GOME-2 POLARISATION MEASUREMENTS

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Abstract

Planned to fly onboard of the European Metop (Meteorological operational) series of satellites, the Global Ozone Monitoring Experiment 2 (GOME-2) will be the successor of the GOME-1 spectrometer on ERS-2 and contributes to the continuity of space measurements for atmospheric chemistry, meteorological purposes and long-term climate monitoring. Launch of the first Metop satellite is scheduled for 2005. GOME-2 is based upon the GOME-1 design which measures in the wavelength range 240-790 nm and which allows for the measurement of atmospheric trace gases and ozone. GOME-2 will observe in scanning nadir view with a horizontal resolution of 40x80 km^2. The instrument is, like GOME-1 sensitive to polarisation and the measured radiance needs to be corrected for the polarisation of the incoming light.

In order to reduce the radiance error due to the polarisation correction compared to GOME-1, significant hardware changes have been made. A second Polarisation Measuring Device (PMD) which measures polarisation perpendicular to the first PMD has been added to minimize the effects of degradation and to make a more straightforward Polarisation Correction Algorithm (PCA) possible. In addition, the number of spectral bands for the PMDs has been increased from three (broadband) for GOME-1 to up to 15 (narrow band) for GOME-2.

In this paper we demonstrate the results of the study performed by the Space Research Organization Netherlands (SRON) which includes the development of the GOME-2 PCA adapted to the use of multiple PMD spectral bands. Worst-case scenarios show that the GOME-2 main channel radiance error due to the polarisation correction in the Huggins band will be of the order of one percent [3]. The effect of the polarisation error on ozone profile retrieval was then estimated by the Rutherford Appleton Laboratory (RAL) for both GOME-1 and GOME-2 showing retrieval errors in the troposphere of 20 percent for GOME-1, whereas this is less than 4 percent for GOME-2, respectively. Note that the analysis in this paper does not reflect the end-to-end error since other error sources are not included.

