CLOUD DETECTION FOR MIPAS: AN INITIAL FEASIBILITY STUDY AND TECHNICAL SPECIFICATIONS FOR A CLOUD DETECTION ALGORITHM

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1 Introduction

Cloud effects will be an important feature affecting the limb sounding observations of the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) since the clouds absorb, emit, and potentially scatter radiation over a broad range of wavelengths in the infra-red. As defined in this study, clouds are conglomerates of particles present in localised formations and regions. These clouds include most notably cirrus clouds in the upper troposphere and polar stratospheric clouds in the lower stratosphere. Previous work has shown that cirrus clouds occur at tropopause altitudes with frequencies of up to 40% in the tropics but also with strong gaps in different regions. Particularly notable are the analyses of *Wang et al.* [1996], *Mergenthaler et al.* [1999], and *Spang et al.* [2001]. The studies of Mergenthaler and Spang demonstrate that cloud features are present in observations by infra-red instruments and will therefore need to be accounted for in the altitude scan range of the MIPAS.

This study has investigated the feasibility of cloud detection for the MIPAS case by employing observations from the CRyogenic Infrared Spectrometer and Telescopes for the Atmospheres (CRISTA) experiment [*Offermann et al.,* 1999]. The CRISTA experiment flew on the space shuttle in November 1994 and August 1997, and measurements are therefore global in the time period concerned. This provides an opportunity to develop a validated tool for the MIPAS analyses using the CRISTA spectra both to observe the presence of clouds and to perform cloud detection.

For the MIPAS operational analysis, a cloud detection tool is necessary to flag spectra containing optically thick clouds so that the retrieval does not ingest such radiances (or "sweeps") into the retrieval stage, thereby reducing the propagation of errors into non-cloudy layers above. Ideally such a flag should be able to distinguish between "thick" and "thin" clouds; gas concentrations may well be retrievable in the latter case since the MIPAS retrieval scheme includes a continuum term in the state vector. Therefore the ideal cloud detection flag should allow flexible tuning of thresholds to allow the maximum "good" data to be employed in the retrieval.

The cloud detection scheme presented here provides a simple and effective means of setting cloud thresholds whilst operating on the entire global MIPAS dataset. The cloud index profiles generated allow a cloud top height to be easily assigned and also provides information which is required in the validation of the retrieved gas profile data from MIPAS, particularly that retrieved in the presence of optically thin clouds. A related benefit of this method is that it is sensititve to enhanced values of sulphate or other aerosol extinctions which may also be present in the atmosphere at certain times and locations. The same masking procedure will therefore apply.

2 CRISTA Instrument

The CRISTA is a limb-scanning instrument, which measures the thermal emission of 18 trace gases in the 4–71 μm range [*Offermann et al.,* 1999, *Riese et al.*, 1999]. The instrument is especially designed for high spatial resolution in all three dimensions by using three telescopes looking 18° horizontally apart. The optics and the infrared detectors are cooled by cryogenic helium. This results in high sensitivity of the detectors and the IR-spectra being scanned very fast (4-15 μm in 1.2 s), which consequently yields a high spatial resolution. The spectral resolution is in the order of 2 cm^{-1}. The instrument was flown in space twice (on the NASA Space Shuttle) for a measurement period of around one week in November 1994 (5–12) and August 1997 (8–16). During the missions CRISTA was integrated in the free-flying satellite ASTRO-SPAS. For the first flight the latitudinal coverage was 57°S–64°N. Due to the pointing capabilities of the ASTRO-SPAS system the coverage was extended to 74°S–74°N for the second mission by slewing the satellite (57° orbit inclination) at high northern latitudes to the north and at southern latitudes to the south. Therefore CRISTA-2 has made observations deep inside the south polar vortex for mid-winter conditions.

