

IASI on Metop: The Operational Level 2 Processor

Peter Schlüssel

EUMETSAT

Am Kavalleriesand 31, 64295 Darmstadt, Germany

Abstract

The operational IASI level 2 processor will be part of the EPS Core Ground Segment. Starting with IASI level 1c data the level 2 processor generates vertical profiles of temperature and humidity, ozone columns of deep layers, and columnar amounts of carbon monoxide, methane, nitrous oxide, and carbon dioxide, along with surface temperature, surface emissivity, cloud amount, cloud-top height, and cloud phase. The processor not only makes use of IASI data but also utilises information from the companion instruments AVHRR, AMSU-A, MHS, as well as level 2 products from the ATOVS instrument suite.

Introduction

The Infrared Atmospheric Sounding Interferometer (IASI) will be flown on the Metop satellites as part of the EUMETSAT Polar System (EPS). The main purpose of IASI is to deliver temperature and water vapour profiles for the numerical weather prediction (NWP) at accuracies of 1K or 5%, respectively, at high vertical resolution. Cloud parameters to be derived from IASI include cloud fraction, cloud top temperature, cloud height, and cloud phase. Surface skin temperature over land and ocean are to be derived from IASI along with a surface emissivity characterisation over land. Trace gases that will be derived from IASI are ozone profiles and columnar amounts of carbon monoxide (CO), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄).

The IASI Level 2 Product Processing Facility (PPF) is being built by industry in the frame of the EPS Core Ground Segment development, according to specifications given by EUMETSAT. The specifications have been written according to current scientific knowledge as expressed in literature, results from scientific studies, heritage of AIRS (Atmospheric Infra-Red Sounder flown on Aqua), and from research results of the IASI Sounding Science Working Group (ISSWG).

Properties of the IASI Level 2 Processor

For a best use of IASI measurements the level 2 processing can combine IASI data with concurrent measurements of the Advanced Very High resolution radiometer (AVHRR), the Advanced Microwave Sounding Unit A (AMSU-A), and the Microwave Humidity Sounder (MHS), which are flown together with IASI on Metop. Also, the Level 2 products of the Advanced TIROS Operational Vertical Sounder (ATOVS, a combination of AMSU-A, MHS, and the High-resolution Infrared Radiation Sounder, HIRS) are used to support the IASI Level 2 processing. They are mainly used in aiding cloud detection and the initialisation of the geophysical-parameters retrieval, but also for inclusion in the latter. Consequently, the processing chains show complex interdependencies (Figure 1).