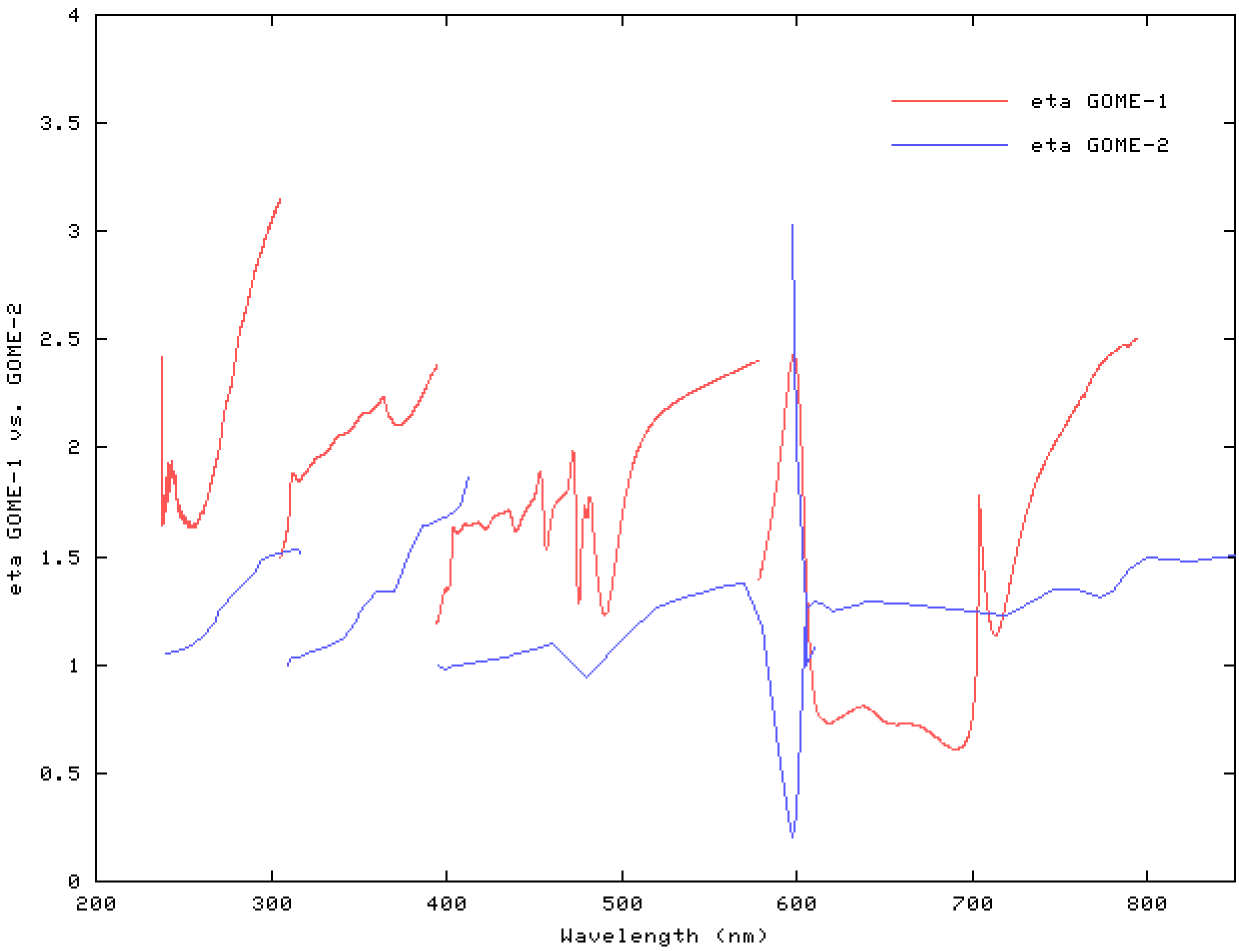

Fig. 1: Ratio of the radiometric response functions for parallel (s) and perpendicularly (p) polarised light, expressed by η, indicating the polarisation sensitivity for GOME-1 and GOME-2. A value of η=1 indicates polarisation insensitivity. GOME-1 η is measured end-to-end; GOME-2 is based on component characterization data.

Introduction

Both GOME-1 and GOME-2 are nadir viewing spectrometers in the ultraviolet and visible regions. The goal is to provide continuous global observations of atmospheric minor constituents including ozone. In order to derive concentrations of trace gases, like O_3, NO_2, SO_2 etc., aerosols, PSCs, and many other data products, the GOME instruments measure the spectral (ir)radiance of the sun and the earth at the top of the atmosphere. Accurate (ir)radiance measurements are the basis of the accuracy of the retrieved data products. Since GOME-1 and GOME-2 are polarisation sensitive spectrometers and the earth's radiation is in general polarised, the earth radiance measurements must be corrected for the polarisation of the incoming light. Nadir viewing space-borne spectrometers have two options to treat the atmospheric polarisation of the incoming light. Either the polarisation information is destroyed by scrambling, like it is done in the American TOMS and SBUV type instruments and in the Dutch/Finnish OMI instrument, or the polarisation of the incoming light has to be measured with sufficient accuracy to correct for the polarisation dependence of the instrument, like it is done in GOME-1 and GOME-2. The charm of the latter approach is that the polarisation detector information can be used for other aims like cloud detection, aerosol detection, and high spatial and low spectral resolution radiance measurements of the atmosphere. In this paper we will refer to s- and p- polarised light, indicating light that is polarised parallel and perpendicular to the optical plane, respectively.

The design of GOME-2 has undergone several changes compared to GOME-1. Changes, which are of particular interest to the Polarisation Correction Algorithm (PCA), are:

- reduced polarisation sensitivity of the four main channels, see figure 1.
- addition of a second PMD to measure the s-polarised light
- the GOME-2 PMDs measure 15 spectral bands across the 312-790 nm wavelength range compared to three bands in GOME-1

