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CLOUD PROCESSING FOR METEOSAT SECOND GENERATION (MSG)

The paper provides an outline of the prototype development of the cloud processing for MSG at EUMETSAT. The prototype of the cloud processing algorithms has been applied to data of different satellites, e.g. Meteosat, GOES-8 imager and sounder.

CLOUD PROCESSING FOR MSG

1 INTRODUCTION

Cloud processing is an important pre-processing step to derive operational products from meteorological satellites. For current satellite systems several operational and experimental cloud detection and cloud analysis schemes have been developed, e.g. APOLLO (Saunders and Kriebel, 1988), SCANDIA (Karlson, 1996), CMS cloud processing (Derrien et al. 1993). These cloud processing schemes are developed to process AVHRR data (five channels, 1km-resolution at sub-satellite point (SSP)). Histogram analysis schemes are used for the operational cloud processing of current geostationary Meteosat data (Tomassini, 1981). The reason for that is the lack of spectral information of the current Meteosat (three spectral channels (VIS, WV, IR)) and a coarser horizontal resolution of 5 km at SSP.

In the year 2000 a new generation of geostationary Meteosat satellites (Meteosat Second Generation (MSG)) will be launched. It will have 12 spectral channels with a horizontal resolution of 3 km at SSP and an image scan rate of 15 minutes (compared to 30 minutes for the current Meteosat). In preparation of the operational meteorological product extraction for MSG at the Meteorological Product Extraction Facility (MPEF), a prototype algorithm for cloud processing has been developed.

The cloud processing task within MPEF has to serve to other follow-on products derived at the MPEF, e.g. provide a cloud mask for the calibration support, provide a detailed cloud analysis for the generation of atmospheric motion vectors. Therefore the cloud processing within MPEF is split into to separate tasks - the cloud detection (called scenes analysis (SCE)) and the cloud analysis (CLA). The scenes analysis derives a cloud mask (cloud/no cloud decision), while the cloud analysis derives detailed information on the cloud type.

2 DESCRIPTION OF THE CLOUD PROCESSING METHODS

2.1 Scenes Analysis

The basic purpose of Scenes Analysis is to provide information on whether a pixel is clear or cloud contaminated. This information is passed on to the subsequent product derivation processes, e.g. cloud analysis, atmospheric motion vectors, calibration, clear sky radiances etc. Each of these processes will need an estimate for the confidence in the results of Scenes Analysis, e.g. the calibration support function and the clear sky radiance product are using only pixels which have been declared cloud-free with a confidence of 100%.

2.1.1 Description of the SCE algorithm

Due to the fact that the Scenes Analysis is a very important pre-processing task, which is a pre-requisite for almost all subsequent processes, it has to be very flexible and robust. Therefore, the Scenes Analysis algorithm is based on threshold techniques (e.g. Saunders and Kriebel, 1988), i.e. spectral measurements of a particular scene are compared against the predicted clear sky reference value. Based on the outcome of this comparison, the scene is classified. For MSG the following groups of threshold tests have been identified:

Group 1: reflectance tests using the solar channels (4 tests)
Group 2: reflectance difference tests (using all combinations of the solar channels) (6 tests)
Group 3: temperature tests using the IR window channels (4 tests)
Group 4: temperature difference tests (using all combinations of the 10.8µm and 12.0µm channel with all other IR/WV channels) (11 tests)
Group 5: standard deviation tests for the window channels on a moving 3 x 3 pixel target (8 tests)
Group 6: special cloud test for sun glint conditions (1 test)
Group 7: snow and ice test (1 test)

In total there are 35 tests defined. The threshold tests themselves can be enabled/disabled with a pre-defined set of parameters depending on the availability of channels, the pixel location (land/sea), the viewing geometry, and the solar zenith angle (day/night/dawn/dusk and sun glint). However at a maximum only half of the tests in groups 1 to 5 will be selected and the other tests remain as backup tests. This configuration ensures a continuous operation of the Scenes Analysis, since in the case of a failure of a channel, all tests using this channel will be disabled and backup tests with similar capabilities will be enabled. It also provides a maximum of flexibility of the algorithm, i.e. it can be used with input data from other satellites, e.g. METEOSAT, AVHRR and GOES (imager and sounder) data.

The threshold tests will be applied completely independent, i.e. if a test detected a cloud the processing will still continue to perform all other tests. The information of which of the tests detected a cloud is stored, and it is used to define the level of confidence of the cloud/no cloud decision.

