NOVEL APPROACH TO TROPOSPHERIC NO_2 RETRIEVAL FOR TROPOMI

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ABSTRACT

The current retrieval of tropospheric NO_2 data from satellite measurements – called DOMINO for OMI data and TM4NO2A for GOME, SCIAMACHY and GOME-2 data – will be continued and improved in the light of the forthcoming Tropospheric Monitoring Instrument (TROPOMI), aboard the Sentinel-5 Precursor mission, which is due for lauch in March 2015. The DOMINO / TM4NO2A processing applies a DOAS retrieval on the satellite data and to determine the tropospheric NO_2 column it uses an AMF look-up table and a data assimilation system. For the latter a number of improvements are already planned. This paper describes the possible replacement of the DOAS retrieval and AMF look-up table by a novel retrieval method, called DISMAS, which potentially provides a better data product: more accurate tropospheric NO_2 data, with better error estimates. Results of some first sensitivity tests of DISMAS retrievals using simulated data are presented as well.

Key words: tropospheric NO_2, TROPOMI.

1. INTRODUCTION

Nitrogen dioxide (NO_2) in the troposphere is a key species in air quality issues, as it affects human health and ecosystems, and it is one of the most important precursors of ozone. Though in itself a minor greenhouse gas, NO_2 has indirect effects on the global climate by affecting the concentrations of ozone and methane. NO_2 enters the troposphere as a result of anthropogenic activities (notably fossil fuels and biomass burning) and natural processes (notably microbiological processes in soils, wildfires, lightning, and transport from the stratosphere).

Because of its importance to climate and air quality issues, tropospheric concentrations of NO_2 are monitored all over the world by a variety of methods – ground based, in-situ (balloon, aircraft) or satellite based – each with its own specific advantages. Over the past 15 or so years tropospheric NO_2 has been measured from satellite instruments such as GOME (ERS-2; 1995–2011), SCIAMACHY (ENVISAT; 2002–2012), OMI (EOS-Aura; 2004–present) and GOME-2 (MetOp-A; 2006–present) – the latter two provide (almost) global coverage in one day.

For these four instruments, the Royal Netherlands Meteorological Institute (KNMI) operates a very successful processing of tropospheric NO_2, the results of which are freely available via the TEMIS website[1]. For this approach – called DOMINO (for OMI) and TM4NO2A (for GOME, SCIAMACHY and GOME-2), and based on a DOAS retrieval, a precalculated air-mass factor (AMF) look-up table and a data assimilation / chemistry transport system – a number of improvements are planned.

At the moment a new instrument, called Tropospheric Monitoring Instrument (TROPOMI), is begin developed and built, as a successor to OMI and SCIAMACHY. The instrument will measure in the UV, visible and near-infrared, focussing on tropospheric species. TROPOMI will be aboard the Sentinel-5 Precursor mission, planned to be launched in March 2015 [1]. KNMI is the lead institute for operating TROPOMI and it will be responsible for the processing of tropospheric NO_2 data, ozone profile data, aerosol data, and supportive cloud cover data.

For the retrieval of tropospheric NO_2 from TROPOMI in principle a version of the DOMINO / TM4NO2A processing system (with the planned improvements) will be made. Currently it is being investigated whether a novel retrieval method, called DISMAS, can be implemented to replace the DOAS retrieval and the AMF look-up table, to provide a better tropospheric NO_2 data product: more accurate retrieval results with better error estimates.

The present paper describes the current and the novel approach in Sect. 2, focussing on the near-real time processing of the satellite data. Sect. 3 provides a short description of the two different retrieval methods, as well as some remarks regarding the planned improvements in the data assimilation part of the processing. Some first results of sensitivity tests using DISMAS and based on simulated data are presented in Sect. 4. A few concluding remarks are formulated in Sect. 5.

