Synergy between middle infrared and mm-wave limb sounding of atmospheric temperature and minor constituents in different cloudy scenarios

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OUTLINE

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SCOPE AND OBJECTIVES OF THE STUDY

The study was conducted as part of the ESA project «PREMIER Analysis of Campaign Data» and further refined by subsequent activities, whose consolidated results we report hereafter.

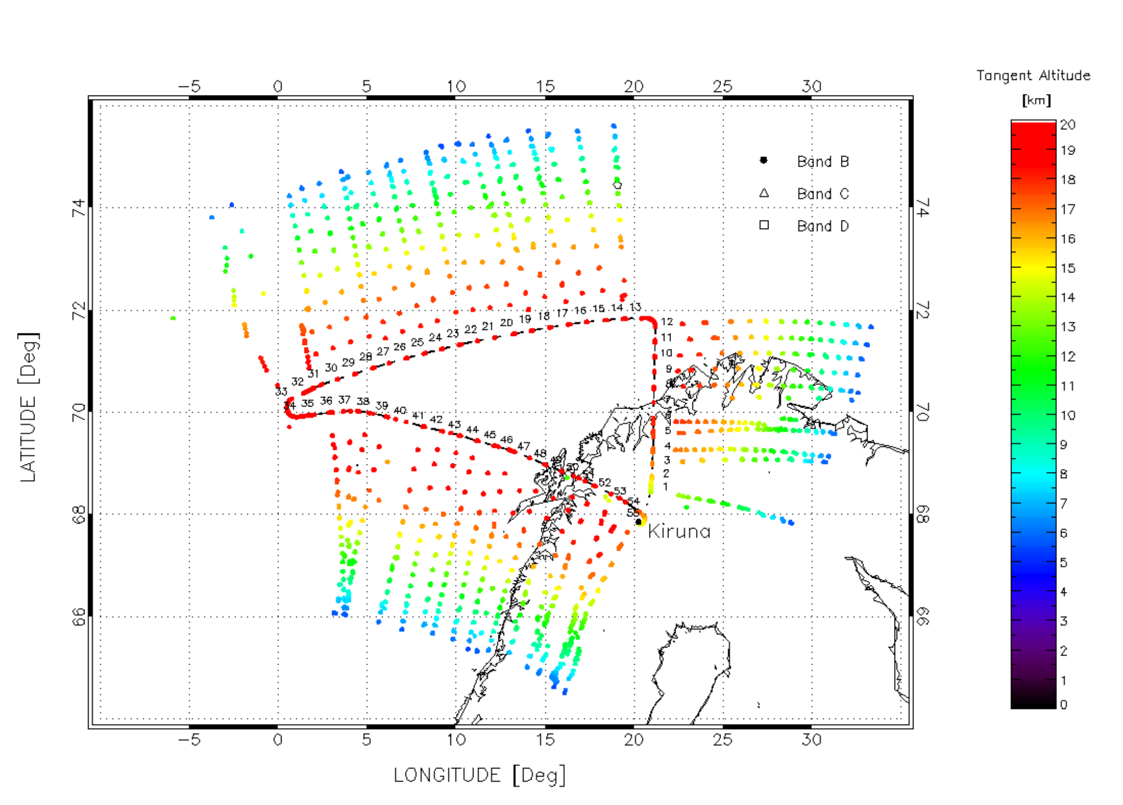
The primary objective of the study was to investigate the potential synergy between collocated infrared and millimetre-wave limb sounding measurements acquired by the MIPAS-STR and MARSCHALS instruments during the airborne campaigns in preparation to the PREMIER («Process Exploration through Measurements of Infrared and millimeter-wave Emitted Radiation n) mission candidate for the Earth Explorer 7.

The activity aimed at comparing the quality of individual and synergistic data products and to evaluate the performance of different approaches for the combination of information from independent and simultaneous measurements of the same atmospheric targets.