Additionally the Scenes Analysis takes advantage of the geostationary satellite data by using the information of the previous repeat cycle. For selected channels the difference of the measurements between the current and the previous repeat cycle are built to verify whether the information content has changed or not. If there are no changes detected (for a pixel), the results of the previous repeat cycle are used (for that pixel). Otherwise the Scenes Analysis continues its normal processing. For the IR channels the measurements of the previous repeat cycle are also used as a predictor for the current repeat cycle (as described in section 2.1.2).

2.1.2 Derivation of the thresholds

The result and the quality of the Scenes Analysis depend heavily on the quality of the determination of the thresholds.

Thresholds for Group 1 tests

For the Group 1 tests (reflectance tests) climatological reflectance data will be used, which are based on a surface type map (Loveland and Belward, 1997) with 18 different surface types.

The climatological reflectance data is corrected for bi-directional effects according to the given solar/satellite angles. During operational processing this climatological data set will be replaced by a clear sky reflectance map extracted from the actual satellite images for each solar channel. This map will be updated on a weekly basis.

Thresholds for Group 2 tests

For the Group 2 tests (reflectance difference tests) the thresholds are determined using static coefficients (different for each test of Group 2, and different for land/sea conditions) and the reflectance measured in the reference channel (e.g. 0.6 µm).

Thresholds for Group 3 tests

The thresholds for the Group 3 tests (brightness temperature tests) are derived using a combination of the following information:

- forecast data, converted into clear sky radiances/brightness temperatures via the radiative transfer model (RTM) (Tjemkes and Schmetz, 1997), and interpolated to the pixel location (depending on land/sea location);
- neighbouring clear sky pixel data from the previous image;
- clear sky radiance product of the previous image.

The predicted clear sky brightness temperature (T_{PCS}) is derived for each pixel from a combination of the above data. The final threshold for Group 3 tests is determined by adding a corrective term to the T_{PCS}, to denote the brightness temperature difference between the clear surface and a cloud. The corrective term depends on land/sea, day/night and surface elevation.

Thresholds for Group 4 tests

For tests of Group 4 the thresholds are determined by using static coefficients (different for each test of group 4, and different for day/night, land/sea conditions), the predicted clear sky brightness temperature of 10.8 µm or 12.0 µm channel, and the predicted clear sky brightness temperature of the other IR/WV channel used in the test.

Thresholds for Group 5 tests

For tests of Group 5 static thresholds are used, which are different for each channel and for land and sea.

Thresholds for Group 6 tests

For the cloud test under sun glint conditions the thresholds are determined by using static coefficients and the reflectance measured in the 0.6 µm channel .

Thresholds for Group 7 tests

For the snow and ice test static thresholds are used.

2.1.3 Output data of SCE

The output of SCE for each pixel consists of:

- The scenes, i.e. cloud/no cloud information (for clear pixels the surface type is provided);
- The quality flag, i.e. the level of confidence in the cloud/no cloud decision;
- The predicted clear sky brightness temperature for all IR/WV channels as derived for Group 3 tests;
- The threshold test flag, i.e. the information which of the tests detected the cloud;
- The clear sky reflectance map for all solar channels (updated weekly).

2.2 Cloud Analysis

The Cloud Analysis (CLA) uses the information of SCE to perform a detailed analysis of the cloudy pixels. The following parameters are derived for cloud contaminated pixel for every repeat cycle:

- Cloud phase
- Flag for potentially semi-transparent clouds or partly cloudy pixels
- Cloud top pressure
- Cloud top temperature
- Effective cloud amount
- Cloud type (e.g. fog, cirrus, stratus type, cumulus type)

In the near future it is also foreseen that the CLA algorithm will derive cloud optical properties, e.g. cloud optical thickness.

2.2.1 Description of the CLA algorithm

The CLA performs additional analyses on all pixels, which have been flagged as cloudy within SCE. It uses the threshold test flag of SCE (i.e. the information on which of the tests in SCE detected the cloud) together with additional threshold tests to derive information about the cloud type, cloud phase, and semi-transparency check. These threshold tests and the determination of the thresholds will be different for daytime and night-time conditions. The cloud top height (pressure), the cloud top temperature and the effective cloud amount are derived using a composite of i) the CO-2 slicing method (Menzel et al. 1983), ii) the WV/IR rationing method (WV7.3/IR10.8 and WV6.2/IR10.8) and iii) the direct IR10.8 cloud height determination.

