The EUMETSAT
Network of
Satellite
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Facilities

NWC SAF
Support to Nowcasting and
Very Short Range Forecasting

Algorithm Theoretical Basis Document for Cloud Top Temperature, Pressure and Height of the NWC/PPS

NWC/CDOP2/PPS/SMHI/SCI/ATBD/3, Issue 1, Rev. 0

15 September 2014

Applicable to SAFNWC/PPS version 2014

Applicable to the following PGE:s:

PGE	Acronym	Product ID	Product name	Version number
PGE03	CTTH	NWC-068	Cloud Top Temperature and Height	4.0

Prepared by Swedish Meteorological and Hydrological Institute (SMHI)

REPORT SIGNATURE TABLE

Function	Name	Signature	Date
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DOCUMENT CHANGE RECORD

Version	Date	Pages	Changes
1.0d	22 January 2014	34	Replacing CDOP-document: SAF/NWC/CDOP/SMHI-PPS/SCI/ATBD/3 First version for SAFNWC/PPS v2014 Changes since v2012: -Updated the document according to scientific changes of v2014. -Updated the output format, according to v2014 changes.
1.0	15 September 2014	35	Implemented RIDs from PCR-v2014: -Action4: Provided rationale for using the RTTOV radiative transfer model. -DF2 (rewriting section 1.6; updating to RTTOV 11; option to use actual surface emissivity together with RTTOV) -LSc1 (formal issues) -LSc2 (summary of requirements) -LSc3, PW24-PW25, PW28, PW30-PW33, PW35-PW36 (editorials and clarifications) -PW29 (updating terminology: histogram => scatter plot) General changes: -Added short description about surface emissivity, in scientific updates, and in list of inputs.

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List of Tables and Figures

1. INTRODUCTION

The EUMETSAT "Satellite Application Facilities" (SAF) are dedicated centres of excellence for processing satellite data, and form an integral part of the distributed EUMETSAT Application Ground Segment (http://www.eumetsat.int). This documentation is provided by the SAF on Support to Nowcasting and Very Short Range Forecasting, SAFNWC. The main objective of SAFNWC is to provide, further develop and maintain software packages to be used for Nowcasting applications of operational meteorological satellite data by National Meteorological Services. More information can be found at the SAFNWC webpage, http://www.nwcsaf.org . This document is applicable to the SAFNWC processing package for polar orbiting meteorological satellites, SAFNWC/PPS, developed and maintained by SMHI (http://nwcsaf.smhi.se).

1.1 PURPOSE

This document is the Algorithm Theoretical Basis Document for the PGE03 (CTTH, Cloud Top Temperature and Height) of the SAFNWC/PPS software package.

This document contains a description of the algorithm, including scientific aspects and practical considerations.

1.2 SCOPE

This document describes the algorithms implemented in the PGE03 version 4.0 of the 2014 SAFNWC/PPS software package delivery.

1.3 DEFINITIONS AND ACRONYMS

Acronym	**Explanation**
ACPG	AVHRR/AMSU Cloud Product Generation software (A major part of the SAFNWC/PPS s.w., including the PGE:s.)
AEMET	Agencia Estatal de Meteorología (Spain)
AHAMAP	AMSU-HIRS-AVHRR Mapping Library (A part of the SAFNWC/PPS s.w.)
AMSU	Advance Microwave Sounding Unit
AVHRR	Advanced Very High Resolution Radiometer
CDOP	Continuous Development and Operational Phase
CDOP-2	Second Continuous Development and Operational Phase
CMA	Cloud Mask (also PGE01)
CPP	Cloud Physical Products
CT	Cloud Type (also PGE02)
CTTH	Cloud Top Temperature, Height and Pressure (also PGE03)
EPS	EUMETSAT Polar System
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites

Acronym	**Explanation**
GEO	
MHS	Microwave Humidity Sounding Unit
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PC	Precipitating Cloud (also PGE04)
PGE	Process Generating Element
PPS	Polar Platform System
RGB	Red Green Blue
RTM	Radiative Transfer Model
RTTOV	Radiative Transfer for TOVs
SAF	Satellite Application Facility
SAFNWC	Satellite Application Facility for support to NoWcasting
SMHI	Swedish Meteorological and Hydrological Institute
TBC	To Be Confirmed
TBD	To Be Defined
TOA	Top Of Atmosphere
VIIRS	Visible Infrared Imaging Radiometer Suite

See [RD.1.] for a complete list of acronyms for the SAFNWC project.

1.4 REFERENCES

1.4.1 Applicable documents

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]

For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the current edition of the document referred applies.

Current documentation can be found at SAFNWC Helpdesk web: http://www.nwcsaf.org

Ref	Title	Code	Vers	Date
[AD.1]	NWCSAF Project Plan	NWC/CDOP2/SAF/AEMET/MGT/PP	1.2	28/06/13
[AD.2]	NWCSAF Product Requirements Document	NWC/CDOP2/SAF/AEMET/MGT/PRD	1.5	05/06/14
[AD.3]	System and Components Requirements Document for the SAFNWC/PPS	NWC/CDOP2/PPS/SMHI/SW/SCRD	1.0	15/0914

Table 1: List of Applicable Documents

1.4.2 Reference documents

The reference documents contain useful information related to the subject of the project. These reference documents complement the applicable ones, and can be looked up to enhance the information included in this document if it is desired. They are referenced in this document in the form [RD.X]

For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the current edition of the document referred applies

Current documentation can be found at SAFNWC Helpdesk web: http://www.nwcsaf.org

Ref	Title	Code	Vers	Date
[RD.1.]	The Nowcasting SAF Glossary	NWC/CDOP2/SAF/AEMET/MGT/GLO	2.0	18/02/14
[RD.2]	Validation of CM-SAF cloud products derived from AVHRR data in the Arctic region"	SAF/CM/SMHI/SR/CLOUDS-ORR/B	1.0	19/01/09
[RD.3]	Output Data Format of the SAFNWC/PPS	NWC/CDOP2/PPS/SMHI/SW/DOF	1.1	15/0914
[RD.4]	Algorithm Theoretical Basis Document for the Cloud Mask of the NWC/PPS	NWC/CDOP2/PPS/SMHI/SCI/ATBD/1	1.0	15/09/14
[RD.5]	Algorithm Theoretical Basis Document for the Cloud Type of the NWC/PPS	NWC/CDOP2/PPS/SMHI/SCI/ATBD/2	1.0	15/09/14
[RD.6]	Scientific and Validation Report for the Cloud Product Processors of the NWC/PPS	NWC/CDOP2/OOS/SMHI/SCI/VR/Cloud	1.0	15/09/14

Table 2: List of Referenced Documents

1.4.3 Scientific references

Chevallier, M. M. F. and Tjemkes, S., 2001. An improved general fast radiative transfer model for the assimilation of radiances observations. Technical Memorandum 345, European Center for Medium Range Weather Forecasting (ECMWF). Available from the librarian at ECMWF.

Derrien, M., Lavanant, L., and Gleau, H. L., 1988. Retrieval of the cloud top temperature of semi-transparent clouds with AVHRR. In *Proceedings of the IRS'88, Lille, France*, pp. 199-202.

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Inoue, T., 1985. On the temperature and effective emissivity determination of semi-transparent cirrus clouds by bi-spectral measurements in the 10 μm window region. *Journal of the Meteorological Society of Japan* ***63***(1), 88-98.

Karlsson, K.-G. and Dybbroe, A., 2009. Evaluation of Arctic cloud products from the EUMETSAT Climate Monitoring Satellite Application Facility based on CALIPSO-CALIOP observations. *Atmos. Chem. Phys. Discuss.*, ***9***, *16755-16810, 2009.*

Karlsson, K.-G., Rühelä A., Müller R., Meirink J.F., Sedlar J., Stengel M., Lockhoff M., Trentmann J., Kasper F., Hollmann R. and Wolters E., 2013. CLARA-A1: a cloud, albedo and radiation dataset from 28yr of global AVHRR data.. *Atmos. Chem. Phys.* ***13***,*5351-5367, 2013 doi:10.5194/acp-13-5351-2013*

Karlsson, K.-G. and Johansson E, 2013, On the optimal method for evaluating cloud products from passive satellite imagery using CALIPSO-CALIOP data: example investigating the CM SAF CLARA-A1 dataset. *Atmos Meas. Thech.* ***6***, *1271-1286, 2013 doi:105194/amt-6-1271-2013*

Korpela, A., Dybbroe, A., and Thoss, A., 2001. Retrieving Cloud Top Temperature and Height in Semi-transparent and fractional cloudiness using AVHRR. Reports Meteorologi 100, SMHI, Folborgsvägen 1, SE-60176 Norrköping, Sweden. NWCSAF Visiting Scientist Report.

Menzel, W. P., l. Smith, W., and Stewart, T. R., 1983. Improved Cloud Motion Wind Vector and Altitude Assignment using VAS. *Journal of Climate and Applied Meteorology* ***22***, 377-384.

Saunders, R. W., Matricardi, M., and Brunel, P., 1999, April). An Improved Fast Radiative Transfer Model for Assimilation of Satellite Radiances Observations. *QJRMS* ***125***(556), 1407-1425.

Saunders, R., Matricardi, M., and Geer, A., 2008, RTTOV9.1 user guide, *UK Met office publication, NWPSAF-MO-UD-016*, 57p.

