Satellite-pointing retrieval from atmospheric limb-scattering of solar UV-B radiation


Abstract: We present a new algorithm for tangent height retrievals from limb-scattering observations. These observations are performed by satellite-based spectrometers operating in the UV, visible, and short-wave IR spectral ranges. They record the solar radiation scattered in Earth’s atmosphere in limb-viewing geometry and aim at vertically resolved retrievals of the atmospheric composition with global coverage. Inaccuracies in the knowledge of the instrument’s pointing frequently dominate the error budgets of the atmospheric composition products. Therefore, additional information on satellite pointing is crucial for the quality of all products derived from limb-scattering observations. The information is commonly expressed in terms of the tangent heights. The presented algorithm determines the tangent heights directly from the observed limb radiances by analyzing the shapes of the so-called knee in several UV-B radiance profiles. All vertical pointing information contained in a UV-B fit window is exploited by simultaneously retrieving the ozone profile. The algorithm has been implemented in the toolbox SCIARAYS and named Tangent height Retrieval by UV-B Exploitation (TRUE) knee method. We have applied it to five orbits of SCIAMACHY’s limb observations. It achieves a precision of about 200 m when applied to an individual limb scan. The broadband structure of the observations can be reproduced within 1% RMS. A comparison of the retrieved tangent heights with the engineering ones delivered by ESA reveals that the engineering tangent heights exhibit a systematic error, which varies with an amplitude of about 3 km. Its origin is traced to the on-board orbit model of Envisat.

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Résumé: Nous présentons un nouvel algorithme pour déduire les hauteurs tangentes des observations de diffusion dans le limbe. Ces observations sont faites par des spectromètres à bord de satellites et opérant dans l’UV, le visible et les IR de courte longueur d’onde. Ils enregistrent la radiation solaire diffusée dans le limbe de l’atmosphère terrestre, dans le but d’en déterminer la distribution verticale des composants dans une vue globale. Les imprécisions dans la direction où pointent les instruments sont la plus grande source d’erreurs.
pour déterminer les composantes de l’atmosphère. Conséquemment, des renseignements additionnels sur l’orientation du satellite sont cruciaux pour la qualité des résultats déduits de l’observation. L’information est souvent décrite comme des hauteurs tangentes. Le présent algorithme détermine les hauteurs tangentes directement à partir de la radiance du limbe observée en analysant les formes des coudes dans plusieurs profiles de radiation UV-B. Toute l’information pointant vers la verticale contenue dans la fenêtre UV-B est utilisée en recouvrant simultanément le profil de l’ozone. L’algorithme a été placé dans la boîte à outil SCIARYS et baptisé « Tangent height Retrieval by UV-B Exploitation (TRUE) ». Nous l’avons utilisé sur cinq orbites d’observation de radiance du limbe par SCIAMACHY. Nous parvenons à une précision d’environ 200 m lorsque appliqué à un balayage du limbe. Les structures à large bande des observations peuvent être reproduites avec une précision meilleure que 1% RMS. Une comparaison des hauteurs tangentes avec celles fournies par l’instrumentation ESA native du satellite indique que ces dernières ont une erreur systématique qui varie avec une amplitude de 3 km. L’origine de cette erreur peut être attribuée au modèle d’orbite à bord de Envisat.

[Traduit par la Rédaction]

1. Introduction

1.1. Limb-scattering observation

The space-borne spectrometer SCIAMACHY was launched aboard ESA’s Envisat in March 2002. The instrument observes Earth’s radiance in the nadir, limb, and occultation geometries in the spectral range 240–2380 nm with a spectral resolution of 0.22–1.48 nm. The observed radiance consists of solar electromagnetic radiation that is scattered onto the instrument’s line of sight by the molecules, basically nitrogen and oxygen, as well as the aerosols in the Earth’s atmosphere. Additionally, the radiation is attenuated by absorption by atmospheric trace gases. The horizontally and vertically resolved atmospheric composition, e.g., O3, NO2, and aerosol loading, is determined by combining results from all three geometries [1, 2].