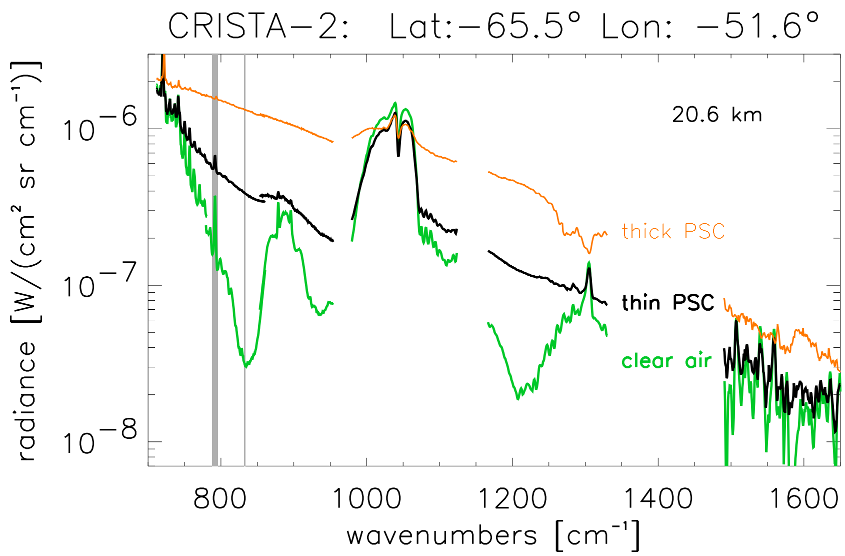

Figure 1: Three single spectra in the Southern hemisphere polar region for clear air (grey thick curve), optically thin (black thick curve), and optically thick conditions. The wavenumber regions for the defined cloud index are indicated by grey vertical bars.

One of the scientific objectives of CRISTA is the study of specific cloud features around the tropical tropopause as well as in the cold stratospheric polar vortex by means of the information content of the measured spectra [*Spang et al.*, 2001a,b]. In the tropics a horizontal resolution was achieved of around 200–400 km along the orbit track and 600 km crosstrack respectively. The resulting dense measurement net allows high quality occurrence statistics for clouds in spite of the short measurement periods of only one week [*Spang et al.*, 2001c]. The sample volume has a length along the view direction of roughly 280 km and a sample volume width across the view direction of around 20 km. The vertical field of view is on the order of 1.5 km. One tilting mirror for each telescope realizes the altitude scan through the atmosphere. For CRISTA-1 an altitude step spacing of 1.5 km has been applied, and 2 km for the second mission. The vertical resolution is on the order of 2.0 km [*Riese et al., 1999*].

3 Spectra of clouds from CRISTA

During the second CRISTA mission the enhanced altitude grid and latitudinal coverage provided the observation of tropospheric (>8 km) and polar stratospheric clouds (PSC). Figure 2 shows an example of limb radiance spectra in the 700–1650 cm^{-1} region for cloudy (black) and non-cloudy (grey) conditions in the tropics at around 17 km. The spectral resolution is on the order of 500. The spectral coverage is not continuous but includes some gaps resulting from the instrument design. Tremendous intensity changes could be observed, when the instrument looks into a cloudy region. The enhanced radiation by clouds produces a significant change in

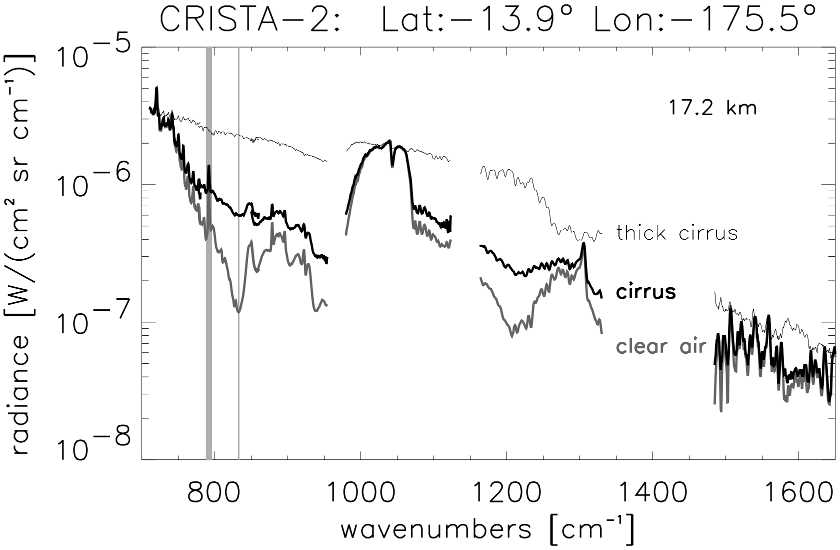

Figure 2: Three single spectra in the tropical tropopause region for clear air (grey thick curve), optically thin (black thick curve), and optically thick conditions. Clear air and thin cirrus spectra are measured at 17.2 km altitude in two subsequent profiles around 300 km apart. The optically thick spectrum represents a measurement 2 km below the optically thin case.