1.5 DOCUMENT OVERVIEW

This document contains a theoretical description of the algorithms for cloud top Temperature, Pressure and Height derivations. The document has been structured in the following sections:

- Section 1 contains the current introduction along with the list of used acronyms and applicable and reference documents.
- Section 2 A short introduction to the ctth product
- Section 3 A short overview of the ctth algorithm
- Section 4 Algorithm description in more detail

1.6 SCIENTIFIC UPDATES SINCE PPS VERSION 2012

For v2014 PGE03 has been updated to process faster, be able to retrieve cloud heights for almost all cloudy pixels, and give more accurate results. Major contributing updates were:

- The curve fitting algorithm in the semitransparent CTT scheme has been exchanged, optimized and parallelized, leading to
  - More valid fits since the search is restricted to realistic parameter combinations
  - More accurate heights for low- and medium-level clouds due to a new quality measure.
  - Speed-up in processing time
- More clouds are now being treated as semi-transparent, by taking into account both cloud type and brightness temperature differences, leading to improvement of height for high level clouds and multilevel clouds.
- Strategies to identify best fit of cloud top temperature to NWP height profile were refined, by adding uncertainties to the NWP temperature, in order to better fit clouds to corresponding temperature inversions, leading to:
  - Reduction of systematic overestimation of cloud height for some low level clouds which before missed assignment to corresponding temperature inversion
  - Treatment of cloud height assignment around troposphere was updated, leading to that occasional gross misclassifications to mesosphere heights are avoided
  - Treatment of cloud height for warm clouds (warmer than NWP surface temperature) was updated, leading to that occasional gross miss-classifications to stratosphere heights are avoided
- The strategy for use of RTTOV simulations has been simplified, leading to both reduced computation time and a slight increase of accuracy since rounding errors between pressure levels are now avoided. In previous versions there was a preparation step simulating Tb11 for opaque clouds at each pressure level. TB was than interpolated between pressure levels. Now only cloud-free land and cloud-free sea Tb11 temperatures are simulated and used to calculate the atmospheric corrections at the surfaces. Those are then used together with the specific humidity profile to find a temperature profile corrected for atmospheric absorption. Profiles corrected for atmospheric absorption are now also used for semi-transparent clouds.
  - RTTOV version was updated from RTTOV 9 to RTTOV11.x
  - Actual surface emissivity can now be used in the RTTOV calculations, if configured for. The default setting is to have it off. See [RD.6] for arguments.

2. INTRODUCTION TO THE SAFNWC/PPS CTTH

The cloud top temperature, pressure and height (CTTH) retrieval based on polar orbiter data developed within the SAFNWC project aims at nowcasting applications. The main use of this product is in the analysis and early warning of thunderstorm development and the height assignment for aviation forecasting. The product may also serve as input to mesoscale models for use in Nowcasting in general, or as input to other satellite retrievals used for Nowcasting. The SAFNWC CTTH retrieval, based on imager data from polar orbiter, will also be used to build up cloud climatologies within the CMSAF.

The CTTH product aims at providing information on the cloud top temperature and height for all pixels identified as cloudy in the satellite scene.

Many NMSs of EUMETSAT member states (including SMHI) use still today the uncorrected brightness temperature information from IR imagery as a rough estimation of cloud top temperatures. For the optically thick clouds this estimation is in most cases acceptable. However, for pixels containing semi-transparent or fractional clouds (often representing a large fraction of cloudy pixels) this information is definitely misleading, yielding sometimes to quite a large underestimation of true cloud top heights.

The objective of the SAFNWC CTTH product has been to create a retrieval that as far as possible (considering both computational accuracy and CPU efficiency aspects) compensates for the semi-transparency effect and the effect of an absorbing atmosphere between the cloud top and the satellite sensor.

It must, however, be remembered that neither the NOAA, Metop nor the EOS satellites does provide the most optimal platform for semi-transparency correction and cloud top temperature and height retrieval in general. The derivation of the cloud top height using the instruments on these satellites will naturally be rather indirect requiring a lot of ancillary data like NWP model output. Other more direct techniques exist, e.g. using stereo-scope imagery requiring a setup of two geostationary satellites with overlapping fields of view.

Sounding channels as on the HIRS instrument would provide the possibility for applying the radiance rationing technique, as detailed by Menzel et al. (1983). This technique applies to single layers of high semi-transparent clouds. The HIRS channels do, however, have rather poor horizontal and vertical resolution. The AVHRR and similar instruments provides window channels which may be used to build up two dimensional scatter plots according to a technique based on the work of Inoue (1985) and Derrien et al. (1988). This technique is neither particularly direct, but though it is designed for single layers of semi-transparent cirrus it may also work on broken/sub-pixel clouds.

For the SAFNWC CTTH we have chosen the latter technique to be applied to AVHRR data and likewise channel combinations from other instruments.

2.1 REQUIREMENTS

The requirements for the SAFNWC/PPS products are described in the Product Requirements Document [AD.2]. In Table 3 is given a summary of the requirement specific for the CTTH product.

Table 3 Accuracy requirements for Cloud Top Height

	Bias (opaque clouds)	**Standard deviation (opaque clouds)**	**Bias (semi-transparent clouds)**	**Standard deviation (semi-transparent clouds)**
Threshold accuracy	1000 m	2000 m	2000 m	2000 m
Target accuracy	500 m	1500 m	1500 m	1500 m
Optimal accuracy	200 m	500 m	200 m	500 m

3. ALGORITHM OVERVIEW

The CTTH product is derived using two algorithms, one for opaque and one for fractional and semi-transparent clouds, and is applied to all cloudy pixels as given by the CT product. The algorithms are summarised below, and further details may be found in the next sub-sections.

- Cloudfree TOA radiances and brightness temperatures are calculated for the 11 and 12µm channels applying the RTTOV radiative transfer model version 11 (Eyre, 1991, Saunders et al., 1999, Chevallier and Tjemkes, 2001) using temperature and humidity profiles taken from NWP (analysis or a short range forecast). The selection of RTTOV for calculations of brightness temperatures was driven mainly by its performance speed. Since these calculations are done online, speed counts even more than for the application in look-up table calculation (compare discussion in RD.4). Atmospheric correction (difference between temperature and channel 11 brightness temperature) for the surface are calculated using the cloudfree RTTOV simulation and the NWP surface temperature. Atmospheric corrections for each pressure level are calculated using the surface correction and the humidity profile. The overcast simulation for each pressure level is calculated using the NWP temperature adjusted with the atmospheric correction derived for that level. The radiance simulations are done on a coarse horizontal resolution (segments of high-resolution pixels). The segment size in number of high-resolution pixels is configurable for the user, but should be chosen so as to be comparable to the grid resolution of the NWP model used. The lower the resolution the faster the algorithm. The NWP field used are the one closest in time to the satellite overpass.
- Retrieve the cloud top pressure or temperature depending on the cloud type:
  - For most pixels classified into one of the opaque cloud types: The cloud top pressure is derived from the best fit between the simulated and the measured T11. The simulated T11 from the segment closest in space to the given pixel is chosen.
  - For all pixels classified as semi-transparent cirrus or fractional water cloud and for some of the pixels classified as opaque but with the risk of being semi-transparent: A scatter plot technique based on the work of Derrien et al. (1988) and Inoue (1985) and detailed by Korpela et al. (2001) is applied. The technique is based on two-dimensional scatter plots using 11 and 12µm channel composed over the larger segments from where a thermodynamical cloud top temperature valid for all broken and thin clouds inside the segment is derived.
- Retrieve the cloud top height and temperature from the pressure for the opaque cloud pixels, and retrieve the cloud top height and pressure from the temperature for the semi-transparent cirrus and fractional water cloud pixels.

The processing can be divided into a preparation phase, an opaque cloud retrieval step and finally a retrieval step for thin and broken clouds.

The preparation procedure is so that first NWP data are remapped to a coarse resolution (typically of size 32 by 32 high-resolution pixels) on the area of interest. Then the RTTOV simulations (for cloud free TOA radiances) are performed on the NWP data and the RTM results, the NWP data, sun- and satellite view angles and land cover characterisation and elevation are stored. These segment data are valid for the centre of each segment and to be applied for all satellite data inside this segment.

Next follows the opaque cloud retrieval step and finally the CTTH retrieval for semi-transparent/ fractional clouds. The result of the last step is merged with the opaque results filling out the gaps (the non-opaque cloud pixels) left by that algorithm. This is the on-line pre-processing which also described in Figure 2.