The viewing geometry of the limb-scattering observations is illustrated in Fig. 1. SCIAMACHY scans the Earth’s limb recording scattered solar radiation. A typical scan sequence consists of 35 horizontal scans, each with a different tangent height (TH). The nominal difference between two adjacent THs is 3.3 km. The field of view has a vertical angle of 0.045°. This translates to 2.4–2.6 km at the tangent point, depending on the TH and satellite position.

Limb-scattering observations yield vertically resolved profile information on the atmosphere [3–6]. The observations are particularly challenging because of the complexity of the data analysis. As a prerequisite the vertical pointing, i.e., the tangent heights, must be known accurately. Erroneous pointing information may dominate the error budget of the limb retrieval [7].

Arguably, because of these two points only two other satellite-based spectrometers have been dedicated to limb-scattering observations: SME [3] recorded several narrow spectral bands in 1982–1986 and OSIRIS [8] has been observing spectra aboard the Odin satellite since 2001. GOMOS and SAGE III, both designed for occultation observations, are also capable of recording limb-scattering spectra.

1.2. Sources of pointing information

The so-called engineering-pointing information is calculated from knowledge on SCIAMACHY’s internal scan-mirror positions and on the satellite’s location and orientation. The latter two are obtained on-board using an orbit model. The model is regularly updated with observed coordinates. This pointing information is delivered by ESA in the SCIAMACHY radiance products.

The engineering-pointing information can be validated indirectly by comparison of retrieved profiles with independent observations. For example, Sioris et al. [10] found an altitude offset between NO2 profiles retrieved from SCIAMACHY and HALOE.
The THs may also be retrieved directly from the scattered limb radiance. All published TH retrievals are based on the so-called knee method originally suggested by Janz et al. [11]. It uses the so-called knee feature of the UV radiance profiles, see Sect. 2.1 for a detailed description. The method has been applied to the observations of SOLSE/LORE with 345 nm wavelength by McPeters et al. [4]. Sioris et al. [12] have adapted the method by analyzing several wavelengths around 305 nm for which OSIRIS had observed the same knee height. It has also been applied to the observations of 215 and 236.5 nm wavelength of the Student Nitric Oxide Explorer [13].

Additional pointing information is implicitly contained in other observed spectral regions arising from the influence of the temperature and pressure dependencies of various trace-gas absorption cross sections. However, this information has not been utilized yet as the analysis would be relatively complex and very sensitive to inaccuracies in a priori trace gas profiles.

1.3. This paper

We introduce a conceptual extension to the knee method. The new method, denoted Tangent height Retrieval by UV-B Exploitation (TRUE) knee method, extracts all pointing information inherent in a UV-B limb-fit window. The method is applied to the limb measurements by SCIAMACHY. A comparison with the engineering-pointing information yields precision estimates for both retrieved and engineering THs.

2. Retrieval method

2.1. Physical background

If the atmosphere is optically thin along the line of sight then the scattered limb radiance decreases exponentially with increasing TH. This behavior dominates the visible radiation at stratospheric tangent heights, cf. Fig. 2. It is also typical in the near- and short-wave IR [14]. The decrease is caused by the exponential behavior of the atmospheric neutral density profile and, thus, the Rayleigh scattering (also called molecular scattering) near the tangent point. The profiles shown in Fig. 2 differ as the Rayleigh-scattering cross section varies with the inverse of the fourth power of the wavelength, $\lambda^{-4}$.

In the UV-B spectral range, the decrease is limited to THs in and above the upper stratosphere. Smaller THs display the opposite behavior, i.e., an increase of the radiance with increasing TH, cf. Figs. 2 and 3, top left plot. The increase is caused by the strong absorption of the stratospheric ozone; since the line of sight becomes optically thick in the middle stratosphere, only radiation scattered in higher altitudes contributes to the observation. The path lengths of the line of sight in higher altitudes increase geometrically as the TH rises. Hence, the scattered radiance increases. The combination of altitude-dependent Rayleigh-scattering intensity and ozone absorption creates a radiance maximum. It is evident in Fig. 2 in the observed radiance profile at 300 nm. This maximum is called the knee feature of the radiance profile.
Fig. 2. Limb radiances profiles between 300 and 700 nm wavelength observed by SCIAMACHY in orbit 2999 near latitude 44° N. Average of east and west pixels. Tangent-height scale according to the engineering information. Visible features: knee at 300 nm, exponential behavior at visible wavelengths, and low radiance at 600 nm in the lower stratosphere due to the Chappuis absorption band of ozone. Above 70 km, baffle scattering appears at 400, 500, and 600 nm.