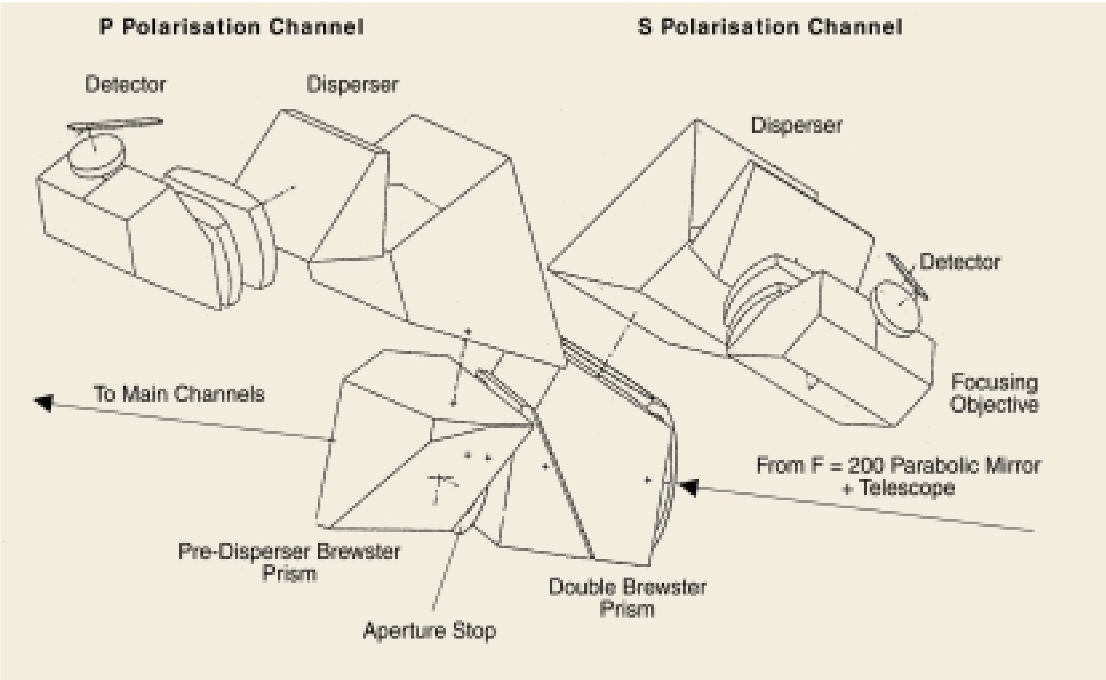

Fig. 2: Optical layout of the GOME-2 PMDs

GOME-2 PMD technical description

The design drivers for this new PMD subsystem have been the optical similarity of both s- and p- channel to ensure an identical field of view amongst s- and p- channel, as well as the main channels, and the use of the same detector array as in the main channel. The need for a compact weight minimized system is obvious. In a trade off a grating solution was compared with a prism solution. The latter is simpler, more robust and was therefore selected. A complete description of the GOME-2 instrument can be found in Callies [1]. As shown in figure 2 the incoming light is focused by a telescope on the entrance slit and passed to a collimation mirror. The collimated beam of mirror (200 mm) is passing a double Brewster prism that extracts the s-polarised light into the s-channel. This light is leaving the prism group orthogonal to the optical bench. The prism group (see figure 2) is composed of two prisms with two parallel surfaces tilted at the Brewster angle. This compensates the wedge effect of the prism for the main channels. The light of the main channels enters a predisperser prism like on GOME-1, which generates the p-polarised beam and predisperses the light of the main channel. In the two polarisation channels a disperser assembly composed of two prisms disperse the light and redirects the light again parallel to the optical bench. A dioptric focusing objective (f=48 mm) forms together with the 200 mm parabolic mirror a relay of magnification 0.24. Hence, the field of view overlap between the main channels and the 2 PMD channels is guaranteed. For accommodation reasons an additional prism has been placed between the lenses and the detectors. The detector array is tilted by 30 degrees in spectral dispersion to compensate chromatic aberrations.

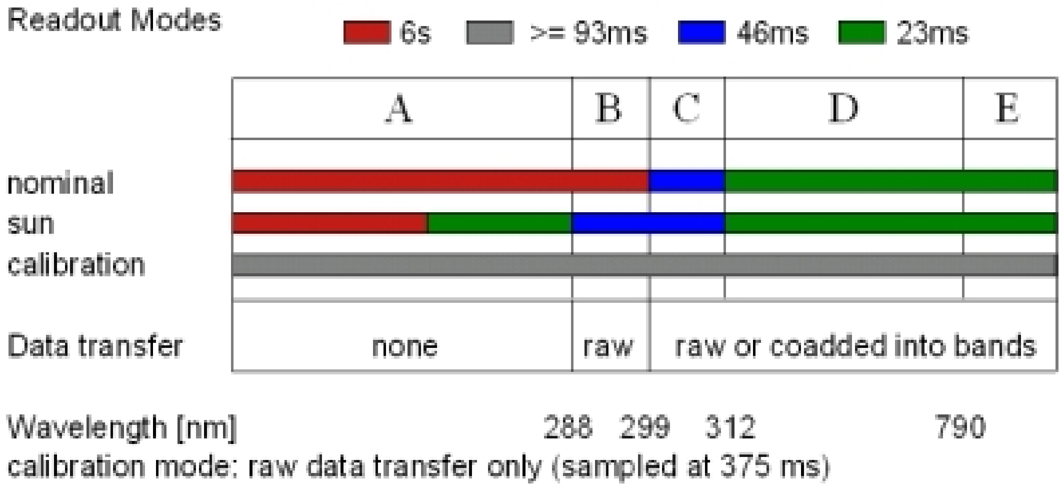

Fig. 3: Readout modes and data transfer options of the GOME-2 PMDs.

