EUMETSAT Satellite Application Facility on Climate Monitoring

Algorithm Theoretical Basis Document

CM-SAF Product CM-15 and CM-16

Cloud Top (Temperature, Pressure, Height) from AVHRR

Reference Number:	**SAF/CM/SMHI/ATBD/CTO_AVHRR**
Version:	**2.0**
Date:	**13 January 2011**

Preface

This Algorithm Theoretical Basis Document was produced by the Satellite Application Facility on Nowcasting (NWC-SAF). The Satellite Application Facility on Climate Monitoring (CM-SAF) has implemented the herein described PPS software. The document has a CM-SAF version number that will be updated whenever a new version of the PPS software is introduced into the CM-SAF processing system. The version number assigned by NWC-SAF is kept in the appended document.

Algorithm Theoretical Basis Document for SAFNWC/PPS “Cloud Top Temperature, Pressure and Height” (CTTH-PGE03 v3.0)

SAF/NWC/CDOP/SMHI-PPS/SCI/ATBD/3, Issue 2.3

Document Revision 1

15 April 2010

Applicable to SAFNWC/PPS version 2010

Applicable to the following PGE:s:

PGE	**Acronym**	**Product ID**	**Product name**	**Version number**
PGE03	CTTH	SAFNWC/PPS/PGE03	Cloud Top Temperature and Height	3.0

Prepared by SMHI

REPORT SIGNATURE TABLE

Function	Name	Signature	Date
Prepared by			
Reviewed by			
Authorised by	Anke Thoss SAFNWC PPS Manager		15 April 2010

DOCUMENT CHANGE RECORD

Version	Date	Pages	CHANGE(S)
2.2.0	28 November 2008	28	New document. Replaces parts of the SCI-SUM.
2.2.1	1 February 2009	34	Changes after DRI2009: New section 1.6 Product Overview New section 1.7 Scientific Updates Add *pressure* to the title and in section 2 Introduction. Included RTTOV version number 7.1; algorithm overview and Table 8. Section 3 in the algorithm overview two new figures; sketch over CTTH pre-processing and on-line processing. Section 4.1.1 added a table with AVHRR acronym and description. Figure 4, 10 and 11 more information and color bar. Figure 12, 13 and 14 information on where to find color bar. Section 4.2.4 took away Cloud Top Cloudiness. Totally new Figure 6, showing the arc shape Tb4-Tb4 versus Tb4 histogram. Splitted the section "Quality control and validation strategies" to two sections "Validation" and "Quality control" Added a reference (in section Validation) to the CM-SAF validation report.
2.3.0	31 January 2010	34	- Generalized channel and instrument names - Added MODIS channel table - Supplemented abbreviation list - Reference for RTTOV9 added - Description of changes since v2009 added - General cosmetics - Added reference, 4.2.1 and 5 -Update the section with scientific updates since last version.
2.3.1	15 April 2010	34	Changes after DRI-2010: -RID Faucher2/LSc1: replaced the logo:s in the header

Table of contents

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://www.smhi.se/saf).

1.1 Scope of the document

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 Software Version Identification

This document describes the algorithms implemented in the PGE03 version 3.0 of the 2010 SAFNWC/PPS software package delivery.

1.3 Definitions, Acronyms and Abbreviations

Acronym	Explanation
ACPG	AVHRR/AMSU Cloud Product Generation 9oftware (A major part of the SAFNWC/PPS s.w., including the PGE:s.)
AEMET	Agencia Estatal de Meteorología (Spain)
AHAMAP	The 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
CM	Cloud Mask (also PGE01)
CM-SAF	Climate Monitoring SAF
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
HIRS	High Resolution Infrared Sounder
INM	Instituto Nacional de Meteorología (Spain) (old name of AEMET)
IR	Infrared
MHS	Microwave Humidity Sounding Unit
MODIS	Moderate Resolution Imaging Spectroradiometer
MW	Microwave
NMS	National Meteorological Service

Acronym	Explanation	Acronym	Explanation
NOAA	National Oceanic and Atmospheric Administration	**RTM**	Radiative Transfer Model
NWP	Numerical Weather Prediction	**RTTOV**	Radiative Transfer for TOVs
PC	Precipitating Cloud (also PGE04)	**SAF**	Satellite Application Facility
PCPN	Precipitation	**SAFNWC**	Satellite Application Facility for support to NoWcasting
PGE	Process Generating Element	**SMHI**	Swedish Meteorological and Hydrological Institute
PPS	Polar Platform System	**SW**	SoftWare
RGB	Red Green Blue	**TOA**	Top Of Atmosphere

Table 1: List of Acronyms and Abbreviations

For a list of SAF-acronyms see also [RD.1].

1.4 REFERENCE

1.4.1 Applicable Documents

Reference	Title	Code	Vers	Date
[AD. 1]	Validation Report for v.2009 of the SAFNWC/PPS	SAF/NWC/CDOP/SMHI-PPS/SCI/VR/3	2.2.2	13/03/09
[AD.1b]	Validation Report for v.2010 of the SAFNWC/PPS	SAF/NWC/CDOP/SMHI-PPS/SCI/VR/4	2.3.1	15/04/10
[AD.2]	Algorithm Theoretical Basis Document for SAFNWC/PPS "Cloud Mask" (CM-PGE01 v3.0)	SAF/NWC/CDOP/SMHI-PPS/SCI/ATBD/1	2.3.1	15/04/10
[AD.3]	Algorithm Theoretical Basis Document for SAFNWC/PPS "Cloud Type" (CT-PGE02 v1.5)	SAF/NWC/CDOP/SMHI-PPS/SCI/ATBD/2	2.3.1	15/04/10
[AD.4]	Algorithm Theoretical Basis Document for SAFNWC/PPS "Precipitating Cloud" (PC-PGE04 v1.5)	SAF/NWC/CDOP/SMHI-PPS/SCI/ATBD/4	2.3.1	15/04/10

Table 2: List of Applicable Documents

1.4.2 Reference Documents

Reference	Title	Code	Vers	Date
[RD.1]	The Nowcasting SAF Glossary	SAF/NWC/CDOP/INM/MGT/GLO	1.3	10/11/09
[RD.2]	SAFNWC Product Requirements Document	SAF/NWC/INM/MGT/PRD	1.0	28/07/09
[RD.3]	Software Requirements Document for the Polar Platform System Software Package of the SAFNWC	SAF/NWC/CDOP/SMHI-PPS/SW/RQ/1	2.1.1	19/03/08
[RD.4]	List of TBD:s and TBC:s for the Polar Platform System Software Package of the SAFNWC	SAF/NWC/CDOP/SMHI-PPS/SW/TBD/1	2.3.1	15/04/10
[RD.5]	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

Table 3: List of Referenced Documents

1.5 List of TBD:s and TBC:s

There are no open TBD:s or TBC:s in this document. For a full list of TBD:s, both already closed ones and TBD:s in other documents see [RD.4].

1.6 Product overview

The PPS in general provides four cloud and precipitation products derived from polar orbiter data. They are the

- *Cloud Mask (CM)*
- *Cloud Type (CT)*
- *Cloud Top Temperature and Height (CTTH)*
- *Precipitating Clouds (PC)*

The Cloud Mask as a mandatory input to the CT product, the CT is in turn mandatory input to both the CTTH and PC products, see Figure 1. This document however describes solely the Cloud Type algorithm.