Between 200 and 300 nm, the knee is a maximum at higher THs. In an intermediate wavelength region between 300 and 400 nm the knee is said to be a “kink” rather than a maximum. In this spectral region, the line of sight becomes optically thick due to the extinction by Rayleigh scattering instead of ozone absorption. The knee is absent from the radiances with wavelengths of 400 nm and higher. The heights and shapes of the knees at different wavelengths depend almost exclusively on the neutral density and ozone profiles in the upper stratosphere.

2.2. Algorithm description

2.2.1. Layout

Previous knee algorithms [11, 12] derive the pointing information from a single, theoretically calculated knee altitude. In contrast, the algorithm presented here determines the THs by fitting modeled radiances to the observed ones in an UV-B wavelength range and an upper stratospheric TH range. The fit is simultaneously performed for all wavelengths and THs with an iterative optimal estimation algorithm [15]. Additionally, the dependency on the ozone climatology may be reduced by fitting ozone simultaneously. Since the knee heights, strengths, and shapes of several radiances profiles throughout the UV-B-fit window are exploited we call the algorithm the TRUE knee method.

2.2.2. Measurement vector

In this study, the normalized radiances \( I(\lambda, h) \) are calculated from the radiance data product \( R(\lambda, h) \) by division by the spectra at 43 km TH:

\[
I(\lambda, h) = \frac{R(\lambda, h)}{R(\lambda, 43 \text{ km})}
\]  

(1)

where \( \lambda \) and \( h \) denote the wavelength and the tangent height. Thus, all multiplicative radiative transfer and instrument effects and most of the structure of the solar irradiance is compensated. Subsequently, the
normalized radiances are interpolated linearly and sampled at the 11 wavelengths 295, 296, … 305 nm.

The measurement vector \( y \) analyzed by the inversion algorithm is composed of the normalized radiance samples at the five engineering tangent heights 37, 40, 43, 46, and 49 km:

\[
y = \begin{pmatrix}
  I(295 \text{ nm}, 37 \text{ km}) \\
  \vdots \\
  I(305 \text{ nm}, 37 \text{ km}) \\
  \vdots \\
  I(295 \text{ nm}, 49 \text{ km}) \\
  \vdots \\
  I(305 \text{ nm}, 49 \text{ km})
\end{pmatrix}
\] (2)

The wavelengths and THs have been chosen such that the measurement vector dimension is minimized while maintaining full TH sensitivity.

2.2.3. Retrieval parameters

A simultaneous retrieval of the ozone and neutral density profiles along with the THs would be desirable to minimize the error introduced by inaccuracies in the climatologies of ozone and the neutral density. Since such a simultaneous retrieval from SCIAMACHY’s UV-B observations is an ill-posed problem some regularization must be used. It can be achieved with a priori values and appropriate covariance matrices. In this case, vanishing variances are equivalent to not fitting the corresponding parameters. Alternatively, a priori knowledge can be introduced with a parameterization of the retrieval parameters.

In this analysis the TH sequence \( h_i \) is parameterized by the offset parameter \( \Delta h \):

\[
h_i = h_i^{\text{eng}} + \Delta h
\] (3)

where \( h_i \) and \( h_i^{\text{eng}} \) denote the modeled and engineering THs. Thus, the entire TH sequence is shifted vertically during the retrieval of \( \Delta h \). This parameterization is justified by the stability of the tangent height step size established before launch [16].