[1] http://www.temis.nl/airpollution/no2.html

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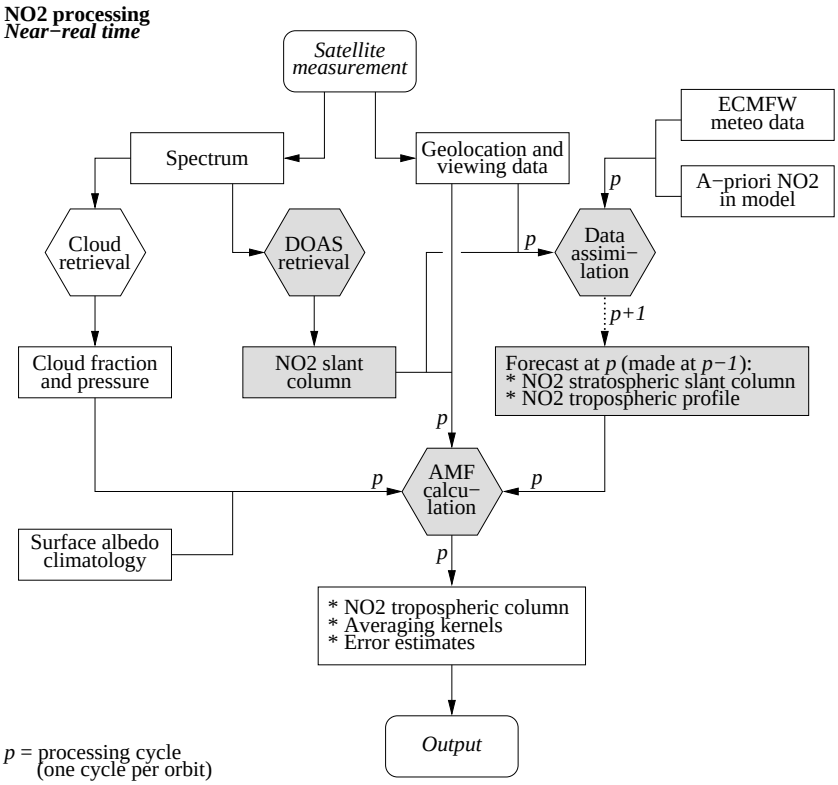

Figure 1. Schematic representation of the near-real time processing of tropospheric NO_2 data in the current processing system DOMINO / TM4NO2A, which applies a DOAS retrieval. The scheme shows processing cycle p in which, say, one orbit of measurements is processed. Key elements in the scheme are shaded. See Sect. 2.1 for details.

Further investigations, using real satellite data, will have to show whether implementing DISMAS does indeed provide a better tropospheric NO_2 data product and whether it can do so within the time constraints of the required near-real time processing, which means that the data product must available within three hours after the measurements were taken.

2. TROPOSPHERIC NO_2 RETRIEVAL

This section describes the processing of satellite observations to provide tropospheric NO_2 data in near-real time (NRT) currently in use at KNMI for the GOME, SCIAMACHY, OMI and GOME-2 instruments (Sect. 2.1) and proposed to be implemented for the forthcoming TROPOMI instrument (Sect. 2.2). Furthermore, some remarks are made regarding off-line (re)processing of satellite data (Sect. 2.3) and the retrieval of cloud cover data needed by the NO_2 processing system (Sect. 2.4).

2.1. Current processing using DOAS

The current NRT processing that derives tropospheric NO_2 data from OMI measurements at KNMI, called DOMINO, is described in detail in [2] and references therein. For the NRT processing of GOME-2 data a system called TM4NO2A is used, which differs from DOMINO only in some details.

Fig. 1 is a schematic representation of the DOMINO / TM4NO2A system for a given process cycle, p, in which a given set of measurement data (say: one orbit) is processed. The heart of the system – shaded grey in Fig. 1 – is a three step procedure: (1) the retrieval of an NO_2 slant column density (SCD) from the measured spectrum using a DOAS retrieval (see Sect. 3.1 for a brief description), (2) the separation of the SCD into a stratospheric (SCD_{st}) and a tropospheric (SCD_{tr}) part, and (3) the conversion of the tropospheric slant column density (SCD_{tr}) into a tropospheric NO_2 vertical column (VCD_{tr}) by applying an appropriate tropospheric airmass factor (AMF) from a look-up table.

In process cycle p the last two steps use results of a forecast for cycle p made after cycle $p-1$ by a data assimilation / chemistry transport model (currently TM4; see Sect. 3.3 for some details) for the satellite measurement being processed: a stratospheric NO_2 slant column (SCD_{st}) and a tropospheric NO_2 profile. The latter is one of the input parameters to a pre-calculated look-up table that provides the appropriate tropospheric AMF.

Other input to the AMF look-up table is: geolocation (latitude, longitude, measurement time), viewing geom-

