GOME PRODUCTS VALIDATION WITH THE SAOZ NETWORK

J.-C. Lambert[1], M. Van Roozendael[1], P.C. Simon[1], M. De Mazière[1], J.-P. Pommereau[2], F. Goutail[2], A. Sarkissian[2], L. Denis[2], V. Dorokhov[3], P. Eriksen[4], E. Kyro[5], J. Leveau[6], H.K. Roscoe[7], G. Vaughan[8] and C. Wahlstrom[9]

1. Belgian Institute for Space Aeronomy, BIRA-IASB, Brussels, Belgium
2. Service d'Aéronomie du CNRS, Verrières-le-Buisson, France
3. Central Aerological Institute, Dolgoprudny, Russia
4. Danish Meteorological Institute, Copenhagen, Denmark
5. Finnish Meteorological Institute, Sodankyla, Finland
6. Faculté des Sciences, Université de la Réunion, France
7. British Antarctic Survey, Cambridge, UK
8. University College of Wales, Aberystwyth, UK
9. Norwegian Institute for Air Research, Kjeller, Norway

Abstract

The first 45 days of GOME total ozone and nitrogen dioxide measurements have been compared to those provided by the SAOZ ground-based network over a wide range of latitudes from the Arctic to the Antarctic. It is concluded that total ozone provided by the current GOME retrieval algorithm is already accurate within ±5% for all seasons at the tropics, from spring to fall at northern mid-latitudes and during summer up to 60°N. During other seasons and up to 75° SZA, the difference with the ground-based instruments does not exceed 12%. Below 75° SZA, the comparison demonstrates a SZA dependence of the GOME measurements as well as a relatively lower sensitivity. At high latitude in summer, GOME seems to overestimate the ozone column by 10-20%, as well as in the ozone hole in Antarctica at spring. At high latitude and SZA larger than 75° where multiple scattering and the sphericity of the Earth are not taken into account in the GOME retrieval, the ozone data are not yet reliable. Finally, compared to those of the SAOZs, the preliminary NO_2 measurements show an extremely large spread which indicates that the current retrieval of this species needs improvement.

1. INTRODUCTION

The SAOZ (Système d'Analyse par Observation Zénithale) is a UV-visible spectrometer which measures total ozone and nitrogen dioxide twice daily at twilight by looking at the sunlight scattered by the atmosphere at the zenith. Since identical instruments are deployed world-wide, it was proposed to use the data of this network to investigate the performances of GOME over a wide range of latitudes from the Arctic to the Antarctic. A first comparison with GOME ozone measurements in the Huggins bands was conducted at northern mid-latitude using a variety of instruments including a SAOZ spectrometer, part of the NDSC/Alpine station (Lambert et al., same issue). This first exercise concluded to a small underestimation of total ozone by GOME of 2 to 8% and to a significant Solar Zenith Angle (SZA) dependence when compared to SAOZ. Here, the comparison is extended to all latitudes using the methodology already described by Lambert et al., which will not be repeated. The only difference, unless specified, is the use of preliminary SAOZ results transmitted in real time from the remote stations. However, changes between preliminary and final SAOZ data are generally small, and therefore are not expected to modify significantly the conclusions drawn from the present analysis. The largest limitation of the comparison to date consists in the limited time period of the validation: 45 days, from July to December 1995. It is anticipated that more precision will be gained in the future when longer time series of data will be available.

2. THE SAOZ NETWORK

The SAOZ instrument is a grating spectrometer which looks at the sunlight scattered at zenith (Pommereau and Goutail, 1988). The UV-visible part of the zenith-sky spectrum is recorded during twilight periods for SZA ranging from 86° up to 91°. Column densities along the line of sight, or slant columns, are retrieved by the Differential Optical Absorption Spectroscopy method (DOAS) applied in the visible Chappuis bands (450-580 nm) for ozone and in the 406-526 nm window for nitrogen dioxide. Slant columns are converted into vertical columns by using a standard Air Mass Factor (AMF), calculated with a radiative transfer model which has been validated by comparison (a) with other calculations following a variety of numerical schemes (Sarkissian et al., 1995) and (b) with integrated balloon profiles (Sarkissian et al., 1996).