Results from two algorithm setups are presented; in the “fix ozone” case only \( \Delta h \) is fitted while in the “fitted ozone” case \( \Delta h \) and the ozone profile are fitted simultaneously. Thus, the state vector \( x \) fitted by the inversion algorithm is defined differently for the two setups:

- fix ozone: \( x = (\Delta h) \) (4)
- fitted ozone: \( x = \begin{pmatrix}
  \Delta h \\
  n_{O_3}(z_1) \\
  \vdots \\
  n_{O_3}(z_n)
\end{pmatrix} \) (5)

where \( n_{O_3}(z_1) \ldots n_{O_3}(z_n) \) denotes the ozone number density profile.

In the latter case, an uncertainty of 20% and a correlation with a 1.5 km scale height are assumed for the a priori ozone profile.

2.2.4. Auxiliary input

Pressure and temperature profiles are taken from Nagatani et al. [17]. The zonally and monthly averaged SBUV ozone climatology [18] is used for the a priori ozone profile. Since the climatology only extends up to 60 km, the ozone densities are extrapolated to higher altitudes using an exponential function with the ozone density scale height at 60 km altitude, i.e., about 4.5 km. Background stratospheric aerosol is modeled with properties extracted from GOMETRAN [19].
2.3. Forward model

2.3.1. Radiative transfer model

The radiative transfer calculations are performed with the toolbox SCIAMACHY [20]. It models two orders of scattering and surface reflection in a spherical, horizontally stratified, cloud-free atmosphere with refractive bending. Thus, all ray paths shown in Fig. 1 are included. The model is fully linearized, i.e., the weighting functions for all atmospheric parameters are calculated quasi-analytically.

The required input parameters for the model include the observational geometry, i.e., tangent heights; solar zenith; relative azimuth angles; and the ozone, pressure, and temperature profiles. The neutral density profile is internally calculated from the latter two using the ideal gas law.

The model is used to calculate the pencil-beam\(^2\) limb radiance \(I^{\text{pencil}}(\lambda, h_{i}^{\text{fine}})\) on a fine TH grid \(h_{i}^{\text{fine}}\) of 1 km spacing. The third and higher orders of scattering are negligible as the UV-B fitting window falls entirely within the spectral region of single scattering [9].

2.3.2. Instrument model

The pencil-beam radiance \(I^{\text{pencil}}(\lambda, h_{i}^{\text{fine}})\) calculated by the ideal radiative transfer model described above should not be directly compared with the observed radiance as the latter contains smoothing by the spatial instrument response function. The critical parameter in our context is the extent of the instrument’s field of view.

To make both radiance quantities directly comparable, the instrument model convoloves the pencil-beam limb radiance \(I^{\text{pencil}}(\lambda, h_{i}^{\text{fine}})\) calculated by the ideal radiative transfer model with SCIAMACHY’s vertical field of view. The field of view has an approximate boxcar characteristic with a total width of 2.6 km. The quadrature weights are chosen such that their products with the field of view yield an exponential function of the sixth power of the tangent height difference to the center of the field of view:

\[
I(\lambda, h) = \sum_{i} b \times \exp \left[ \left( \frac{h - h_{i}^{\text{fine}}}{1.3 \text{ km}} \right)^{6} \right] \times I^{\text{pencil}}(\lambda, h_{i}^{\text{fine}}) \tag{6}
\]

where \(b\) normalizes the exponential function to unity. The choice of quadrature weights is a tradeoff between maintaining a boxcar-like characteristic and avoiding numerical integration artifacts in the behavior of \(I(\lambda, h)\) in the \(h\)-dimension.

The TH weighting functions, which are required by the inversion algorithm, are calculated by numerical perturbation on the convolution (6). The weighting functions of all atmospheric parameters are convoloved consistently with (6).

The instrument model in SCIAMACHY also calculates the signal-to-noise ratio depending on the modeled radiance and the spectral characteristics of SCIAMACHY observed in the laboratory before launch. The ratios are used for constructing the measurement variance needed by the inversion algorithm. An in-flight characterization of the instrument is not available yet.

2.4. A priori error sensitivity

The two atmospheric quantities shaping the UV-B limb radiance profiles are the vertical profiles of neutral density and ozone, see Sect. 2.1. Therefore, the accuracy of the information on these quantities limits the accuracy of the TH retrieval. The TH retrieval sensitivities with respect to these quantities as calculated with the fix ozone setup (4) are discussed below. This setup is more sensitive than the fitted ozone setup (5), which partially corrects for inaccuracies in the ozone climatology.