<u>Determination of the cloud phase</u>

Currently four cloud phases are specified: unknown phase, water phase, ice phase, and mixed phase. The cloud phase is derived from the following information:

- Difference in reflectance between channels 0.6 µm and 1.6 µm
- Difference in reflectance between channels 0.6 µm and 3.8 µm (solar part of ch. 3.8 µm)
- Difference of the brightness temperatures between channels 10.8 µm and 8.7 µm
- Difference of the brightness temperatures between channels 10.8 µm and 12.0 µm
- Brightness temperature channel 10.8

Setting of the flag for potentially semi-transparent clouds or partly cloudy pixels

Within the CLA algorithm a flag will be set stating whether a cloud is opaque, semi-transparent or partly cloudy. All clouds in ice phase are considered as potentially semi-transparent. For thick Cirrus clouds the determination of the effective cloud amount will show values close to 100% and the semi-transparency flag will be re-set to opaque. All clouds in water phase will be considered as opaque. If the cloudy pixel has neighbouring pixels, which are determined as, clear, it will be considered as partly cloudy.

Determination of the cloud top height, cloud top temperature and effective cloud amount

The cloud top height will be derived for each cloudy pixel. In a first step the level of best agreement between the measured radiances in channel 10.8 µm (or channel 12.0 µm) and the calculated radiances from the RTM tables is determined. The pressure of that level is considered to be the cloud top pressure of an opaque cloud. If a pixel has been flagged as semi-transparent or partly cloudy, the CO-2 slicing method (Menzel et al. 1983) will be applied. If channel IR13.4 is not available the WV/IR rationing method (using WV7.3 and IR10.8 or using WV6.2 and IR10.8, in case WV7.3 and IR13.4 fail) will be applied. If channel 10.8 µm is not available, channel 12.0 µm will be used as a backup for the determination of the cloud top height.

The forecasted temperature of the derived cloud level is used as the cloud top temperature.

With the CO-2 slicing and/or the WV/IR rationing method the effective cloud amount (i.e. cloud amount * cloud emissivity) can be derived (Menzel et al. 1983). If for a cloud which has been flagged as semi-transparent or partly cloudy, the effective cloud amount is higher than a threshold the cloud is considered to be opaque.

Determination of the cloud type

Following information is used to determine the cloud type:
- cloud top height
- cloud phase
- local standard deviation of the channel 10.8 µm brightness temperature (to distinguish between stratus type and cumulus type)
- difference of the brightness temperatures between channels 10.8 µm and 3.8 µm (determination of fog/low stratus)

Again channel 12.0 µm will be used as a backup for channel 10.8 µm.

From the above information ten cloud types are currently specified, which are divided into sub-groups according to their height (low-level, mid-level, high-level).

2.2.2 Output data of CLA

The output of CLA is split in two parts. For the further internal processing within MPEF, the results (as described above) for every pixel and for every repeat cycle are provided as an "intermediate product". For the end-users a final CLA product is derived on a segment basis using the pixel-based results of the intermediate product, which has been determined closest to the extraction time of the final product. This final product provides following information for each segment:

- cloud amount of all clouds
- cloud amount of all low-level clouds
- cloud amount of all mid-level clouds
- cloud amount of all high-level clouds
- cloud amount of each cloud type in the segment
- mean cloud top height of each cloud type in the segment
- mean cloud top temperature of each cloud type in the segment
- cloud phase of each cloud type in the segment

An automatic quality control will be applied for the final Cloud Analysis product using the information of the SCE quality information (level of confidence of the cloud detection), and the information of the horizontal consistency of the cloud top temperature and the cloud top pressure.

3. APPLICATION OF THE SCE AND CLA ALGORITHMS

The SCE and CLA algorithms were tested with different sets of satellite data, i.e. Meteosat-5 (INDOEX), Meteosat-6, Meteosat-7, GOES-8 imager, GOES-8 sounder, and AVHRR. Parts of the tests were performed to support the cross-satellite calibration (see CGMS-XXVII-EUM-WP-23). Additionally the algorithms were applied to support the development and testing of the prototype algorithm for the MSG Atmospheric Motion Vector product. Also a sensitivity study was performed using 24 hours of Meteosat-6 data.

