Stratospheric ozone profiles retrieved from limb scattered sunlight radiance spectra measured by the OSIRIS instrument on the Odin satellite

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[1] Stratospheric ozone density profiles between 15 and 40 km altitude are derived from scattered sunlight limb radiance spectra measured with the Optical Spectrograph and InfraRed Imager System (OSIRIS) on the Odin satellite. The method is based on the analysis of limb radiance profiles in the centre and the wings of the Chappuis-Wulf absorption bands of ozone. It employs a non-linear Newtonian iteration version of Optimal Estimation (OE) coupled with the radiative transfer model LIMBTRAN. The derived zonally averaged ozone field for August 2001 is in excellent agreement with the main characteristics of the global morphology of stratospheric ozone, indicating that the limb scatter technique is capable of providing ozone profiles with high accuracy and high vertical resolution on a global scale and a daily basis. *INDEX TERMS:* 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 0394 Atmospheric Composition and Structure: Instruments and techniques; 1640 Global Change: Remote sensing. **Citation:** von Savigny, C., et al., Stratospheric ozone profiles retrieved from limb scattered sunlight radiance spectra measured by the OSIRIS instrument on the Odin satellite, *Geophys. Res. Lett.*, *30*(14), 1755, doi:10.1029/2002GL016401, 2003.

1. Introduction

[2] Satellite-based remote sensing experiments to measure the chemical composition of the atmosphere have traditionally been of two types: (a) nadir viewing spectrometers, and (b) solar occultation experiments. The nadir viewing spectrometers, e.g., TOMS (Total Ozone Mapping Spectrometer) and SBUV (Solar Backscatter UltraViolet experiment) [*Heath et al.*, 1975] are capable of producing global maps of the total ozone column with high spatial resolution, but the retrieved ozone profiles have very limited vertical resolution [e.g., *Bhartia et al.*, 1996]. The solar occultation experiments, e.g., SAGE (Stratospheric Aerosols and Gas Experiment) [*McCormick et al.*, 1989] provide ozone density profiles with high vertical resolution, but suffer from poor geographical coverage.

[3] A new technique, i.e., limb scatter of sunlight, that combines the advantages of the other techniques provides vertical profiles of ozone density with high vertical resolution (1–3 km) and (near) global coverage on a daily basis. One of the instruments applying this technique is the Optical Spectrograph and Infrared Imager System (OSIRIS) [*Llewellyn et al.*, 1997; *Warshaw et al.*, 1996] aboard the Odin satellite [*Murtagh et al.*, 2002] launched in February 2001. Another instrument capable of limb scanning is SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) [*Bovensmann et al.*, 1999] aboard ENVISAT-1, launched on March 1, 2002. The limb scatter technique has already been successfully applied to limb radiance profiles measured by the LORE/SOLSE (Limb Ozone Retrieval Experiment/Shuttle Ozone Limb Sounding Experiment) instruments flown in 1997 on NASA's space shuttle mission STS-87 and yielded ozone profiles that agreed to within 10% with ozone sondes [*Flittner et al.*, 2000; *McPeters et al.*, 2000].

[4] This paper presents first results of ozone density profiles retrieved from OSIRIS limb scatter observations.

2. OSIRIS on Odin

[5] OSIRIS is one of two scientific instruments onboard the Swedish/Canadian/French/Finnish Odin satellite. The other instrument is a Submillimeter and Millimeter Radiometer (SMR) designed for both aeronomy and astronomy studies. Odin was launched on February 20, 2001 from Svobodny in eastern Russia into a polar, sun-synchronous, near-terminator orbit with an inclination of 97.8° and an ascending node at 18:00 LST (Local Solar Time). OSIRIS and the SMR are co-aligned and the nodding satellite enables both instruments to scan the Earth's limb with tangent heights (TH) ranging from

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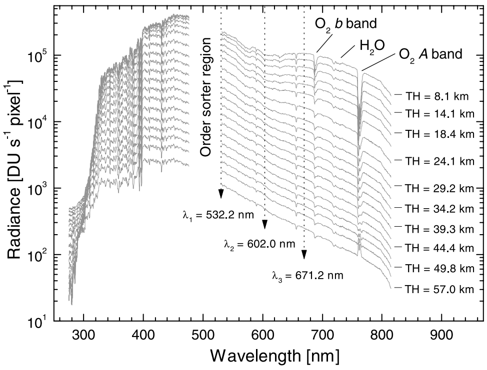

Figure 1. OSIRIS stratospheric limb scan (DU stands for digital unit). Clearly visible is absorption in the Huggins and Chappuis-bands of ozone. The vertical lines indicate the wavelengths used for the ozone profile retrieval in the Chappuis-Wulf system.

about 10 km to 70 km in the normal Odin stratospheric observation mode.