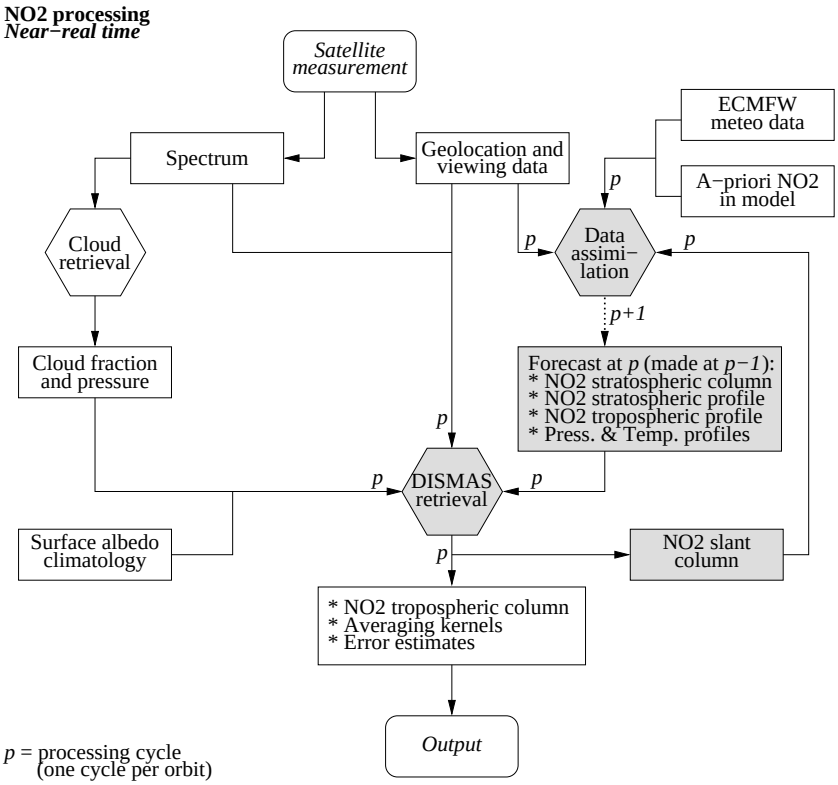

Figure 2. Schematic representation of the near-real time processing of tropospheric NO_2 data in the proposed processing system for TROPOMI, which applies a DISMAS retrieval. The scheme shows processing cycle p in which, say, one orbit of measurements is processed. Key elements in the scheme are shaded. See Sect. 2.2 for details.

etry (solar and viewing zenith and azimuth angles), cloud cover data (which is calculated in process cycle p prior to the NO_2 processing; see Sect. 2.4 for a few remarks on the cloud retrieval), and a surface albedo climatology. The latter is the same albedo climatology as is used for the cloud cover retrieval, to ensure that possible systematic errors in that climatology are compensated in the selection of the appropriate AMF.

Once processing cycle p has been completed – i.e. once all measurements of process cycle p are converted to tropospheric NO_2 column values – the retrieved slant columns are used in a run of the data assimilation system to provide a forecast for the next processing cycle, $p + 1$, of NO_2 stratospheric slant columns and NO_2 tropospheric profiles. Hence the use of a dotted arrow in Fig. 1 at the output of the data assimilation. The data assimilation system scales NO_2 profiles in the chemistry transport model (TM4) to be consistent with the retrieved NO_2 slant column. For the transport of NO_2 it uses up-to-date ECMWF meteo data (pressure, temperature and wind fields), received once every 6 hours.

The reason to use the data assimilation in the forecast mode is that when processing cycle p starts (which is immediately after new data has arrived), the requiered information (stratospheric slant columns and tropospheric profiles) must be readily available: the NRT processing cannot afford to wait for the data assimilation to be ready. Since the forecast is provided for several hours ahead (up to three days), the NRT processing can always provide tropospheric NO_2 data, even if the data assimilation system itself is slowed down for some reason or other.

2.2. Proposed processing using DISMAS

A novel way of determining the tropospheric NO_2 column is offered by a newly developed retrieval method called DISMAS (see Sect. 3.2 for a short description). Fig. 2 sketches the tropospheric NO_2 processing system in case DISMAS is used. This new approach changes the heart of the processing system, as can be seen from comparing the grey shaded elements in Fig. 1 and 2.

With DISMAS there is no separate NO_2 slant column retrieved, nor is there need of a pre-calculated AMF look-up table. Instead, DISMAS directly determines the vertical tropospheric NO_2 column VCD_{tr} from the measurement spectrum, thus combining the three separate steps of the DOMINO / TM4NO2A process mentioned in Sect. 2.1 into one step. Not using an AMF look-up table implies that DISMAS has to perform radiative transfer calculations for every individual spectrum, but only at a limited number of wavelengths (see Sect. 3.2).

To be able to determine the VCD_{tr} directly, DISMAS needs in process cycle p a forecast of a stratospheric NO_2

column VCD_{st}, an NO_2 profile for the stratosphere and for the troposphere, as well as profiles of temperature and pressure. These data sets must be provided by the data assimilation / chemistry transport system as forecast at the end of process cycle $p-1$, similar to the DOMINO / TM4NO2A processsing.

From the by DISMAS determined tropospheric vertical NO_2 column, the available NO_2 profiles and the internally computed AMF, the NO_2 slant column must then be reconstructed for use in the next forecast run of the data assimilation system for process cycle $p+1$.