A number of SAOZ are currently operating. There are listed in Table 1. The SAOZ of Oslo is the one of Ny-Ålesund which was operated at Oslo for a limited period in August 1995. In addition, a DOAS UV-visible zenith-sky spectrometer of BIRA-IASB design, described in Van Roozendael et al. (1995[a]), is operated at Harestua (60°N, Norway). Since the GOME products were not available in the Pacific sector, the data of Dumont d'Urville and Tarawa were not used in the present analysis. The station of Kerguelen started in December 1995 only.

3. SAOZ ACCURACY

In the visible range, between 400 and 630 nm, slant total amounts of O_3, NO_2, $(O_2)_2$, O_2 and H_2O are retrieved by a least squares iterative procedure using high resolution absorption cross-sections published in the literature and convolved with the SAOZ slit function. The precision of the measurements is given by

Location	Lat	Long	Institute
Ny-Ålesund	79N	12E	NILU
Thule	77N	69W	DMI
Scoresbysund	70N	22W	CNRS/DMI
Zhigansk	67N	123E	CNRS/CAO
Sodankylä	67N	27E	CNRS/FMI
Harestua (UV-vis)	60N	9E	BIRA-IASB
Oslo	60N	11E	NILU
Aberystwyth	52N	4W	U. of Wales
Jungfraujoch	47N	8E	BIRA-IASB
O. Haute Provence	44N	6E	CNRS
Tarawa	01N	172E	CNRS/NIWA
Reunion	21S	55E	U. Reunion
Bauru	22S	48W	CNRS/UNESP
Kerguelen	49S	70W	CNRS
Faraday	65S	66W	BAS
Dumont d'Urville	67S	142E	CNRS

Table 1 The SAOZ network.

the one sigma confidence level of the least squares fit calculated for each spectrum. On average at twilight, the precision is better than 0.5% for ozone and 1.5% for NO_2. The high resolution ozone absorption cross-sections used are those of Brion et al. (1993), scaled by -1.9% to those of Anderson and Mauersberger (1992), the most accurate data published so far (0.5% accuracy) but available at discrete wavelengths only. As shown by Brion et al., the temperature dependence of the ozone cross-sections in the visible is not significant (<1%). The overall accuracy of the SAOZ ozone slant total amounts is better than 2%. For NO_2, the uncertainty of the absorption cross-sections (Merienne et al., 1994) is of the order of 5%, but a rather large temperature dependence was shown by Harwood and Jones (1994) and Coquart et al. (1995), and is not taken into account in the present analysis. If corrected for this temperature dependence, the NO_2 stratospheric columns would have to be reduced by about 15%.

The conversion of the slant column into a vertical or total column requires the use of an AMF dependent on the vertical distributions of the atmospheric constituents controlling the penetration of the solar radiation in the atmosphere. According to Sarkissian et al. (1996), the use of an average standard AMF at mid-latitude instead of an AMF calculated from daily ozone soundings, introduces a deviation smaller than 3%. In addition, as shown by Van Roozendael et al. (1995[b]), Hoiskar et al. (1995) and Denis et al. (1995), the seasonal cycles of density and ozone profiles would introduce a systematic seasonal AMF variation of 5-6% amplitude at 67°N, 3-4% at 44°N and negligible at the tropics. Compared to the standard SAOZ AMF, it also introduces an average latitudinal dependence of -3% at 67°N to +2.8% at the tropics (Denis et al., 1995). Since a standard AMF is used for the real time preliminary analysis, the above systematic errors need to be kept in mind in the discussion.