[6] The Optical Spectrograph consists of a grating spectrometer covering the spectral range from 280 nm to 800 nm with a resolution of about 1 nm. The accuracy of the pointing in the limb scanning mode is generally within about ±15 seconds of arc, which translates to about 200 m in terms of TH.

[7] Figure 1 shows a sample limb scan measured with the Optical Spectrograph on July 30, 2001, when the tangent point passed over Spitsbergen (78°N, 20°E). The gap around 500 nm corresponds to the instrument's order sorter region, where spectral information can not be used and was never intended to be used [*Warshaw et al.*, 1996]. Interesting features are, e.g., the O_2 A band appearing in absorption at lower THs and in emission at higher THs. Note also that at lower THs the Chappuis-bands of ozone centered at about 600 nm are easily discernible. Absorption in the ozone Huggins-bands is responsible for the sharp decrease in the limb radiance below 320 nm.

3. The Retrieval Algorithm

[8] The method used to recover ozone density profiles from OSIRIS observations closely follows that employed by *Flittner et al.* [2000] and *McPeters et al.* [2000] to recover ozone density profiles from the LORE/SOLSE limb scatter measurements in the Chappuis absorption bands of ozone.

[9] The first step of the retrieval scheme consists of normalization of the limb radiance profiles: $I_n(\lambda, TH_i) = \frac{I(\lambda, TH_i)}{I(\lambda, TH_{ref})}$, with $I(\lambda, TH_i)$ denoting the limb radiance at wavelength λ and tangent height TH_i. The wavelengths used are λ_1 = 532.2 nm, λ_2 = 602.0 nm, λ_3 = 671.2 nm and the reference TH is TH_{ref} = 50 km. The effect of normalization is (a) to reduce the sensitivity to ground albedo and clouds, (b) to render the absolute calibration of the instrument unnecessary.

[10] In a second step the normalized limb radiance profiles in the centre and the wings of the Chappuis-Wulf system of ozone are combined to give the *Chappuis retrieval vector*:

$$y_C(TH_i) = \frac{I_n(\lambda_2, TH_i)}{exp\left[\frac{1}{2}\{\ln I_n(\lambda_1, TH_i) + \ln I_n(\lambda_3, TH_i)\}\right]} \qquad (1)$$

with $i = 1, \ldots, N_{TH}$, where N_{TH} is the number of elements of each limb radiance profile. Figure 2 shows simulated (for Solar Zenith Angle SZA = 70°, and azimuth angle $\Delta\phi$ = 90°) and observed retrieval vectors $y_C(TH_i)$ for different albedos and stratospheric aerosol loadings. Clearly, albedo and stratospheric aerosols have some impact on the Chappuis retrieval vector, but this is relatively small. For comparison the retrieval vector for an ozone free atmosphere (solid line) is also shown in Figure 2.

[11] Figure 2 also shows two retrieval vectors derived from OSIRIS limb radiance profiles. The first corresponds to a limb scan performed when Odin passed over the Canary Islands off the Atlantic coast of Africa on August 22, 2001 at 18:48 UTC (29.1°N/16.0°W). The second vector was derived from a limb scan on August 08, 2001 at about 7:32 UTC over Spitsbergen in the Arctic Sea (76.7°N/12.8°E). For these two scans coincident ozone density profile measurements were made by ozone sondes launched from Santa Cruz on Teneriffa (Canary Islands, 28.3°N, 16.5°W, 11:17 UTC) and from Koldewey station on Spitsbergen (78.9°N, 11.9°E, 10:59 UTC) [*König-Langlo and Marx*, 1997].

[12] In order to retrieve stratospheric ozone density profiles from these measurements a nonlinear Newtonian iteration version of Optimal Estimation (OE) [*Rodgers*, 1976] was combined with the pseudo-spherical multiple scattering radiative transfer model LIMBTRAN [*Griffioen and Oikarinen*, 2000]. Above 40 km the method becomes insensitive to ozone, due to the small ozone densities. Below 15 km the method's sensitivity decreases with decreasing TH, because the LOS (line of sight) optical depth becomes large (τ_{LOS} > 1.5) and most of the scattered photons do not originate from the LOS tangent point.

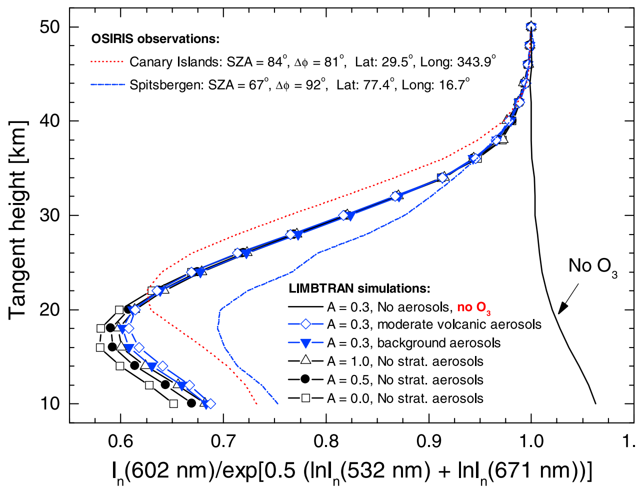

Figure 2. Chappuis retrieval vectors $y_C(TH)$ (a) modelled with LIMBTRAN for different ground albedos and different stratospheric aerosol loadings (SZA = 70° and $\Delta\phi$ = 90°), (b) measured with OSIRIS.