For its retrieval, DISMAS also needs geolocation and viewing data, cloud cover data and an a-priori guess of the surface albedo. Contrary to the DOMINO / TM4NO2A proces, DISMAS will in the retrieval not only fit the NO_2 column but also the surface albedo (and possibly the cloud cover data) in the wavelength window used for the NO_2 retrieval (405–465 nm).

The reason is that DISMAS needs to use the surface albedo to determine the continuum of the spectrum. If DISMAS is not allowed to fit the surface albedo (i.e. if it is kept fixed, as it is in the DOMINO / TM4NO2A proces) then DISMAS will not be able to converge and find an NO_2 column if the a-priori (climatological) albedo $a_{\rm ap}$ differs from the true (unknown) albedo $a_{\rm tr}$.

To test this, retrievals using simulated data have been performed for a range of NO_2 values with $a_{\rm ap}-a_{\rm tr}$ up to ± 0.010, and the results can be summarised as follows.

For low NO_2 values (1×10^{14} molec/cm^2), the retrieval does not converge for $a_{\rm ap}-a_{\rm tr}=\pm0.001$ (±0.002) for low (high) albedo values. For moderate NO_2 values (1×10^{15} molec/cm^2), the retrieval does not converge for $a_{\rm ap}-a_{\rm tr}<-0.001$ for all albedo values. On the other hand, the retrieval converges for $a_{\rm ap}-a_{\rm tr}=+0.001$ for low albedo, and the higher the albedo the larger $a_{\rm ap}-a_{\rm tr}>0$ may be for convergence to be reached. For high NO_2 values (1×10^{16} molec/cm^2) all cases with $a_{\rm ap}-a_{\rm tr}>-0.002$ converge; and the higher the albedo is, the more negative $a_{\rm ap}-a_{\rm tr}$ may be. All in all, the retrieval is quite sensitive for differences between $a_{\rm ap}$ and $a_{\rm tr}$, notably for low albedo and low NO_2, if DISMAS is not allowed to fit the albedo.

Allowing DISMAS to adjust the surface albedo in the retrieval fit may, however, introduce an inconsistency between the surface albedo used for the NO_2 and the surface albedo used for the cloud cover data. Whether this inconsistency significantly affects the retrieval results needs to be investigated.

2.3. Off-line (re)processing

The above describes the processing cycle of NRT data, for which it is important that the processing goes fast enough and therefore, as mentioned, the information necessary from the data assimilation system is used in forecast mode: the processing system cannot afford to have to wait for the assimilation results to be available. In case of (re)processing off-line data the data assimilation system can, in principle, be used in analysis mode, providing the best data sets required for the determination of the tropospheric NO_2 column amount.

For the DOMINO / TM4NO2A processing this means a change in the order of the steps mentioned in Sect. 2.1. Once the NO_2 slant columns have been retrieved with DOAS, those slant columns are first used in the data assimilation system to provide the stratospheric column and the profile for the measurements being processed. When that is done, the AMF is determined and the vertical column is computed.

In case of the off-line DISMAS processing, the change in the processing order would be bigger if the full analysis mode of the data assimilation has to be used. The reason for this is that there is no NO_2 slant column to begin the assimilation with: the slant column is derived *after* the retrieval of the total NO_2 column. Since the DISMAS retrieval requires input from the data assimilation system, which in turn depends on the NO_2 slant column, some sort of iteration would be needed, making this approach cumbersome and slow.

From the DOMINO / TM4NO2A results it is known, however, that the difference between results of the data assimilation of analysis and forecast for one day ahead are small. This means that the error made in the NO_2 retrieval when using the forcast mode are small, so that using the NRT retrieval system for the off-line processing for DISMAS will most likely be sufficiently accurate.

2.4. Cloud cover data

For the retrieval of trace gas concentrations it is necessary to have information on the cloud cover: the cloud fraction, the cloud albedo, and the cloud height. These three quantities cannot be retrieved independently and so one of them has to be fixed – usually this is the cloud albedo, which is usually set at 0.8 for non-snow/ice cases (snow/ice cases are treated separately).

For GOME, SCIAMACHY and GOME-2 measurements, the cloud data are retrieved with the FRESCO algoritm from the oxygen (O_2) A-band around 760 nm [3]. For OMI measurement, the cloud cover data cannot be derived from the O_2 A-band, as that band is not available for OMI. Instead, cloud cover data for OMI is derived from the O_2-O_2 absorption band around 477 nm [4].

For TROPOMI, which will measure also in the O_2 A-band, the FRESCO algorithm will be run for the NRT retrieval of trace gas concentrations. Investigations are ongoing to improve the cloud cover data product by using an optimal estimation approach [5].