Finally, the ozone and NO_2 data do show some dispersion because of the multiple scattering in the lower tropospheric layer in presence of dense clouds or haze combined with the local pollution (Van Roozendael et al., 1994). This contribution varies from one station to another depending on their location with respect to sources of pollution. Long time series of comparisons with Dobson and Brewer measurements show that this contribution does not exceed 1% on average for ozone. For NO_2, it is negligible at a remote location, but can introduce large spikes in the data in populated regions like Europe, which must be removed by adequate criteria.

The SAOZ instruments have been intercompared at several occasions in the field to other DOAS UV-visible spectrometers, SAOZ, Dobson, Brewer and ozone soundings: during the NDSC UV-visible intercomparison held in New Zealand in 1992 for NO_2 (Hofmann et al., 1995), at Camborne (UK) in September 1994 in the frame of the SESAME campaign for ozone (Vaughan et al., 1996), and within the NOAA/WMO Dobson Intercalibration Campaign held at Arosa (Switzerland) in July-August 1995. At Camborne, four SAOZ and the UV-visible spectrometer of BIRA-IASB were intercompared, and their results were consistent within 3% (10 DU) for ozone and 5% for NO_2 and consistent also with Dobson measurements and ozone soundings within 3% (Vaughan et al., 1996). Long time series of SAOZ total ozone measurements were also compared with those of the TOMS-Nimbus 7 and TOMS-Meteor 3, showing a scatter of ±2.5%, but with a systematic seasonal dependence at high latitude attributed partly to the inversion of the TOMS nadir measurements at large SZA and partly to changes in the shape of the ozone profiles compared to the climatology used in the TOMS inversion procedure (Pommereau et al., 1995).

4. SELECTION OF CO-LOCATED EVENTS

Since the ozone field may display large horizontal gradients and high day-to-day variability in total amounts, particularly at high latitudes, the real locations of the measurements of both the nadir viewing GOME and the zenith viewing ground-based spectrometers must be taken into account.

The viewing geometry and the light path were modelled for the zenith-sky observations. The effective geolocation of the stratospheric part of the air mass sampled by a ground-based zenith-sky instrument at twilight, is located in the direction of the Sun between 100 and 350 km from the instrument at 87° SZA and between 150 and 550 km at 91° SZA. Its azimuth varies from sunrise to sunset as well as with the season. Therefore, the GOME pixel is selected at the geolocation calculated by the model. The effective geolocation of the GOME measurements, which can move up to 30 km from the ground pixel in summer and up to 100 km in winter, is not taken into account in this first validation exercise, because of the 30 km discrepancy between the location of the pixel in the GOME data files and that provided by the ESA orbit propagator.

5. TOTAL OZONE COMPARISONS

The 45 days of relative differences between GOME and SAOZ total ozone at all stations are depicted in Figure 1-a versus the latitude of the centre of the selected GOME pixel and in Figure 1-b versus the SZA of the GOME measurement. At SZA<75°, the comparison is reasonably good, although there is on average a significant SZA dependence of the relative differences. The GOME total ozone is larger than that of SAOZ by 5% at high Sun and for low ozone in the tropics and becomes smaller at high latitude, -12% at 60°N and 70° SZA. At SZA>75° where the GOME retrieval does not take into account the multiple scattering and the Earth's sphericity, the GOME total ozone is on average larger by 15% and the deviation from SAOZ becomes rapidly negative after 90° SZA.

The plot versus latitude in Figure 1-a shows that the scatter increases on average from ±5% at the tropics and mid-latitudes, to ±20% at high latitude and for SZA larger than 75°. Although total ozone varies rapidly there, the increasing scatter largely exceeds that observed with TOMS (Pommereau et al., 1995).
The correlation between the GOME and SAOZ total ozone for a variety of stations distributed from the tropics up to 60°N, is shown in Figure 2. There is a large spread due to the SZA dependence already identified. For removing partly this contribution from the correlation, the data have been sorted into four SZA classes. The regression coefficients for each class of SZA (GOME = a + b x SAOZ (DU)) are shown in table 2. The similar slopes for the four classes (between 0.6 and 0.77) indicate some systematic lower sensitivity of GOME compared to SAOZ, for ozone total amounts ranging from 250 up to 340 DU.
The spread of the data combining all the stations shown in Figure 1 is thus the result of several factors: a SZA dependence and a smaller relative sensitivity of GOME, the temporal variability of the ozone field, and a latitudinal/seasonal dependence of the SAOZ AMF.