the spectral shape, especially in the wavenumber regions 800–950 cm^{-1} and 1150–1250 cm^{-1}. Parts of these wavenumber regions act as atmospheric windows for clouds and aerosols, because only few gases with low emissions are present. For optical thick conditions (thin grey contour) most of the emission features disappear, the spectrum is similar a grey body spectrum, and in addition absorbition features occur. Figure 1 gives an example for the observation of PSCs in souther polar vortex. Tropical and polar clouds produce very similar changes in the shape of the spectra. Therefore a cloud detection scheme by means of changes in the spectra can work in a similar manner both in the upper troposphere/lower stratosphere (UT/LS) region and in the polar stratosphere.

4 A Standard Cloud Index

4.1 Method Description

In the present study, the cloud detection is accomplished by using the ratio of radiances in the 788-796 cm^{-1} CO_2 dominated and the 832–834 cm^{-1} aerosol dominated wavenumber regions (Fig.2 and 1: grey shaded areas). The latter region contains only weak emissions of ozone and CFC11 in comparison to the background aerosol and the enhanced cloud emissions. In the following the defined ratio will be referred to as the standard CRISTA Cloud-Index (CI_{CR}). The detailed description of the computation of CI_{CR} is given in section 5. Typical values for CI are shown in Figure 3 under conditions with no PSCs (dashed curve) and with PSCs (solid line) in the instrument FOV. The radiance ratio decreases rapidly from one altitude step to the next. Constant values of $CI_{CR} <2$ ($\sim$ 1) indicates optical thick conditions. Sensitivity studies for CI_{CR}) with the CRISTA forward radiance model [*Riese et al.*, 1999] were carried out and reported in *Spang et al.*, [2001b,c]. The analyses show that in the height regime 12–40 km a ratio of CI_{CR} =2 or smaller can only be produced by a radiation background anomalously enhanced by aerosols or clouds. The temperature dependence of CI_{CR} is especially weak (<1%/K in the 10 to 30 km range).

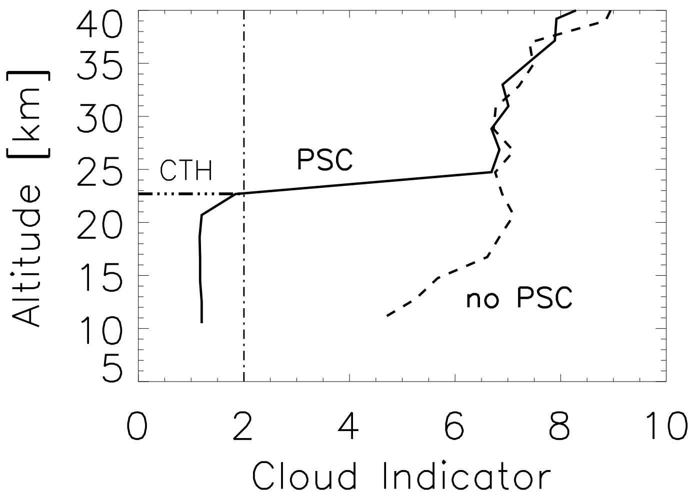

Figure 3: PSC affected and non-affected single height profiles (68°S, 25°W at AUG 13 02:39 respectively 71°S, 174°E at AUG 13 10:05) of the so called cloud index in the south polar vortex. The cloud top height (CTH) is also indicated

The analysis also allows an approximate *cloud top height* (CTH) to be defined by computing the first tangent height where CI_{CR} falls below the specified threshold (Fig. 3). A map of CTHs computed for one specific day during the CRISTA-2 mission is shown in Figure 5 (top). The analysis is shown for the left and right CRISTA viewing direction only, so including around 5000 profiles; the central view was not suitable for this analysis due to calibration problems on this day. Obviously large amount of profiles are influenced by clouds in the height range 8-18 km for the tropics and mid-latitudes as well above 18 km in the south polar region. The data can be used for the determination of cloud occurrence frequencies. Comparison with SAGE observations of subvisual cirrus and opaque clouds are in generally good agreement [*Spang et al.*, 2001c].