\(^2\)The so-called pencil-beam radiance would be observed by an instrument with ideal \(\delta\)-function shaped field of view.
2.4.1. Neutral-density profile

The neutral density is calculated with the ideal gas law from the pressure and temperature. Therefore, inaccuracies in the climatologies of the two quantities affect the accuracy of the neutral-density profile and consequently that of the TH retrieval.

The impact on the TH retrieval accuracy was tested by scaling the entire neutral-density profile by a factor of 1.05 and repeating the TH retrieval for the Envisat orbits discussed in Sect. 3 below, i.e., orbits 2995–2999. It was found that the differences in the TH retrievals with the scaled and the standard input was less than 400 m for all limb measurements considered.

In an additional test, the neutral density was scaled with height-dependent factors: 1.05 below 30 km, 0.95 above 60 km, and linearly decreasing from 1.05 to 0.95 between 30 and 60 km. The effect on the retrieved THs was always smaller than 320 m in this test.

Thus, systematic errors of several hundred metres should be expected in situations with extreme pressure or temperature anomalies.

2.4.2. Mesospheric ozone

The climatological ozone profiles are extrapolated to altitudes above 60 km using a scale height parameter, see Sect. 2.2.4. To investigate the influence of this parameter on the TH retrievals, test retrievals with unrealistically low- and high-ozone density-scale height values of 1 and 10 km were performed. It was found that the difference to the standard retrieval is only about 100 m at most. In an extreme scenario, the ozone profile was truncated at 60 km leading to differences to the standard retrieval of 250 m at the very most. These values show that the pointing retrievals are rather insensitive to the ozone density profile above 60 km.

2.4.3. Stratospheric ozone

To test the sensitivity of the retrievals on the stratospheric part of the climatological ozone profile, the entire ozone profile was scaled by different factors and the retrieval results compared with those of the standard retrieval. This approach is justified by the weak influence of mesospheric ozone. It was found that scaling factors of 0.5 and 2 lead to differences in the retrieved THs of up to 3 km. Factors of 0.8 and 1.2 yield differences on the order of 1 km at most.

In an additional test, the ozone profile was scaled with height-dependent factors: 1.2 below 30 km, 0.8 above 60 km, and linearly decreasing from 1.2 to 0.8 between 30 and 60 km. In this case, the retrieved THs deviated less than 510 m from the standard retrieval results. Thus, the uncertainty of the ozone gradient seems less influential than an uncertainty of comparable size in the stratospheric ozone column.

We conclude that the uncertainty of the stratospheric ozone climatology is the dominant source for errors in the TH retrievals with the fix ozone setup.

3. Retrieval results

We have applied the TRUE knee method to the limb measurements obtained on 26 September 2002 during Envisat orbits 2995–2999.

3.1. Fitted radiances

Typical examples of the observed limb radiances along with the retrieval residuals are shown in Fig. 3. The knee is clearly pronounced in the radiances profiles (top left plot). Its wavelength dependence is also evident. It manifests itself in the spectra (bottom left plot), too.

The observed radiances are selected for analysis according to their engineering THs. However, Fig. 3 shows the radiances as functions of the retrieved THs. The plotted TH range is lower than the
Fig. 3. Observed (left) normalized limb-scattering radiances and the relative fit residuals with fix ozone (middle) and fitted ozone (right) setups plotted as profiles for each wavelength (top) and spectra for each tangent height (bottom). The normalized radiances are dimensionless [-]. Orbit 2999, latitude 44° N, east pixel.

The residuals display a measurement noise of about 1%. The residual from the fix ozone fit (middle plots) additionally features a systematic behavior of about 3% amplitude in both spectral and TH dimensions. Since this behavior is absent from the residuals obtained with simultaneous retrievals of TH and ozone (right plots) it must be interpreted as the part of the ozone signature that is not correlated with the TH signature. We conclude that independent information on ozone is contained in the observations. Furthermore, the systematic behavior in the fix ozone residual reveals the inaccuracies in the ozone climatology.