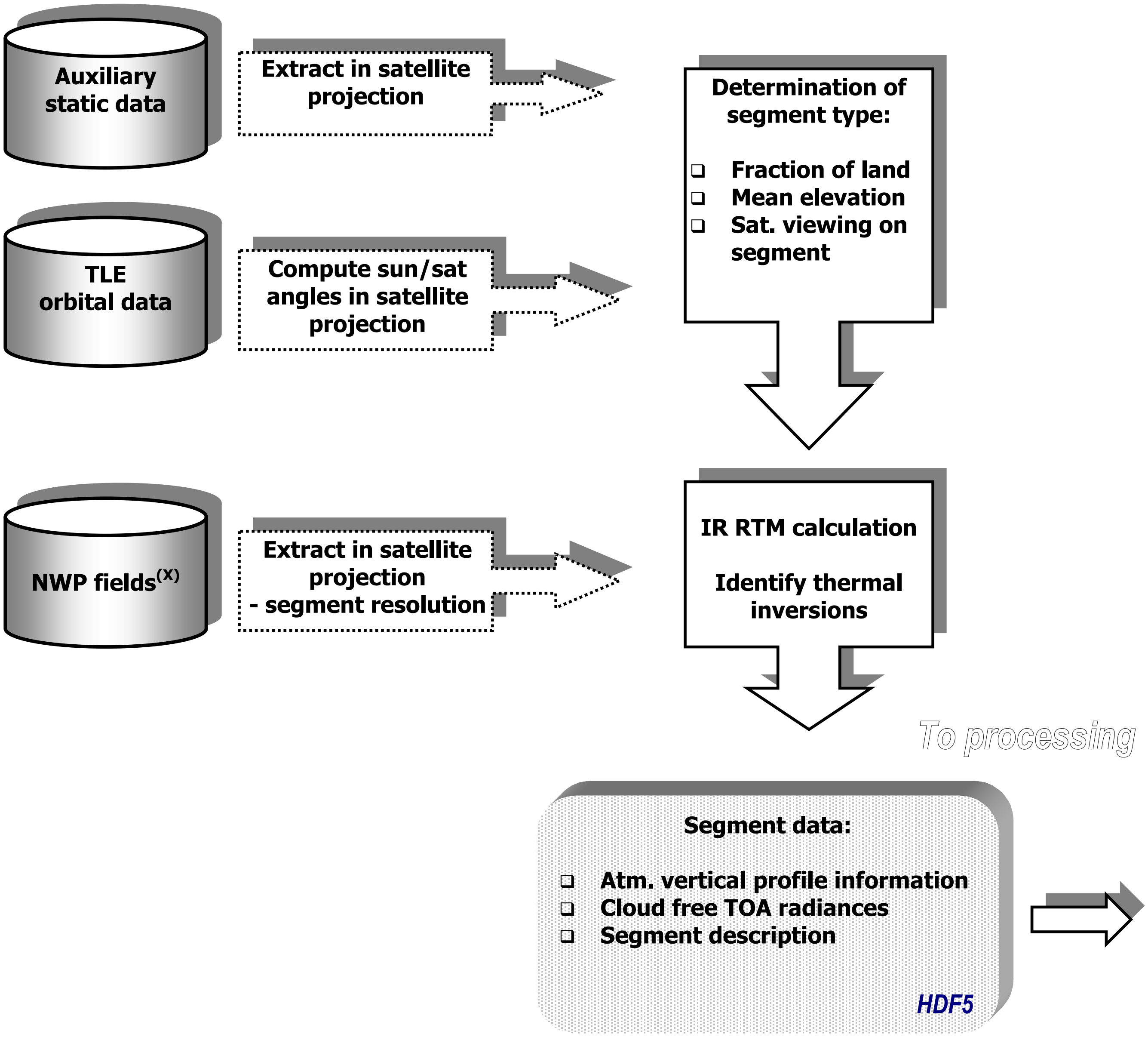

Figure 1 The CTTH pre-processing..The main processing is described in Figure 2.

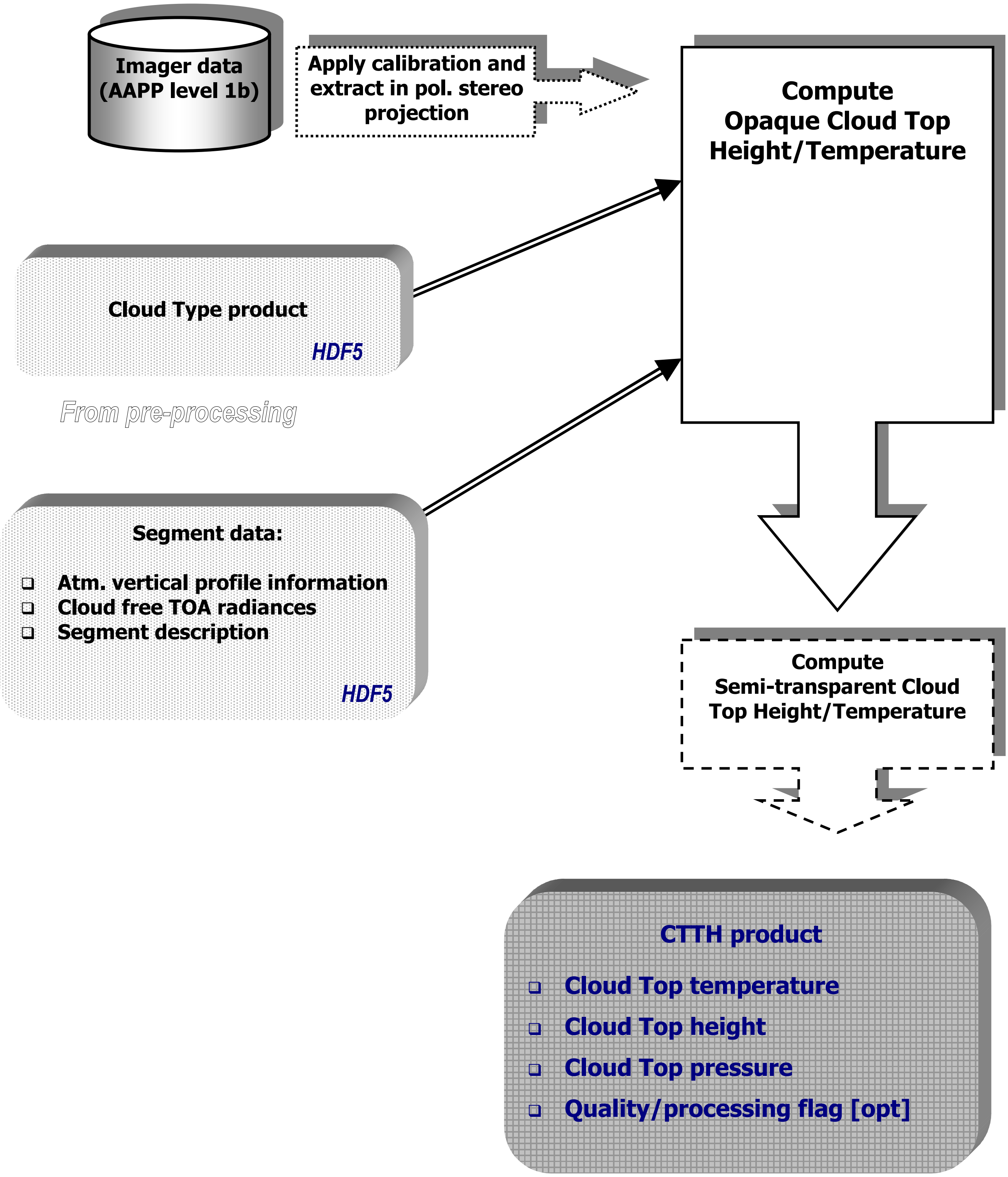

Figure 2 The CTTH main processing.

4. ALGORITHM DESCRIPTION

4.1 THEORETICAL DESCRIPTION

4.1.1 Physics of the Problem

As described in ATBD-01 [RD.4] and ATBD-02 [RD.5] also this algorithm tries to extract information from radiances, observed by the detector. In this case the cloud top temperature (and derived properties) is assigned by relating it to the measured brightness temperature.

There are certain differences for pixels with and without contributions from ground. Cases where information from emissions underneath the cloud do not contribute to the signal (opaque clouds) are relatively easy to handle in this sense. The situation turns difficult if this is not true (semi-transparent or fractional clouds). These circumstances require a statistical analyse of a larger sample to allow for a qualified cloud top assumption of the population in view.

Radiation is not emitted from a clouds facet (however this is defined) but from the whole cloud. Emission is a volume property. Before a certain beam reaches a detector, it underlies a complex interplay of absorption and emission. This means that the observed brightness temperature is representative for a layer somewhat below the cloud top. How far below depends on the optical properties if the cloud.

Table 4 Instrument channel acronyms used by CTTH

Acronym	**Description**
T11	**Brightness temperature at 11 µm**
T12	**Brightness temperature at 12 µm**

4.1.2 Mathematical Description of the Problem

4.1.2.1 Opaque cloud retrieval

The opaque retrieval is applied to all opaque cloud categories as classified by the CT. Opaque cloud pixels with a risk of being semi-transparent are also treated with the semi-transparent scheme. This pixels is the ones which have a difference in $T_{11} - T_{12}$ exceeding 1K ($T_{11} - T_{12} > 1.0K$) and a T_{11} temperature below the NWP temperature at 850hPa. In the combined output the values received by the semi-transparent scheme is used if they are not no-data. This is because the semi-transparent scheme performs quite well also for opaque clouds where as the opaque scheme gives much too low heights for semi-transparent clouds. If no semi-transparent result is found, the opaque value is used for those pixels.

The opaque retrieval uses the measured T_{11} for each pixel and performs a best fit to the vertical pressure profile of cloudy 11µm channel brightness temperatures derived from the NWP temperature profile together with the RTM simulations of atmospheric corrections. For the pixels where the measured T_{11} is lower than the tropopause temperature for the segment, the tropopause temperature is used instead of measured T_{11}. This is done to avoid clouds at (or close to) the tropopause beeing accidently placed in the mesosphere. In case there are inversions present, a relaxation of 0.5K are allowed for the fit at the inversion. This means that if the measured tb4 temperature is 255K and we have an inversion at 255.5K at the simulated profile, we consider it to be a fit at the inversion. For pixels with measured T_{11} above the maximum temperature below the tropopause, the maximum temperature is used instead. This can occur for example if the NWP-temperature profile is slightly underestimated and the cloud is a very low cloud. From the pressure, the height in meters and thermodynamic temperature are derived to give the full CTTH; the temperature and the height in meters above sea level are derived from the NWP profile. The height above ground is derived from the height above sea level, using a high resolution elevation map

Figure 3 shows an example of the CTTH product over north of Norway during summer 2012. Two cloudy areas are identified (blue circles in the left panel of Figure 3) in the image. Figure 4 illustrates, for those two cases, the derivation of the CTTH height from temperature. The vertical profiles of atmospheric temperature (solid black curve) and simulated cloudy T_{11} (dashed black curve) are displayed together with the observed T_{11} (dashed blue line) and the thermodynamic cloud top temperature (red plus), for low clouds (left panel of Figure 4) and for high clouds (right panel). It is observed how the correction of atmospheric absorption in general is small and only significant for low clouds. The small deviation between the observed T_{11} and the derived cloud top temperature in the case of the high cloud is almost entirely due to rounding errors (see 4.2.5).