4.2 Alternative Spectral Windows

The spectral regions employed for computing CI_{CR} are sampled in the MIPAS Filter-A band. In the case of missing sweeps in the Filter-A band due to spikes or other instrument disturbances it might be necessary to select another MIPAS channel.. Different wavelength region have been tested. Due to gaps in the wavelength coverage for CRISTA as well for MIPAS only a few atmospheric window regions can be studied and validated using CRISTA data, as described for the standard cloud index in this report. These window regions will be investigated in more detail in future studies. A first good result for an alternative wavelength region is shown in Figure 4. The computation of the new cloud index in the MIPAS Filter B range (CI_B) around 1230 cm^{-1} is described in section 5. In comparison to the standard CI profile CI_B looks obviously different. A similar threshold for thick cloud indication was achieved by scaling the simple radiance ratio.

In the ideal case both cloud indices would detect exactly the same clouds. Figure 5 show a comparison of computed cloud top heights by both detection methods. Obviously both methods

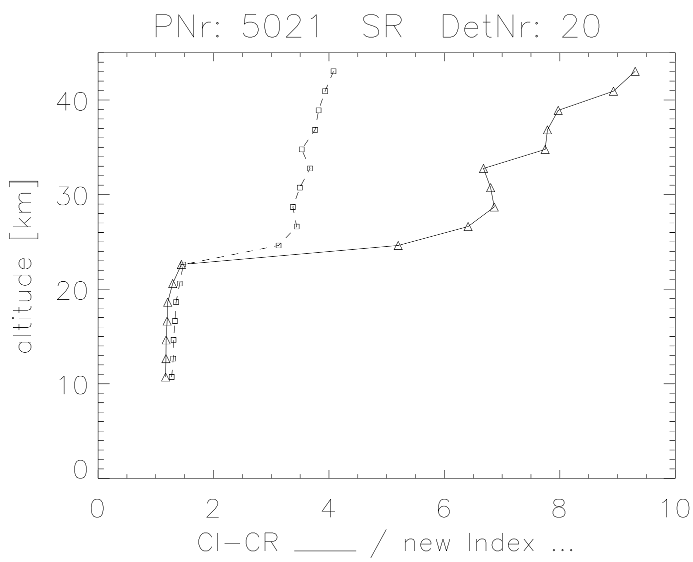

Figure 4: Comparison of a standard cloud index profile (CI-CR) and the new index profile in the MIPAS Filter B range (dashed line).

results in a very similar distribution and similar CTH values. Absorption and scattering characteristics of clouds are depending on the wavelength. Therefore changes in the shape of spectra by clouds also depending on the wavelength and differences in the sensitivity of the detection of clouds by both approaches might be expected. For more quantitative comparison Figure 6 shows each individual CTH for both detection methods in a scatter plot and differences are now easy to determine. Due to the CRISTA altitude grid of around 2 km any higher or lower detected cloud is shifted by ±2 km or a multiple of 2 km in reference to the standard cloud index. In the UT/LS region both methods agree very well. The new index detects 3.6% cloud events at higher altitudes and 7.7% at lower altitudes. In addition, the new index detects 7% more cloudy spectra especially in the lower altitudes (8-10 km) where both methods have some limitations due to enhanced continua emissions.

4.3 Layering of clouds

The observation of less cloudy conditions below optical thick conditions is quite conceivable and in some cases a successful retrieval below the first detected CTH might be possilbe. If the cloud has a very small vertical extension (e.g. $\sim 1-2$ km) the length of optical limb path through the clouds change extremely from on altitude step to the other. For example the optical path length through a 2 km thick layer at 20 km tangent height is around 320 km. For tangent height at 18 km the path through the layer at 20 km is only ~60 km and the observed spectra can change from optical thick to thinner conditions.

The standard cloud index was used to obtain an estimate of how often this effect might be occur. For the whole CRISTA mission of August 1997, only 8% of the detected cloud profiles (15200) show an enhancement in CI ($CI_{CR} > 2$, thin clouds or clear air conditions) below the cloud top height i.e. a return to “clear” air below an optically thick cloud. The probability increases for the case of the PSC profiles (16% of 1300 profiles) which occur at high altitudes in the Antarctic vortex during the CRISTA mission.