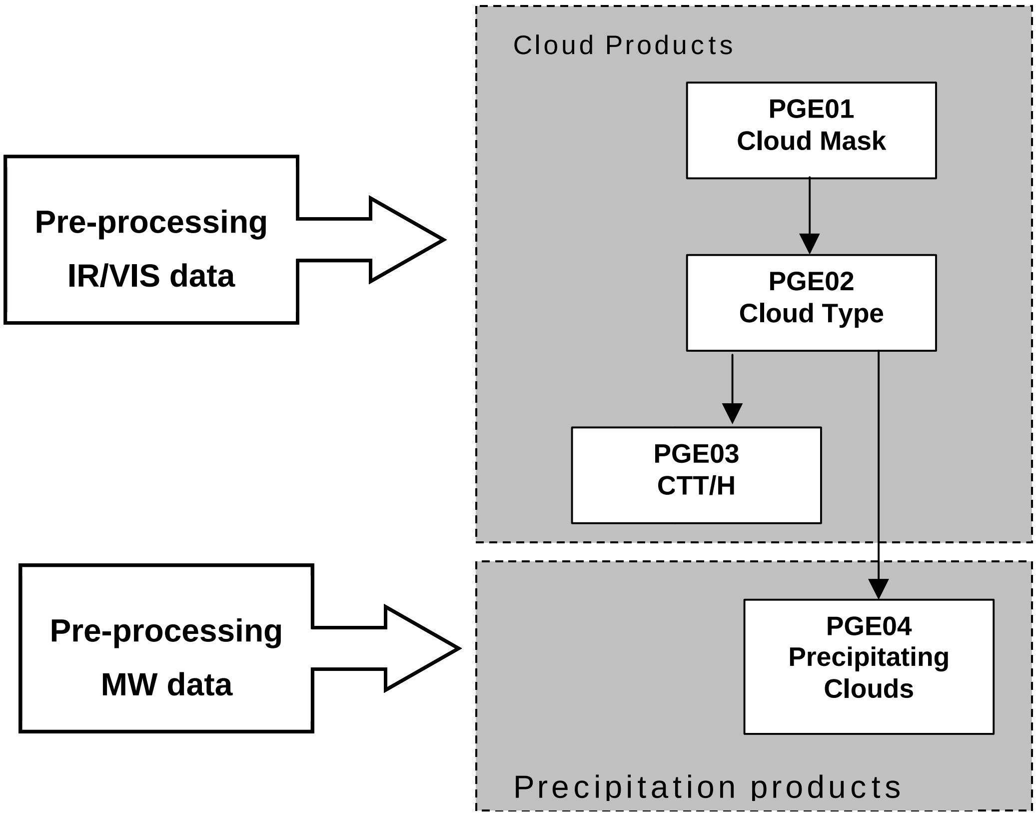

Figure 1 Product dependencies

1.7 Scientific Updates since PPS Version 2009

The current version has been updated to handle RTTOV9 and all the changes, introduced since RTTOV version 7. Therefore the interface, controlling inline radiative transfer calculations, is completely rewritten.

Furthermore , the algorithm has been generalized to deal with MODIS data and allow for easier adaptions of instruments on future platforms.

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 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 histograms 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. .

3. ALGORITHM OVERVIEW

The CTTH product is derived using two algorithms, one for opaque and one for fractional and semitransparent 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 and cloudy TOA radiances and brightness temperatures are calculated for the 11 and 12µm channels applying the RTTOV radiative transfer model version 9 (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 overcast simulation results are available for each pressure level given by RTTOV and are derived using an emissivity of one (black clouds). 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 all 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: A histogram 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 histograms 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 step can be performed without having the satellite data available and is normally performed before the actual satellite overpass, Figure 2.

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 (both cloud free and cloudy 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 semitransparent/ 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 3.

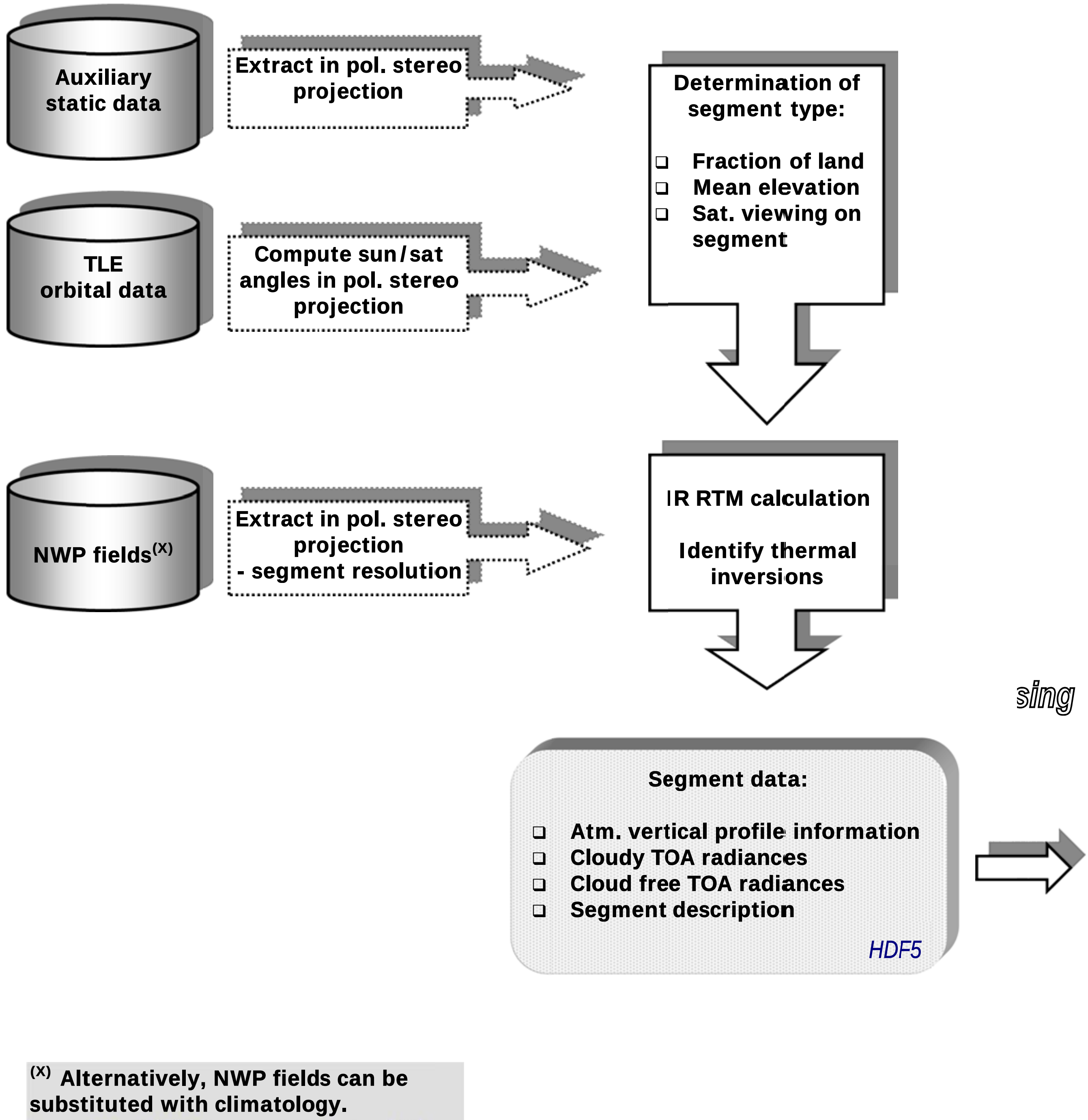

Figure 2The CTTH pre-processing which processed before the satellite data reception. Figure 3 describe the on-line processing.