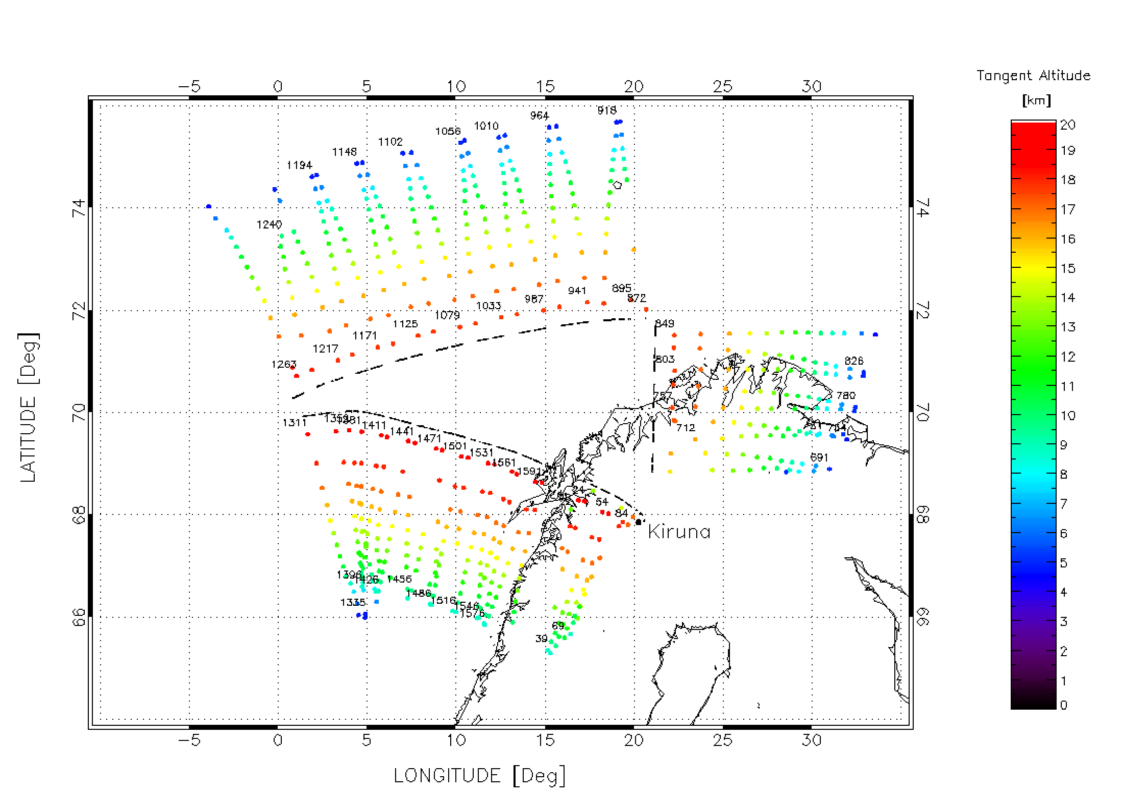
The PremierEx campaign

The investigation on middle infrared and millimetre-wave data sinergy based on the measurements acquired by MIPAS-STR and MARSCHALS limb sounder operated onboard the M-55 Geophysica stratospheric aircraft during the scientific flight of the PremierEx campaign on 10.03.2010 from Kiruna, Sweden for the study of the Arctic UTLS.

Geolocations of MARSCHALS tangent points



Geolocations of MIPAS-STR tangent points



MARSCHALS instrument

MARSCHALS is an heterodyne spectrometer for the measurement of high resolution spectra of the atmospheric emission in the millimetre and sub-millimetre region with limb sounding geometry.

MARSCHALS observes in three bands centered around 300, 320 and 345 GHz.

