Network of Remote Sensing Ground-Based Observations in support of the Copernicus Atmospheric Service

Uncertainty Budgets

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I. Intention of this document

The aim of this report is to outline the unified scheme for reporting the error budgets for all ground-based remote-sensing techniques involved in NORS. The required pieces of data characterisation have already been identified in previous activities within the NORS and e.g. the NDACC remote sensing communities. In addition, this document is intended to be a guideline for the data user not experienced to work with remote sensing data - explaining how to interpret remote sensing data and the associated error budget.

II. Overview

All remote sensing measurements share a common principle: The measurement process requires interpretation of a measured signal which can be either radiation from a natural light source such as the sun, the moon or the thermal emission of the atmosphere or scattered radiation from an artificial light source. In the case of passive remote sensing, e.g. using the solar light as the source of the signal, let us assume that the measured signal is a set of solar UV radiances recorded at ground in different spectral windows, and let us assume that the aim of this measurement is to exploit this signal for an estimation of the ozone column. In the analysis process, a comparison of the measured radiances with a simulation is required. The ozone column, which gives the best agreement between simulation and measurement, possibly subjected to constraints (commonly termed as a priori knowledge), is the final result of the measurement. The analysis process will rely on implicit assumptions on the atmospheric state, e.g. the assumed temperature profile in the atmosphere, it will rely on the accurateness of ingredients for the simulation as the cross-sections of ozone, and it will inject a-priori knowledge (or expectation), in the example under consideration this is the expected shape of the ozone profile as function of altitude and the expected variability of this profile.

Active remote sensing methods rely on the interaction of the atmosphere with an artificial source of acoustic or electromagnetic waves. In the case of Lidar (LIght Detection And Ranging) active remote sensing, intense pulsed laser radiation is used. For example, the ozone number density can be measured using the DIfferential Absorption Lidar (DIAL) method. This method uses a pair of pulsed laser sources operating at wavelengths characterized by different absorption cross-section. Contrary to passive remote sensing technique, the restitution of ozone concentration as a function of altitude does not need a comparison with a simulation. It is computed from the difference of the slopes of the logarithm of both lidar backscattered signals detected by a receiving optical system.

In case of a passive remote sensing measurement, the reconstruction process leaves characteristic traces in the retrieved set of variables, e. g. crosstalk between different retrieved quantities. In Table 1 we collect the NORS remote-sensing instruments and associated data products under consideration.

Instrument	Data products
FTIR	CO, CH_4, O_3
UV/VIS, MAX-DOAS	Strat. O_3 columns, strat. NO_2 columns and profiles, trop. NO_2 columns and profiles, trop. HCHO columns
Microwave spectrometer	O_3 profiles (~20…70 km)
LIDAR	O_3 profiles (~10…50 km)

Table 1. Ground-based remote-sensing instruments within NORS

III. Characterisation of errors

A useful error budget should discriminate statistical and systematic error sources. Statistical errors will average out in a larger set of data (contributing to the scatter in an ensemble of intercomparisons, but not generating a bias), while systematic errors will not. The overall statistical and systematic error budgets are comprised of various method-specific contributions. All relevant error sources need to be taken into account in a thorough error budget, but there is little value in reporting all kinds of error sources to the data user separately. Instead, we suggest to construct overall statistical and systematic error budgets and to report these error budgets to the data user. It is to be expected that the quality of the data in a time series of observations is variable, depending e.g. on atmospheric conditions and viewing geometry, so an individual error estimate should be attached to each observation.

In the case of passive remote sensing, significant interdependency between different retrieved variables is often found. If the interdependency occurs between relevant sections of the state vector (e.g. between a tropospheric and a stratospheric partial column), then the reporting of error bars is insufficient. Instead, a full error covariance matrix is required (which in our example would be of dimension 2 x 2. It provides the error budgets for the two partial columns along the diagonal. The off-diagonal elements indicate the crosstalk which occurs between these two partial columns). The two following sections, “characterisation of sensitivity” and “the smoothing error”, refer to the peculiarities of passive remote sensing observations.