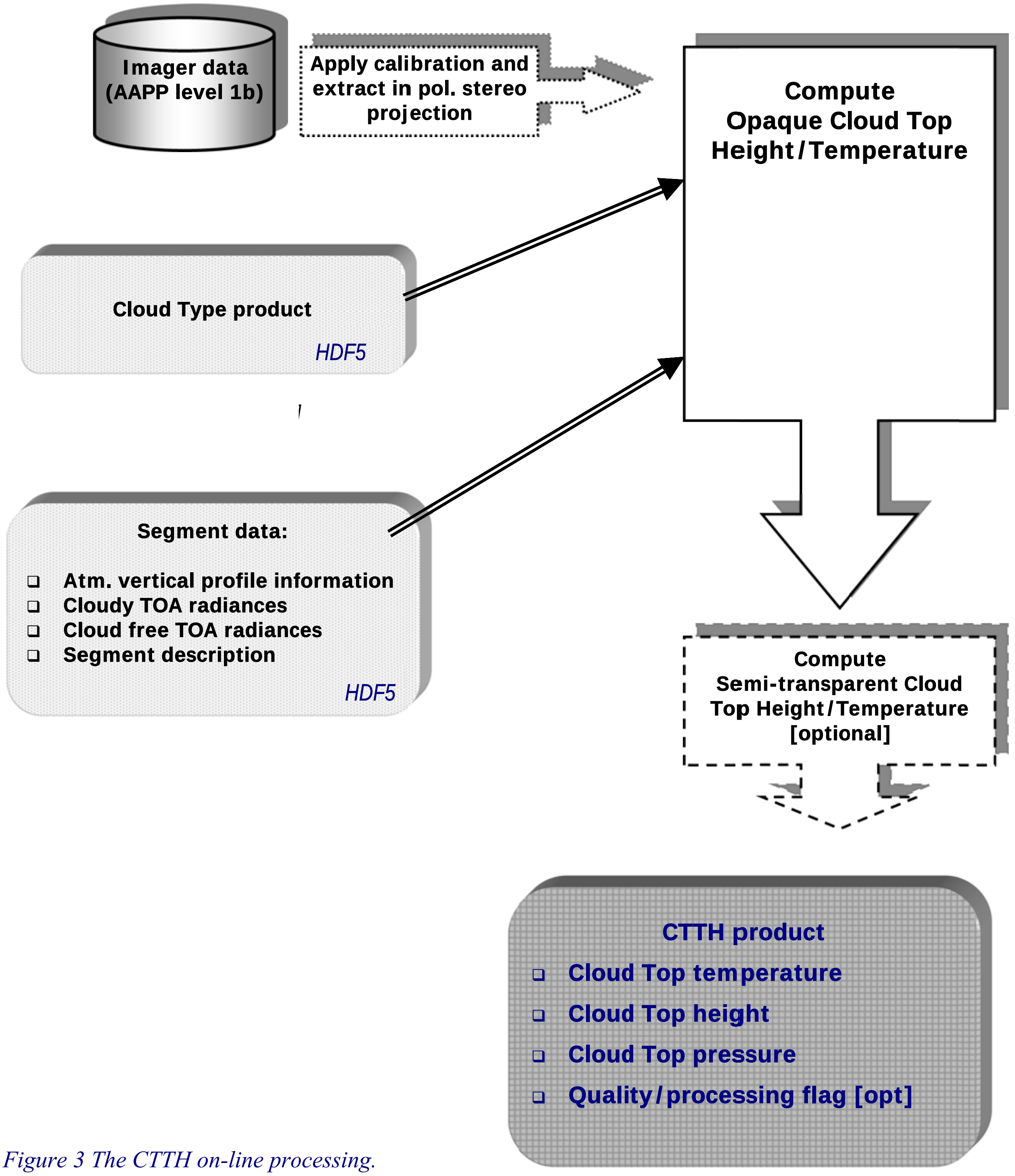

Figure 3 The CTTH on-line processing.

4. ALGORITHM DESCRIPTION

4.1 THEORETICAL DESCRIPTION

4.1.1 Physics of the Problem

As described in [AD.2] and [AD.3], 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 (semitransparent 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.

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. It uses the measured T11 for each pixel and performs a best fit to the vertical pressure profile of cloudy 11µm channel brightness temperatures derived in the RTM simulations. From the pressure the height in meters and thermodynamic temperature are derived to give the full CTTH.

Figure 4 shows an example of the CTTH product over western central Europe during late spring 2003. Two cloudy areas are identified (black circles in the right panel of Figure 4) in the image. Figure 5 illustrates the derivation of the CTTH. The vertical profiles of atmospheric temperature (solid black curve) and simulated cloudy T11 (dashed black curve) are displayed together with the observed T11 (dashed blue line and blue circle) and the thermodynamic cloud top temperature (red plus), for low opaque clouds (left panel of Figure 5) and for high opaque 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 T11 and the derived cloud top temperature in the case of the high opaque cloud is almost entirely due to rounding errors and the resolution of the CTTH product being 1.0K (see 4.2.5).

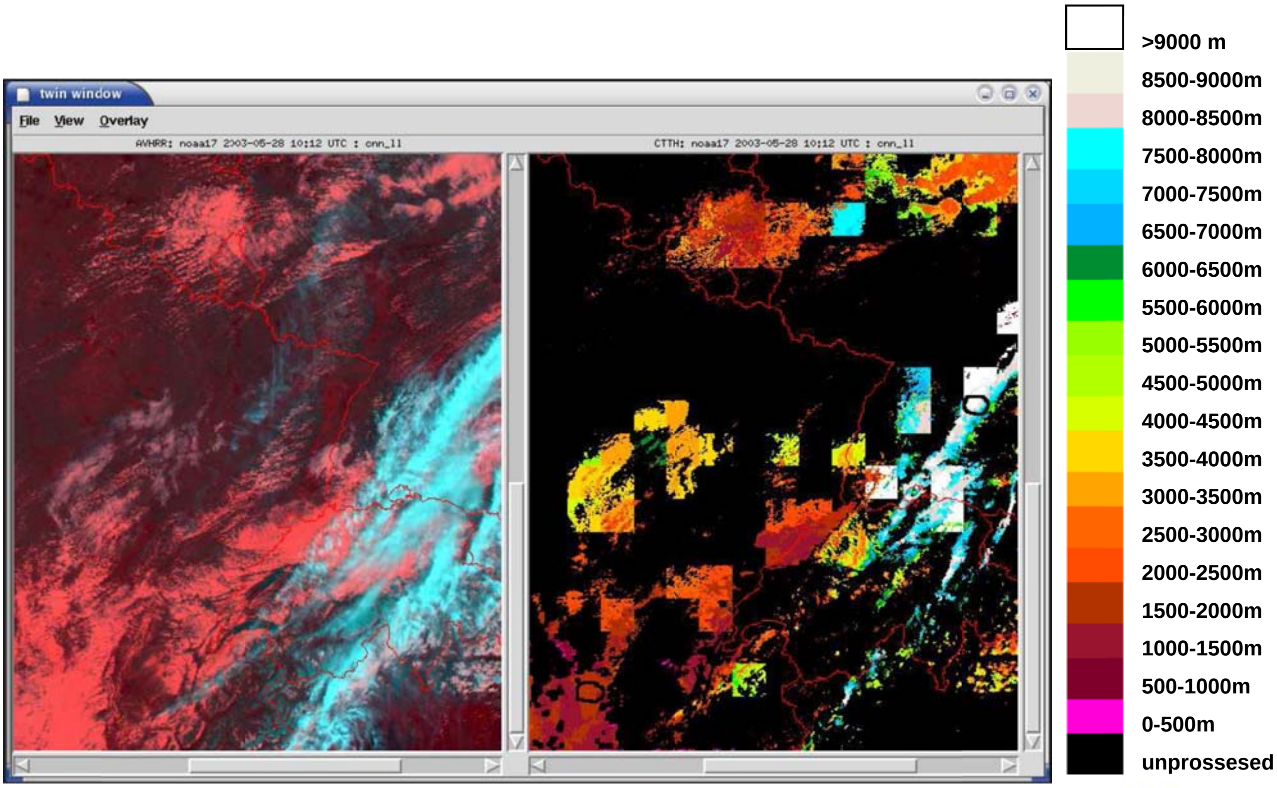

Figure 4 CTTH product (right) and RGB colour composite using channels 3A, 4, and 5 (left) for a NOAA 17 scene May 28, 2003, 10:09 UTC (orbit 4803) over central western Europe. The two black circles in the CTTH product panel corrrespond to the profiles shown in Figure 5.