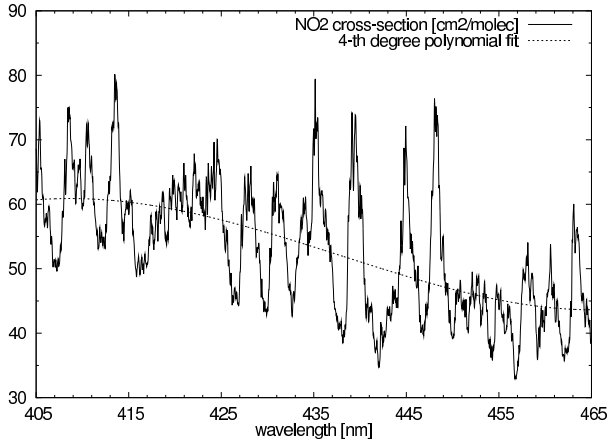

Figure 3. NO_2 absorption cross section (solid; in cm^2/molec*) in the wavelength window used for NO_2 retrieval, at a resolution of 0.02* nm *and at room temperature, and a 4-th degree polynomial fit through it (dashed).*

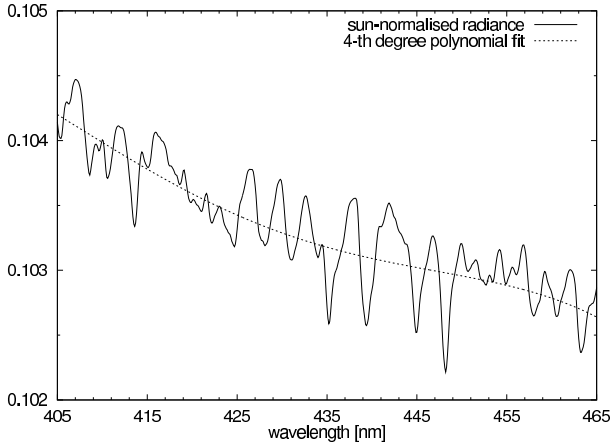

Figure 4. Example of a sun-normalised radiance (solid; dimensionless) of a simulated spectrum with a large NO_2 concentration and a high surface albedo, and a 4-th degree polynomial fit through it (dashed).

3. RETRIEVAL METHODS & IMPROVEMENTS

This section provides a brief description of the two retrieval methods mentioned above: DOAS (Sect. 3.1) and DISMAS (Sect. 3.2), looking specifically into the differences between these two, without going into details. Sect. 3.3 presents a short overview of the improvements planned to the data assimilation / chemistry transport system currently in use for DOMINO / TM4NO2A, which will also be used for processing TROPOMI data.

The retrieval of (tropospheric) NO_2 from the satellite measurements mentioned here is performed in the wavelength range used in DOMINO and planned for TROMOPI: 405–465 nm (for other satellite instruments somewhat different wavelength ranges are used). Both approaches use the NO_2 absorption spectrum (see Fig. 3) in the analysis. For simplicity only NO_2 absorption is considered in the description below.

3.1. DOAS retrieval

DOAS – or in full Differential Optical Absorption Spectroscopy – as retrieval method performs a spectral fit of a reference spectrum (set up using, in this case, the NO_2 cross section) and a satellite-measured spectrum.

To this end the measured spectrum (Fig. 4, solid line) is split up in a spectrally smooth part and a differential part, where the smooth part (Fig. 4, dashed line) is modeled by a polynomial fit through the spectrum. The differential spectrum is then compared to the differential cross section, constructed in a similar manner (cf. Fig. 3).

This comparison provides the NO_2 slant column – the amount of NO_2 along the line-of-sight, from the sun to the satellite, i.e. the average photon path through the atmosphere. The retrieval calculation takes little computational time, making DOAS well suited for operational use with large amounts of satellite data.

An AMF representative for the wavelength window is needed for the conversion of slant to vertical NO_2 column, as described in Sect. 2.1. This AMF follows either from an on-the-fly radiative transfer calculation or from a look-up table, depending on the application.

3.2. DISMAS retrieval

Retrieval with DISMAS – or in full Differential and Smooth Absorption Separated – treats the smooth and differential part of the absorption differently, combining elements of DOAS with an Optimal Estimation approach, to provide a better retrieval with proper estimates of the errors in the retrieved parameters [6]. The DISMAS approach can only be applied for weak absorbers (e.g. NO_2, O_3, SO_2, BrO, etc.), not for strong absorbers (e.g. CH_4, CO, H_2O) or line absorbers (e.g. the O_2 A-band).

Optimal Estimation (OE; also known as Direct Fitting) performs a line-by-line calculation of the spectrum using a radiative transfer model. These calculations need to be performed at all wavelengths in the wavelength window. Though this provides the best possible retrieval results, for operational retrieval OE is too time consuming to use.