The polarisation units monitor the range between 312 to 790 nm by 200 detector pixels with a spectral resolution from 2.8 nm at 312 nm to about 40 nm at 790 nm with an integration time of 23 ms. The light polarised parallel (s) and perpendicular (p) to the optical plane will be measured, simultaneously. As the data rate of GOME-2 is limited, the information of the 200 detector pixels is co-added on board to 15 programmable bands.

The operative read out modes of the PMDs and the data transfer are rather complex. The whole wavelength range from below 288 and above 790 nm is separated into 5 segments indicated A - E. The useful range is represented by segment B,C,D and covers 288 to 790 nm. Three different readout modes can be selected: nominal, sun or calibration mode, which have different integration times in the different segments. The data transfer can be as raw pixel data or coadded into bands. Figure 3 shows the readout modes and data transfer possibilities.

In the Nominal Read out mode Area D, E are read out every 23.43 ms. Area C is read out at 46 ms and the pixels in A and B are read out every 6 second. The data of area C and D are transferred in 15 bands. B data are inserted in the science data packet fields every 6 s.
In the Sun readout mode segment D and E segment are read with an integration time of 23.43 ms, while B and C segment are read with IT= 46.86 ms. Segment B data are transferred as raw data with a resolution of 6 seconds. Segment C and D data are transferred either as bands with resolution of 23.43 msec or as raw data. When this mode is commanded, the pixels adjacent to the 288 nm region (256 pixels) are periodically discharged to avoid saturation effects. Nothing is done on the 256 pixels, which are outside the useful range.
The last mode is the calibration readout. In this mode the overall detector is read out with integration times (IT) selectable in the same table as for the main channels. When this mode is commanded the data packetisation is fixed: the pixels of the B and CDE (256 pixel) block are inserted as raw data in every 375 ms packet.

Polarisation Correction Algorithm (PCA)

For GOME-1 the polarisation information of the incoming light is obtained by combining the polarisation sensitivities of the main channel signals with that of the PMD in the polarisation correction algorithm (PCA). As it appears, the main disadvantage of this approach lies in the fact that the light at the main channel and the PMD detectors has gone through very different optical paths. As a result, degradation of the instrument's polarisation characteristics appears hard to pinpoint and to correct for. Moreover, the three GOME-1 PMD channels are broadband (PMD1 : 300-400 nm, PMD2 : 400-600 nm, PMD3 : 600-800 nm) and as a result the PCA has to reconstruct the polarisation spectrum across the full wavelength range based on three broadband measurements which introduces a large error source.
Changes in the GOME-2 design with respect to that of GOME-1 are aimed to minimize the problems mentioned above. Two PMDs are used to determine the polarisation of the incoming light, independent of