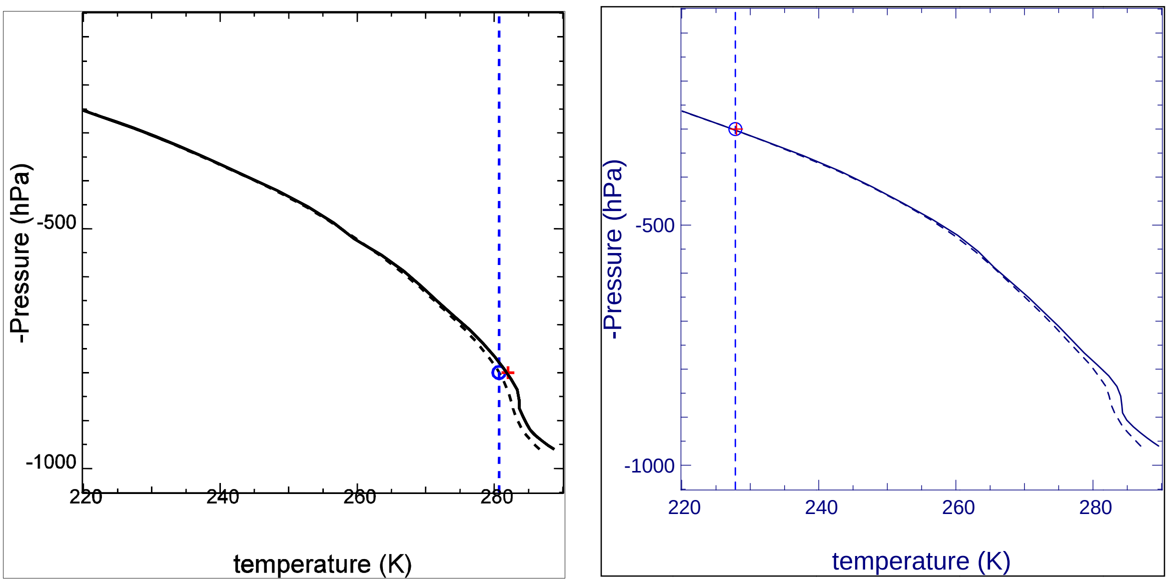

Figure 5 Example showing the derivation of the cloud top temperature and height retrieval over opaque clouds. NOAA 17 scene over central western Europe May 28, 2003, 10:09 UTC (orbit 4803). The solid black curves are the vertical profiles of atmospheric temperature, and the dashed one show the vertical profiles of simulated cloudy T11. The left panel gives the curves for the low stratus cloud over France encircled in Figure 4 and the right panel show the curves for the high

cirrus cloud over southern Germany encircled in Figure 4. The blue dashed line indicates the observed T11 and the blue circle identify its intersection with the simulated T11. The red plus gives the derived thermodynamic cloud top temperature. The low stratus cloud top temperature is estimated to 282.0K, and the height is 800hPa and 1107m above ground. The observed T11 was 280.7K. The high cirrus cloud top is estimated to 228.0K, 300hPa and 8355m. The observed T11 was 227.8K.

The opaque cloud top temperature and height derivation is as follows: The intersection of the observed T11 with the simulated black cloud T11 determines the height of the cloud top in pressure space. The temperature and the height in meters above sea level is then derived from the NWP profile. Finally the height above ground is derived using a high resolution elevation map.

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. However, in situations when the lowest solution is too close to the ground (within 20hPa) or if the modelled 11µm channel brightness temperature change rapidly the CTTH will be set to non-processed (in the processing flags) and the outputs will be assigned the no-data value. Especially the right panel of Figure 5 shows tendencies for a low level inversion. In that particular case the cloud top is well above the inversion and the top temperature can be derived unambiguously.

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.

4.1.2.2.1 Approach

The method is based on the often observed arc-like structure in two-dimensional histograms $T11-T12$ versus $T11$ over regions of semi-transparent or broken clouds, like the one shown in Figure 6.. 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).

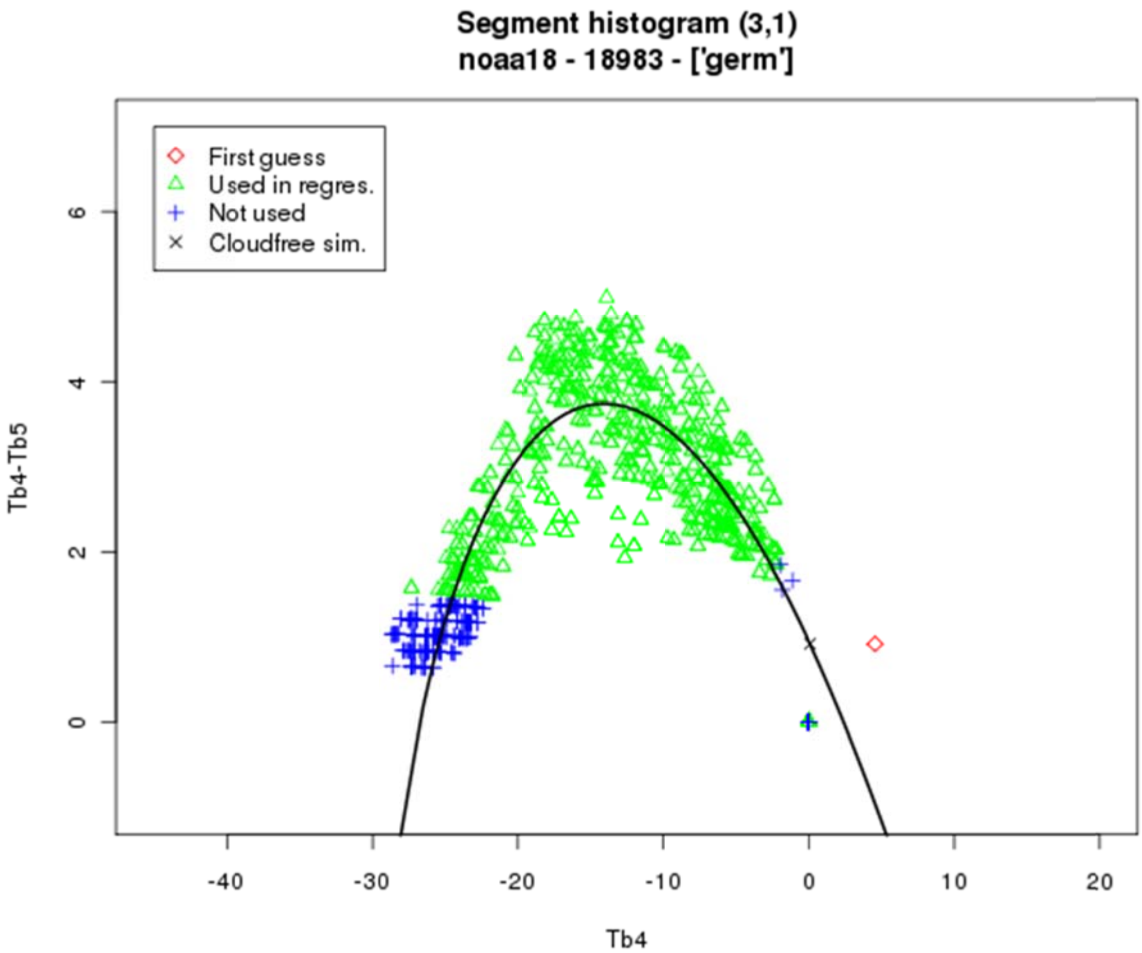

Figure 6: Example distribution of pixels from a 32x32 size image segment. From a NOAA 18 overpass received at Norrköping, orbit number 18983, over the North Sea at 11:26 UTC 2009-01-25. Brightness temperature difference in AVHRR channels 4 (11µm) and 5 (12µm) is shown as a function of brightness temperature (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.