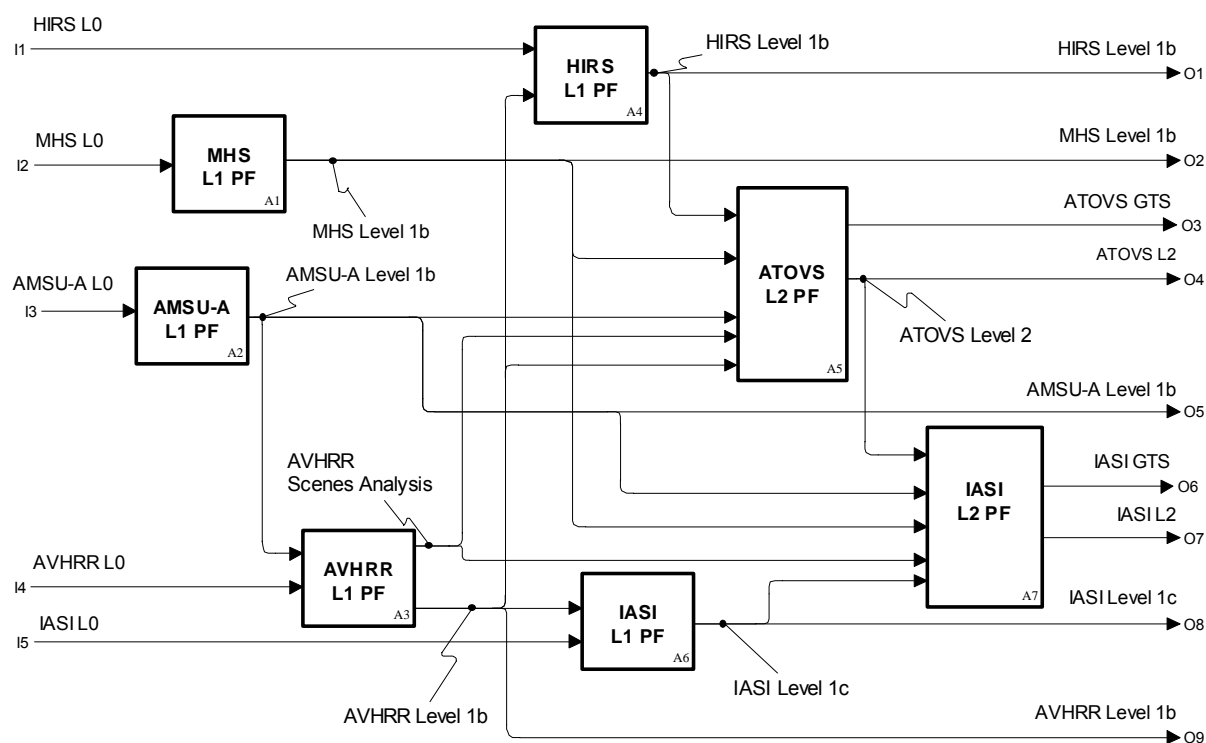


Fig. 1: Processing chain interdependencies

IASI stand-alone processing is possible if other measurements are not available, or if the PPF is explicitly configured to exclude other instruments. NWP forecast is included to provide surface pressure as reference for the temperature and humidity profiles to be retrieved and NWP supplied surface wind speed over sea is used for the calculation of surface emissivity. Optionally, the NWP forecast profiles of temperature, water vapour and ozone can be used to initialise or constrain the retrieval.

The processing is steered by configuration settings, the specification of 80 configurable auxiliary data sets, including data such as threshold values, radiative transfer coefficients, error covariances, processing choices etc., allows for the optimisation of PPF before and during commissioning. As soon as physical knowledge changes the corresponding auxiliary data sets can be updated to improve on the level 2 processing.

An online quality control supports the choice of the best processing options in case of partly unavailable IASI data or in cases of missing or corrupt side information (e.g. data from other instruments or NWP forecast). Part of the online quality control is the generation of 40 flags. These steer the processor according to configuration, data availability and data quality. The flags are part of the level 2 product.

The IASI measurements are represented as spectra, resolving the domain between 645 and 2760 cm^{-1} at 0.35 to 0.5 cm^{-1} . The spectra are sampled at 0.25 cm^{-1} , so that 8461 IASI “channels” can be identified. The spectra are divided in three bands, due to the use of different detectors (Figure 2). If available, all IASI channels are used in the retrieval to maximise the extracted information. However, besides the nominal instrument mode the PPF also supports the processing of data from degraded modes, for example, reduced number of spectral bands in case of failed detectors.