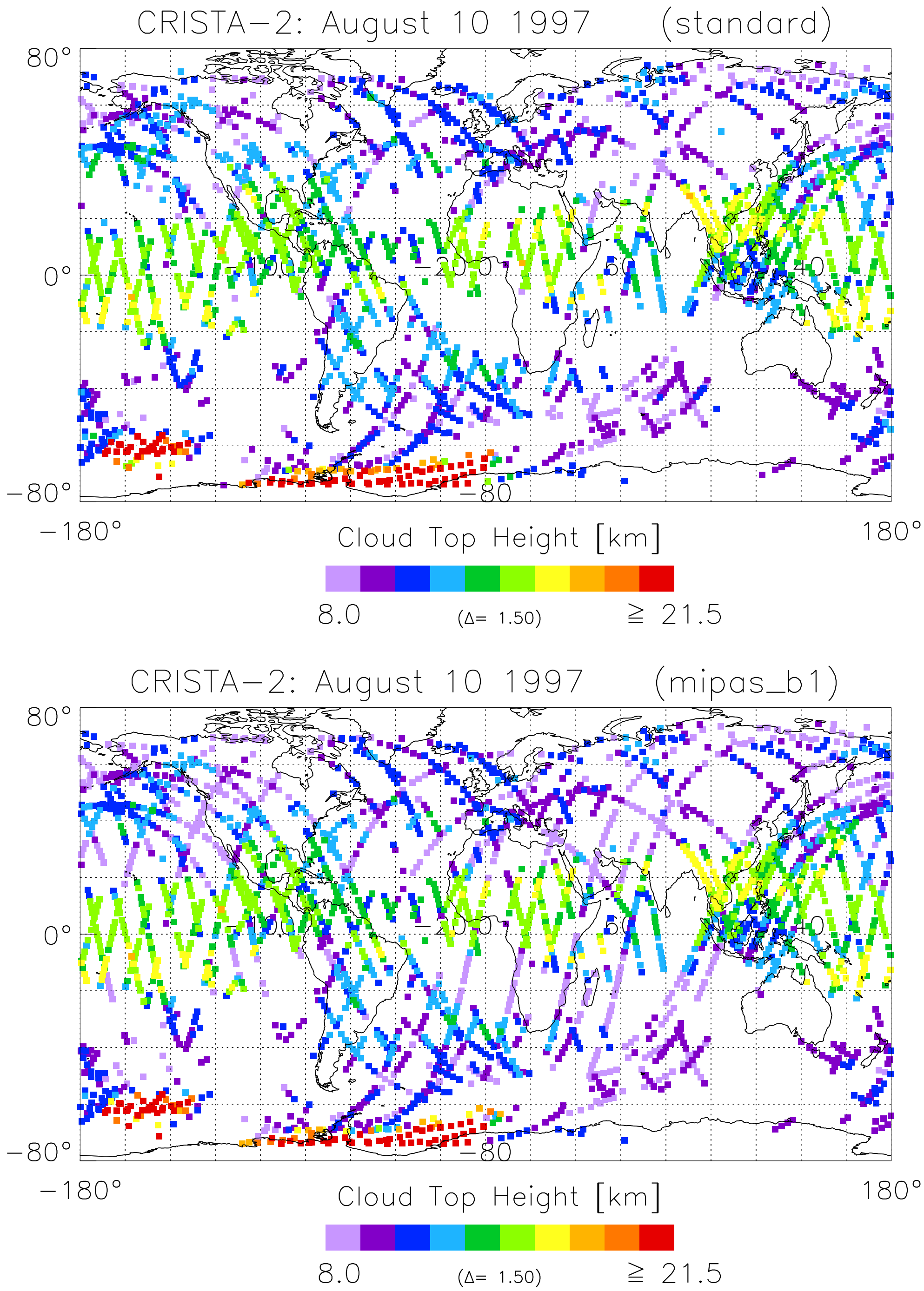

Figure 5: Comparison of CTH computed by the standard CRISTA cloud index (top) and the new alternative cloud index in the MIPAS B-filter range (bottom). Only the left and right viewing direction of CRISTA was used because the detector of the central spectrometer for the wavelength region of CI_B had problems in the calibration.