Table 2 Regression coefficients between the GOME and SAOZ total ozone measurements sorted into four classes of SZA and for seven sites distributed from the tropics up to 60°N.

SZA	(a)	(b)	r^2
< 45°	81	0.71	0.55
45° < SZA < 55°	103	0.6	0.5
55° < SZA < 65°	75	0.66	0.63
65° < SZA < 75°	33	0.77	0.6

5.1 Northern Mid-latitudes

This latitude belt has already been investigated by Lambert et al. (same issue). The results obtained with SAOZ, Dobson and Brewer observations at the NDSC/Alpine sites show a good agreement. After taking properly into account the 3-4% seasonal cycle of the SAOZ AMF and the altitude of the station of the Jungfraujoch (47°N), it is concluded that on average GOME underestimates total ozone by about 3%. In addition the comparison demonstrates a smaller relative sensitivity of GOME compared to the ground-based measurements and probably also a SZA dependence, but less evident because of the relatively limited range of SZA. The results obtained with the SAOZ data at Aberystwyth (52°N) and at the Observatoire de Haute Provence (44°N) confirm these results.

5.2 Summer Northern Latitudes

At Harestua (60°N), where the final data of the BIRA-IASB UV-visible spectrometer were corrected for the 5-6% AMF seasonal dependence, the comparison with GOME does show a SZA dependence of 6% between 50 and 75° SZA, as shown in Figure 3.
Further north at the polar circle, the preliminary data of Sodankylä and Scoresbysund show a systematic offset compared to Harestua, partly due to the underestimation of large ozone columns by GOME, partly to the use of standard AMF and perhaps also partly to the residual ozone amount in the reference spectrum used in the SAOZ real time processing. However, these plots confirm the SZA dependence of GOME. At the very high latitude stations of Thule (77°N) and Ny-Ålesund (79°N), the GOME total ozone is larger than that measured by the SAOZ by 10 to 20% and the reason for this has not yet been identified. It exceeds by far the 5-6% anticipated from the use of a standard AMF not corrected for the season. It can be noticed that the spread increases also at high latitude, which can be attributed partly to the large differences in time between the SAOZ measurements around midnight in summer and that of the GOME about local noon.

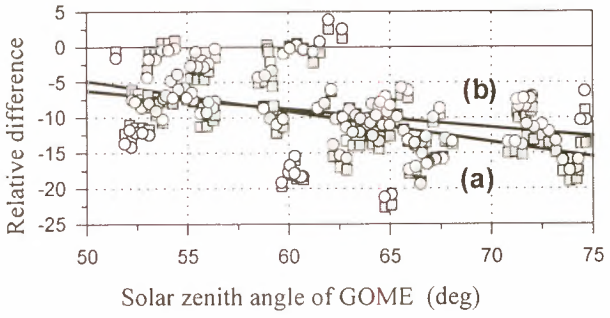

Figure 3 Relative differences between the GOME and UV-vis total ozone ([GOME - UV-vis] / UV-vis, in per cent) at Harestua (60°N) as a function of the GOME SZA. Dark squares and the regression line (a) stand for the UV-vis total ozone retrieved with the SAOZ standard AMF while open circles and the regression line (b) are obtained with an AMF calculated by means of ozone soundings.