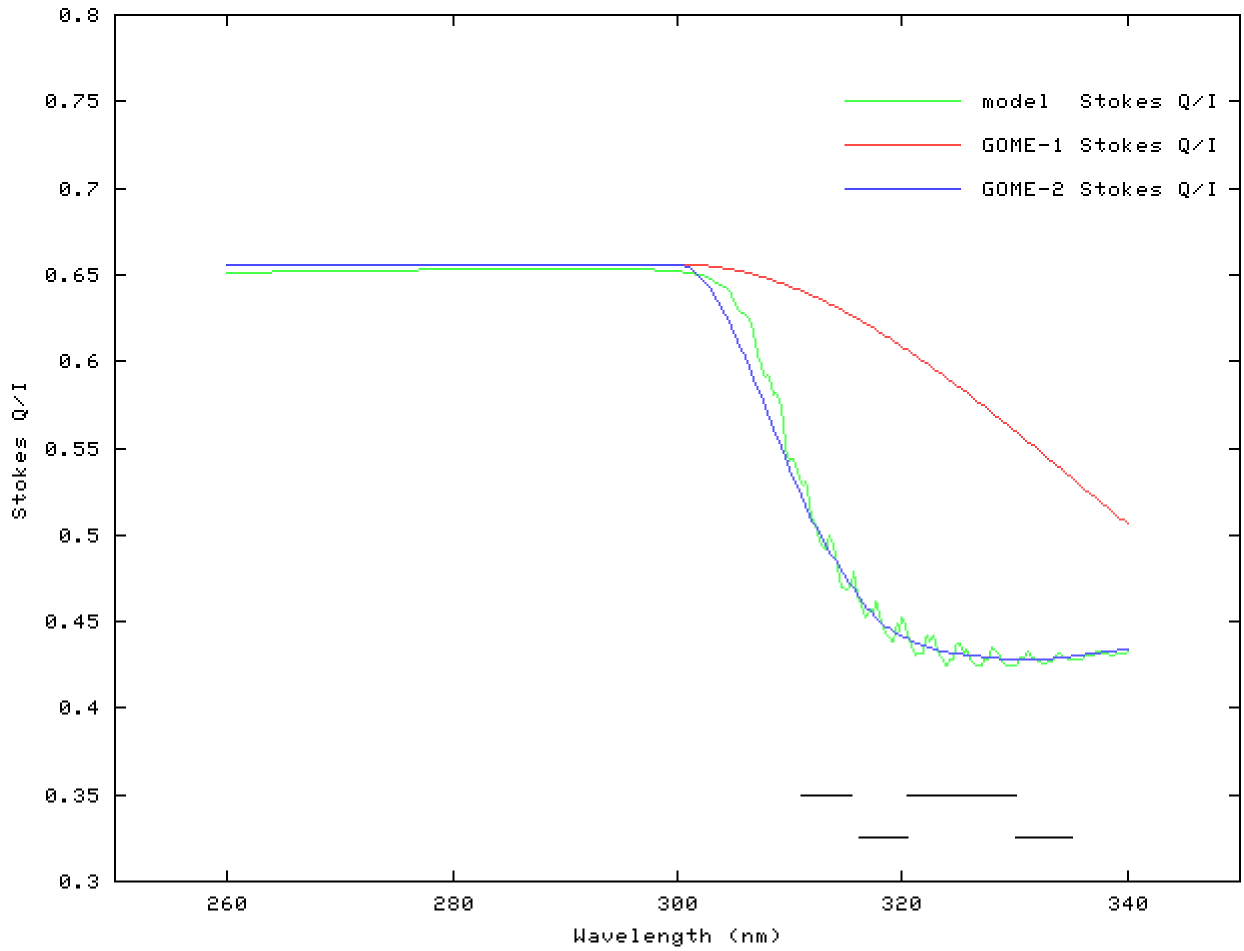

Fig. 4: Radiance normalized Stokes fraction Q/I as input from the model (green dotted line), as reproduced by GOME-1 (red solid line) and as reproduced by GOME-2 (blue dashed line). The GOME-2 PMD spectra bands in this wavelength region are indicated (black lines).

the main channels. The only difference in the optical paths of the PMDs is the double Brewster prism, which separates the parallel (s) and perpendicular (p) polarised light. The cross-sensitivity of the p- and s-PMD to s- or p-polarised light, respectively, is extremely low. Thus the GOME-2 PCA is very straightforward and does no longer call upon the polarisation sensitivity of the main channels.

In GOME-2 up to 15 PMD spectral bands are used to measure the polarisation curve between 310 to 790 nm. Especially between 310 and 340 nm there are four PMD spectral bands with small spectral width, also indicated in figure 4, which closely correspond to the TOMS bands.