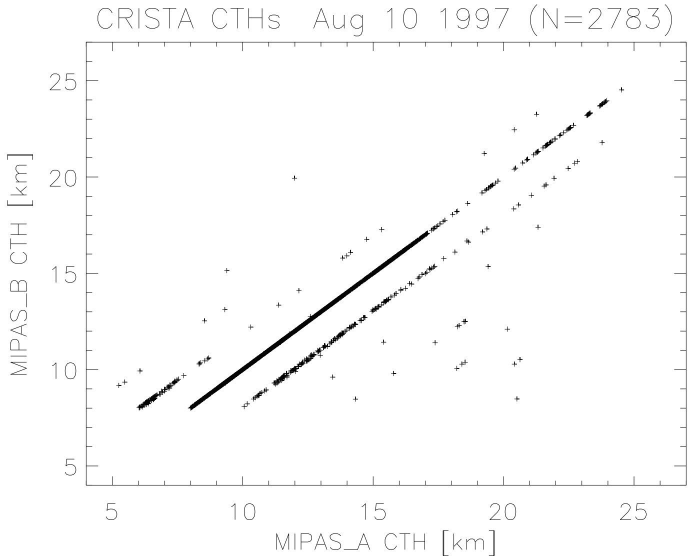

Figure 6: Computed cloud top heights (CTH) using the standard CRISTA cloud index in the MIPAS Filter A range versus CTHs by the the additional cloud index in the MIPAS Filter B range.

5 Technical Method

5.1 MIPAS Filter A range

The standard CRISTA cloud index works in the MIPAS wavelength region of filter A. CI_A ($= CI_{CR}$) is computed by the ratio of two spectral meso-windows:

$$\mathrm{MWa1}: \ 788.20 - 799.25\,\mathrm{cm}^{-1}$$
$$\mathrm{MWa2}: \ 832.30 - 834.40\,\mathrm{cm}^{-1}$$

In each meso-window the mean radiance have to be computed, which results in the simple formula:

$$CI_A = \frac{\mathrm{MEAN(MWa1)}}{\mathrm{MEAN(MWa2)}}$$

A threshold value for strong cloud indications in the line of sight is specified by:

$$CI_A < 2$$

for the height range 10–40 km. Below 10 km CI_A has to specified in more detail in future studies, but it seems to be difficult to use the same simple approach for altitudes below 10 km.

5.2 MIPAS Filter B range

A second set of meso-windows have been defined in the MIPAS B filter range:

$$\mathrm{MWb1}: \ 1246.3 - 1249.1\,\mathrm{cm}^{-1}$$
$$\mathrm{MWb2}: \ 1232.3 - 1234.4\,\mathrm{cm}^{-1}$$

In each meso-window the mean radiance have to be computed and scaled by the same empirical simple formula as above. For this different meso-window, the vertical profiles of CI look quite different. An example for a comparison of both cloud index profiles is illustrated in Figure 4. For these meso-windows, the threshold value is 1.2. In this Figure we have scaled the cloud index using the formula below to enable a direct comparison between the standard index and the new one (also in Figure 5).

$$CI_B = (\frac{\text{MEAN(MWb1)}}{\text{MEAN(MWb2)}} - 0.2) \times 2.0$$

6 Issues and Requirements

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References

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MIPAS CLOUD INDEX ALGORITHM - TECHNICAL SPECIFICATIONS

Technical specifications are provided in this annex for a cloud algorithm required for MIPAS operational processing.

Task description:

A cloud algorithm is required which calculates the ratio of mean radiance (signal) in 2 microwindows and tests this ratio against threshold values specific to the microwindow pair, the altitude and latitude. Where the ratio is smaller than the threshold value, then the "sweep" at this tangent altitude is declared to be cloudy and not used in subsequent processing at level 2. The microwindow test performed on one channel is assumed to be relevant to all channels. If a "sweep" is determined to be cloudy, this flag should be applied to all channels measured at this tangent altitude and this vertical scan (profile).