In the case of the lidar observation of an O_3 profile, there is no significant crosstalk between different profile sections, but still, the vertical resolution needs to be characterised. Due to the rapid decrease of the signal-to-noise ratio with increasing altitude, it is necessary to degrade the vertical resolution of the measurement in order to limit the statistical error at higher altitudes.

IV. Characterisation of sensitivity

The reported errors are attached to the retrieved variables, which are not to be confused with the actual physical quantities they intend to approximate. Let us assume that a passive remote sensing instrument reports a “stratospheric column” in a defined altitude interval. However, the limited ability to discriminate signal contributions from different altitudes will not allow to completely gate out signal contributions from altitudes outside the specified interval. In general, the column sensitivity will differ from an ideal boxcar-shaped function of value 1.0 inside and 0.0 outside the defined region. The complete information of the sensitivity behaviour of a set of retrieved variables (N variables) is collected in the averaging kernel matrix. Row i in this N x N matrix collects the response of each element in the state vector to a disturbance applied on variable i (e.g. a 1 ppmv excess applied on the O_3 profile on each level of the model atmosphere).

The retrieved state X_{retr} is connected to the actual state vector X_{true} by

$$\vec{X}_{retr} = AK(\vec{X}_{true} - \vec{X}_{ap}) + \vec{X}_{ap} \qquad \text{(Eq. 1)}$$

AK denotes the averaging kernel matrix, X_{ap} is the assumed a-priori state of the atmosphere. A concrete example could identify the elements of the state vector with the ozone mixing ratios at different altitude levels. If we imagine that the true ozone profile has been recorded with an imaginative ideal sensor, the smoothing according to Eq. 1 provides the profile which would be determined by the remote sensing experiment. Without specification of the matrix *AK* and the assumed a-priori state X_{ap} the solution X_{retr} is meaningless, so these quantities have to be included in the reporting of the results.

V. The smoothing error

According to Eq. 1, the remote sensing experiment will in general not perfectly reproduce the true state (unless AK is the unity matrix). This gives rise of the smoothing error. If the variability of the true atmospheric state is characterised by the climatological mean profile X_{ap} and its actual variability S_{true}, then the smoothing error S_{sm} follows from Eq. 1:

$$S_{sm} = (AK - 1)S_{true}(AK - 1)^T \qquad \text{(Eq. 2)}$$

The smoothing error *must not be mixed* into the error budgets of the statistical and systematic errors S_{stat} and S_{sys} in the reporting of error budgets. The reason for this recommendation is that in many circumstances, it can be eliminated before it is tested whether two results are in agreement. If, e.g., model or in-situ sonde data are to be compared with remote sensing data (imagine ozone mixing-ratio profiles), it is advisable to feed the high-resolution data through Eq. 1 before evaluating the differences. Even in the case of an intercomparison between two different kinds of remote sensing data, often one with superior resolution can be identified, and the same recipe can be applied. Note that the smoothing error can be constructed at any time a-posteriori from Eq. 2, if the averaging kernel matrix *AK* is provided (the data user has solely to introduce an estimation for the actual variability of the atmospheric state S_{true}), whereas the substantial error sources, e.g. of instrumental origin, require an expert guess provided by the operator and cannot be recalculated by the data user.

Identification of collocations: Remote sensing instruments tend to sample a finite volume of the atmosphere, often along a line-of-sight (LOS) defined by geometric aspects of the setup. Therefore, the location of the sounded air needs to be provided to the data user, to identify collocations with other sensors or to compare the measured value with a model field. For many purposes, specification of the instrument's geographic location and time (and duration) of the measurement is fully sufficient. If a more accurate specification is required, we suggest providing in case of FTIR and microwave observations the actual azimuth and elevation of the line-of-sight. Based on this specification, the observed airmass is unambiguously identified, and the location of the LOS penetration point with a model level follows from elementary geometry. In case of a DOAS observation, which relies on solar radiation scattered by the atmosphere, providing an improved estimation of the location of the probed air volume as function of altitude is significantly more difficult, as this location depends not only on the instrumental LOS, but also on the position of the Sun in the sky and other parameters which affect the observed radiation field (clouds, surface albedo, aerosols). Nevertheless, the analysis process of the DOAS measurement includes a comprehensive simulation of the radiative transfer. For this reason, an effective LOS can be determined. We discourage using the concept of a global "effective observer location", because the effective location might depend on the context of data use (example: a high latitude FTIR site performs solar absorption measurements at low solar elevation, observing the ozone profile along a slant line-of-sight. If the data user is interested in evaluating the tropospheric partial ozone column, the effective location of the measurement will differ from the location appropriate for assignment to a stratospheric partial column. On the other hand, if the solar elevation is high enough to justify ignoring this error, the actual observer position is a sufficient proxy for the location of the observation). The most sensible way is to use the observer location and observation time e.g. for selecting coincident measurements in the database, the additional line-of-sight information can be used as a corrector in the rare cases where this effort is justified.