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 σ_{11} forms an arc shaped curve opening downwards (as pictured in Figure 6), 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 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 plot a $T_{11} - T_{12}$ vs. T_{11} histogram, just as it is done in Figure 6. 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

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

Equation 4

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

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 histogram 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 the free Starpac statistical algorithm software package for this purpose. More details on the least-squares fitting can be found in (Korpela et al., 2001).

4.1.2.2.3 Procedure

For each segment of the remapped imager data a two dimensional histogram of $T11-T12$ versus $T11$ is built up using all cloud free and non-opaque cloud pixels plus the opaque cloud pixels which have a difference in $T11-T12$ exceeding 2K ($T11-T12>2.0K$). 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 4.

The two-dimensional histogram 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 7 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 in Figure 7, 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.

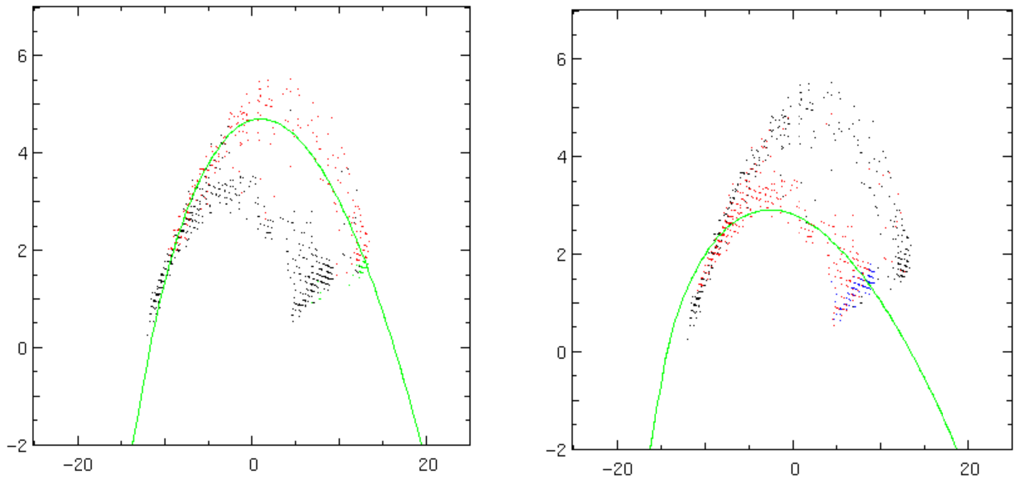

Figure 7 Model fitting done separately for the pixels over land (left) and for the pixels over water (right) in a single image segment histogram of T11 – T12 versus T11 (temperatures in °C). The green points are clear pixels over land, the blue points are clear pixels over water, the red points are the 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.

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 such useless results. The rmse of the distribution against the assumed model may not exceed

PGE03pMAX_LIMIT_RMSE=0.7K. The smallest acceptable probability for the distribution χ^2 value to be as large (or larger) than the value from the actual distribution when assuming the best fit model is PGE03pMINP=0.001. Furthermore the solution cloud top temperature has to be inside the interval specified by the first guess surface temperature and PGE03pMIN_ALLOWED_CTT=-55.0°C.

The theoretical model for the arc shape histogram 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 two parameters are always left free for the fitting algorithm to solve, but T_s and δ_s could be fixed using forward radiative transfer estimates for their values. 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, but within a reasonable interval.

If PGE03pNUM_FREE_PARAM is set to 2, then the first two parameters are free, and the curve fitting is similarly tried several times with both T_s and δ_s having fixed values around the first guess point. With the implemented least-squares algorithms the PGE03pNUM_FREE_PARAM=3 gave convergence most often, hence it is the default.

The iterative least-square fitting is being fed with a qualified first guess specific for the surface regime (land or water). The first guess T_c is set to the minimum of $\{-20°C, T11_{\min}\}$ where $T11_{\min}$ is the minimum channel 4 brightness temperature of the histogram pixels. The first guess for the parameter β is set to 1.5. The first guess of T_s is set to the simulated clear T11 for the given surface ($T11_{clear}$). However, it is not allowed to be lower than the maximum 11µm channel brightness temperature of the histogram pixels ($T11_{max}$) and higher than the the maximum of $\{T11_{\max}, T_s + 2K, T11_{clear} + 5K\}$, where the T_s is the surface temperature and $T11_{clear}$ the channel 4 clear simulation of the dominating surface inside the segment.

The first guess δ_s is set to the simulated clear $T11 - T12$ for the given surface ($T11 - T12_{clear}$). But it is not allowed to be lower than 0.0K or higher than 5.0K or higher than the lowest observed $T11 - T12$ of all cloudfree pixels inside the segment.

4.1.2.2.4 The 'moving window' functionallity

The CTTH semi-transparent scheme has an optional functionality called 'moving window'. This functionality is used for giving more pixels with values, in the CTTH-semi-transparent product. Quite many semi-transparent pixels do not get a cloud top value, but the moving window functionality will assign values to a greater part of them.

The processing area we use is divided into segments for the CTTH-semi-transparent processing. When moving window is off, the procedure of fitting the measured values to an arc, described in the earlier part of section 4.1.2.2, is applied once for each segment. When 'moving window' is on, the same procedure of fitting values to an arc is used; but it is performed several times per segment. Onwards in this section is described how the CTTH processing is performed when the moving window functionality is in use.

We always use the same size of the segment. The segments we run it on are shifted so as to overlap each other. So the procedure has to be run four times per segment (of those segments having semi-transparent clouds at all), i.e. in the following ways:

- for the original segments
- for segments shifted half a segment size to the right
- for segments shifted half a segment size upwards
- for segments shifted diagonally: half a segment size to the right and half a segment size upwards.

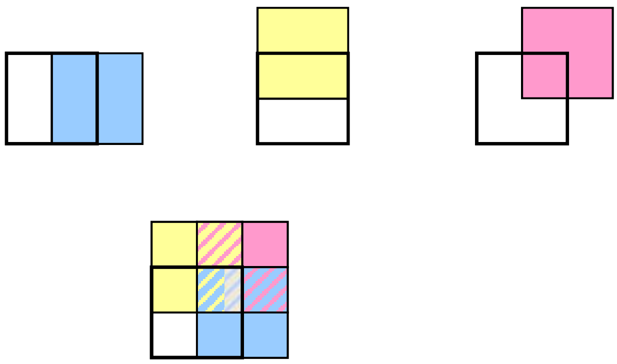

Figure 8 How the segments are shifted in moving window: The bold black square is our original segment. The coloured squares are differently shifted segments. In the bottom picture we see how 4 segments (one original and 3 shifted segments) are overlapping each other.

This means that each spot of the area is covered by four segments. Let us look at an example, Figure 8, how this shifting can be done. If the bold black square is our original segment, then the blue square is the right shifted segment, the yellow square is the upwards shifted segment and the pink square is the diagonally shifted segment. Then we see that the upper right quarter-square of our original segment (or say: the small square right in the middle, in the lower picture) is covered by both the black square, the blue square, the yellow square and the pink square. Another example is the upper left quarter-square, which is covered by the black square and by the yellow square and by two other squares shifted in from the left side. Of course this applies to all parts of our area, all parts are covered by four overlapping segments of different shift.

