MIPAS-STR data analysis of APE-GAIA measurements

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ABSTRACT

Airborne measurements by MIPAS-STR (Michelson Interferometer for Passive Atmospheric Sounding-STRatospheric aircraft) during the APE-GAIA (Airborne Polar Experiment - Geophysica Aircraft In Antarctica) campaign were analysed. For phase correction of the interferograms and radiometric calibration specific schemes were applied to correct for beam splitter emission and atmospheric signatures in the deep space spectra. Characteristic features of the instrumental performance and auxiliary data needed for the retrieval are described. The retrieval of temperature along the flight track is shown for one selected day. These data are compared with independent in-situ measurements and global temperature analysis fields.

1. INTRODUCTION

In September/October 1999 the APE-GAIA campaign took place from Ushuaia/Argentina. The high-altitude aircraft Geophysica performed several flights outside, at the edge and inside the Antarctic stratospheric vortex. The Fourier transform spectrometer MIPAS-STR was one of the remote sensing instruments on board with the goal to measure 2-dimensional cross sections of temperature and concentration of various trace gases along the flight track. The instrument records atmospheric mid-infrared emission with high spectral resolution. The data analysis chain of MIPAS measurements consists of three major steps: 1) Fourier transformation and phase correction to obtain spectra from interferograms, 2) calibration to transform spectra in radiance units, and 3) retrievals resulting in altitude profiles of atmospheric parameters. In the following this sequence will be illustrated by means of data obtained during the flight on Sept. 23, 1999 in spectral channel 1 (770-970 cm⁻¹).

2. MEASUREMENT SEQUENCE

Figure 1 illustrates the measurement scenario of MIPAS-STR by plotting the elevation angle of the line-of-sight versus time. The atmosphere below flight level was observed in a limb sounding mode. The vertical sampling grid with was one FOV (field-of-view) for high tangent altitudes while for lowest tangent points ½ FOV-overlapping was applied in order to increase the vertical resolution there. Additionally, the atmosphere above flight level was sounded with three positive elevation angles. The horizontal resolution from one atmospheric scan was about 30 km.

Fig. 1: Line-of-sight scan sequence of MIPAS-STR during APE-GAIA.

3. PHASE CORRECTION

MIPAS-STR recorded 2-sided interferograms with a maximum optical path difference of 14.1 cm. As in previous MIPAS experiments a conventional phase correction for transforming the interferogram to the spectrum was not possible due to an imaginary contribution by beamsplitter
emission (Revercomb et al., 1988, Blom et al., 1996). For phase correction we used a scheme based on the minimization of the correlation between the real and the imaginary part of the spectrum (Trieschmann et al., 1999). An example of a real and imaginary part after correction is shown in Figure 2. Indicating the correctness of the procedure no atmospheric signatures show up in the imaginary part.

4. CALIBRATION

4.1 Deep-space correction

Three kinds of calibration measurements were performed during the flight as shown in Figure 1: one atmospheric ‘deep-space’ observation with 10° upward elevation, one calibration point with 90° and one with -90° to observe internal blackbodies. Since the magnitude of the atmospheric signal was in between the cold blackbody (= 205 K) and the deep-space measurement these two were used for calibration in order to avoid non-linearity effects.

The deep-space measurements could not be used directly for calibration since due to the flight level of about 19 km and the maximum elevation of 10° atmospheric signatures were present in the spectra. Therefore, we used an iterative correction method based on simulated broadband spectra:
1. For the time and position of each deep-space measurement forward calculations (with a spectral resolution of 2 cm⁻¹) are made using the actual temperature profiles from ECMWF analysis and standard vmr trace gas profiles.
2. Calibration gain functions are derived from the blackbody measurements and the (not yet corrected in the 1st iteration / corrected from the previous iteration) deep space spectra.
3. The deep space spectra are calibrated using the gain functions (from 2).
4. The simulated deep space spectra (from 1.) are subtracted from the calibrated deep-space spectra (from 3.).
5. Corrected gain functions are determined using the corrected deep-space spectra (from 3.) and the blackbody measurements.
6. Steps (2.-5.) are repeated until convergence is obtained.

Three iterations are shown in Figure 3. Good convergence was already achieved after the first iteration. Only small differences are visible between first and second iteration near the CO₂ Q-branch at 790 cm⁻¹.

Calibration errors resulting from the correction procedure mainly stem from insufficient simulation of deep-space spectra due to the unknown actual vmr-profiles and uncertainties in the ECMWF temperatures. These calibration errors were investigated for HNO₃. The calibration correction was performed 1.) for simulations with standard mid-latitude HNO₃ and 2.) with the standard profile multiplied by 0.5. The resulting maximum error in the gain calibration was less than 1%. The offset error was considerably larger, in the order of the instrumental offset itself. For trace gas retrievals only the gain error is significant since an addictive spectral offset is set as second fit quantity besides the atmospheric profile. Therefore, the relative systematic error in volume mixing ratio (vmr) due to our calibration correction is in first order identical with the relative gain error. For even better results the complete procedure might be repeated with retrieved vmr and temperature profiles instead of the assumptions used for the forward calculation under step number 1.

Fig. 3: Iterative deep-space correction of the calibration gain function.

4.2 Calibration stability

The stability of the instrumental response was tested by comparing calibration gain functions derived from the blackbody and deep space measurements along the flight track. Figure 4 shows the results at two different wavenumbers in channel 1. The noise in the gain function seems to be caused by vibrations of the aircraft. The standard deviation of the values is about 6-8% for single calibrations. Mean gain functions from the different contiguous regions were used for calibration of atmospheric data.