VI. Database content required

The performance of a remote sensing setup will not remain constant, but instead vary as function of instrumental parameters, of geometric aspects of the observation and of atmospheric conditions. We therefore recommend attaching an individual sensitivity characterisation (averaging kernel matrix, lidar vertical resolution) and an individual estimation of errors (statistical and systematic error budget) to each measured value instead of providing a global, much less significant error estimate.

This results in the following pieces of information, which should be available for each measurement result:

- Location, time and duration of measurement (for FTIR and microwave: in addition specification of line-of-sight, azimuth and elevation of LOS; for UV/VIS: specification of the (effective) LOS)
- Statistical and systematic error budgets

- For passive remote sensing observations: averaging kernel matrix and a-priori information (if available. Failing this, specify vertical resolution and sensitivity)
- For lidar observations: vertical resolution as function of altitude

Appendix: status for specific techniques

FTIR:

Leading error sources (per species):

CH_4: The statistical error budget is in the troposphere dominated by the quality of the continuum underlying the CH_4 signatures (influenced by channelling, zero level offsets due to variable transmission during recording of centerburst, …). At higher altitudes, spectral noise becomes an important error source which dominates in the upper stratosphere. The systematic error budget is dominated by the uncertainty of CH_4 line intensities.

O_3: With respect to the statistical error budget, the uncertainty of the atmospheric temperature profile is the leading error source, in the stratosphere the uncertainty of instrumental line shape and spectral noise are of importance. The systematic error budget is dominated by the uncertainty of O_3 line intensities.

CO: The statistical error budget is in the troposphere dominated by the quality of the continuum underlying the CO signatures (influenced by channelling, zero level offsets due to variable transmission during recording of centerburst, …). In addition, the atmospheric CO lines suffer from strong overlap by solar CO lines, the associated model uncertainties contribute to the statistical error budget. The systematic error budget is dominated by the uncertainty of CO line intensities.

HDF data format contains:

- ✓ Location, time and duration
- ✓ Ground pressure and temperature
- ✓ LOS orientation
- ✓ temperature, pressure profiles (used for the retrieval)
- ✓ Mixing ratio profile of target species
- ✓ Partial column vector of target species
- ✓ Total column amount of target species
- ✓ Averaging kernel matrix and a-priori mixing-ratio profile
- ✓ Statistical and systematic error covariance matrices (specific error sources listed below)

- ✓ H_2O mixing-ratio profile

Specific error sources:

Offset of zero baseline in spectrum

Optical resonances in background continuum (“channeling”)

Instrumental line shape errors

Pointing error (deviation between LOS and apparent solar disc center)

Deficiencies in the modelling of the solar background spectrum

Deviations from the atmospheric temperature profile used for the analysis

Spectroscopic data, interfering species (intensities and pressure-broadening parameters)

HDF variables (example O_3):

```
DATETIME

LATITUDE.INSTRUMENT

LONGITUDE.INSTRUMENT

ALTITUDE.INSTRUMENT

SURFACE.PRESSURE_INDEPENDENT

SURFACE.TEMPERATURE_INDEPENDENT

ALTITUDE

ALTITUDE.BOUNDARIES

PRESSURE_INDEPENDENT

TEMPERATURE_INDEPENDENT

INTEGRATION.TIME

O3.MIXING.RATIO_ABSORPTION.SOLAR

O3.MIXING.RATIO_ABSORPTION.SOLAR_APRIORI

O3.MIXING.RATIO_ABSORPTION.SOLAR_AVK
```