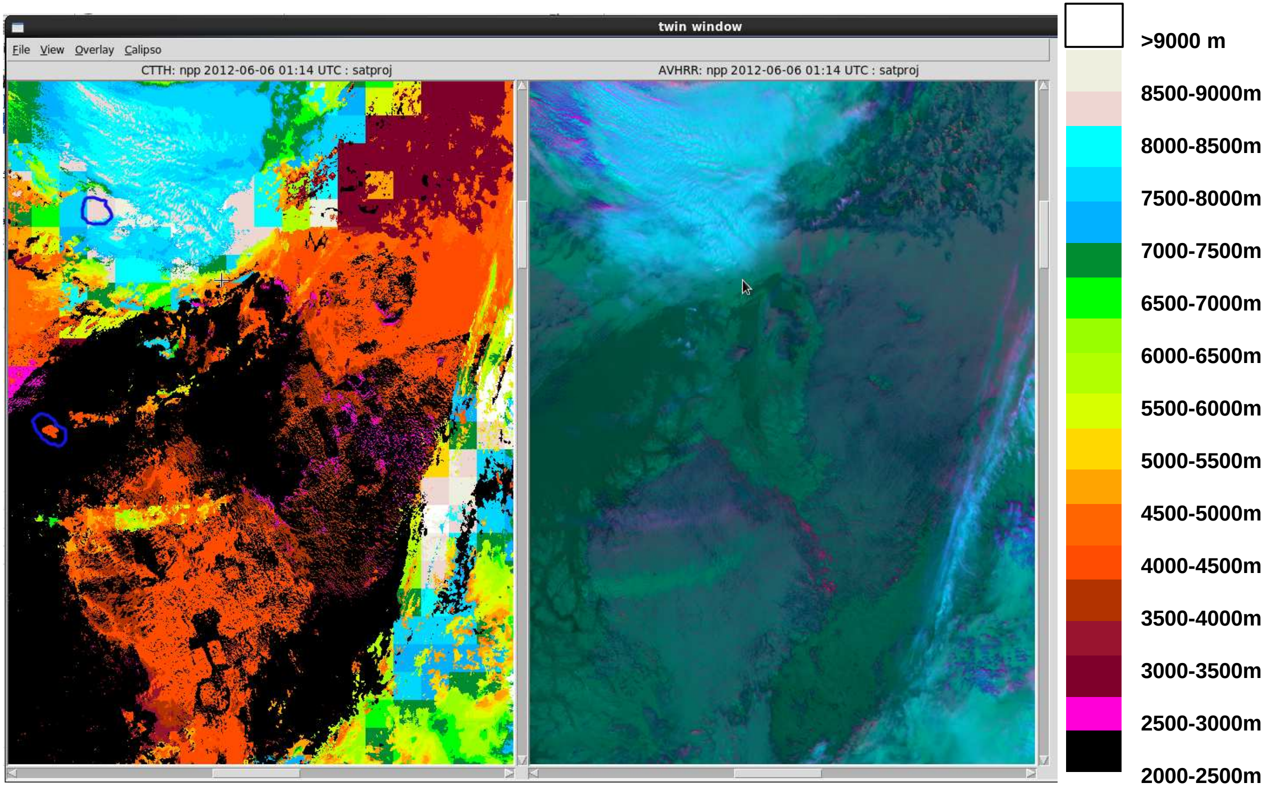

Figure 3 CTTH product (right) and RGB colour composite using channels M10, M12, and M14 (right) for a suomi-NPP scene June 06, 2012, 01:14 UTC (orbit 3145) over north of Norway. The two blue circles in the CTTH product panel corrrespond to the profiles shown in Figure 4.

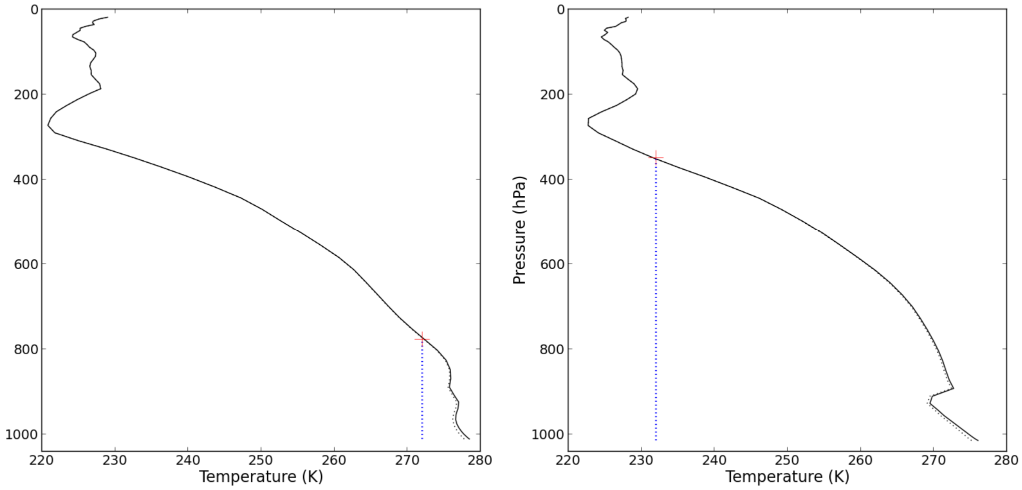

Figure 4 Example showing the derivation of the height retrieval over semi-transparent cloud, Suomi-NPP scene over north of Norway June 06, 2012, 01:14 UTC (orbit 3145). The solid black curves are the vertical profiles of atmospheric temperature, and the dashed ones show the vertical profiles of simulated cloudy T11. The left panel gives the curves for the low cloud encircled in Figure 3 and the right panel show the curves for the high cloud encircled in Figure 3. The blue dashed line indicates the observed T11. The red plus gives the derived thermodynamic cloud top temperature. The low cloud top temperature is estimated to 272K, pressure 775hPa and 2200m above ground. The observed T11 was 274K. The high cirrus cloud top is estimated to 232K, 350hPa and 8200m. The observed T11 was 240K.

When temperature inversions prevail, according to the NWP profile, there might be several possible solutions to the cloud top height. In such cases the algorithm tries to assign the lowest solution while setting a processing flag informing about the presence of an inversion.

4.1.2.2 Semi-transparent cloud retrieval

The CTTH retrieval for semi-transparent and broken clouds is applied to all non-opaque cloud pixels according to the CT, and also to the pixels being opaque according to CT, but suspected to be semi-transparent. Opaque cloud pixels which have a difference in $T_{11}-T_{12}$ exceeding 1K ($T_{11}-T_{12} > 1.0K$) and a T_{11} that is below the NWP temperature at 850hPa are treated with the semi-transparent scheme.

4.1.2.2.1 Approach

The method is based on the often observed arc-like structure in two-dimensional scatter plots $T_{11}-T_{12}$ versus T_{11} over regions of semi-transparent or broken clouds, like the one shown in Figure 5. This arc-like distribution can be explained theoretically for a combination of IR window (or near window) channels like the mentioned 11 and 12µm channels of the instruments used here, making a few simple assumptions. Below we describe how. An even more detailed theoretical derivation and description of the method can be found in (Korpela et al., 2001).