3.1 Application to Meteosat-6 data

The only adoption for the SCE and CLA algorithms to the Meteosat data is the use of a Meteosat specific set of static thresholds. The SCE and CLA algorithms made use of all Meteosat channels (VIS, WV, IR) for their analysis. During night only the WV and IR channel were used. The VIS channel was used from 05:30 UTC until 19:30 UTC. As a maximum four tests were applied within SCE:

- test1a (VIS reflectance test)
- test3c (IR brightness temperature test)
- test4b (IR - WV brightness temperature difference test)
- test5g (IR standard deviation test)

Figures 1a and 1b are showing the performance of the different tests. It demonstrates that test3c is by far the most powerful test for Meteosat and resolves more than 90% of the clouds, which have been detected (Figure 1a). However at a maximum 6% of the clouds are not detected by test3c or test5g (Figure 1b). As an example the performance of the SCE tests for Meteosat-6 (day 97171, 12 UTC) is given in the table below.

Table 1a: performance of the SCE tests for Meteosat-6 (in % of the pixels determined as cloudy)

Test No.	**Clouds detected by this test (%)**	**Clouds detec. <u>only</u> by this test (%)**
Test1a	50.1 %	3.8 %
Test3c	91.8 %	27.2 %
Test4b	18.7 %	0.0 %
Test5g	36.6 %	3.8 %

Most of the CLA parameters could only be provided with a limited accuracy due to the lack of spectral information (i.e. MTP does not have the required channels). Figure 2 shows the CLA results (cloud type) for the 12 UTC slot for the Meteosat field of view. The clouds are separated into low-, mid- and high-level.

One of the main goal of the 24 hour run of SCE and CLA was to verify the sensitivity of SCE and CLA on changes to the dependency on the previous image data and previous SCE and CLA results. Four different scenarios were used ranging from the single slot analysis (no dependency from the previous image and analysis) to a very strong dependency from the previous image and analysis (Figure 3). The test scenario with the very strong dependency of SCE and CLA on the previous image and its results show a total cloud cover, which is 5% lower compared to the single image analysis. Also a sudden failure of the VIS channel was simulated for one slot during midday was simulated, to test the ability of SCE and CLA to recover from the failure (Figure 4). It clearly demonstrates that a stronger dependency on the previous image/analysis leads to a longer period to recover to the nominal results.

Additionally the performance of the SCE and CLA algorithms was compared to the operational segment histogram analysis results of the MTP/MPEF. For mid- and high-level clouds an almost perfect agreement between the algorithms can be found (Figure 5a) throughout the day. The differences are less than 1% in cloud cover for most of the slots. For low-level clouds an excellent agreement can be found around midday. However larger differences up to 15% cloud cover are seen during night (Figure 5b). Beside the general problem of detecting low-level clouds with just one channel (10.8 μm) available, the reason for this difference is twofold. As shown in figure 1b, the cloud amount (basically of low-level clouds) is under-estimated by 6%, if only channel 10.8 μm data is used. This means SCE has an under-estimation of the cloud cover of 6% around mid-night. For MSG (and other satellite data like AVHRR, GOES) this problem will not occur due to the fact that in combination with the 3.8 μm, it is possible to detect low-level clouds and fog. On the other hand, the operational histogram analysis of MTP/MPEF has ensured that the data provided for calibration purposes is absolutely cloud-free. This leads to an (wanted) over-estimation of the (low-level) cloud amount of up to 9%.

The results of the SCE algorithm have also been compared to synoptical observations over Germany on 20 June 1997. The SYNOPs were compared to the surrounding pixels. The correlation coefficients for different observation times and for different pixel radii are shown in the table below.

Table 1b: Correlation coefficient of SCE results and synoptical observations

Observation time (UTC)	Radius of 2.5 pixel (~20 km)	Radius of 3.5 pixel (~28 km)	Radius of 4.5 pixel (~36 km)
00:00	0.58	0.61	0.63
06:00	0.36	0.39	0.41
12:00	0.67	0.70	0.71
18:00	0.75	0.77	0.77

The poor correlation for the 06:00 observation is caused by the fact that more than 90 % of the synoptical observations report a cloud cover of 7 octans, which is highly unrealistic.

3.2 Application to GOES-8 imager and sounder data

3.2.1 Application to GOES-8 imager data

The only adoption for the SCE and CLA algorithms to the GOES-8 imager data is the use of a GOES-8 imager specific set of static thresholds. The SCE and CLA algorithms made use of all GOES-8 imager channels (0.65, 3.9, 6.75, 10.7 and 12.0 μm) for their analysis. As a maximum four tests were applied within SCE:

- test1a (reflectance test 0.65 μm)
- test2c (reflectance difference test 0.65 μm - 3.9 μm (solar part))
- test3c (brightness temperature test 10.7 μm)
- test4a (brightness temperature difference test 10.7 μm - 3.9 μm)

- test4b (brightness temperature difference test 10.7 µm - 6.75 µm)
- test4e (brightness temperature difference test 10.7 µm - 12.0 µm)
- test5g (standard deviation test 10.7 µm)

From the table below, it can be seen that with more spectral information available test3c (10.7 µm brightness temperature test) is not as dominant as for Meteosat.