Fig. 4: Development of the calibration gain at two wavenumbers over flight time.

5. RETRIEVAL

5.1 Forward and retrieval model

The forward model KOPRA (Karlsruhe Optimized and Precise Radiative transfere Algorithm) was used to simulate
the spectra measured by the instrument (Höpfner et al., 1998, Stiller et al., 1998). KOPRA is a fast line-by-line code developed for the analysis of data measured by high-resolution interferometers. Supporting all observational geometries it is capable of simulating various physical aspects of atmospheric radiative transfer (like non-spherical ray-tracing, line-mixing, non-local thermodynamic equilibrium, aerosols) and instrumental effects (like finite field-of-view and instrumental line-shape). Besides forward calculations KOPRA determines analytically the derivatives of the spectrum with respect to many atmospheric and instrumental parameters.

Making use of the spectra and derivative spectra from KOPRA the retrieval model is capable of fitting all limb and upward observations of one limb scan in many spectral microwindows simultaneously. For the present analysis the Tikhonov-Phillips regularization scheme was used in the following form:

\[ x_{i+1} = x_i + \left( K^T S^{-1} K + \gamma L^T L \right)^{-1} K^T S^{-1} (y - f(x_i)) - \gamma L^T L (x_i - x) \]

where \( i \) is the index on the iterations, \( x \) the vector with the unknowns, \( x_a \) an a-priori parameter setting, \( y \) the measured spectrum, \( S \) the covariance matrix of \( y, f \) the forward model, \( K \) the matrix of spectral derivatives with respect to retrieval quantities, \( \gamma \) the regularization parameter, and \( L \) the first-derivative regularization operator. In eq. (1) the result is constrained to the shape of an a-priori profile depending on \( \gamma \) and the information content of the measurement. Regularization was necessary because the set up of the retrieval grid with a level distance of 0.5 was denser than the vertical resolution of the instrument.

The regularization parameter \( \gamma \) was determined 1) by test retrievals where the simulated spectra were distorted with the same noise level as in the measurement, 2) by retrievals using actual measurements. Criteria for adjusting \( \gamma \) were 1) to adjust it as small as possible just to avoid instabilities in the profiles 2) to check that the rms (root-mean square) between measured and simulated spectrum is not deteriorated by too large \( \gamma \) values.

5.2 Auxiliary input data

The following auxiliary data were used for atmospheric retrievals:
- The geolocation of the actual measurement was given by GPS whereby short-term distortions of the altitude due to the selective availability were corrected by using data from the aircraft pressure sensor.
- In flight, the viewing direction of MIPAS-STR was stabilized with the aid of a navigation system. After flight, the data was reprocessed to get a better knowledge of the mean elevation angle of each interferogram.
- The field-of-view distribution function of MIPAS-STR was measured between two successive APE-GAIA flights. The vertical FOV weighting function (Figure 5) was obtained by horizontal integration of these measurements.

- Initial guess temperature and pressure profiles were derived from ECMWF–analysis fields with a horizontal resolution of 1.125° × 1.125° and 15 pressure levels from 1000 to 1 hPa. As shown in Figure 6 the temperature profile at the aircraft position can deviate considerably from the profile along the line-of-sight of an MIPAS-STR view. Since the main information for limb-views stems from the tangent points we built the initial guess profiles below the aircraft from the pressure and temperature values at the tangent points. Above, the profile at the aircraft position was used.

- The spectral noise was determined from blackbody measurements during the flight and from window regions in calibrated atmospheric spectra. Its value is 40±8 nW/(cm² sr cm⁻¹).

5.3 Retrieval of temperature

Temperature was retrieved in the spectral region of the CO₂ Laser-band around 950 cm⁻¹ where only small interference by signatures of other trace gases is present. Besides atmospheric temperature, a spectral shift per microwindow and an additive offset per microwindow and observation geometry were fit-parameters. The resulting temperature field along the flight is shown in Figure 7.
Fig. 7: Retrieved temperature distribution along the flight track on 23-9-1999. Upper plot: on the way to the south (between –66° and –68° a dive for the in-situ instruments was performed). Lower plot: return flight. (+) denotes the position of the aircraft for the actual limb scan.

Fig. 8: In-situ, ECMWF and retrieved temperature at flight level.

On all altitudes at and below the aircraft the downward trend of the temperature in southern direction is present. In order to compare with other data Figure 8 shows the retrieved temperatures at flight level together with ECMWF initial guess values and data measured in-situ at the aircraft. ECMWF temperatures are nearly always lower than the in-situ measurements (1.7 K in the mean). For retrieved temperatures on the southbound flight track there is no systematic offset with respect to ECMWF. However, on the return flight retrieved values are about 2.6 K higher than ECMWF. This is probably due to opposite temperature profiles along the line-of-sight for the southbound and the return flight. As shown in Figure 9, the temperatures along the line-of-sight for 0° elevation on the northbound flight are up to 7 K higher than on the way south.

Fig. 9: ECMWF-temperatures along horizontal line-of-sight for same aircraft position but looking in opposite directions on southbound and on northbound flight track on 23-9-1999.

Below the aircraft the systematic difference for the two flight legs between retrieved and ECMWF temperatures at the position of the tangent points is smaller than at flight-level. This might be due to the fact that, compared to upward and horizontal line-of-sights, below the aircraft more radiation stems from the region near the tangent points.

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REFERENCES