Where in DOAS the polynomial is used to represent the background radiance, in DISMAS it represents the reflectance for smooth absorption. Since the latter has a clear physical meaning, its use makes it possible to also fit parameters such as the surface albedo and cloud cover data, as is the case for OE.

Contrary to OE, however, DISMAS does not perform radiative transfer calculations at every wavelength in the selected window, but only at a few wavelengths where the differential cross section is zero. The differential cross

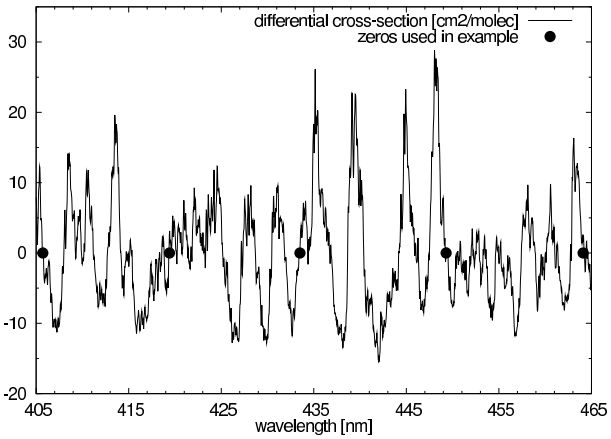

Figure 5. Differential NO_2 cross section (solid line; in cm^2/molec*), the difference between the solid and dashed lines of Fig. 3, and the 5 zero points (filled circles) used for the DISMAS retrieval on the spectrum of Fig. 4.*

section derived from Fig. 3 is shown in Fig. 5. The number of zeros needed depends on the absorber and on the size of the wavelength window. For NO_2 in the 405–465 nm window 5 zeros suffice, with the first and last zero near the end points of the window and the rest evenly spread across the window (see the filled circles in Fig. 5).

The calculation of the reflectance at these few wavelengths provides the smooth reflectance as well as an altitude resolved AMF. The radiative transfer calculations at these few wavelengths are sufficient to reconstruct the reflectance at a high resolution spectral grid very quickly – at least for weak absorbers; for strong and line absorbers, this reconstruction of the reflectance does not work.

Combining this high resolution reflectance with a high resolution solar spectrum and the instrument slit function provides a modelled spectrum that can be compared with the actual measured spectrum. An iterative process with all the fit parameters (trace gas concentration, surface albedo, etc.) will then provide the optimal solution for the measurement, as well as estimates of the errors in the fitted parameters.

Note that in the iterative process, the precise wavelength of the zeros of the differential cross section (Fig. 5) varies per step, because the polynomial subtracted from the cross section depends on the values of the fit parameters.

The fact that DISMAS uses a set of fit parameters in the retrieval offers the possibility to have separate fit parameters for the NO_2 tropospheric (VCD_{tr}) and NO_2 stratospheric (VCD_{st}) columns, rather then performing the separation after the retrieval.

Input for the retrieval is an estimate of VCD_{st} from the data assimilation system, along with NO_2 profiles for the stratosphere and troposphere. In the retrieval fit, DISMAS is then allowed to adjust VCD_{st} within the narrow range specified by uncertainties provided by the data assimilation model ($0.2 - 0.3 \times 10^{15}$ molec/cm^2; [7]), similar to the adjustment of the surface albedo within its uncertainty range. The one fit parameter which DISMAS is thus free to determine is the NO_2 tropospheric column (VCD_{tr}). Whether this retrieval setup indeed works well and how to set up the details is subject of investigation.

Since the DISMAS approach is an approximation, the results will be less accurate than those of an OE retrieval, but the results are expected to be more accurate than those of a DOAS retrieval. And given that the radiative transfer calculations are done only at a limited number of wavelenghts, DISMAS may be fast enough for operational usage – a point which will be investigated with real satellite data in the near future.

3.3. Data assimilation system

The data assimilation system currently used in the DOMINO / TM4NO2A processing is the chemistry transport model TM4, which runs at a resolution of $3 \times 2^{\circ}$.

A number of improvements are planned to be implemented in the course of the next few years, which will lead to a reprocessing of the GOME, SCIAMACHY, OMI and GOME-2 data. These improvements will be implemented independently of whether DISMAS will be selected for the TROPOMI processing or not.

The main improvement will be a switch to a more recent version of the chemistry transport model, TM5, which runs at $1 \times 1^{\circ}$ and thus will provide NO_2 profiles at a higher spatial resolution. Furthermore, TM5 has an improved scheme for the NO_x(=NO+NO_2) chemistry in the stratosphere, and the data base for NO_2 emissions by ships, soil and lightning will be updated.