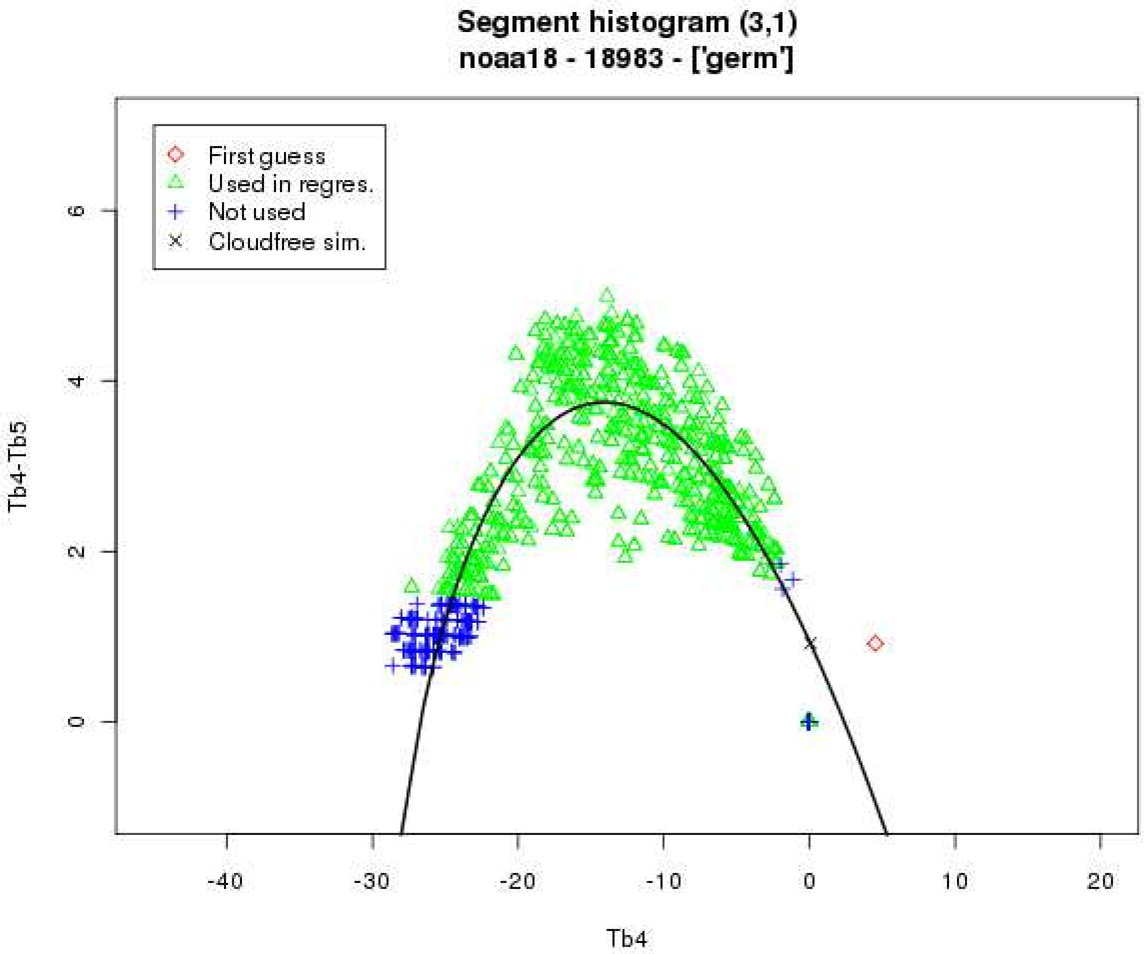

Figure 5: Scatter plot with example distribution of pixels from a 32x32 size image segment. From a NOAA 18 overpass received at Norrköping, orbit number 18983, over the North Sea at 11:26 UTC 2009-01-25. Brightness temperature difference in channels 11µm and 12µm (AVHRR ch 4 and 5) is shown as a function of brightness temperature (in °C) at channel 4. The pixels classified as clear or opaque cloud are shown in blue, and the semi-transparent cloud pixels are shown in green. In the example shown here the resulting cloud top temperature is estimated to -26.71°C, which is where the arc is crossing Tb4-Tb5=0 on the left hand side.

Neglecting atmospheric absorption, assuming local thermodynamic equilibrium and a constant absorption coefficient throughout the cloud layer, and using that at long wave infrared frequencies the brightness temperature depends nearly linearly on the radiance, one may arrive at an expression for the observed brightness temperature at channel i, T_i:

$$T_i = T_c + \sigma_i \left(T_{s,i} - T_c\right)$$

Equation 1

where σ_i is the transmittance at channel i, T_c is the cloud top temperature and $T_{s,i}$ is the cloudfree brightness temperature of channel i. Rearranging Equation 1 gives:

$$\sigma_i = \frac{T_i - T_c}{T_{s,i} - T_c}$$

Equation 2

Combining the two window channels at 11 and 12µm leads to the expression

$$T_{11} - T_{12} = \left(\sigma_{11} - \sigma_{11}^{\beta}\right)\left(T_{s,11} - T_c\right) - \sigma_{11}^{\beta}\left(T_{s,12} - T_{s,11}\right)$$

Equation 3

where $\beta = \alpha_{5}/\alpha_4$ is the ratio of absorption coefficients α at the two channels.

By Equation 3 the measured brightness temperature T_{11} changes from T_C to $T_{s,11}$ as the transmittance varies in the range of [0, 1] . In Equation 3 the difference $T_{11} - T_{12}$ plotted as a function of T_{11} forms an arc shaped curve opening downwards (as pictured in Figure 5), the shape being determined by the ratio β. We see from the expression that on the left hand side of the curve, the 'opaque side', when $\sigma_{11} \to 0$ and $T_{11} \to T_c$, the difference vanishes. On the right hand side of the curve, the 'transparent side', when $\sigma_{11} \to 1$ and $T_{11} \to T_{s11}$, then $T_{11} - T_{12} \to T_{s11} - T_{s12}$ This is the difference of the surface brightness temperatures in the two channels, due to different absorption in the full path through the atmosphere and different emissivities of the surface in the two channels. In the case of AVHRR channels 4 and 5 (for VIIRS it would be channel M15 and M16) the difference is of the order of 1K but will of course vary with surface temperature and the amount of column integrated water vapour.

From a sample of pixels having different transmittances one can make a scatter plot of $T_{11} - T_{12}$ vs. T_{11}, just as it is done in Figure 5. The pixels with thick and nearly opaque clouds will appear on the left hand side, and the pixels with thin and nearly semi-transparent clouds, or the ones being partially filled or totally cloud free, will appear to the right. In between these limiting values there are pixels with semi-transparent or broken (sub-pixel) clouds with variable transmittance. In the case of a single layer of cirrus or broken (water) cloud field, by fitting a curve to the arc one can determine the cloud top temperature T_C through extending the fitted curve on the left hand side to the point $T_{11} - T_{12} = 0$.

4.1.2.2.2 Least-square fitting

When we have the brightness temperature measurements $x_i = T_{11}$ and point $y_i = T_{11} - T_{12}$ from all pixels in a given segment we want to fit against these points the theoretical model (Equation 3), which by using the denotations $T_s = T_{s,11}$ and $\delta_s = T_{s,11} - T_{s,12}$ becomes

$$y_{est}(x,p) = \left(\left(\frac{x - T_c}{T_s - T_c} - \left[\frac{x - T_c}{T_s - T_c}\right]^{\beta}\right)\left(T_s - T_c\right) + \left[\frac{x - T_c}{T_s - T_c}\right]^{\beta}\delta_s\right)$$

Equation 4

where p is a vector in a four-dimensional parameter space, $p = (T_c, \beta, T_s, \delta_s)$.

Our problem is to find the most likely parameter values given the observed distribution, and this is done by minimising a cost function measuring how much the points of the scatter plot differ from the model. As the model depends non-linearly on the parameters the minimisation has to be done iteratively from a set of first guess parameters. The minimisation method applied is the *Levenberg-Marquardt method* which has become a standard of least-squares fitting. We are using least square fititting function leastsq from the python Scipy module for this purpose.

4.1.2.2.2.1 Bounded search

For the four parameters used in the least-square fitting, we determine realistic physical bounds and are only interested in solutions within these limits. All solutions also should have a T_C lower than T_S. To speed-up the fitting and get a larger chance of finding a good solution we use a boundary-penalty term make the fitting search mostly among realistic parameter combinations. In the least square fitting the penalty term is included in one additional last element in the residual vector (y-y_{est}). The penalty term is always zero inside the allowed area for the parameters. If a parameter is outside a boundary $c * L * (boundary - parameter)^2$ is added to the penalty term; where c is a constant and L the number of points in the fit. This means that the penalty increases further away from the border. This penalty term might introduce local minima at the boundary. However all solutions actually used are checked to satisfy conditions on quality. Notice that, if the best unbounded solution where in previous version of PGE03+ a T_C that was too low, we could now end up with the lowest reasonable T_C as solution.

4.1.2.2.3 Procedure

For each segment of the remapped imager data a two dimensional scatter plot of $T_{11} - T_{12}$ versus T_{11} is built up using all cloud free and non-opaque cloud pixels plus the opaque cloud pixels which have a difference in $T_{11} - T_{12}$ exceeding 1K ($T_{11} - T_{12} > 1.0K$). From this distribution of pixels inside the segment an arc-fitting is attempted, and a possible solution is then applied to all semi-transparent and fractional cloud pixels inside the segment. This explains the 'squared clouds' as for example seen in Figure 3.

In the fitting the penalty term is included as one extra data point. It is constructed so that the least square error of the fitting will be large for parameter values that are physically unrealistic. It will not affect the least square errors for parameter combinations inside the set up bounds.

The two-dimensional scatter plot may actually give rise to two separate distributions, one for pixels over land and one for pixels over sea, and may thus require curve fitting for each regime individually. The reason for the two different distributions is the ground temperature, which depending on season and geographical area may be rather different over land and over sea. Figure 6 shows an example of such a dual distribution case, and the two separate curve fittings, giving rise to slightly different but comparable T_C.

A limit (`PGE03pMIN_NUMBER_OF_ARCPOINTS` = 20) defines the minimum number of pixels required in one of the surface regimes or in total. If this limit is exceeded arc-fitting is attempted. In the case of both a land and a sea regime present, one may thus get two solutions, as illustrated in

Figure 6, for the top temperature of the assumed single layer cloud. The cloud top temperature is in that case found from the mean of the two solutions or if one solution has clearly higher quality that one is used for all pixels.