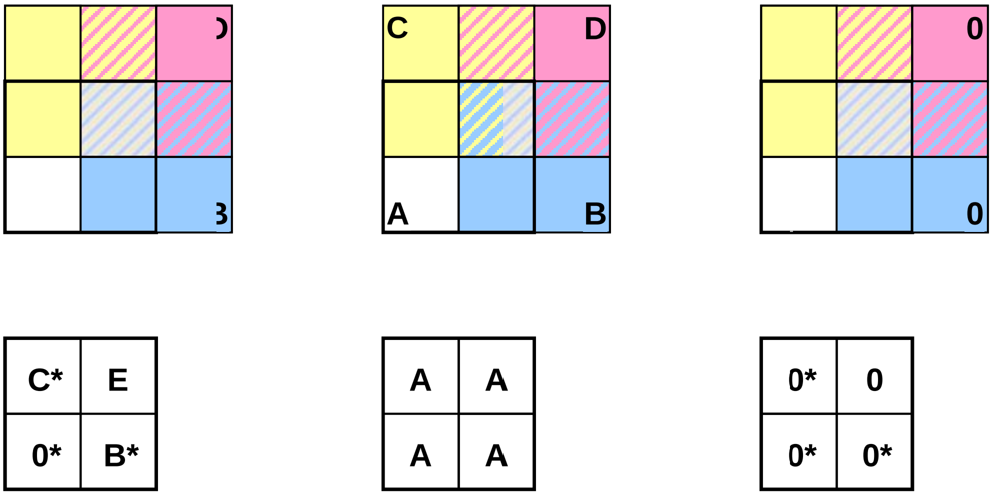

*Figure 9 How the shifted segments are combined: The top figures show which segments that are combined, and their respective values. The bottom figures show the resulting value in the four parts of our original segment. Left figure is when original segment has no-value. Middle figure is when the original segment has got a value. Right figure is when no segment has got a value. The values marked with * means that this value is also, in reality, influenced by other segments, not illustrated here.*

If our original segment had no value, the new value is taken as a mean value of the values from the shifted segments, if they have values. In the left part of Figure 9 the upper right quarter-square gets its value as a combination of the values of the blue, the yellow and the pink square:

$$E = \frac{B + C + D}{3}$$

Equation 5

The other quarter squares also get new values. All those values are all influenced by others segments shifted in from the left or from the downside, so no equations are given for them here.

Let us look at some more cases that can appear:

If e.g. C is no-value, then we set

$$E = \frac{B + D}{2}$$

Equation 6

This is like Figure 9, the left part, but with C being 0.

If our original segment has got a value, that value is kept all over the segment, un-according to the values of the shifted segments. See Figure 9, the middle part.

If neither our original segment nor the shifted segments has any got values, then there is no value to use so we end up with no-value. See Figure 9, the right part.

The moving window functionality becomes useful for a segment, if the original segment did not have any value, and if any of the other three ones might have a value to offer. Thus we increase the amount of semi-transparent data that we get out; we get an extra segment (or quarter-segment) having data, here and there, spread out over the area. And this is from still the same amount of indata.

4.2 PRACTICAL CONSIDERATION

4.2.1 Validation

The only few global tests of quality and performance of this algorithm have been carried out based on global Metop data. As a consequence of global monitoring some adjustments to both product visualisation and height assignment for very high clouds have been implemented in v2009 in order to adequately present the highest cloud tops, specifically for very deep convection as it regularily appears in the tropics. For the Metop Satellite objective validation against Cloudsat /Calipso is unfortunately only possible for arctic regions due to overlap constrains of orbits. Cloud products in the arctic has been undergone a thorough validation by CMSAF ([RD.5]). See also Karlsson et al., 2009. One example of that is given in Figure 11. More comprehensive validation against ATRAIN cloud top products will be carried out globally when the NOAA GAC chain for PPS is operational. Currently CLOUDSAT/Calipso data represents the best available reference dataset for quality assessment of cloudheight products.

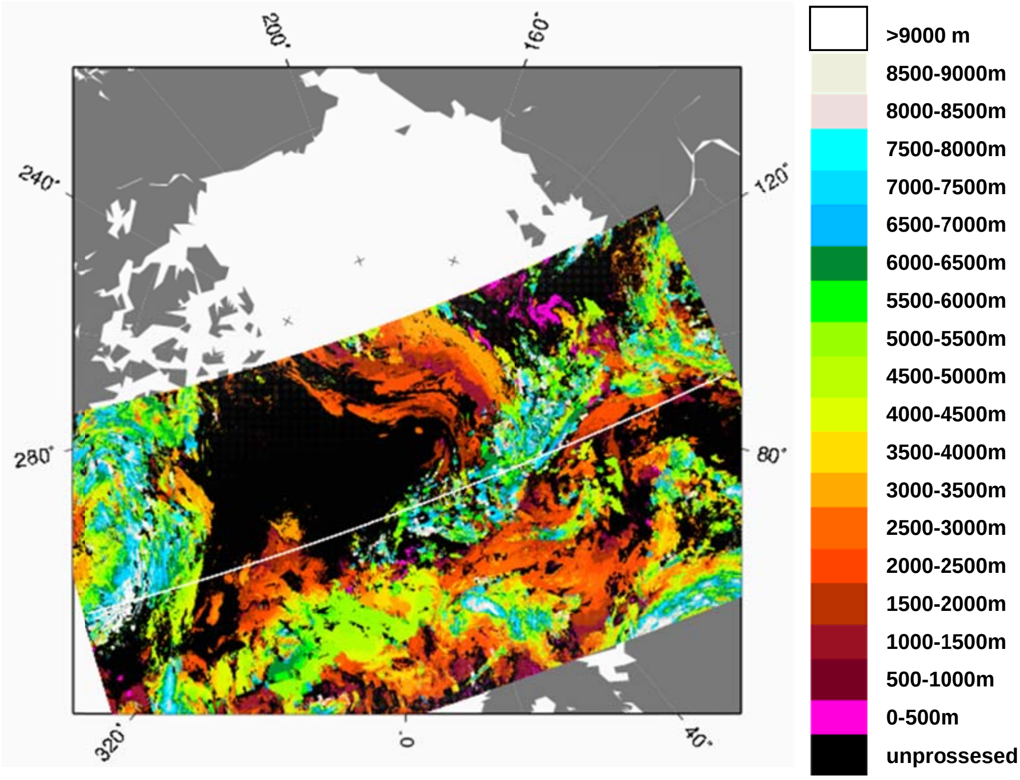

Figure 10 Example of matchup track (white line) along the NOAA-18 overpass superposed over the PPS cloud top height product for 5 June 2007 at 01:43 UTC (i.e., time for first scanline).NOAA-18 flying from right, Siberia, to the left close to the North Pole which is in the centre of the picture. From the Climate Monitoring SAF.