The root mean square (RMS) of the radiance fit residuals is reduced from 1.6 to 1.0% by simultaneously fitting ozone, cf. Table 1. Thus, SCIAMACHY’s limb observations are reproduced roughly within the measurement noise level. We conclude that no further information is contained in this fitting window. Consequently, all pointing information has been exploited.

3.2. Retrieved tangent heights

The retrieved TH offset parameters $\Delta h$ are plotted as functions of latitude in Fig. 4. The average values of corresponding east and west pixels are shown. The more northern observations are obtained earlier in each orbit as the satellite travels southward during the partial (daylight) orbits shown.

The retrieved TH offsets display an instability in southern middle and high latitudes, i.e., south of 30° S. It coincides with strong horizontal gradients both, along-track and across-track, in the total ozone column observed by GOME [21], see Figs. 5 and 6. Horizontal inhomogeneities are not represented in our radiative transfer model. Also, the variations depicted in the total ozone column can obviously not be modeled by the ozone climatology. They are even underestimated by the a priori uncertainty of 20% assumed in the fitted ozone setup. Therefore, the following TH analysis is restricted to latitudes north of 30° S, where a relatively homogeneous total ozone column is observed.

We also limit the analysis to observations south of 60° N, since the method seems less stable at
Fig. 4. Retrieved tangent height offsets $\Delta h$ for orbits 2995–2999 with fix ozone (left) and fitted zone (right) setups.

Fig. 5. Assimilated total ozone columns observed by GOME. Copied from http://www.knmi.nl/gome_fd/tm3 and converted to grey scale.

Fig. 6. Interpolated total ozone columns [DU] observed by GOME and ground footprints of SCIAMACHY limb scans of orbits 2995–2999 (most eastern – most western). Left plot: 15–90° S, right plot: 15–90° N.
Table 1. Statistical properties of different retrievals

<table>
<thead>
<tr>
<th></th>
<th>Ozone</th>
<th>Fix</th>
<th>Fitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual radiance RMS (%)</td>
<td>1.6</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Drift (m/orbit)</td>
<td>220 ± 36</td>
<td>182 ± 22</td>
<td></td>
</tr>
<tr>
<td>Jump (km)</td>
<td>—</td>
<td>2.7 ± 0.24</td>
<td></td>
</tr>
<tr>
<td>Residual Δh RMS (m)</td>
<td>277</td>
<td>201</td>
<td></td>
</tr>
</tbody>
</table>

higher latitudes. This restriction corresponds to requiring the solar zenith angle to be smaller than 60°.\(^3\) Thus, observations with solar zenith angles ranging between 28° and 60° are used.

The TH offset retrievals are relatively stable in the individual orbits 2995–2998. The smoothness of the retrieved TH offsets demonstrates the stabilities of both the TRUE knee algorithm and the engineering information. However, a systematic latitudinal behavior occurs in the results from retrievals with fix ozone. Since it is clearly reduced by fitting ozone simultaneously we attribute it to the uncertainties of the ozone climatology identified in Sect. 3.1.

The TH offsets show a drift from orbit to orbit. Since the measurement geometry varies only slightly between different orbits the drift has to be attributed either to zonal variations in the ozone field at tropical and middle latitudes or to an error in the engineering tangent heights.

At a latitude of 0–20° N a sudden jump of about 3 km occurs in the TH offset in orbit 2999. Since the jump is much larger than the TH retrieval variations in the previous orbits it can hardly be explained by TH retrieval errors, especially, since SCIAMACHY’s operation parameters have not changed during orbit 2999.

However, the discontinuity coincides with an update of the on-board orbit model of Envisat, which was performed near 13° N in orbit 2999. The coincidence supports the assumption that the observed TH offsets are neither caused by incorrect mirror positions etc. within SCIAMACHY itself, nor by unexpected error variations in the TH retrieval. Instead, they seem to be due to errors in the knowledge of the satellite’s pitch.