5.3 Antarctic: Ozone Hole Conditions

The SAOZ #06 operated by the British Antarctic Survey is located at Faraday (65°S) in the Antarctic Peninsula. In August-October 1995, the station was often inside the polar vortex and ozone total columns as low as 130 DU were observed, in addition to the large day-to-day variations in total ozone occuring usually during this season at the stations located near the edge of the vortex. According to Figure 4, the relative difference between GOME and SAOZ within a limited range of SZA (69°-75°) is correlated with the ozone total amount, which is overestimated by GOME at very low values and the opposite when ozone increases rapidly outside the vortex. These findings are confirmed by the measurements of the co-located Dobson spectrophotometer.

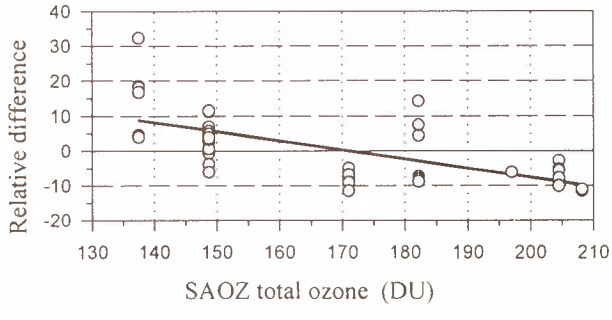

Figure 4 Relative differences between the GOME and SAOZ total ozone ([GOME - SAOZ] / SAOZ, in per cent) at Faraday (65°S) as a function of the ozone total amount.

5.4 Southern Tropics

In the tropics, the number of available co-located events is relatively scarce due to the large spacing between the consecutive satellite swaths. At Reunion Island, the SAOZ preliminary data show a spurious systematic difference between morning and evening. Since this disappeared later after resetting the instrument, it might be due to a drift of the clock which will be easily corrected in the final data.
For the moment, if a daily average is used (which is insensitive to clock drift), GOME and SAOZ

measurements agree within a few per cent. This is confirmed by the new station of Bauru in Brazil installed on 24 November 1995, where the GOME data obtained on 11, 12 and 13 December at 6° SZA, are consistent with those of the SAOZ within ±3%.

5.5 Overall GOME - SAOZ Consistency

From the average differences between the two instruments (less than 5 per cent at 45° SZA and 10 per cent at 60° SZA), a first estimate of the period during which GOME results will be better than a given uncertainty can be derived for each latitude belt (Figure 5). It can be concluded that the current GOME retrieval algorithm already provides ozone columns within an accuracy of 5% at all seasons at the tropics, from April to October at mid-latitudes and from May to September at 60°N. At other seasons and up to 75° SZA, the difference with the ground-based instruments does not exceed 12% except at high latitude in the Arctic or in the ozone hole in Antarctica, where GOME overestimates the ozone column. At SZA > 75°, further algorithm developments, currently in progress, are needed to increase the accuracy of the winter measurements.

6. NITROGEN DIOXIDE

Although the first objective of the validation of the GOME products during the commissioning phase was limited to the ozone total amounts, it was thought useful to have a first look at the preliminary NO_2 data. However, since NO_2 exhibits a diurnal increase between sunrise and sunset and the GOME measurements are performed around local noon, the comparison with dawn and dusk SAOZ data is not straightforward. The first option would be to interpolate linearly the morning and evening SAOZ measurements at the local time of the ERS-2 overpass. Since the diurnal change of NO_2 is not linear but fast in the morning and slower in the afternoon after the complete photolysis of N_2O_5, an alternative approach would be to validate GOME with the evening SAOZ data. If needed, a small correction might be added in the future based on a photochemical model simulation.

The preliminary GOME and the SAOZ NO_2 total columns are compared in Figure 6. The quantification of the discrepancies between both sets of measurements is currently irrelevant. Although some SZA dependence seems to show off, the extremely large scatter between the current GOME and the SAOZ NO_2 data does not allow to conclude, whatever the comparison method. Since long time series of ground-based measurements at remote locations far away from pollution sources, do not show such large dispersion, improvements in the preliminary GOME NO_2 retrieval, currently in progress, are expected to increase significantly the agreement between the satellite and the ground-based data.

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