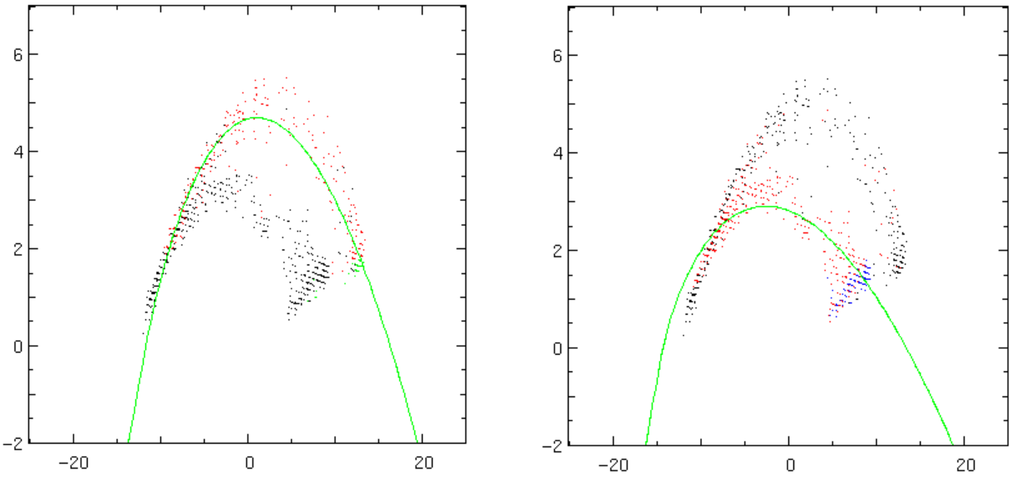

Figure 6 Model fitting done separately for the pixels over land (left) and for the pixels over water (right) in a single image segment scatter plot of $T_{11} - T_{12}$ *versus* T_{11} *(temperatures in °C). The green points are clear pixels over land, the blue points are clear pixels over water, the red points are the target pixels for the temperature retrieval (either semi-transparent or fractional cloud pixels), and finally the black points are the excluded pixels in each case.*

According to Equation 4, the theoretical model for the arc shape scatter plot has four free parameters:

T_C	cloud top brightness temperature (Tb)
B	ratio of absorption coefficients - "the exponent"
T_S	11µm channel surface Tb
δ_s	11µm channel - 12µm channel surface Tb difference

The fitting algorithm needs a first guess for all four, and then it tries to find the best fit by iterative adjustments. The first three parameters are always left free for the fitting algorithm to solve, but δ_s could be fixed using forward radiative transfer estimates for its value. If the configuration parameter `PGE03pNUM_FREE_PARAM` is set to 4, then no fixing is done. If it is set to 3, then the first three parameters are free, and the curve fitting is tried several times for fixed δ_s values which deviate from the first guess by an increasing amount. If the allowed intervals for δ_s or T_s is smaller than PGE03MIN_STEP_SIZE their estimate is set to the middle of that interval and the fitting is done for the other parameters. PGE03MAX_NUM_OF_STEPS lets the user configure how many steps to use for one fitting at most. Step sizes under PGE03MIN_STEP_SIZE are never used.

To find the pressure a best fit is made of T_C to the vertical pressure profile of cloudy 11µm channel brightness temperatures derived from the NWP temperature profile together with the RTM simulations of atmospheric corrections. For the segments where the measured T_C is lower than the tropopause temperature for the segment, the tropopause temperature is used instead of measured T_{11} In case there are inversions present a relaxation of 2.0K are allowed for the fit at the inversion. This means that if the measured tb4 temperature is 255K and we have an inversion at 257K at the simulated profile, we consider it to be a fit at the inversion. From the pressure the height in meters are derived to give the full CTTH.

4.1.2.2.4 Boundaries and first guesses

Realistic bounds are set for the parameters. T_C must be higher than `PGE03pMIN_ALLOWED_CTT`=-85.0°C. The upper boundary for T_C is the maximum of $\{T11_{clear}, T11_{\min}\}$ where $T11_{\min}$ is minimum channel 4 brightness temperature of the scatter plot pixels and $T11_{clear}$ the channel 4 clear simulation of the dominating surface inside the segment. T_S must be higher than the maximum 11µm channel brightness temperature of the scatter plot pixels ($T11_{max}$) and lower than the the maximum of $\{T11_{\max}, T_{sur} + 5C, T11_{clear} + 10C\}$, where T_{sur} is the surface temperature and $T11_{clear}$ the channel 4 clear simulation of the dominating surface inside the segment. δ_s must be higher than 0.0K and lower than both 5.0K and the lowest observed $T_{11} - T_{12}$ of all cloudfree pixels inside the segment. If a combined search is made it must also be lower or equal to both the simulated $T_{11} - T_{12}$ difference over land and over sea.

The iterative least-square fitting is being fed with a qualified first guess specific for the surface regime (land or water or all). The first guess T_C is set to the minimum of $\{-20°C, T11_{\min}\}$. The first guess for the parameter β is set to 1.5. The first guess of T_S and δ_s is set to the middle of their allowed intervals.

4.1.2.2.5 Quality

Though the method assumes single layered cloud fields it is still possible that the model fitting will result in a cloud top temperature even for multi layered cloud fields. However, most likely such a cloud top temperature will not even be representative of any of the cloud fields inside the segment. The algorithm performs various quality checks to sort out useless results. The RMSE of the distribution against the assumed model may not exceed `PGE03pMAX_LIMIT_RMSE`=0.7K. Solutions where T_C is estimated far from all data points are disregarded; Solutions with quality measures under PGE03MIN_ACEPTABLE_QUALITY=0.5 are not used. The equation for quality measure used is:

$$quality = \frac{\min T_{11} - \max T_{11}}{T_C - \max T_{11} + 0.5} .$$

When there are two separate solutions over land and sea with a quality difference more than 0.1 the best one is used. If neither the solution over sea nor the solution over land has quality over 0.75 a combined fit, for both sea and land pixels is made. However if some searches are already made and less than 10% of the pixels are over sea or less than 10% of the pixels are over land, no more search is done for that segment. This to not waste time on searches likely to give the same result already obtained. Furthermore the solution cloud top temperature has to be inside the interval specified by the first guess surface temperature and `PGE03pMIN_ALLOWED_CTT`=-85.0°C.

4.1.2.2.6 Interpolation

The semi-transparent results can be interpolated for those segments missing temperatures. Interpolation is made with the python Scipy Interpolate module. We are using linear interpolation with the griddata function. Segments for which all eight neighbour segments also miss data will not be interpolated. Information on which pixels were interpolated are stored in the quality-flag. It is configurable (CTTH_SEMITRANS_INTERPOLATE = True/False in pps_basic_configure.py) for the user to use interpolation or not.

4.1.2.2.7 The ‘moving window’ functionality

The moving window functionality from version 2012 is still available but not longer needed and not recommended in version 2014 of PGE03.

4.2 PRACTICAL CONSIDERATION

4.2.1 Validation

Currently CLOUDSAT/CALIPSO data represents the best available reference dataset for quality assessment of cloud height products. Validation on locally received data at Norrköping and noaa19 GAC-data against CALIPSO is done for version 2014 of PGE03, see the validation report for results [RD.6]. See Figure 7 and Figure 8 for an example of visual comparison with of CTTH and CALIPSO-data. The CM SAF cloud dataset CLARA-A1, used PPS version 2010 to retrieve cloud top temperature and height. CLARA-A1 have been validated against CLOUDSAT/CALIPSO (see Karlsson and Johansson 2013 and Karlsson et al. 2013). For the Metop validation against CLOUDAT/CALIPSO it is unfortunately only possible for arctic regions due to overlap constrains of orbits. See also Karlsson et al., 2009 for validation of earlier version of PPS in the Arctic.

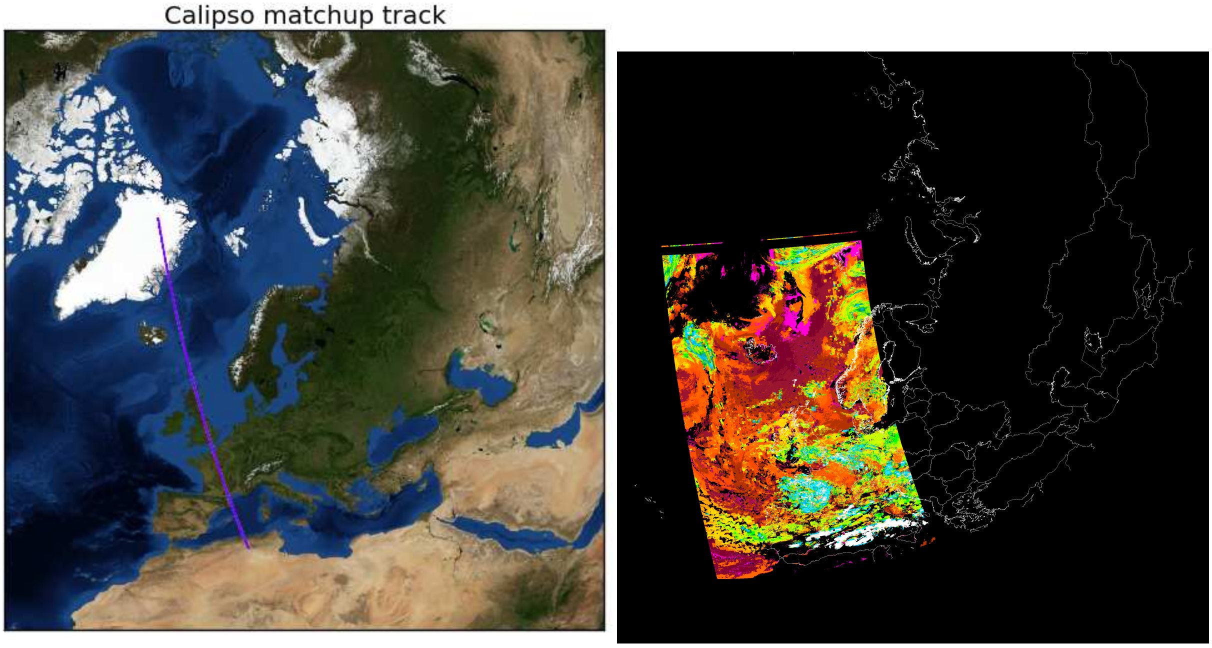

Figure 7 Example of matchup track (purple line left) along the Suomi-NPP overpass to the left the PPS cloud top height product for 11 June 2012 at 12:53 UTC (i.e., time for first scanline).

