances : cloud free 7.3 μ m and 6.2 μ m radiances are computed over the whole image at the segment spatial

resolution from cloud free individual pixels and pixels containing opaque clouds too low to affect these measurements. They are used instead the simulated ones.

- modification of opaque 7.3 μm and 6.2 μm simulated radiances : the cloudy 7.3 μm and 6.2 μm radiances are modified to account for the discrepancy between the simulated and observed cloud free radiances : the radiance for clouds at the tropopause remain unchanged, the radiance for the lowest clouds are replaced by the cloud free observed radiance, whereas the modification for the other clouds is linearly linked to its 10.5 μm radiance. This modification is performed only if it leads to an increase of the simulated radiances.

Calculation of the cloud top pressure

A straight line is adjusted, using the 13.4 μm (or 7.3 μm or 6.2 μm) and 10.5 μm radiances of all pixels previously classified as semitransparent, high thick clouds or cloud-free. The intersection of this straight line with the opaque cloud curve will give the cloud top pressure. This process is successively applied to the three sounding channels (7.3 μm , 6.2 μm and 13.4 μm). When cloud top pressure can be obtained from more than one sounding channel, the final retrieved cloud top pressure corresponds to the minimum value obtained with the individual sounding channels.

Calculation of the effective cloudiness

The effective cloudiness ($N\epsilon$) of each pixel is calculated from the 10.5 μm window radiance, using the retrieved cloud pressure.

Rejection

The retrieved cloud pressure is assumed to be unreliable in the following cases :

1. unreliable regression :

- too few pixels (less than 50)
- too low spread of the pixels in the 10.5 μm channel is observed (less than 15 $\text{mWm}^{-2} \text{sr}^{-1} \text{cm}$ between the 10.5 μm radiance of the coldest and the warmest pixels)
- too low correlation coefficient (lower than 0.7)

2. not adequate regression line :

- slope of the regression line too small
- regression line too close to opaque cloud curve

If no intersection has been found, but if the regression seems reliable (large number of pixels (more than 100), large spread of the pixels in the 10.5 μm channel (more than 23 $\text{mWm}^{-2} \text{sr}^{-1} \text{cm}$ between the 10.5 μm radiance of the coldest and the warmest pixels), large correlation coefficient (larger than 0.9), large regression's slope), then the cloud top pressure is assumed to be the tropopause's pressure minus 50hPa, but the retrieval is flagged as bad quality.

Quality flag

The pressure retrieval is flagged as good confidence if :

- The final cloud top pressure is a minimum value obtained from at least two sounding channels, the maximum difference between each individual cloud top pressure being less than 75hPa.
- The final cloud top pressure is obtained using a single sounding channel, but:
 - a high number of pixel is used in the regression (more than 100 pixels),
 - a large spread of the pixels in the 10.5 μ m channel is observed (more than 23 mWm⁻²sr⁻¹cm between the 10.5 μ m radiance of the coldest and the warmest pixels),
 - a high correlation coefficient is observed (larger than 0.8)

3.5.3.7 Identification and Characterisation of Thermal Inversions from Forecast NWP Fields

The NWP forecast air temperature and relative humidity on user-defined pressure levels are analysed as follows to identify and characterize thermal inversions:

- thermal inversion is detected if layers exist between the surface and 700hPa where the air temperature increases with decreasing pressure.
- this thermal inversion is said "subsident" if the relative humidity between 850 and 600hPa is lower than 30%.

3.5.3.8 Tropopause Height Estimation

The module used has been developed by the aeronautic forecast service in Toulouse. The pressure and height of the tropopause is extracted from a vertical profile (temperature, height and pressure), the ground height and the latitude. The tropopause estimation is mainly based on the WMO definition of the tropopause : the lowest level (above 5000m) corresponding to a temperature decrease of less than 2°C/km during 2km. A maximum height of the tropopause level is assumed (20km at the equator, 12-13km at the poles) to check the result's coherency.

3.5.3.9 Cloud Top Height (above Sea Level) Retrieved from its Pressure

A module is used to compute the height vertical profile from the corresponding vertical profile of pressure, temperature & water vapour mixing ratio, the surface height and the latitude. The cloud height (above sea level) is then interpolated using the height of the two nearest pressure levels in the vertical profile. The interpolation used is linear in logarithm of the pressure.

3.5.3.10 Cloud Top Temperature Retrieved from its Pressure

A vertical temperature profile in pressure levels is needed in this process. The cloud temperature is interpolated using the temperature of the two nearest pressure levels in the vertical profile. The interpolation used is linear in logarithm of the pressure.

4 FUTURE DEVELOPMENTS

The three cloud processing modules, in their current version applicable to MSG, are scientifically highly advanced and well validated.

It is, however, expected, that a number of changes/improvements will be done to the software to account for the MTG-FCI specifics:

- The software will have to be adapted to the different spatial sampling distances (1 km and 2 km) for different channels.
- The CT product will offer a separation between cumuliform and stratiform clouds
- The CTTH product will include information of the vertical extent of clouds
- The CT/CTTH products will also include information on the presence of multi-layer cloud situations and their respective heights

It should be noted that such future developments will be more detailed during the NWC-SAF CDOP-2.