Table 2: performance of the SCE tests for GOES-8 imager (in % of the pixels determined as cloudy)

Test No.	Clouds detected by this test (%)	Clouds detec. only by this test (%)
Test1a	42.3 %	0.0 %
Test2c	52.8 %	1.9 %
Test3c	79.0 %	7.3 %
Test4a	74.0 %	8.3 %
Test4b	32.1 %	0.0 %
Test4e	9.1 %	1.0 %
Test5g	32.9 %	0.8 %

Most of the CLA parameters could be provided with a high accuracy, since GOES-8 imager supplies most of the relevant channel information for a proper cloud analysis. Figure 6 shows the CLA results (cloud type) for the 17:45 UTC image on day 97171, for the northern half of the GOES-8 imager field of view. The clouds are separated into low-, mid- and high-level. The application of SCE and CLA with GOES-8 imager data clearly showed the improvement of the performance of these algorithms by using more spectral channels. Especially the detection of low-level clouds/fog was improved by using test4a (brightness temperature difference test 10.7 µm - 3.9 µm). Also the performance in detecting thin cirrus clouds was improved by the use of test4e (brightness temperature difference test 10.7 µm - 12.0 µm).

3.2.2 Application to GOES-8 sounder data

The only adoption for the SCE and CLA algorithms to the GOES-8 sounder data is the use of a GOES-8 sounder specific set of static thresholds. SCE and CLA used 6 out of 19 GOES-8 sounder channels (i.e. 0.70, 3.98, 6.51, 7.02, 11.03, and 13.37 µm). Following tests were applied within SCE:

- test1a (reflectance test 0.70 µm)
- test2c (reflectance difference test 0.70 µm - 3.98 µm (solar part))
- test3c (brightness temperature test 11.03 µm)
- test4a (brightness temperature difference test 11.03 µm - 3.98 µm)
- test4b (brightness temperature difference test 11.03 µm - 6.51 µm)
- test4c (brightness temperature difference test 11.03 µm - 7.02 µm)
- test4f (brightness temperature difference test 11.03 µm - 13.37 µm)
- test5b (standard deviation test 0.70 µm)
- test5g (standard deviation test 11.03 µm)

For test1a, test2c, test4a, test4b, test4c, test4e, test4f, test5b and test5g static thresholds have been used (depending on day/night and surface type). For test3c the thresholds have been derived from RTM output. The forecasted clear sky brightness temperatures from the RTM have been interpolated in space (to pixel location) and time (to the time of the image). The performance of the above listed tests within SCE can be seen in the following table.

Table 3: performance of the SCE tests for GOES-8 sounder (in % of the pixels determined as cloudy)

Test No.	Clouds detected by this test	Clouds detected only by this test
Test1a	35.5 %	0.0 %
Test2c	60.9 %	6.8 %
Test3c	74.6 %	10.2 %
Test4a	32.4 %	0.6 %
Test4b	46.0 %	0.0 %
Test4c	39.1 %	0.0 %
Test4f	41.3 %	0.0 %
Test5b	31.6 %	3.1 %
Test5g	44.7 %	6.7 %

Most of the CLA parameters could be provided with a high accuracy, since GOES-8 sounder supplies most of the relevant channel information for a proper cloud analysis. Figure 7 shows the CLA results (cloud type) for the 17:46 UTC image on day 96200, for the GOES-8 sounder field of view. The clouds are separated into low-, mid- and high-level.

4. CONCLUSIONS

The strategy to derive a cloud mask and to analyse cloudy pixels from MSG data has been presented. The capability of the chosen algorithm has been demonstrated applying it to data from different satellites. Following points should be highlighted:

- the algorithm is robust and works even with a minimum of spectral information (e.g. current Meteosat data)
- the algorithm is flexible, it can cope with a sudden failure of one or more spectral channels
- the algorithm provides accurate analysis of the satellite data to be used in follow-on processes (e.g. calibration support)

The method presented here will be used operationally in the Meteorological Product

Extraction facility for the MSG (MSG/MPEF) at EUMETSAT. It will serve as a pre-processing step to generate upon its results other operational products like atmospheric motion vectors, clear sky radiances and segment based cloud analysis.

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