Table 1. Summary of the Sensitivity Studies

Altitude	15 km	20 km	25 km	30 km	35 km
Ground albedo[a]	<3.5%	<1.5%	<1%	<1%	<0.8%
Stratospheric aerosols[b] (background)	<5%	<5%	<5%	<0.2%	<0.1%
Stratospheric aerosols[c] (mod. volcanic)	<25%	<16%	<14%	<0.5%	<0.4%
Background atmosphere	<2%	<2%	<2.5%	<2%	<2%
Clouds[d]	<2.5%	<3%	<3.5%	<4%	<5%
Instrument noise	<2%	<1.3%	<1.5%	<3%	<5%

[a]for SZA $\geq 60°$, if albedo known to ± 0.2.
[b]if aerosol extinction profile known within a factor of 2.
[c]if aerosol extinction profile known within a factor of 5.
[d]if not appearing in FOV.

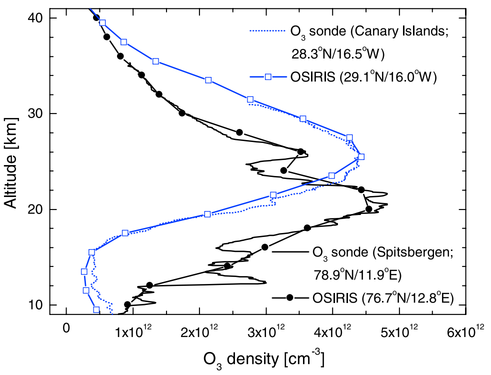

Figure 4. Ozone density profiles retrieved from the retrieval vectors of Figure 2 and comparison with the ozone sondes launched from Koldewey Station in Spitsbergen and Santa Cruz (Canary Islands).

[13] The temperature dependent GOME Flight Model ozone absorption cross sections [*Burrows et al.*, 1999] were used. The a priori covariance matrix is chosen to be diagonal and the standard deviation for each TH is assumed to be 100% of the a priori. LIMBTRAN was operated in full multiple scattering (MS) mode. A constant ground albedo of A = 0.3 was used for all retrievals presented here, and stratospheric background aerosol conditions were assumed.

3.1. Error Budget

[14] A comprehensive error analysis for the ozone density profile retrievals is presented by *von Savigny* [2002]. This includes an assessment of the impact of ground albedo, stratospheric aerosols, clouds and instrumental effects such as internal, and baffle scattering. The most important sources of error are listed in Table 1. The impact of the temperature dependence of the ozone absorption cross sections, internal scattering and the instrument's polarization sensitivity were found to lead to errors of less than 1%. Based on these sensitivity studies the overall accuracy of an individual profile is estimated to be better than 10% for the 15 to 35 km altitude range. This is consistent with a comparison of all (43) coincident OSIRIS and POAM III ozone profile measurements during August 2001, that yielded agreement within 6% between 15 and 35 km [*von Savigny*, 2002].

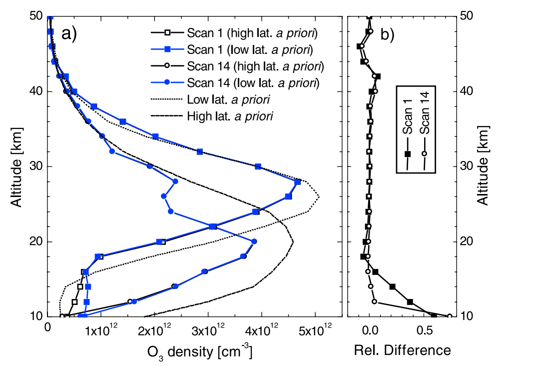

Figure 3. Sensitivity of ozone profile retrievals to the a priori ozone profile: panel (a) shows retrievals of a low-latitude scan (scan 1, lat: 13.6°N, long: 92.0°E) and a high-latitude scan (scan 14, lat: 75.5°N, long: 220.1°E) of orbit 2725 (Aug. 22, 2001) with both a high-latitude and low-latitude a priori; panel (b) shows the relative difference between retrievals with high and low-latitude a priori.