O3.MIXING.RATIO_ABSORPTION.SOLAR_UNCERTAINTY.RANDOM

O3.MIXING.RATIO_ABSORPTION.SOLAR_UNCERTAINTY.SYSTEMATIC

O3.COLUMN.PARTIAL_ABSORPTION.SOLAR

O3.COLUMN.PARTIAL_ABSORPTION.SOLAR_APRIORI

O3.COLUMN_ABSORPTION.SOLAR

O3.COLUMN_ABSORPTION.SOLAR_APRIORI

O3.COLUMN_ABSORPTION.SOLAR_AVK

O3.COLUMN_ABSORPTION.SOLAR_UNCERTAINTY.RANDOM

O3.COLUMN_ABSORPTION.SOLAR_UNCERTAINTY.SYSTEMATIC

ANGLE.SOLAR_ZENITH.ASTRONOMICAL

ANGLE.SOLAR_AZIMUTH

H2O.MIXING.RATIO_ABSORPTION.SOLAR

H2O.COLUMN_ABSORPTION.SOLAR

UV-VIS:

Leading error sources (per species):

Total O_3 and stratospheric NO_2 columns: the statistical error budget is dominated by the uncertainties related to the slant column spectral fit and the calculations of the airmass factors (AMFs). The random errors associated to the spectral fit are due to detector noise, instrumental imperfections, as well as errors or unknowns in the signal modelling. The main sources of uncertainty in the AMF calculation are related to the choice of the radiative transfer model settings, i.e. the O_3 and NO_2 vertical profiles, the aerosol extinction profile, the cloud conditions, and in case of NO_2, the inclusion or not of the rapid twilight photochemistry. In case of significant tropospheric pollution, additional errors can be introduced for NO_2. The uncertainties of the O_3 and NO_2 cross sections used in the spectral fit and the uncertainty on the determination of the residual amount of O_3 and NO_2 in the reference spectra by using the Langley-plot technique dominate the systematic error budget. The temperature dependence of the O_3 and NO_2 cross sections should be considered as a pseudo-random source of error due to the fluctuations of the stratospheric temperature and can be minimized by correction in the fit or use of appropriate a priori data on atmospheric temperature.

MAX-DOAS NO_2 and HCHO profiles and columns: With respect to the statistical error budget, the uncertainties related to the slant column spectral fit and to the vertical profile inversion are the leading error sources. The spectral fit random errors are due to detector noise, instrumental imperfections, as well as errors or unknowns in the signal modelling. The random error on the trace gas profile retrieval is dominated by the smoothing error caused by the limited information content of the measurements. The systematic error budget of the slant column densities is dominated by the uncertainty of the NO_2 and HCHO cross sections used in the spectral fit. The choice of the a priori NO_2 and HCHO vertical profiles and the forward model parameter errors are the main sources of systematic errors in the vertical profile retrieval. Forward model parameter errors include uncertainties in the aerosols content, the assumption of horizontal homogeneity, surface albedo, and cloud conditions. Variations in light path through changing cloud conditions can also introduce a pseudo random noise in the observations if data is not filtered appropriately. Pointing inaccuracies of the instrument, in particular at low elevation angles can introduce systematic errors (if they are constant) or random errors (if pointing repeatability is affected).

MAX-DOAS aerosol extinction profiles and aerosol optical depth (AOD): the main contributors to the statistical error budget are the uncertainties related to the slant column spectral fit and to the vertical profile inversion. The spectral fit random errors are due to detector noise, instrumental imperfections, as well as errors or unknowns in the signal modelling. The random error on the aerosol extinction profile retrieval is dominated by the smoothing error caused by the limited information content of the measurements. The uncertainty of the O_4 cross sections used in the spectral fit contributes significantly to the systematic error budget. In the profile inversion step, systematic error sources include the choice of the a priori settings, i.e. the a priori aerosol extinction profile, uncertainties in the forward model parameters, such as aerosol optical properties, surface albedo, and cloud conditions, as well as the assumption of horizontal homogeneity in the forward model. Variations in light path through changing cloud conditions can also introduce a pseudo random noise in the observations if data is not filtered appropriately. Pointing inaccuracies of the instrument, in particular at low elevation angles can introduce systematic errors (if they are constant) or random errors (if pointing repeatability is affected).