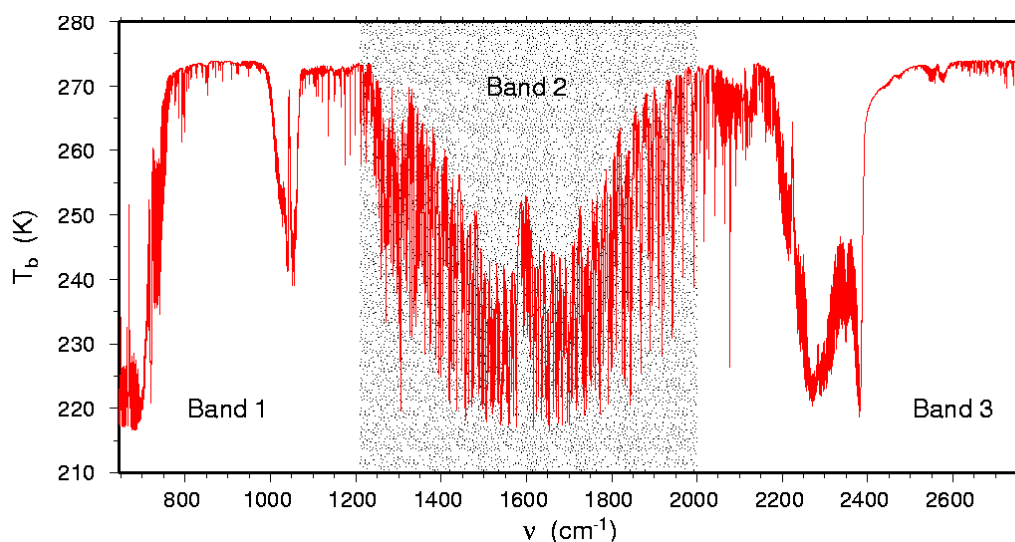


Fig. 2: Example of a (synthetic) brightness temperature spectrum as measured by IASI

A bias tuning is foreseen by configuration setting to allow for the adjustment of the radiative transfer model, included in the final iterative retrieval, to the real atmospheric transfer.

The IASI Level 2 Product contains the following information per sounding

- State vector
- Covariance matrix (compressed)
- Flag Collection
- Pointer to configuration setting
- Location and time information
- Scan geometry

The level 2 product is disseminated to the users within 3 hours after the measurements via Near Real Time (NRT) Terminals. All level 2 products will be archived in the Unified Meteorological Archiving Facility (UMARF) at EUMETSAT HQ, from where they can be obtained for off-line use.

The IASI level 2 processing can be roughly broken down in a pre-processing step, the cloud detection and cloud-parameters determination, and the geophysical-parameters retrieval.

Pre-processing

The pre-processing starts with the acceptance and validation of data. All input data will be checked against valid bounds and invalid or missing data will be flagged. Further processing depends on availability of data, the processing will proceed if possible with available data, and even if incomplete (e.g. IASI stand-alone processing is foreseen). Redundant information is used in case of IASI, for example, highly correlated channels can be used, where available, as proxy if measurements of single channels are invalid or missing.

Tuning coefficients will be applied to the measurements for removal of bias between calculated and measured radiances.

Other data are mapped to IASI:

- Auxiliary data, such as land mask, topography, land surface type, are extracted from data bases and mapped to the IASI IFOV (Instantaneous Field Of View).

- Land/sea fractions are calculated, weighted with the Instrument Point Spread Function (IPSF).
- An IPSF-weighted surface height is calculated.
- The degree of surface height variability within an IFOV is determined.
- The radiances of the secondary instruments AMSU-A and MHS are interpolated to the IASI IFOV.
- The ATOVS level 2 product is interpolated to the IASI IFOV.
- The AVHRR scenes analysis is mapped to the IASI IFOV and IPSF-weighted cloud fraction, surface temperature, and cloud-top temperature are calculated.

The AVHRR scenes analysis is matched with the AVHRR radiance analysis (part of IASI L1c product) to locate cloud and surface formations in IASI IFOV. This is used to correct IASI radiances with respect to ISRF changes due to non-homogeneity in IASI IFOV.

An initial choice of setting for cloud processing and retrieval procedures depends on configuration, environmental conditions (cloud amount, surface type, elevation), data availability, and data quality

Cloud Processing

The cloud processing includes the cloud detection, and the determination of cloud parameters. The latter can be refined by the final, iterative retrieval step.