3.2. Impact of the a Priori on the Retrievals

[15] An important question is as to what extent the assumed a priori ozone profile influences the retrievals. In a worst case scenario low-latitude ozone profiles were retrieved assuming a high-latitude a priori and vice versa. This is illustrated in Figure 3. The dotted and dash-dotted lines in panel a) show the low-latitude and high-latitude *a prioris* that correspond to the zonally averaged and meridionally binned (0–30°N and 70–85°N, respectively) 10 year August mean ozone profiles as determined with the Canadian Middle Atmosphere Model (CMAM) [*de Grandpré et al.*, 1999]. Within the 15 to 35 km altitude region the retrievals are apparently quite insensitive to the a priori, considering that the two a priori profiles are entirely different. Between 20 and 35 km the relative differences (panel b) are 3% at the most and generally well below 1%. For the high-latitude scan 14 the relative difference is smaller than 5% all the way down to 12 km, whereas the differences exceed 20% below 14 km in the case of scan 1. This is partly due to a higher ozone layer at low latitudes leading to greater LOS optical depths at a given TH - and thus less sensitivity to ozone - compared to the high-latitude case.

[16] In practice, a latitude dependent ozone profile climatology will provide a much more realistic a priori than for the worst case scenario discussed above. The systematic errors due to an inappropriate a priori will then be significantly smaller than the above values and present only a minor contribution to the total error budget within the 15–35 km altitude range.

4. Results

4.1. Two Case Studies Coincident with Ozone Sonde Measurements in the Northern Hemisphere

[17] Figure 4 shows the ozone density profiles retrieved from the OSIRIS Chappuis retrieval vectors of Figure 2 compared with the coincident unsmoothed ozone sonde profiles measured at Spitsbergen and Canary Islands. Clearly, the OSIRIS and sonde profiles are in very good agreement in terms of both vertical distribution and absolute magnitude. Apparently the laminae near 15 km and 26 km present in

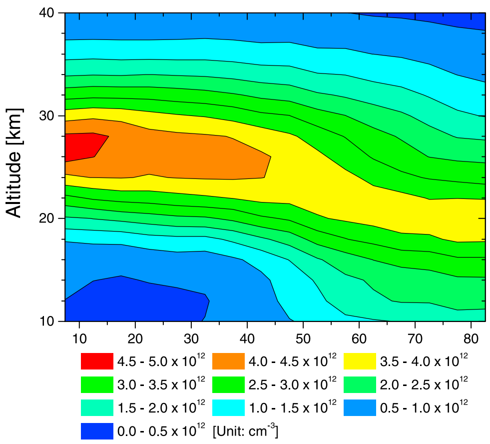

Figure 5. Zonally averaged August 2001 ozone field retrieved from OSIRIS limb radiance profiles.

the Spitsbergen ozone sonde profile are not fully recovered in the OSIRIS profile. This is partly due to the lower vertical resolution of the OSIRIS retrievals of about 2 km. Moreover, the OSIRIS limb scattering observations are associated with horizontal averaging over scales of several hundred kilometers due to: (a) the slant path through the atmosphere along the LOS, and (b) the movement of the spacecraft during a limb scan.

4.2. Summary of OSIRIS Northern Hemisphere 2001 Observations

[18] Due to preliminary problems with Odin's attitude control system during the satellite's commissioning phase, routine limb scanning did not begin until late July 2001. Note that as a consequence of Odin's orbital parameters the northern hemisphere (NH) segment of the orbit is sunlit only between late February and mid-October. All of the limb scattering data obtained during August 2001 (3900 profiles) have been analyzed as described above.

[19] Figure 5 shows the zonally averaged ozone density field averaged over all days in August 2001 when OSIRIS was operating. Clearly, all of the established general features of the stratospheric ozone climatology are reproduced. For example, (a) the tropical peak is narrower and is located at an altitude of about 27 km, (b) with increasing latitude the peak descends and broadens, and, (c) the peak altitude at high latitudes is at about 20 km.

[20] A comparison of EP-TOMS total ozone columns for the August 2001 period with total ozone columns derived from OSIRIS partial stratospheric columns, combined with estimates of tropospheric columns taken from *Fishman et al.* [1990], and mesospheric columns as determined with CMAM [*de Grandpré et al.*, 2000] yielded agreement within about 3–5%.

5. Conclusion

[21] Vertical profiles of ozone density between about 15 and 40 km have been derived with a vertical resolution of about 2 km from OSIRIS observations of limb scattered sunlight radiance spectra. The recovered OSIRIS vertical ozone profiles compare favorably with ozone sonde profiles. A comparison of strato-mesospheric ozone columns derived from OSIRIS and EP-TOMS total ozone columns indicates that the OSIRIS and EP-TOMS columns agree within 5%. This study shows that scattered sunlight measurements made with limb scanning/imaging instruments such as OSIRIS, SCIAMACHY and GOMOS have great potential for contributing to our understanding of stratospheric ozone.

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