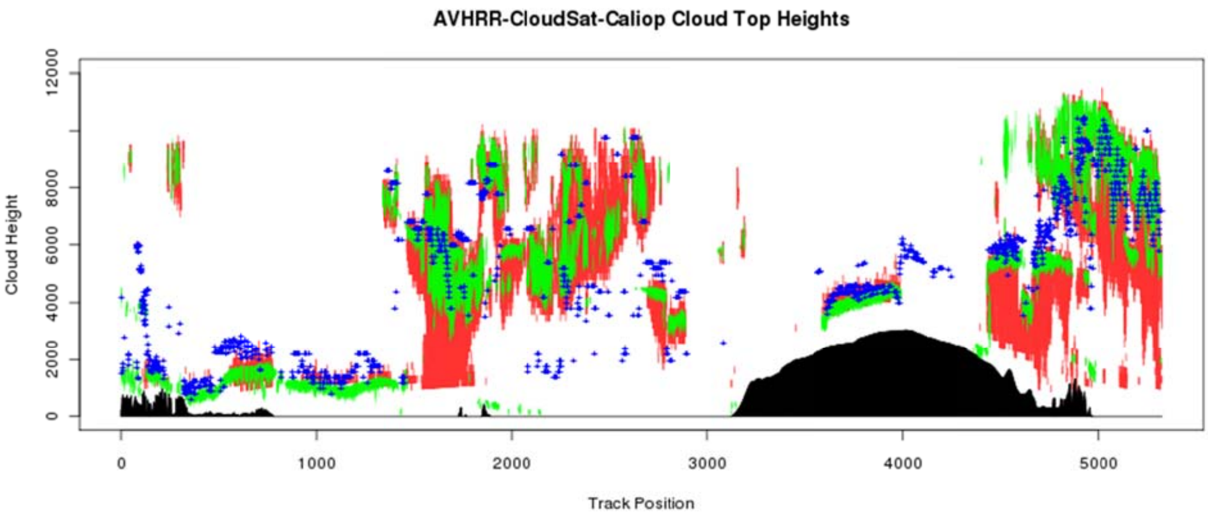

Figure 11 Cross section plot of matched PPS (NOAA-18, 27 July 2007 at 06:12 UTC) and CloudSat/CALIPSO results as a function of the length along the matchup track (in km). Colour description: Red = CloudSat cloud mask, Green = CALIPSO cloud mask, Blue crosses = PPS cloud top heights from the CTTH product. Topography along the matchup track is shown in black (e.g. Greenland in the right part between 3000 to 5000 km).The cross section can be directly compared

with the visualised matchup track (starting at the right part over Siberia) in Figure 10.Looks reasonable, except for some pixels around track position 2000-2500, where the CTTH product is underestimated.

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. When set, also the flag quality is set indicating that some sort of quality assessment has been performed. The extra flag informing about a performed quality assessment is available since situations may occur where it is possible to make a quality assessment and come to the result that the pixel has a higher than average confidence. As currently implemented this will never occur, but future validation may identify such situations and motivate its use in the algorithm.

The flags identifying whether the pixel was classified opaque or semi-transparent or partly cloud covered, the presence of inversion, and the flag identifying the application of the histogram technique all 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 semitransparent clouds. It is assumed that all semitransparent clouds in a processing segment contain the same height, which is not necessarily true and also leaves 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 semitransparent clouds, since the algorithm does not always converge.

4.2.4 List of inputs

4.2.4.1 Satellite data

The same spectral information as needed by the CT is input to the CTTH (see section *List of inputs* in ATBD-01 [AD.2]) and as 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 Mask

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 CM and the CT the CTTH needs information on the sun- satellite viewing geometry in pixel resolution. See section *List of inputs* in ATBD-01, [AD.2].

4.2.4.4 Land cover characterisation and elevation

The same land-use and elevation data needed by the CM is required by the CTTH. See section *List of inputs* in ATBD-01 [AD.2].

4.2.4.5 NWP data

Like the CM 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 CM 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 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

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 cloud cover fraction. But this latter parameter is not retrieved with the current algorithm. It may be retrieved if the radiance rationing 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 four 8 bit datasets and one 16 bit dataset. The 8 bit datasets are for temperature, pressure, height and cloudiness, where there cloudiness is left empty for the moment. The 16 bit dataset contains processing 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 8bit 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
1.0K/count	100.0K	255

Cloud Top Pressure

The cloud top pressure is stored using a linear conversion from 8bit 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
25hPa/count	0.0hPa	255

Cloud Top Height

The cloud top height is stored using a linear conversion from 8bit 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
200m/count	0.0m	255

Processing flags

The processing is sometimes referred to as quality flags, since they, at least indirectly, provide information about the reliability of the cloud top estimation. Several of the bits are left empty (spare) possibly to be used in the future if new retrieval methods are being implemented.

Table 8 Processing bit

Bit number	Flag	Explanation
0	Non-processed	Containing no data (outside satellite swath) or corrupted data
1	Cloudy	Cloud contaminated (either opaque, semi-transparent or fractional)
2	Opaque cloud	Opaque cloud

Bit number	**Flag**	**Explanation**
3	RTTOV	RTTOV derivation available, version 9
4	Missing NWP data	No NWP data available
5	Inversion	Low level temperature inversion present
6	AVHRR missing	Some (one or several channels) AVHRR data missing
7	Using RTTOV	RTTOV simulations applied in the derivation
8	Window T11T12	Window/histogram technique applied (for semi-transparent and fractional clouds)
9	*Spare*	(for possible other algorithms to come)
10	*Spare*	(for possible other algorithms to come)
11	*Spare*	(for possible other algorithms to come)
12	*Spare*	(for possible other algorithms to come)
13	*Spare*	(for possible other algorithms to come)
14	Quality	Quality assessment performed
15	Low confidence	

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 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 12 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 13 shows the same example as shown in Figure 12 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

Figure 14.

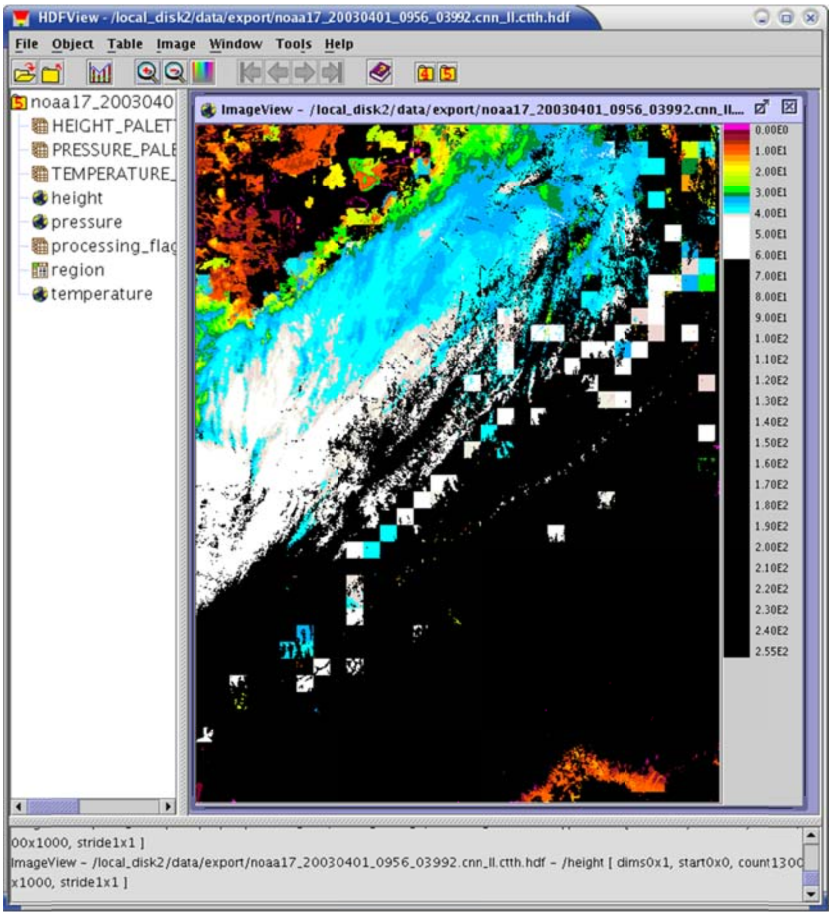

Figure 12 An example of CTTH image display using hdfview: A NOAA 17 scene over West Europe April 1, 2003, 9:56 UTC (orbit 3992). Here only the height in meters is shown. See Figure 10 for ctth colour interpretation.