Zenith-sky tropospheric NO_2 columns: the statistical error budget is dominated by the uncertainties related to the slant column spectral fit and the calculations of the tropospheric and stratospheric AMFs. The random errors associated to the spectral fit are due to detector noise, instrumental imperfections, as well as errors or unknowns in the signal modelling. The main sources of uncertainty in the tropospheric and stratospheric AMF calculations are related to the choice of the radiative transfer model settings, i.e. the NO_2 vertical distributions and aerosol extinction profiles in both the troposphere and stratosphere, the surface albedo, the cloud conditions, and in case of stratospheric NO_2 AMFs, the inclusion or not of the rapid twilight photochemistry. The main contributors to the systematic error budget are the uncertainty of the NO_2 cross sections used in the spectral fit, the uncertainty on the determination of the residual amount of NO_2 in the reference spectra (Langley-plot technique), and the uncertainty on the estimation of the stratospheric NO_2 content (including its possible contamination by tropospheric pollution) which is removed from the measured total NO_2 slant columns to get the tropospheric NO_2 columns.

HDF data format for trace gases contains:

- ✓ Location, time and duration
- ✓ LOS orientation
- ✓ temperature, pressure profiles (used for the retrieval)
- ✓ Cloud conditions
- ✓ Aerosol optical depth (used for the retrieval)
- ✓ Slant columns of target species (zenith viewing geometry)
- ✓ Mixing ratio profile of target species (off-axis and zenith viewing geometries)
- ✓ Tropospheric column of target species (off-axis and zenith viewing geometries)

- ✓ Total column of target species (direct-sun viewing geometry)
- ✓ Stratospheric column of target species (zenith viewing geometry)
- ✓ Stratospheric airmass factor (AMF) of target species (zenith viewing geometry)
- ✓ Partial column vector of target species (zenith and off-axis viewing geometries)
- ✓ Averaging kernel matrix and a-priori column and mixing-ratio profile
- ✓ Statistical and systematic error covariance matrices for both column and mixing-ratio profile

HDF data format for aerosols contains:

- ✓ Location, time and duration
- ✓ LOS orientation
- ✓ Wavelength (used for the retrieval)
- ✓ temperature, pressure profiles (used for the retrieval)
- ✓ Cloud conditions
- ✓ Aerosol single scattering albedo (used for the retrieval)
- ✓ Asymmetry factor of the aerosol phase function (used for the retrieval)
- ✓ Aerosol extinction coefficient
- ✓ Aerosol optical depth
- ✓ Averaging kernel matrix and a-priori optical depth and extinction coefficient
- ✓ Statistical and systematic error covariance matrices for both optical depth and extinction coefficient

Specific error sources (adopted from A. Richter, F. Wittrock and the UV-VIS WP4 team)

Spectral Fit

Cross-sections

Spectral interference

Inelastic effects

Inversion

RTM inaccuracies

Limited knowledge of input variables

Clouds

Aerosol properties

Surface properties

Horizontal inhomogeneities

Temporal inhomogeneities

Clouds

HDF variables for trace gases (e.g., NO_2):

```
DATETIME

DATETIME.START

DATETIME.STOP

INTEGRATION.TIME

LATITUDE.INSTRUMENT

LONGITUDE.INSTRUMENT

ALTITUDE.INSTRUMENT

ALTITUDE

PRESSURE_INDEPENDENT

TEMPERATURE_INDEPENDENT

ALTITUDE.BOUNDARIES

ANGLE.SOLAR_ZENITH.ASTRONOMICAL

ANGLE.SOLAR_AZIMUTH

ANGLE.VIEW_AZIMUTH

ANGLE.VIEW_ZENITH

CLOUD.CONDITIONS

AEROSOL.OPTICAL.DEPTH.TROPOSPHERIC_INDEPENDENT

AEROSOL.OPTICAL.DEPTH.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS
```