Also the ground surface elevation will be improved by taking an average over a satellite ground pixel, rather then just the elevation at the centre of the ground pixel. And for OMI data processing (DOMINO), there will be a correction of the cloud product, to take into account the temperature dependence of the O_2-O_2 absorption used for the cloud data retrieval (mentioned in Sect. 2.4).

4. SENSITIVITY STUDIES WITH DISMAS

In the process of determining whether the DISMAS retrieval approach is both useful and feasible for TROPOMI data, a number of sensitivity studies are performed, leading eventually to an ATBD (Algorithm Theoretical Basis Documents) for the tropospheric NO_2 data product of TROPOMI.

The tests are performed with spectra simulated on a line-by-line basis with at first only NO_2 as absorber, over a large range of concentrations, with a set of NO_2 profiles representing background, moderately polluted and heavily polluted situations (with typical NO_2 levels of 0.1, 1 and 10×10^{15} molec/cm^2, resp.).

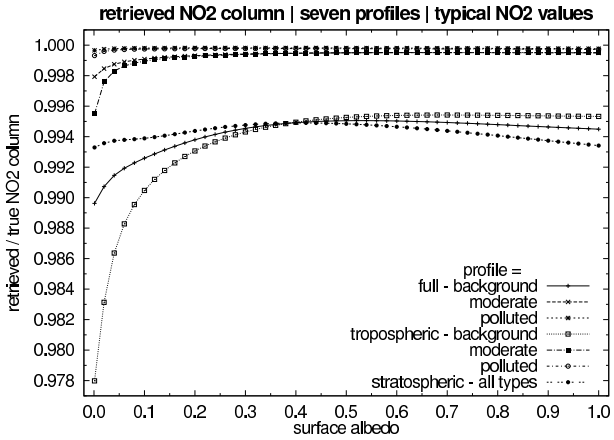

Figure 6. Bias of the retrieved NO_2 column for the seven profiles, with their typical NO_2 levels, as function of surface albedo. The bias is shown as retrieved divided by true NO_2 column.

The NO_2 profiles are currently for full atmosphere NO_2 columns; the retrieval of separate NO_2 columns for troposphere and stratosphere will be investigated later. To meanwhile mimic tropospheric NO_2, full atmosphere profiles are used with concentrations in the stratosphere set to zero. Similarly, stratospheric NO_2 is mimicked by a full atmosphere profile with concentrations in the troposphere set to zero. Thus there are seven profiles used for the tests: three full atmosphere, three tropospheric and one stratospheric (with a typical column value of 0.1×10^{15} molec/cm^2 for the stratospheric profile).

Several quantities relevant for the NO_2 retrieval are varied independently: surface albedo, profile type, cloud fraction, cloud altitude, ... The tests look at the effect of errors in these quantities on the AMF and on the retrieved NO_2 column. Since the AMF is wavelength dependent, the AMF at the centre of the wavelength window is considered to represent the full window.

Below follow a few examples of the first results of sensitivity studies performed with DISMAS.

4.1. Varying surface albedo under clear-sky

Fig. 6 shows the bias – defined here as the retrieved divided by the true NO_2 column – of clear-sky NO_2 retrievals for surface albedos ranging from zero to one in steps of 0.02, for the seven NO_2 profiles, each at its typical NO_2 level, with the a-priori albedo equal to the true albedo. Clearly, the bias is largest for the lowest NO_2 levels: the two background profiles and the stratospheric profile.

For these "ideal circumstances", with the a-priori albedo equal to the true albedo, the same cases where retrieved with a DOAS implementation. Comparison of the results (not shown here) made clear that the biases using DISMAS are much smaller than those using DOAS, in particular at low albedo and low NO_2 column, and that the retrieval error of NO_2 for DOAS is about 6 times larger than for DISMAS.

Table 1. Uncertainties in the AMF (ΔAMF) due to an uncertainty of ±0.02 in the surface albedo, as well as the retrieval bias and error, for the seven NO_2 profiles at their typical NO_2 levels (given in molec/cm^2*). Numbers are given as percentages of the true values for typical surface albedo values between 0.02 and 0.10 (with the lowest first, being the value for the highest albedo).*

profile type:	background	moderate	polluted
NO_2 levels:	0.1×10^{15}	1×10^{15}	10×10^{15}
full profiles			
ΔAMF	$3-7\%$	$7-21\%$	$8-28\%$
retr. bias	$0.7-1.0\%$	$0.1-0.2\%$	$<0.03\%$
retr. error	$25-40\%$	$3.1-8.0\%$	$0.3-1.1\%$
tropospheric profiles			
ΔAMF	$8-29\%$	$10-41\%$	$10-45\%$
retr. bias	$1.0-2.2\%$	$0.1-0.5\%$	$<0.07\%$
retr. error	$32-97\%$	$3-18\%$	$0.4-2.0\%$
stratospheric profiles			
ΔAMF	$0.1-0.2\%$		
retr. bias	$0.5-0.6\%$		
retr. error	$20-26\%$		

Table 1 lists the uncertainties in the AMF for an error of ±0.02 in the surface albedo in the typical albedo range of $0.02-0.10$ following from the DISMAS sensitivity studies. The table also lists the retrieval bias and retrieval error found for the same albedo range.