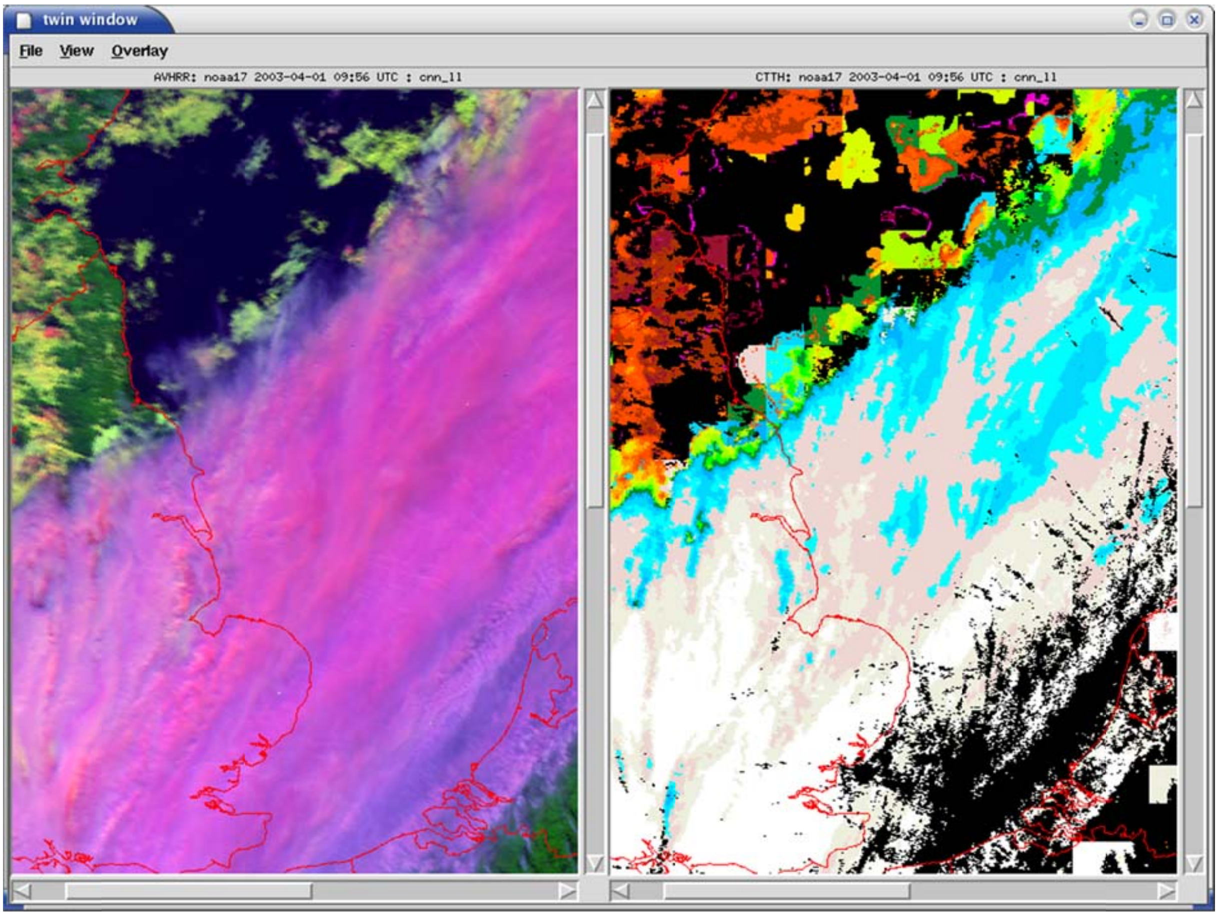

Figure 13 Example of ctth image display using a dedicated PPS image viewer developed at SMHI. Same scene as shown in Figure 12, but here in a close up over the north sea, south eastern Great Britain, and the Netherlands. To the left an RGB image using channels 1, 3A, and 4 is displayed and to the right the corresponding merged CTTH using both the opaque and semi-transparency retrievals.See Figure 10 for ctth colour interpretation.

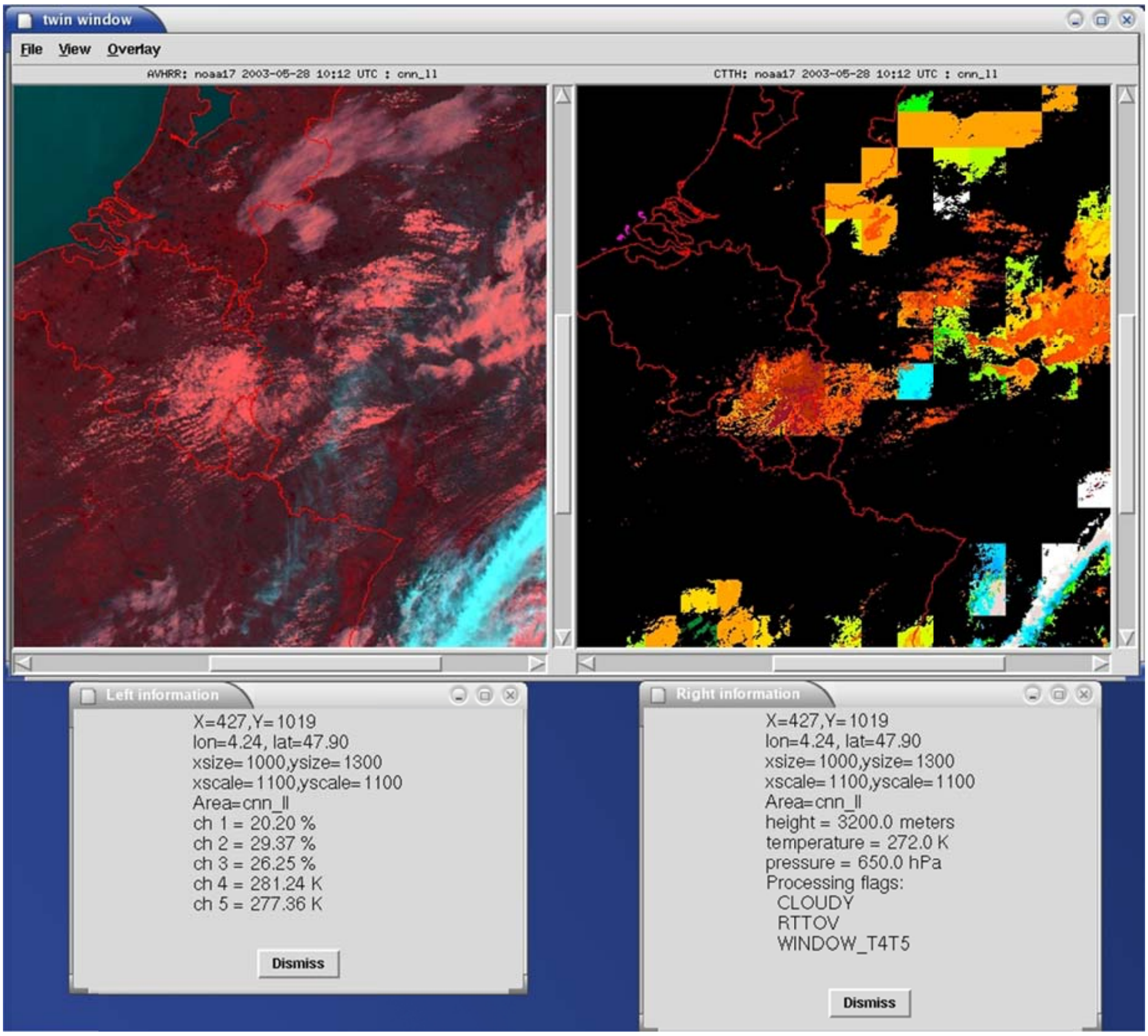

Figure 14 Example visualisation with the PPS viewer developed at SMHI. Same NOAA 17 scene as shown previously in Figure 4. The two information dialogs provide information for the pixel under the mouse-pointer. See Figure 10 for ctth colour interpretation.

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