AEROSOL.OPTICAL.DEPTH_INDEPENDENT

AEROSOL.OPTICAL.DEPTH_ABSORPTION.SOLAR

AEROSOL.OPTICAL.DEPTH.STRATOSPHERIC_INDEPENDENT

AEROSOL.OPTICAL.DEPTH.STRATOSPHERIC_SCATTER.SOLAR.ZENITH

NO2.COLUMN.SLANT_SCATTER.SOLAR.ZENITH

NO2.COLUMN.SLANT.DIFFERENTIAL_SCATTER.SOLAR.ZENITH

NO2.MIXING.RATIO_SCATTER.SOLAR.OFFAXIS

NO2.MIXING.RATIO_SCATTER.SOLAR.OFFAXIS_UNCERTAINTY.RANDOM

NO2.MIXING.RATIO_SCATTER.SOLAR.OFFAXIS_UNCERTAINTY.SYSTEMATIC

NO2.MIXING.RATIO_SCATTER.SOLAR.OFFAXIS_APRIORI

NO2.MIXING.RATIO_SCATTER.SOLAR.OFFAXIS_AVK

NO2.MIXING.RATIO_SCATTER.SOLAR.ZENITH

NO2.MIXING.RATIO_SCATTER.SOLAR.ZENITH_UNCERTAINTY.RANDOM

NO2.MIXING.RATIO_SCATTER.SOLAR.ZENITH_UNCERTAINTY.SYSTEMATIC

NO2.MIXING.RATIO_SCATTER.SOLAR.ZENITH_APRIORI

NO2.MIXING.RATIO_SCATTER.SOLAR.ZENITH_AVK

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS_UNCERTAINTY

.RANDOM

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS_UNCERTAINTY

.SYSTEMATIC

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS_APRIORI

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS_AVK

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.ZENITH

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.ZENITH_UNCERTAINTY

.RANDOM

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.ZENITH_UNCERTAINTY

.SYSTEMATIC

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.ZENITH_APRIORI

NO2.COLUMN.TROPOSPHERIC_SCATTER.SOLAR.ZENITH_AVK

NO2.COLUMN_ABSORPTION.SOLAR

NO2.COLUMN_ABSORPTION.SOLAR_UNCERTAINTY.RANDOM

NO2.COLUMN_ABSORPTION.SOLAR_UNCERTAINTY.SYSTEMATIC

NO2.COLUMN_ABSORPTION.SOLAR_APRIORI

NO2.COLUMN_ABSORPTION.SOLAR_AVK

NO2.COLUMN.STRATOSPHERIC_SCATTER.SOLAR.ZENITH

NO2.COLUMN.STRATOSPHERIC_SCATTER.SOLAR.ZENITH_UNCERTAINTY
.RANDOM

NO2.COLUMN.STRATOSPHERIC_SCATTER.SOLAR.ZENITH_UNCERTAINTY
.SYSTEMATIC

NO2.COLUMN.STRATOSPHERIC_SCATTER.SOLAR.ZENITH_APRIORI

NO2.COLUMN.STRATOSPHERIC_SCATTER.SOLAR.ZENITH_AVK

NO2.COLUMN.STRATOSPHERIC_SCATTER.SOLAR.ZENITH_AMF

NO2.COLUMN.PARTIAL_SCATTER.SOLAR.OFFAXIS

NO2.COLUMN.PARTIAL_SCATTER.SOLAR.OFFAXIS_APRIORI

NO2.COLUMN.PARTIAL_SCATTER.SOLAR.ZENITH

NO2.COLUMN.PARTIAL_SCATTER.SOLAR.ZENITH_APRIORI

HDF variables for aerosols:

DATETIME

DATETIME.START

DATETIME.STOP

INTEGRATION.TIME

LATITUDE.INSTRUMENT

LONGITUDE.INSTRUMENT

ALTITUDE.INSTRUMENT

WAVELENGTH

ALTITUDE

PRESSURE_INDEPENDENT

TEMPERATURE_INDEPENDENT

ALTITUDE.BOUNDARIES

ANGLE.SOLAR_ZENITH.ASTRONOMICAL

ANGLE.SOLAR_AZIMUTH

ANGLE.VIEW_AZIMUTH

ANGLE.VIEW_ZENITH

CLOUD.CONDITIONS

AEROSOL.SINGLE.SCATTERING.ALBEDO_INDEPENDENT

AEROSOL.ASYMMETRY.FACTOR_INDEPENDENT

AEROSOL.EXTINCTION.COEFFICIENT_SCATTER.SOLAR.OFFAXIS

AEROSOL.EXTINCTION.COEFFICIENT_SCATTER.SOLAR

.OFFAXIS_UNCERTAINTY.RANDOM

AEROSOL.EXTINCTION.COEFFICIENT_SCATTER.SOLAR

.OFFAXIS_UNCERTAINTY.SYSTEMATIC

AEROSOL.EXTINCTION.COEFFICIENT_SCATTER.SOLAR.OFFAXIS_APRIORI

AEROSOL.EXTINCTION.COEFFICIENT_SCATTER.SOLAR.OFFAXIS_AVK

AEROSOL.OPTICAL.DEPTH.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS

AEROSOL.OPTICAL.DEPTH.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS_

UNCERTAINTY.RANDOM

AEROSOL.OPTICAL.DEPTH.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS_

UNCERTAINTY.SYSTEMATIC

AEROSOL.OPTICAL.DEPTH.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS_

APRIORI

AEROSOL.OPTICAL.DEPTH.TROPOSPHERIC_SCATTER.SOLAR.OFFAXIS_

AVK

Microwave:

Leading error sources:

Up to the stratopause the leading source of systematic errors are uncertainties in the line shape (air broadening) parameters. In the mesosphere, measurement noise, which is random, becomes the dominant error source since the ozone emission exponentially decreases with altitude. In the lower stratosphere the correct separation between the water vapour continuum and the ozone emission in the line wings is the limiting factor, - particularly at places with high values of tropospheric water vapour. Ozone microwave radiometry is most reliable between 25 and 75 km altitude, depending on the particular setup. At these altitudes, possible biases of ozone measurements of MW are less than 10%, - as cross-validations with satellites, lidars, and ozonesondes showed.

Systematic errors of microwave radiometers can be due to standing oscillations in the front-end part. Generally the technical errors can be neglected if the set-up and the operation of the microwave radiometer are correct.

HDF data format contains:

- ✓ Location, time, duration
- ✓ LOS
- ✓ Opacity
- ✓ Temperature, pressure profiles (used for the retrieval)
- ✓ Random and systematic error profiles for O_3
- ✓ Vertical resolution (profile)
- ✓ Averaging kernel matrix and a-priori mixing-ratio profile
- ✓ O_3 mixing-ratio profile
- ✓ O_3 partial column density

Specific error sources:

Spectroscopic Error Sources

Line intensity

Pressure broadening

Temperature dependence of pressure-broadening

External error sources

Assumed temperature profile

Error in brightness temperature calibration

Error in tropospheric absorption

HDF variables:

```
DATA_VARIABLES=LATITUDE.INSTRUMENT

LONGITUDE.INSTRUMENT

ALTITUDE.INSTRUMENT

DATETIME

ANGLE.VIEW_AZIMUTH

ANGLE.VIEW_ZENITH_MEAN

ANGLE.SOLAR_ZENITH_MEAN

OPACITY.ATMOSPHERIC_EMISSION

DATETIME.START

DATETIME.STOP

INTEGRATION.TIME

ALTITUDE

PRESSURE_INDEPENDENT

TEMPERATURE_INDEPENDENT

O3.MIXING.RATIO_EMISSION

O3.MIXING.RATIO_EMISSION_UNCERTAINTY.RANDOM

O3.MIXING.RATIO_EMISSION_UNCERTAINTY.SYSTEMATIC

O3.MIXING.RATIO_EMISSION_UNCERTAINTY.TOTAL

O3.MIXING.RATIO_EMISSION_RESOLUTION.ALTITUDE
```

O3.MIXING.RATIO_EMISSION_APRIORI

O3.MIXING.RATIO_EMISSION_APRIORI.CONTRIBUTION

O3.MIXING.RATIO_EMISSION_AVK

O3.COLUMN_EMISSION

O3.NUMBER.DENSITY_EMISSION

Lidar:

Leading error sources:

In the ozone retrieval, some error sources such as the temperature dependence of ozone absorption cross-sections or the interference with stratospheric aerosol and with other absorbers such as SO_2 and NO_2 have to be taken into account. The most important effect is linked to volcanic aerosols when the Raman channels are used, the bias on Raman ozone retrieval reaches about 5% and decreases at a rate of 1 to 4% per year in the 15–20 km altitude range after large volcanic eruptions. The temperature dependence of ozone absorption cross-sections is considered in the retrieval and a trend error of 0.1 K per year in the temperature data used in the ozone retrieval can induce a trend of about 0.02% per year in ozone. Concerning the interference with SO_2 and NO_2. The SO_2 mixing ratio usually decreases rapidly above the planetary boundary layer so this constituent does not interfere with DIAL stratospheric ozone measurements. However, major volcanic eruptions can inject massive amounts of SO_2, with number densities reaching 10^{11} cm^{-3} up to 25 km. Since the SO_2 absorption cross sections are of the same order as the ozone ones, the corresponding error on DIAL ozone measurements could then reach a few percents. However, the residence time of SO_2 in the stratosphere is reported to be around 30–40 days, so massive injection of SO_2 in the stratosphere do not perturb durably DIAL stratospheric ozone measurements. The error linked to NO_2 absorption can be estimated using NO_2 climatological profiles. The error linked to NO_2 absorption on ozone measurements reaches thus a maximum value of 0.4% between 25 and 30 km and does thus not need to be corrected.

HDF data format contains:

- ✓ Location, time and duration provided
- ✓ O_3 number density
- ✓ Altitude resolution of O_3 number density
- ✓ Statistical and systematic error budget
- ✓ Temperature, pressure profiles (used for the Rayleigh extinction correction)
- ✓ O_3 mixing-ratio profile
- ✓ O_3 partial column

Specific error sources:

Uncertainties in O_3 cross-sections

Differential Rayleigh and Mie extinction, differential aerosol backscatter, differential extinction by other absorbing species.

Detector nonlinearity

Background light correction

Statistical error due to the random character of the detection process (Poisson statistics)

HDF variables:

```
LATITUDE.INSTRUMENT

LONGITUDE.INSTRUMENT

ALTITUDE.INSTRUMENT

DATETIME

DATETIME.START

DATETIME.STOP

INTEGRATION.TIME

ALTITUDE

O3.NUMBER.DENSITY_ABSORPTION.DIFFERENTIAL

O3.NUMBER.DENSITY_ABSORPTION.DIFFERENTIAL_UNCERTAINTY.COMBINED
            .STANDARD

O3.NUMBER.DENSITY_ABSORPTION.DIFFERENTIAL_UNCERTAINTY.ORIGINATOR

O3.NUMBER.DENSITY_ABSORPTION.DIFFERENTIAL_RESOLUTION.ALTITUDE.DF
            .CUTOFF

O3.NUMBER.DENSITY_ABSORPTION.DIFFERENTIAL_RESOLUTION.ALTITUDE
            .ORIGINATOR

O3.MIXING.RATIO_DERIVED

O3.MIXING.RATIO_DERIVED_UNCERTAINTY.COMBINED.STANDARD
```

O3.MIXING.RATIO_DERIVED_UNCERTAINTY.ORIGINATOR

O3.COLUMN.PARTIAL_DERIVED

O3.COLUMN.PARTIAL_DERIVED_UNCERTAINTY.COMBINED.STANDARD

O3.COLUMN.PARTIAL_DERIVED_UNCERTAINTY.ORIGINATOR

PRESSURE_INDEPENDENT

TEMPERATURE_INDEPENDENT

PRESSURE_INDEPENDENT_SOURCE

TEMPERATURE_INDEPENDENT_SOURCE

O3.NUMBER.DENSITY_ABSORPTION.DIFFERENTIAL_RESOLUTION.ALTITUDE.DF

.NORMALIZED.FREQUENCY

O3.NUMBER.DENSITY_ABSORPTION.DIFFERENTIAL_RESOLUTION.ALTITUDE.DF

.TRANSFER.FUNCTION

O3.NUMBER.DENSITY_ABSORPTION.DIFFERENTIAL_RESOLUTION.ALTITUDE

.IMPULSE.RESPONSE.FWHM

O3.NUMBER.DENSITY_ABSORPTION.DIFFERENTIAL_RESOLUTION.ALTITUDE

.IMPULSE.RESPONSE

SOURCE.PRODUCT