Cloud Detection

No single cloud detection method is able to detect clouds properly in all situations, so that a number of cloud detection methods are used concurrently. The variety of method also takes account of the possibility that IASI can be processed in a stand-alone mode or in combination with the ATOVS and AVHRR instruments.

AVHRR Based Cloud Detection

The AVHRR scenes analysis results mapped to the IASI IFOV gives a direct estimate of the cloud coverage within the IASI IFOV. Additionally, the cloud-top temperature as derived from AVHRR, together with the temperature profile from the ATOVS level 2 product gives the cloud-top pressure.

Window Channel Tests

Clouds usually assume different temperatures than the underlying surfaces due to varying temperature in the atmosphere. The IASI brightness temperatures in window channels near 3.7, 4.0, 8.7, 11, and 12 μm are checked against pre-defined thresholds for the cloud detection. The exact selection of channels and the threshold values are configurable. The thresholds typically vary with surface condition, latitude, and season.

IASI Inter-Channel Regression Tests

Three empirically derived multi-channel regression methods using IASI channels in transparent and opaque spectral regions near 3.95, 4.40, 4.46, 6.28, 6.30, 7.53, 7.70, 10.35, 12.80, and 14.70 μm are derived to detect clouds. Different linear combinations of the brightness temperatures in those channels are checked against pre-defined threshold values. The latter are dependent on latitude, season, surface type and surface elevation.

IASI-AMSU Inter-Channel Regression Tests

Two empirically derived multi-channel regression methods using IASI channels near 4.00, 4.40, 4.50, 4.55, and 11.10 μm are used together with AMSU-A channels 1, 4, 5, 6, 7, 8, 9, 10, and 15 are derived to detect clouds. Different linear combinations of the brightness temperatures in those channels are checked against pre-defined thresholds. The thresholds depend on latitude, season, surface type, and surface elevation.

Horizontal Coherency Test

Usually, the surface temperature is horizontally more homogeneous than the cloud-top temperature, in particular for convective clouds. The brightness temperature in a channel near $3.7 \mu\text{m}$ is checked against a pre-defined threshold to detect clouds. The threshold value is configurable and depends on the surface condition.

Thresholds on IASI EOF Residuals

A limited number of pre-calculated principal component scores of measured spectra are used to re-construct clear-sky spectra. The difference between measured and re-constructed spectra is checked against a pre-defined threshold to detect clouds. The pre-calculated eigenvectors of the clear-sky spectra and the threshold values are configurable.

Window Cross-Correlation Test

The atmospheric window regions cover many atmospheric absorption lines, which make up a unique spectral signature in clear situations. This signature partly disappears in cloudy cases. A cross-correlation between clear-sky reference spectrum and measured spectrum is tested against a pre-defined threshold to detect cloudy spectra. The threshold value and the reference spectrum are configurable and depend on surface type and elevation, season, and latitude.

Test for Clouds over Elevated Polar Regions

Strong surface inversions of the temperature profile over elevated polar regions in winter lead to higher radiation emission in water vapour bands than in window channels. In cloudy situations the emission in window channels, apart from absorption lines, increases, leading to changed brightness temperature differences between 11 and $12 \mu\text{m}$. This difference is checked against a pre-defined threshold to detect clouds. The threshold value is configurable.

Detection of Dust Storms

Increasing dust optical depth increases the difference in brightness temperatures at 11 and $12 \mu\text{m}$ due to higher reflectivity of dust at $12 \mu\text{m}$ (Ackerman, 1997). Over desert areas this difference is checked against pre-defined thresholds to detect dust clouds. The threshold value and the area covered by this test are configurable.

Thin Cirrus Detection

This test utilises the lower emissivity of ice particles at $11 \mu\text{m}$. If the brightness temperature at $11 \mu\text{m}$ is below a pre-defined threshold then the brightness temperature difference between 11 and $12 \mu\text{m}$ is checked against another threshold to detect thin cirrus clouds. The selection of the channels and the threshold values are configurable.