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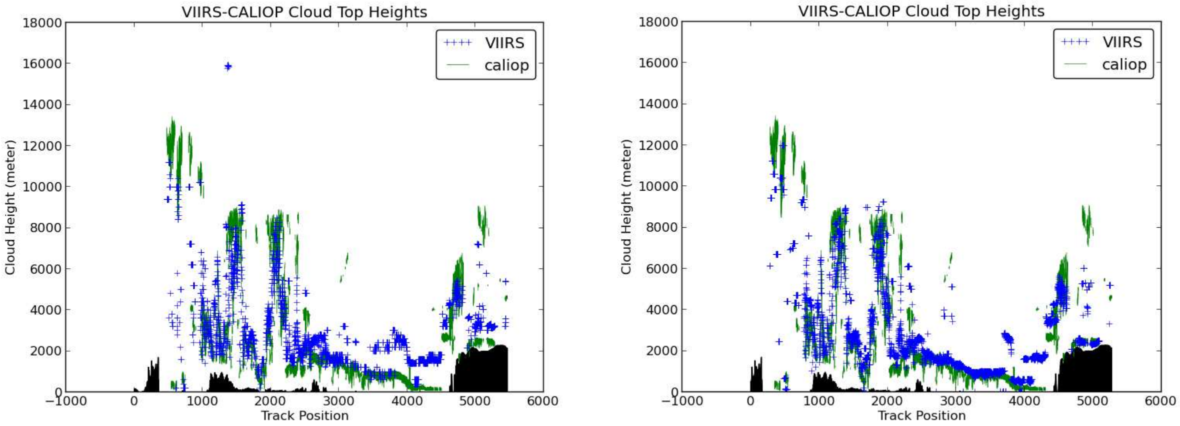


Figure 8 Comparison of a Suomi-NPP (2012-06-11, orbit 3223) scene with calipso.Same scene as in Figure 7. To the left is pps v2012 and to the right pps v2014. In the picture we can see that the number of low clouds being 2km too high is decreased (pos. 3000-4000). The very much too high cloud, at 16km, is now improved (pos. 1500). The heights of the semi-transparent clouds to the left

are now better, around 8km and not 6km, even if the real height is higher around 11km (pos. 0-1000).

4.2.2 Quality control

The CTTH processing flags include a flag for low confidence (see 4.2.5). This flag is currently only being set in situations when a temperature inversion is encountered and more than one possible solution is identified. There are also flags identifying whether the pixel was classified opaque or semi-transparent, the presence of inversion, and a flag identifying the application of the scatter plot technique and if the result has been interpolated. All these flags indirectly are quality indicators to the user.

4.2.3 Assumptions and limitation

Important assumptions and limitations are primarily connected to the estimation of cloud top for semi-transparent clouds. It is assumed that all semi-transparent clouds in a processing segment contain the same height, which is not necessarily true and also gives a segmented less user-friendly display of results for the user.

Despite efforts undertaken, it is not always possible to supply a cloud height estimate for semi-transparent clouds, since the algorithm does not always converge. However with the updates for version 2014, most clouds now get heights.

4.2.4 List of inputs

4.2.4.1 Satellite data

The same spectral information as needed by the CMA and CT is input to the CTTH (see section *List of inputs* in ATBD-01 [RD.4] and as the cloud type (and thus indirectly the cloud mask) is mandatory input to the CTTH, all channels except the 0.9 and 8.5 µm channels are mandatory also for the CTTH.

4.2.4.2 Cloud Type

The cloud type product as provided by the CT is a mandatory input for the CTTH.

4.2.4.3 Sun and satellite angles

Similar to the CMA and the CT the CTTH needs information on the sun- satellite viewing geometry in pixel resolution. See section *List of inputs* in ATBD-01, [RD.4].

4.2.4.4 Land cover characterisation and elevation

The same land-use and elevation data needed by the CMA is required by the CTTH. See section *List of inputs* in ATBD-01 [RD.4].

4.2.4.5 NWP data

Like the CMA and the CT, CTTH uses NWP parameters as either provided by a short range forecast (lead times between 6 and 24 hours) in case of nowcasting, or as provided by a valid analysis in case of off line processing (as e.g. in re-processing for climate applications).

As compared to the cloud mask and cloud type the CTTH is, however, much more dependent on NWP information. The CTTH requires the temperature and specific humidity at the highest possible vertical resolution.

In contrary to the CMA and CT the NWP parameters are not needed in full (map-projected) pixel resolution but it is advantageous to have them mapped to a horizontal resolution comparable to the grid resolution of the NWP model.

4.2.4.6 Surface Emissivity

CTTH can be configured for using surface emissivity as input to RTTOV. In that case, the same surface emissivity is needed as required by CMA. See section *List of inputs* in ATBD-01 [RD.4].

Anyhow, we recommend not to use that setting, see [RD.6] for arguments.

4.2.4.7 Parameter files and algorithm configuration files

The CTTH has a few configuration parameters related to how much is wanted in the final output. These can be found in the file `pps_config_common.cfg` and are listed here:

- GENERATE_TEMPERATURE (default yes): Whether the cloud top temperature output is wanted.
- GENERATE_PRESSURE (default yes): Whether the cloud top pressure output is wanted.
- GENERATE_HEIGHT (default yes): Whether the cloud top height (in meters) output is wanted.
- GENERATE_CLOUDINESS (default no): Whether the effective cloudiness output is wanted.
- GENERATE_PROCESSING_FLAG (default yes): Whether the processing flags are wanted

Anyhow, we recommend: **not** to change these settings. All the datasets: temperature, pressure and height, need to be generated, to assure full functionality. Otherwise the opaque CTTH product might be generated, but most likely not the semi-transparent or combined CTTH product.

The effective cloudiness is not derivable using the current algorithms available, and therefore `GENERATE_CLOUDINESS` shall always be set to ‘no’. In addition the algorithm to derive the CTTH in semi-transparent and fractional cloudiness has a few algorithm specific configuration parameters, defined in the file `ppsCtthHisto_config.py`. These parameters should **not** be altered by the user.

4.2.5 Description of output

The CTTH produces three parameters for the cloud top, namely the temperature, the height in meters and the height in pressure units. Also the output format is prepared for the generation of a parameter called cloudiness thought to give the effective cloud cover fraction. But this latter parameter is not retrieved with the current algorithm. It might be retrieved if the radiance ratioing method is to be applied in the future.

In addition, for each pixel a set of processing flags describe the method applied and provide information on the conditions under which the pixel was processed, and thought to be important for the assessment of the quality of the cloud top estimation.

So in total the content of the CTTH consists of six 16 bit dataset. Three datasets are for temperature, pressure and height. Three datasets contains information in the status, quality and conditions flags. They are all described in more detail below.

The CTTH algorithm tries to produce an output for every pixel classified as cloudy by the CT. Cloud free pixels and pixels outside the satellite swath become non-processed. In addition there are conditions when the algorithm is unable to provide an unambiguous estimation, see further in sections 4.1, and in these cases the no-data value will be assigned to the pixel.

Cloud Top Temperature

The cloud top temperature is stored using a linear conversion from 16bit count to temperature, as

$T = \text{gain} \times \text{count} + \text{intercept}$

The gain, intercept and no-data value (for missing data = outside swath - or no data = no result due to failed retrieval or corrupt input data) are listed below:

Table 5 Gain, intercept and no-data values for cloud top temperature

Gain	**Intercept**	**Nodata**
0.01K/count	**0.0K**	**65535**

Cloud Top Pressure

The cloud top pressure is stored using a linear conversion from 16bit count to pressure like as done for the temperature. The gain, intercept and no-data value are listed below:

Table 6 Gain, intercept and no-data values for cloud top pressure

Gain	**Intercept**	**Nodata**
10Pa/count	**0.0Pa**	**65535**

Cloud Top Height

The cloud top height is stored using a linear conversion from 16bit count to height like as done for the temperature. The gain, intercept and no-data value are listed below:

Table 7 Gain, intercept and no-data values for cloud top height

Gain	**Intercept**	**Nodata**
1m/count	**0.0m**	**65535**

Processing flags

In version 2014 of PGE03 there are three flags ctth_quality, ctth_conditions and ctth_status. They contain information about the quality and conditions of each pixel. See Table 8 for a more detailed description.

Table 8 CTTH flags

Bit number	**Flag: ctth_quality**	**Explanation**
0	Non-processed	Containing no data. Cloudfree pixel or pixel where no cloud height could be retrieved.
1	Spare	
2	Spare	
3 to 5	Quality	0: N/A nodata 1: Good 2: Questionable 3: Bad (Set if low level inversion and several solutions) 4: Interpolated
Bit number	**Flag: ctth_status**	**Explanation**
0	Cloud-free	Cloud-free
1	No reliable method	No reliable method
2	Opaque clouds	Opaque clouds
3	Multilayer suspected	Multilayer suspected
4	Inversion	Low level thermal inversion in NWP

5	NWP low quality	NWP data suspected low quality
6	Using RTTOV	Using RTTOV
7	Scatter plot method	Using semi-transparent windowing technique