Below this tangent altitude, all "sweeps" in the same scan vertical should also be flagged so they are not used in subsequent processing at level 2. [At a later stage, it may be desirable to enable lower altitude data which is "non cloudy" to be passed on for further processing at level 2. This option is required].

Inputs:

1. Pairs of microwindows in priority order.
2. Threshold values for each pair of microwindows. The threshold values will be a function of altitude and latitude.
3. Calibrated MIPAS level 1b radiance (signal) spectra.

Selection of microwindows:

1. A pair of microwindows shall be selected in priority according to the order in which they appear in the microwindow file.
2. If the first pair of microwindows cannot be used because ofproblems (e.g. spikes, data corruption) with the required MIPAS radiance, then the next priority microwindows shall be used.
3. If there is no suitable data for the cloud tests, then.....

Computation:

A pair of microwindows (MWc1 and MWc2) are read from the MW file along with threshold values, ThV(z,lat), which are a function of altitude,z, and latitude (lat).

Microwindow (MW) parameters: MW low frequency MW_f1 and MW high frequency MW_f2. No. of MW points = MW_N(f2-f1)

Using MIPAS level 1b calibrated radiance (signal) data, MIPRAD, in the appropriate microwindows, a ratio is calculated at each altitude, z, for a given vertical scan.

MEAN(MW1) = SUM(MIPRAD(MWc1_f1).....MIPRAD(MWc1_f2)) / MWc1_N(f2-f1)
MEAN(MW2) = SUM(MIPRAD(MWc2_f1).....MIPRAD(MWc2_f2)) / MWc2_N(f2-f1)
RATIO = MEAN(MW1) / MEAN(MW2)

RATIO (z, scan) < ThV(z,lat) : CLOUDY at z
RATIO (z, scan) > ThV(z,lat) : CLEAR AIR

The term RATIO is known as the cloud index and is a profile since it is a function of z.

If CLOUDY:

1. All MIPAS radiances (all channels) at z for the same vertical scan are declared unsuitable for processing at level 2.
2. All MIPAS radiances at heights below z (in the same vertical scan) are declared to be unsuitable for processing at level 2 (optionally, radiances below z are allowed to pass to level 2 for processing).

Outputs:

1. MIPAS level 1b data flagged for clouds so as to determine use in level 2 processing.
2. Cloud index profiles should be output as a diagnostic for operational retrieval quality control and validation.

MIPAS CLOUD INDEX ALGORITHM - ISSUES AND REQUIREMENTS

There are a number of issues which must be considered with the implementation of the cloud algorithm.

1. A cloud algorithm is an important requirement for MIPAS operational processing and will result in level 2 products capable of meeting specifications.

2. The cloud algorithm has been validated globally with CRISTA data but in a restricted time period and for an instrument with different vertical resolution to MIPAS.

3. The characteristics of different microwindows will lead to mostly the same spectra being flagged as cloudy, but there will also be small differences.

4. In addition, the cloud impact itself may vary from channel to channel at the same altitude and in the same scan.

5. The cloud algorithm is formulated on the assumption that the different MIPAS channels have the same field-of-view, an issue which remains to be resolved.

6. The ability of level 2 processing to successfully determine gas concentrations is known to be reasonable in the case of "thin" clouds but this remains to be quantified. This ability arises from the continuum retrieval performed jointly with the gas retrieval.

7. The ability of the level 2 processor to determine gas concentrations below thin cloud is promising but has not been fully characterised.

8. A cloud algorithm will reduce the amount of data processed at level 2 at lower altitudes leading to a reduction in CPU time for level 2 processing.

In addition to the implementation of the cloud algorithm, the following steps are required:

1. The results from use of different pairs of cloud detection microwindows needs to be characterised and understood.

2. The use of the pairs of cloud microwindows should be prioritised so that the best (most conservative) cloud index is employed. This exercise will need to be performed with both simulated and real MIPAS data.

3. Cloud index profiles should be output for each day of MIPAS data processed and made available to quality control and cal/val teams.

4. The results from different pairs on microwindows should be validated by off-line calculations with real MIPAS data and comparisons to the operational estimates of cloud index.

5. In the commissioning phase, and beyond, the retrieved level 2 products of gas concentrations should be compared to cloud index profile data to determine residual cloud effects on the level 2 products and to ensure good settings of the cloud threshold values.