Cloud Parameters Retrieval

If a cloud has been identified in the IASI IFOV a number of cloud parameters is determined, namely the cloud-top pressure, the cloud amount and the cloud phase.

Cloud-Top Pressure and Cloud Amount

The cloud-top pressure and the cloud amount are determined by the CO_2 Slicing Method, adapted for hyper-spectral sounding (Smith and Frey, 1990). If clouds are detected this method is used to calculate cloud-top pressure and cloud amount in single IASI IFOVs, using a sub-set of 500 IASI channels. The measured radiances of each channel and a reference channel are used together with synthetic radiances calculated for the clear-sky and overcast situations with the same temperature and water vapour profiles. For each channel/reference-channel pair a cloud-top pressure is obtained, which enters the calculation of a weighted mean, where the weight is the temperature weighting function.

Once the cloud-top pressure is known the cloud fraction can be calculated from the measured radiance and the synthetic radiances for the clear-sky and overcast situations. The calculation requires a temperature profile, which is taken from the ATOVS level 2 product or from NWP forecast, depending on configuration.

Cloud Phase

The emission spectrum of the atmosphere between 11 and 12 μm shows a steeper slope for liquid water than for ice clouds (Figure 3). This spectral behaviour is used to discriminate between ice clouds, mixed phases, and liquid-water clouds. The sum of brightness temperature differences between 12 and 11 μm and that between 8 and 11 μm are tested against pre-defined thresholds for the cloud-phase determination.

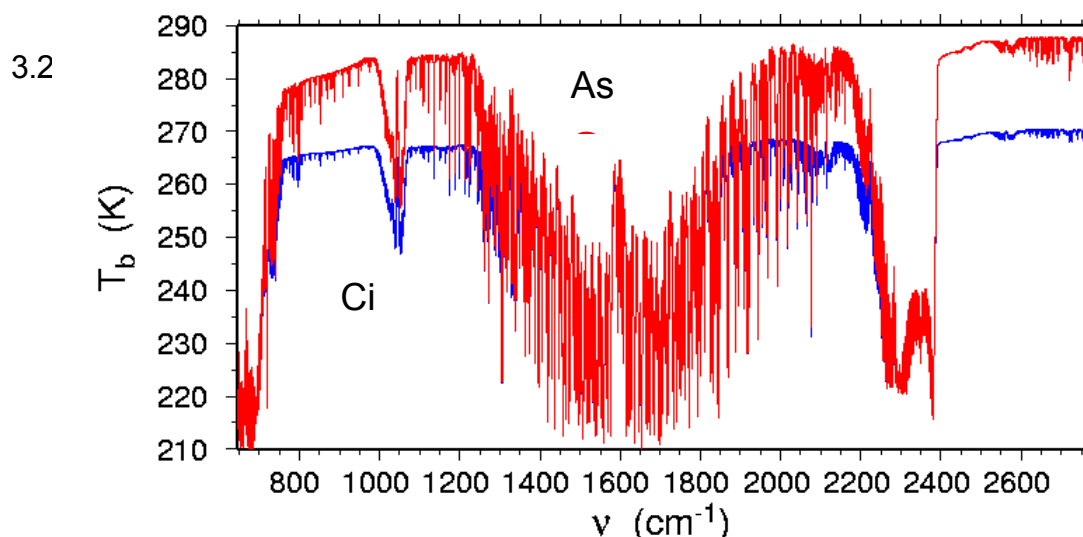


Fig. 3. IASI brightness temperature spectra (simulated) for a liquid-water cloud (As: alto stratus) and a cirrus cloud (Ci)

Geophysical Parameters Retrieval

Once the cloud detection and cloud parameters retrieval have been completed further geophysical parameters are derived. The number of variables retrieved from the measurements depends on the cloud conditions, which also determine the set-up of the retrieval scheme. Depending on configuration, data availability, surface and cloud conditions different retrieval types are foreseen.