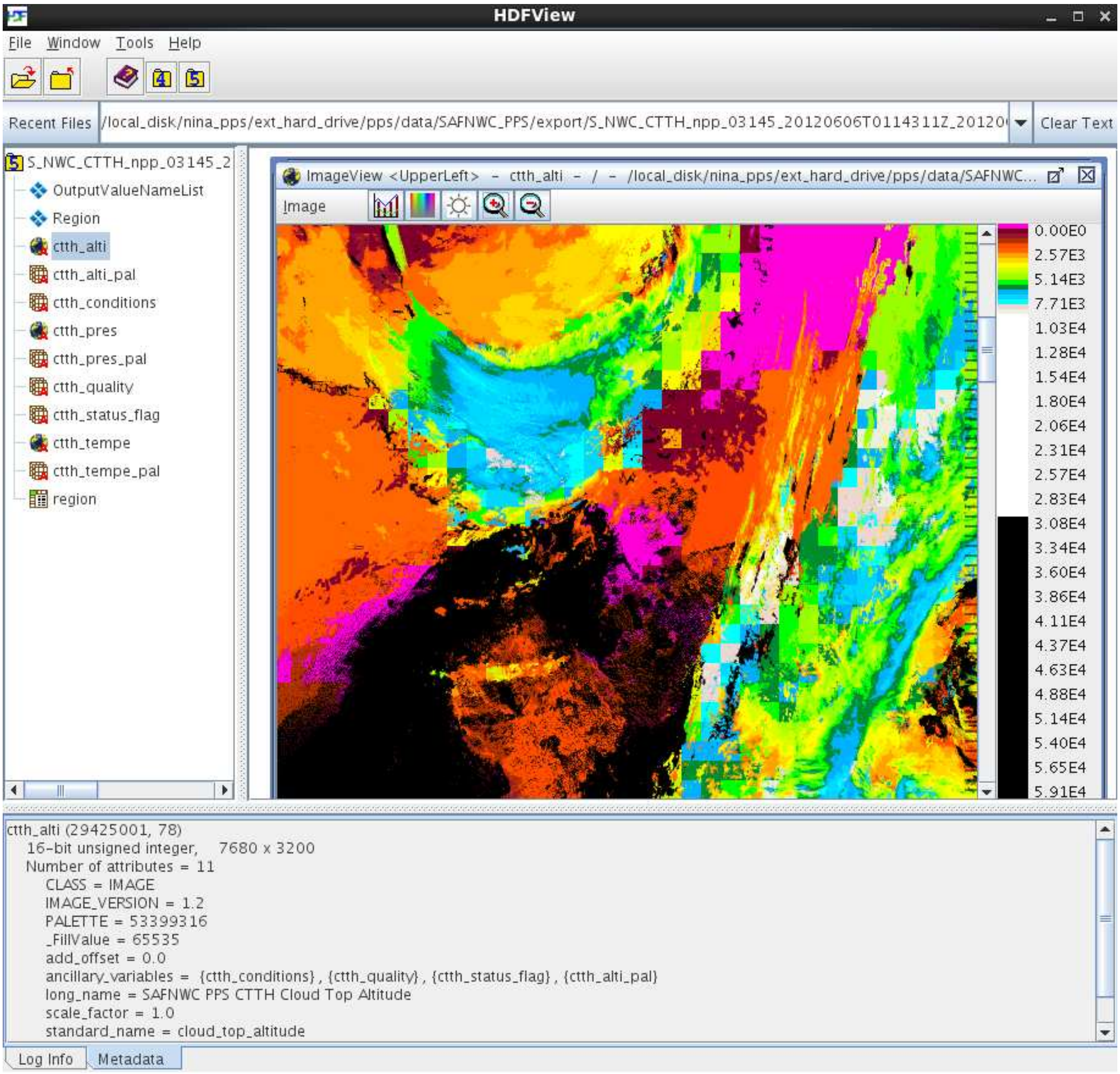
Bit number	**Flag: ctth_conditions**	**Explanation**
0	Outside swath	Pixel is out of swath or points to space
1-2	Illumination	Defines the illumination condition: 0: N/A 1: Night 2: Day 3: Twilight
3	Sunglint	Sunglint
4-5	Land Sea	Defines whether it is land or sea: 0: N/A 1: Land 2: Sea 3: Coast
6	High Terrain	High terrain
7	Rough Terrain	Rough terrain
8-9	Satellite input data	Satellite input data status: 0: N/A 1: All satellite data are available 2: At least one useful channel is missing 3: At least one mandatory channel is missing
10-11	NWP input data	NWP input data status: 0: N/A 1: Data Available 2: Useful data missing

		3: Mandatory data missing
12-13	Product input data	Product input data status: 0: N/A 1: Data Available 2: Useful data missing 3: Mandatory data missing
14-15	Auxilary input data	Auxiliary data status: 0: N/A (not classified pixel or auxiliary data not used) 1: All auxiliary data are available 2: At least one useful auxiliary field is missing 3: At least one mandatory auxiliary is missing

4.2.6 Visualisation

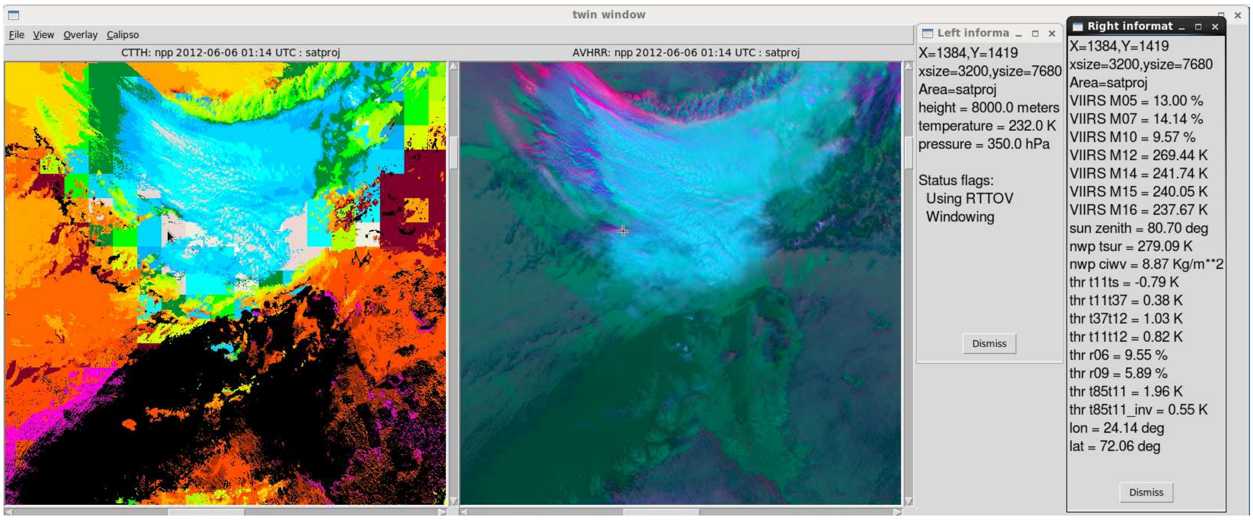
The CTTH product is like the other PPS cloud and precipitation products first of all a digital product available in HDF5 and NetCDF which should be used together with the appended flags, e.g. as input to an automatic mesoscale analysis or nowcasting scheme. A plain CTTH image showing just the temperature for example using a colour palette, without additional flags or quantitative numbers, is even more difficult to use than a plain cloud mask or type image. Figure 9 shows such a plain image of the height in meters of a CTTH product.

The SMHI PPS viewer shown earlier may be rather useful in the case of the CTTH. Figure 10 shows the same example as shown in Figure 9 but with the SMHI PPS viewer. With the PPS viewer it is possible to get the full information available in the HDF5 file for the pixel under the mouse-pointer, as illustrated in 2.



```
ctth_alti (29425001, 78)
  16-bit unsigned integer,    7680 x 3200
  Number of attributes = 11
    CLASS = IMAGE
    IMAGE_VERSION = 1.2
    PALETTE = 53399316
    _FillValue = 65535
    add_offset = 0.0
    ancillary_variables = {ctth_conditions}, {ctth_quality}, {ctth_status_flag}, {ctth_alti_pal}
    long_name = SAFNWC PPS CTTH Cloud Top Altitude
    scale_factor = 1.0
    standard_name = cloud_top_altitude
```

Figure 9 An example of CTTH image display using hdfview: Here only the height in meters is shown. Same scene suomi-NPP scene June 06, 2012, 01:14 UTC (orbit 3145) over north of Norway as shown in Figure 3 . See Figure 3 for ctth colour interpretation.



```
X=1384,Y=1419
xsize=3200,ysize=7680
Area=satproj
height = 8000.0 meters
temperature = 232.0 K
pressure = 350.0 hPa

Status flags:
  Using RTTOV
  Windowing
```

```
X=1384,Y=1419
xsize=3200,ysize=7680
Area=satproj
VIIRS M05 = 13.00 %
VIIRS M07 = 14.14 %
VIIRS M10 = 9.57 %
VIIRS M12 = 269.44 K
VIIRS M14 = 241.74 K
VIIRS M15 = 240.05 K
VIIRS M16 = 237.67 K
sun zenith = 80.70 deg
nwp tsur = 279.09 K
nwp ciwv = 8.87 Kg/m**2
thr t11ts = -0.79 K
thr t11t37 = 0.38 K
thr t37t12 = 1.03 K
thr t11t12 = 0.82 K
thr r06 = 9.55 %
thr r09 = 5.89 %
thr t85t11 = 1.96 K
thr t85t11_inv = 0.55 K
lon = 24.14 deg
lat = 72.06 deg
```

Figure 10 Example of ctth image display using a dedicated PPS image viewer developed at SMHI. Same scene suomi-NPP scene June 06, 2012, 01:14 UTC (orbit 3145) over north of Norway as shown in Figure 3 and Figure 9. To the right an RGB image using channels M10, M12, and M14 and to the left the corresponding merged CTTH using both the opaque and semi-transparency retrievals. See Figure 3 for ctth colour interpretation. The two information dialogs, to the rightmost, provide information for the pixel under the mouse-pointer.

ANNEX A. List of TBC, TBD, Open Points and Comments

TBD/TBC	Section	Resp.	Comment