The albedo sensitivity of the AMF found for the profiles with their different typical values with DISMAS is similar to but somewhat larger than what is reported by [2], notably for the background case. The reason for this is, most likely, that [2] took as typical error in the albedo ±0.012 (instead of ±0.02 as for Table 1) and that for the albedo values the average over one month of data was used (instead of the range $0.02-0.10$ as for Table 1).

Typical errors in the surface albedo, as reported by e.g. [8, 9], are of the order of ±0.01 for most circumstances. To study the effect of such an error in the surface albedo on the retrieved NO_2 column value, the a-priori (assumed) albedo is varied ±0.01 around the true albedo, with DISMAS being allowed to fit the albedo too. The retrieved albedo is then equal to the true albedo to within 2×10^{-6}.

Fig. 7 shows the difference between the biases of the retrieved NO_2 column for a-priori albedos $a_{\rm tr}+0.01$ and $a_{\rm tr}-0.01$, with $a_{\rm tr}$ the true albedo. The centre bias values, i.e. for the cases where the a-priori (assumed) albedo equals the true albedo, are shown in Fig. 6. The retrieval bias varies most for the low NO_2 level profiles: around 0.2% of the true column value of 1×10^{14} molec/cm^2. For the two moderate profiles, the bias differences are 0.05% or better. For the two polluted profiles, at 1×10^{16} molec/cm^2, the bias variation is even smaller.

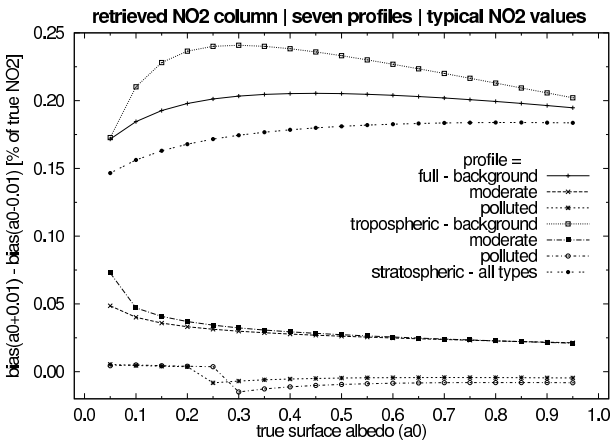

Figure 7. Difference between the NO_2 retrieval biases for the assumed albedos $a_0 + 0.01$ and $a_0 - 0.01$, with a_0 the true albedo. The bias is a percentage of the true NO_2 column for the seven profiles at their typical NO_2 values.

In case of scenes that are much brighter or darker than expected (e.g. the presence of snow/ice where it is not expected, or vice versa), the true albedo will be much further away from the a-priori albedo than ± 0.01. It remains to be investigated how DISMAS treats such situations, and what the error in the retrieved tropospheric NO_2 column will be.

5. CONCLUDING REMARKS

The retrieval of the tropospheric NO_2 column data from satellite measurements by OMI (called DOMINO) and by GOME, SCIAMACHY and GOME-2 (TM4NO2A), currently operational at KNMI, will be continued and improved. That processing system will also be implemented for use on data of the Tropospheric Monitoring Instrument (TROPOMI), to be launced in March 2015 aboard the Sentinel-5 Precursor mission.

The DOMINO / TM4NO2A processing applies a DOAS retrieval on the satellite data and to determine the tropospheric NO_2 column it uses an AMF look-up table and a data assimilation system. For the latter a number of improvements are already planned: the switch to a more recent version of the chemistry transport model, with a higher spatial resolution and a better NO_x chemistry in the stratosphere, updated emission data bases, and improved handling of the variation of the surface elevation across a satellite ground pixel.

This paper describes the possible replacement of the DOAS retrieval and AMF look-up table in the tropospheric NO_2 processing system by a novel retrieval method, called DISMAS, which potentially provides a better data product: more accurate tropospheric NO_2 data, with better error estimates. Sensitivity studies of DISMAS retrievals using simulated data are currently being carried out and the first results look promising.

A comparison of DISMAS retrieval results using real satellite data against the currently available DOMINO / TM4NO2A data will have to show whether the proposed approach of a direct tropospheric NO_2 column retrieval works, whether indeed DISMAS provides a better tropospheric NO_2 data product, and whether the processing will be fast enough for the required NRT processing of TROPOMI data.

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