State Vector

The state vector to be retrieved consists of the following parameters:

- Temperature profile at a minimum of 40 levels
- Water vapour profile at a minimum of 20 levels
- Ozone columns in deep layers (0-6km, 0-12 km, 0-16 km, total column)
- land or sea surface temperature
- surface emissivity at 12 spectral positions
- Columnar amounts of N_2O , CO , CH_4 , CO_2
- Cloud amount (up to three cloud formations)
- Cloud top temperature (up to three cloud formations)
- Cloud phase

In case of clouds and elevated surfaces the state vector has to be modified to reflect the actual situation.

First Retrieval

The first retrieval consists of statistical methods, based on a linear EOF regression (Schlüssel and Goldberg, 2002) or a non-linear artificial neural network (ANN). For temperature and water-vapour profiles, ozone columns of deep layers, surface temperature, and surface emissivity the entire IASI spectrum is used to calculate principal component scores, which enter the linear regression retrieval. Likewise, the principal component scores can be entered into a feed-forward ANN to retrieve temperature and water-vapour profiles. Up to 100 principal component scores are used in the regression or the ANN retrievals. The retrieval of trace-gas columns is done using an ANN with a set of selected IASI radiances (Hadji-Lazaro et al., 1999), sensitive to the particular trace gases, together with the previously derived temperature profile. The selection between linear regression and ANN, the number of principal component scores, as well as all weights and regression coefficients are configurable.

The results from the first retrieval may constitute the final product or may serve as input to the final, iterative retrieval; the choice depends on configuration setting and on quality of the first retrieval results.

Final, Iterative Retrieval

The final retrieval is a simultaneous iterative retrieval, seeking the maximum a-posteriori probability solution for the minimisation of a cost function seeking by the Marquardt-Levenberg method (e.g. Rodgers, 2000). The cost function aims at minimising the difference between measured and simulated radiance vectors, subject to a constraint given either by climatology, the ATOVS level 2 product, or NWP forecast. The chosen constraint can be tightened or removed, depending on configuration. As the iterative retrieval involves radiative transfer calculations of radiances and Jacobians it is too costly to include all IASI channels. A selection of up to 500 channels or super-channel clusters is made via configuration. The super-channel clusters consist of channels with highly correlated radiances, which are represented by a weighted mean of the measured radiances and by a selected lead channel in the radiative transfer calculations. The advantage of using super channels is the reduced radiometric noise of the average measured radiance. However, super channels are not available to replace all IASI channels, of which some carry unique information. Therefore, super channels and single channels are used concurrently in the same iterative retrieval.

The iterative retrieval is initialised with results from first retrieval. Other choices of initialisation may be selected, depending on configuration setting and availability (e.g. NWP forecast, climatology, or ATOVS Level 2 product).

The composition of the state vector to be iterated depends on cloud conditions and configuration setting. In case of very small cloud amounts (< 2%) the sounding can be considered as cloud-free and a corresponding retrieval is made for the atmospheric and surface parameters. At higher cloud amounts the cloud amount and the cloud-top pressure for up to three cloud formations are explicitly included in the state vector. At cloud amounts exceeding a second threshold the retrieval of parameters below the cloud top is no longer possible on a single IFOV basis. Under the assumption of homogeneity within four adjacent IFOVs, except for the cloud amount, a variational cloud clearing (Joiner and Rokke, 2000) is done, deriving a mean state vector for the IFOV quadruples. If the cloud amount exceeds a third threshold no information from below the cloud top is available and the atmospheric parameters will be derived only above the cloud top.

Radiative transfer calculations are parameterised according to the fast model RTIASI (Matricardi and Saunders, 1999). It is a semi-empirical model that supplies radiances and analytical Jacobians at the top of the atmosphere. Radiation included comes from the upwelling atmospheric emission, the downwelling atmospheric emission reflected at the surface and transmitted to the satellite, the surface emission transmitted to the top of the atmosphere, and the solar radiation transmitted to the surface and reflected to space.