Model calculations from a doubling-adding radiative transport code [2, 6] accounting for polarisation of the earth's atmosphere are combined with the GOME-2 optical throughput [7] to obtain simulated PMD signals. The model includes Huggins and Chappuis band opacities. The simulated PMD signals are integrated over the PMD spectral bands after several noise contributions have been added. Given a particular viewing geometry and applying the GOME-2 PCA the Stokes fraction Q/I, related to the degree of polarisation, can be retrieved from the PMD spectral bands. Below 300 nm the Rayleigh single scattering assumption enables the degree of polarisation to be calculated from the viewing geometry alone. Polarisation information at any wavelength can then be obtained by interpolating the polarisation datapoints using simple Akima interpolation. Figure 4 shows an example of a measurement simulation of a Stokes Q/I curve after application of the GOME-2 PCA. The original input model curve is also shown. Note that the general behaviour of the curve is well reproduced, but also that a significant discrepancy occurs between the theoretical single scattering point at 300 nm and the first measured datapoint around ~312 nm. Between ~300 and 320 nm this curve can be very steep (especially for a high single scattering degree of polarisation) and the slope is poorly reproduced by the interpolation between the theoretical (single scattering) point and the first data point. This is particularly important since the polarisation sensitivity of the first main channel peaks around these wavelengths, see figure 1. Other, smaller deviations from the model polarisation curve appear as well at other wavelengths but there the polarisation sensitivity of the respective main channels is generally lower. In figure 4, the GOME-1 simulation shows a much larger difference with the model.

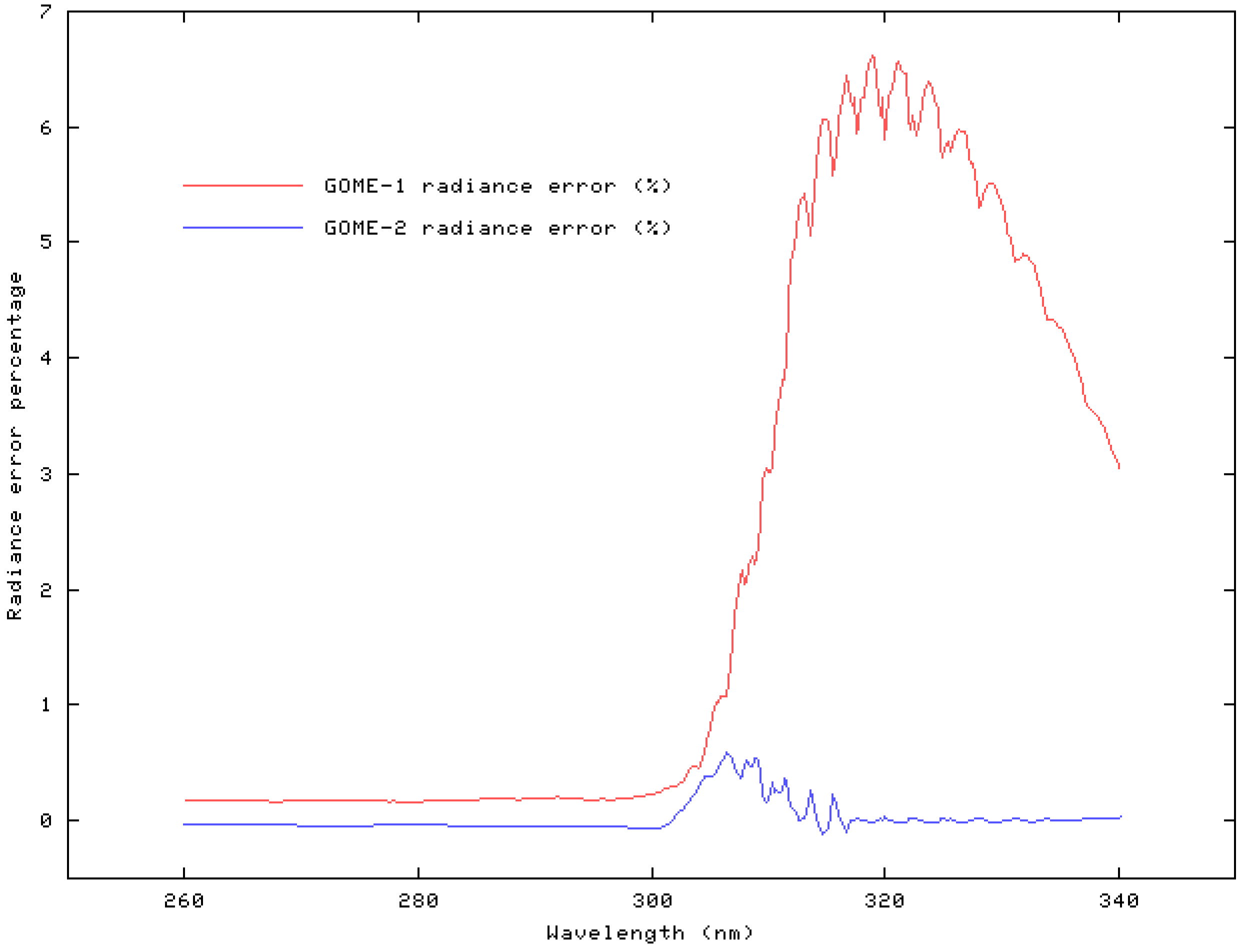

Fig. 5: Radiance error contributions due to the polarisation correction for GOME-1 (solid red line) and GOME-2 (dashed blue line) in the O_3 Huggins band.