The size of the TH jump is calculated from the retrievals in orbit 2999, cf. Table 1. Assuming daily updates of the on-board orbit model, i.e., every 14 orbits, the obtained jump of 2.7 km corresponds to a drift of 193 m/orbit. The jump is not calculated for the fix ozone setup as the latitudinal behavior would introduce an unquantified systematic error.

The observed drift is quantified by fitting a straight line into the retrieved offsets over time. Only observations between 30° S and 60° N are analyzed. Additionally, the analysis is restricted to observations before orbit 2999 in the case of the fix ozone setup and to those before the jump in the case of the fitted ozone setup. Thus, drift values of roughly 200 m/orbit and uncertainties are obtained, cf. Table 1. They are consistent with the value estimated from the jump assuming daily on-board orbit model updates.

The residual TH offset from the linear fit may be used for an end-to-end estimation of the TH retrieval precision. The calculated RMS is shown for both retrieval setups in Table 1. The difference proves that simultaneous retrieval of ozone significantly improves the TH retrieval result. The improvement is also evident in the reduced latitudinal behavior of the fitted ozone TH offset in Fig. 4. In conclusion, an overall

\(^3\)The restriction on the solar zenith angle (SZA) is rather a consequence of Envisat’s orbit than an intrinsic property of the TRUE knee method. We have verified with model calculations that the single-scattering approximation is valid in the entire analyzed fit window for all SZA < 90°. It is actually best at 90° SZA with errors in the radiances well below 1%. We attribute the reduction in stability at high latitudes either to the variability in the ozone distribution or to the variation of the SZA in across-track direction. (The observed field of view azimuthally extends 960 km at the tangent points.) Therefore, we expect the method to work for all SZA < 90°, provided the ozone profile is sufficiently well-known and provided the variation of the SZA across the azimuthal extent of the field of view is adequately accounted for.
retrieval precision of about ±200 m is achieved by performing a simultaneous fit on an individual limb scan.

4. Conclusions and outlook

The implementation of the new TRUE knee method in the toolbox SCIRAYES is capable of reproducing SCIAMACHY’s middle and upper stratospheric normalized limb radiance measurements within 1% RMS. This is of the order of the noise in the normalized measurements. The stability of the retrieved tangent height (TH) offsets shows that retrievals with a statistical 1σ-precision of ±200 m can be obtained from individual limb scan sequences of SCIAMACHY. However, the application appears to be limited to scenes with a horizontally stratified stratosphere.

Since the statistical precisions derived from the TH retrieval stability are smaller than the estimation of errors induced by inaccuracies in the climatological pressure, temperature, and ozone profiles we conclude that our sensitivity study in Sect. 2.4 can be considered a conservative approach describing realistic but atypical situations.

The TRUE knee algorithm performs well due to three design elements that constitute qualitative steps beyond previous retrievals from the UV and visible spectral ranges: (1) the instrument’s field of view is modeled explicitly, (2) the broadband structure of the normalized radiance is analyzed, and (3) ozone is retrieved simultaneously with the THs.

The offset between retrieved and engineering THs exhibits a systematic drift of about 200 m/orbit and a jump of roughly 3 km when Envisat’s on-board orbit model is updated. This behavior has also been found by the MIPAS pointing analysis for both the orbits 2081–2083 [22] and 2993–2998, 3000, 3002. For example, MIPAS observes average tangent height offsets of 2.5 km and 0.1 km for the orbits 2998 and 3000. The sign is opposite to the one of our results as the instruments look in opposite directions.

The good agreement between SCIAMACHY and MIPAS TH retrievals in terms of sign, magnitude, and temporal behavior together with the fact that the pointing discontinuity in orbit 2999 coincides with the update of the on-board orbit model can only be explained consistently by errors in the model’s representation of the satellite pitch. Consequently, ESA has implemented an improved version of the on-board orbit model on 9 December 2003.

This paper focuses on the statistical properties of the retrieved TH offsets to obtain an end-to-end validation of the TH offset retrieval. Ongoing work will complement the assessment by validating the retrieved ozone profiles and by quantifying the different error components individually. Further investigations aim at retrieving independent information on the individual THs and the neutral density.

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