Together with the iterated state vector an error covariance matrix is calculated, which is part of the level 2 product. The final product is composed of the results from the geophysical parameters retrieval

and from the cloud processing. Besides the full product, which is generated for every IFOV, a vertically and horizontally sub-sampled product is prepared for GTS (Global Telecommunications System for the exchange of meteorological data among the WMO members) distribution.

Online Quality Control

The online quality control plays an important role, as only the knowledge of the product quality lets the user judge whether and how to use the data. The main quality indicator is the error covariance of the product, giving the errors of the single state vector variables, together with their inter-dependencies. Besides this 40 flags are part of the product, informing the user about details of the processing and any deficiencies, processing options, data corruption or unavailability, surface conditions, cloud conditions and how they were identified, completeness of the product, and overall quality of the product.

Performance

As there are no IASI data available yet, the performance analyses made so far are given are based on synthetic data, created by different radiative transfer models. Some validation with real data has been done by adaptation of the methodologies to other instruments like IMG (Interferometric Monitor for Greenhouse Gases), AIRS (Atmospheric Infra-red Sounder), and NAST-I (NPOESS Airborne Simulator Test-bed-Infrared).

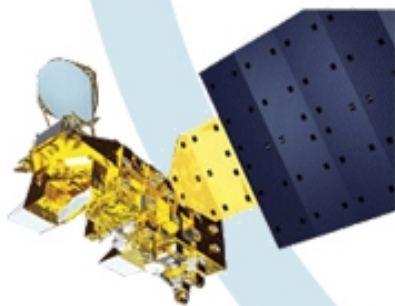
The temperature and humidity retrievals reach an accuracy of 1K and 15%, respectively, in the lower atmosphere. The land surface emissivity is derived with a relative accuracy between 1.8% and 2.4%, depending on the spectral region. Trace gas columnar amounts are retrieved with an accuracy of 5 to 6% (Turquety et al., 2002), the deep ozone columns with an accuracy between 15 and 22%.

References

- Ackerman, S.A. (1997) Remote sensing aerosols from satellite infrared observations, *J. Geophys. Res.*, **102**, 17069-17079.
- Hadji-Lazaro, J., Clerbaux, C., Thiria, S. (1999) An inversion algorithm using neural networks to retrieve atmospheric CO total columns from high resolution nadir radiances, *J. Geophys. Res.*, **104**, 23841-23854.
- Joiner, J. and Rokke, L. (2000) Variational cloud-clearing with TOVS data, *Q. J. Roy. Met. Soc.*, **126**, 725-748.
- Matricardi, M. and Saunders, R.W., (1999) Fast radiative transfer model for simulation of infrared atmospheric sounding Interferometer radiances, *Appl. Optics*, **38**, 5679-5691.
- Rodgers, C.D. (2000) Inverse methods for atmospheric sounding - theory and practice, World Scientific, Singapore, 238 pp.
- Schlüssel, P. and Goldberg, M. (2002) Retrieval of atmospheric temperature and water vapour from IASI measurements in partly cloudy situations, *Adv. Space Res.*, **29**, 11, 1703-1706.
- Smith, W.L. and Frey, R. (1990) On cloud altitude determination from high resolution interferometer sounder (HIS) observations, *J. Appl. Meteorol.*, **29**, 658-662.
- Turquety, S., Hadji-Lazaro, J., Clerbaux, C. (2002) First satellite ozone distribution retrieved from nadir high-resolution infrared spectra, *Geophys. Res. Lett.*, **29**, 2198, doi:10.1029/2002GL016431.

Proceedings of the Thirteenth International TOVS Study Conference

INTERNATIONAL
ATOVS
WORKING GROUP



Sainte-Adèle, Québec, Canada
29 October – 4 November 2003