To demonstrate the combined effect of the polarisation sensitivity of the main channels shown in figure 1 and the measured polarisation curve the full GOME-2 PCA is applied to the modeled radiance from the radiative transfer code. The dashed blue line in figure 5 shows the resulting radiance error curve. The general shape is caused by the reproduction of the slope of the polarisation curve in combination with the polarisation sensitivity of the main channels at the respective wavelength bands. Also recognizable is the O_3 Huggins band structure, which is of course not reproduced by the Akima interpolation. The solid red curve in figure 5 represents a similar estimate for the radiance error of GOME-1. The errors are in general much larger because of the larger polarisation sensitivity of the GOME-1 main channels and the poor interpolation between the theoretical single scattering point at 300 nm and one GOME-1datapoint around 350 nm.

Ozone retrieval simulations

Retrieval simulations have been conducted to assess the impact of errors introduced into ozone profile retrieval by imperfect polarisation correction. The simulations consists of applying the optimal estimation technique [5] to calculate (a) the expected precision on retrieved ozone assuming some *a priori* knowledge of the profile shape and random observation errors and (b) the impact, on the retrieved ozone, of perturbations in the measurement caused by imperfect polarisation correction. Instrument characteristics (spectral coverage, resolution, photon and read-out noise) appropriate to GOME-2 are assumed.

The retrieval algorithm closely follows the approach adopted by the Rutherford Appleton Laboratory (RAL) GOME-1 operational scheme [4]. It is important to note that retrieval results reported here are dependent on the detail of the scheme adopted. The RAL scheme adopts a 2-step approach to cope with differences in field of view and the difficulty of obtaining *absolute* back-scattered radiance spectra of adequate accuracy to exploit temperature dependent structure in the Huggins bands:

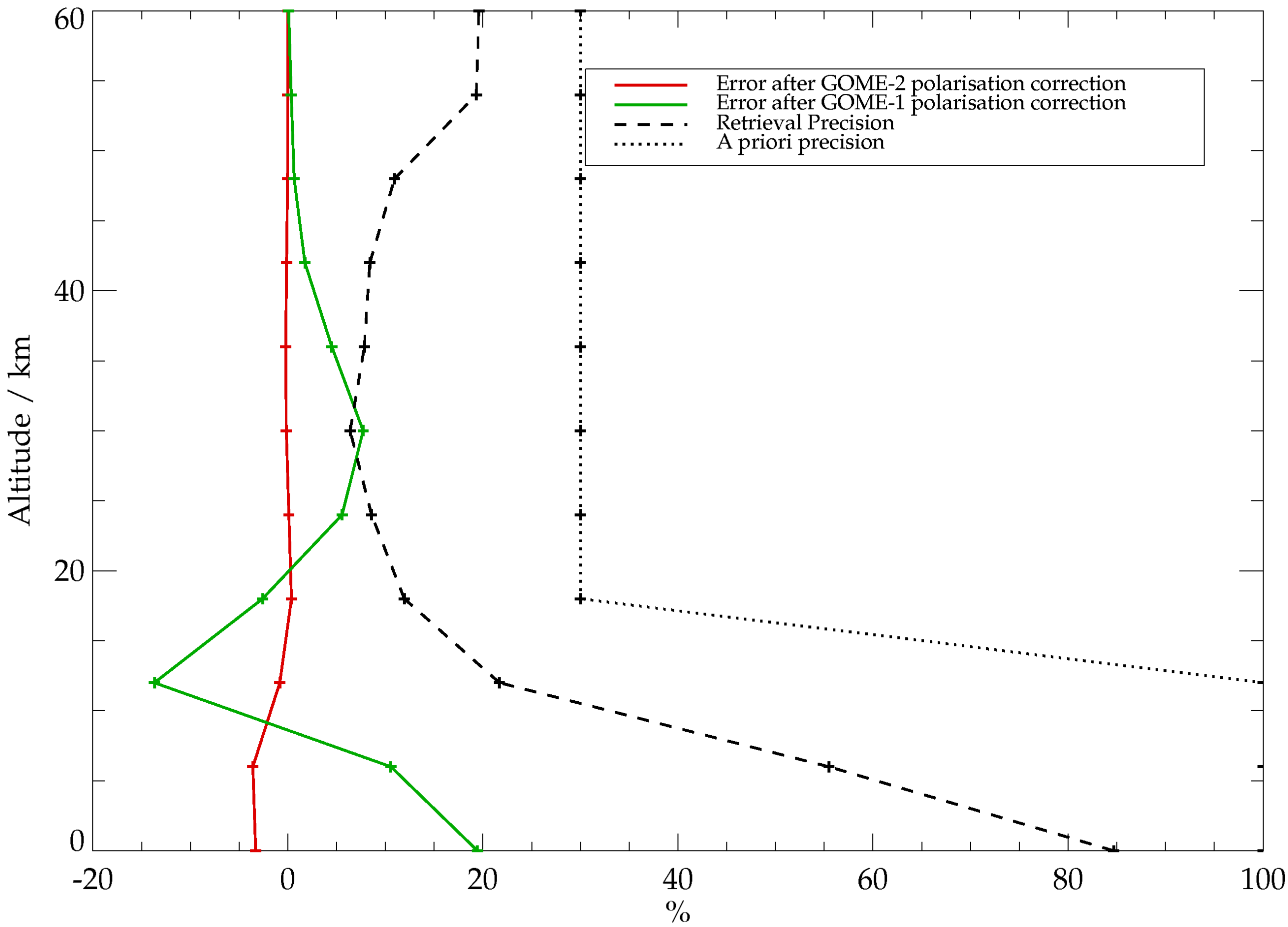

Fig. 6: Simulations of ozone retrieval errors for GOME-1 and GOME-2.

1. An ozone profile is retrieved from sun-normalized radiances in the Hartley band between 265 and 307 nm, contributing information mostly in the stratosphere. Small regions within this spectral range are excluded to avoid NO gamma-bands. A retrieval grid spacing of 6km was adopted, assuming *a priori* errors of 100% at 0,6 and 12 km and 30% above. A vertical correlation length of 6 km was also imposed. Lambertian surface albedo, Ring effect scaling parameter and wavelength calibration are retrieved jointly. A minimum measurement error of 1% in sun-normalized radiance units is imposed to represent forward model error and prevent over-fitting of the measured spectra. (I.e. where the random noise on the GOME-2 measurement is better than 1%, a 1% precision is imposed, elsewhere the modeled instrument noise is assumed).

2. Ozone information is extended downwards into the troposphere by fitting measurements in the Huggins bands between 323 and 334 nm. The profile from step-1 is taken as *a priori* and the associated covariance is formed by taking the retrieval precision from the step-1 retrieval and imposing an 8km correlation length. To enable precise fitting to the temperature dependent structure in the band, the measurement used in the retrieval is formed by taking the logarithm of the sun-normalized radiance and subtracting a second order polynomial. Also retrieved jointly are Ring effect scaling parameter, radiance spectrum wavelength calibration parameters, column amounts of BrO and NO_2. (Surface albedo appropriate to this spectral range is retrieved separately from wavelengths near 340 nm). A minimum measurement error of 0.075% is applied in this band.

Note that the subtraction of a polynomial from the spectra used above 323 nm mitigates the effect of instrument errors with low-order spectral structure (including that due to imperfect polarisation correction).

The figure shows the expected retrieval precision from the application of the RAL profile retrieval scheme to GOME-2 measurements for the October case (75 degrees south, albedo 0.05), together with the expected errors on the retrieved profile due to both GOME-1 and GOME-2 polarisation correction schemes.

Summary

Significant hardware changes with respect to GOME-1 are implemented in the design of GOME-2, such as a reduced polarisation sensitivity of the main channels, the addition of the s-PMD and the possibility of having 15 PMD spectral bands. The aim is to have two identical orthogonal PMD subsystems. It is shown that these changes will reduce the radiance error in the UV due to the PCA to ~1 percent, whereas this can be as high as 10 percent for GOME-1. The errors for GOME-1 and GOME-2 upon the ozone profile retrieval due to imperfect polarisation correction in the troposphere can be as high as ~20 percent for GOME-1 and less than ~4 percent for GOME-2. In the stratosphere the GOME-2 error is even below 1 percent.

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