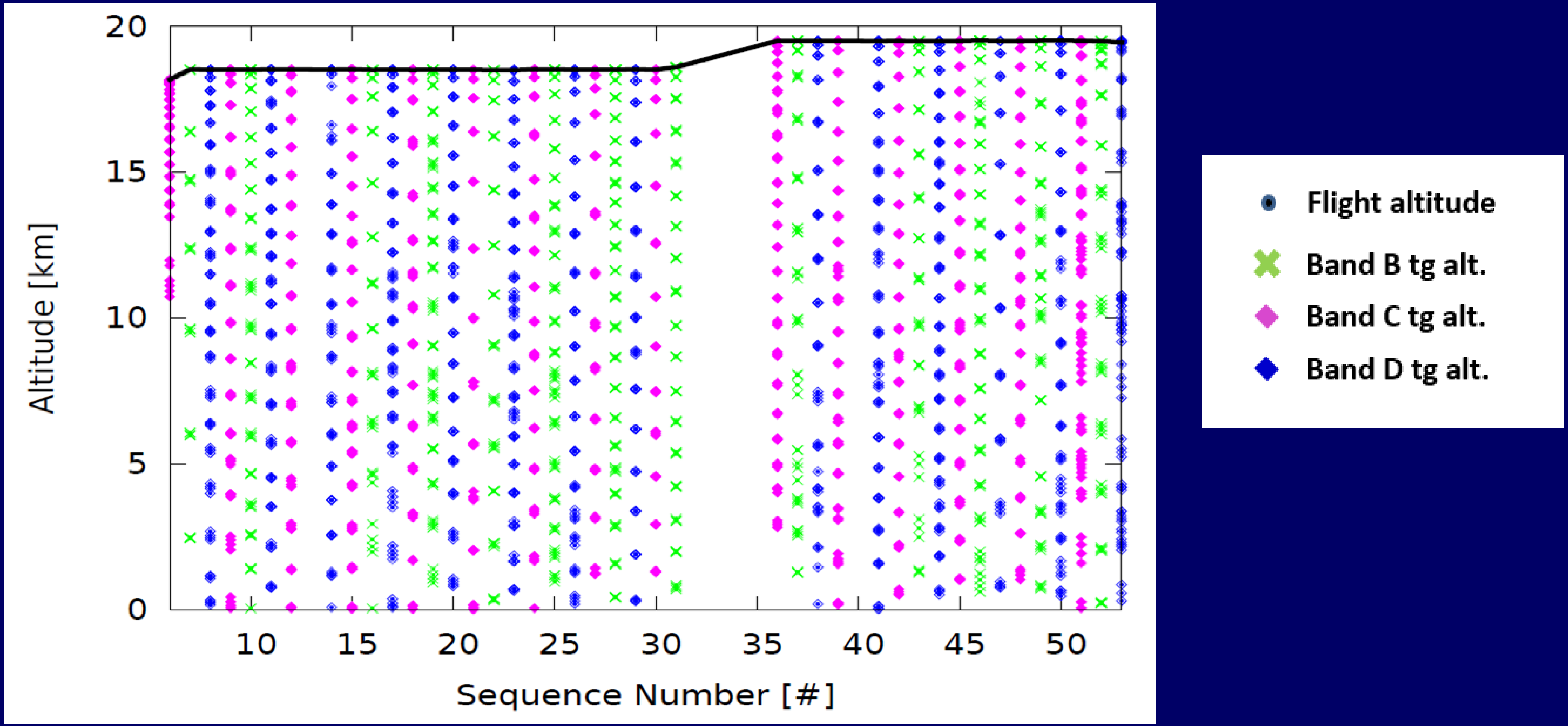
Incoming radiation is coupled to each of three millimetre-wave heterodyne radiometers, where it is down-converted to the range 12–24 GHz, amplified, and detected using a single channeliser spectrometer.

Observation time is shared between the three spectral bands by means of alternating atmospheric scans:

Scan 1, 4, 7, …	Band B
Scan 2, 5, 8, …	Band C
Scan 3, 6, 9, …	Band D

The total spectral band-width of the channeliser spectrometer is 12 GHz, split up in 60 channels of 0.2 GHz channel bandwidth.

MARSCHALS tangent altitudes



Flight altitude and vertical distribution of MARSCHALS tangent points during the PREMIEREX scientific flight on 10.03.2010

MIPAS-STR instrument

MIPAS-STR is a cryogenic mid-infrared limb sounder and employs four spectral channels in the spectral range from 725 to 2100 cm^{-1}. Here, channel 1 spectra with a ange from 725 to 990 cm^{-1} were used.

The unapodized spectral sampling of MIPAS-STR is 0.036 cm^{-1}. After application of the Norton-Beer Strong apodization, an effective spectral resolution of 0.069 cm^{-1} (full width at half maximum) is achieved.

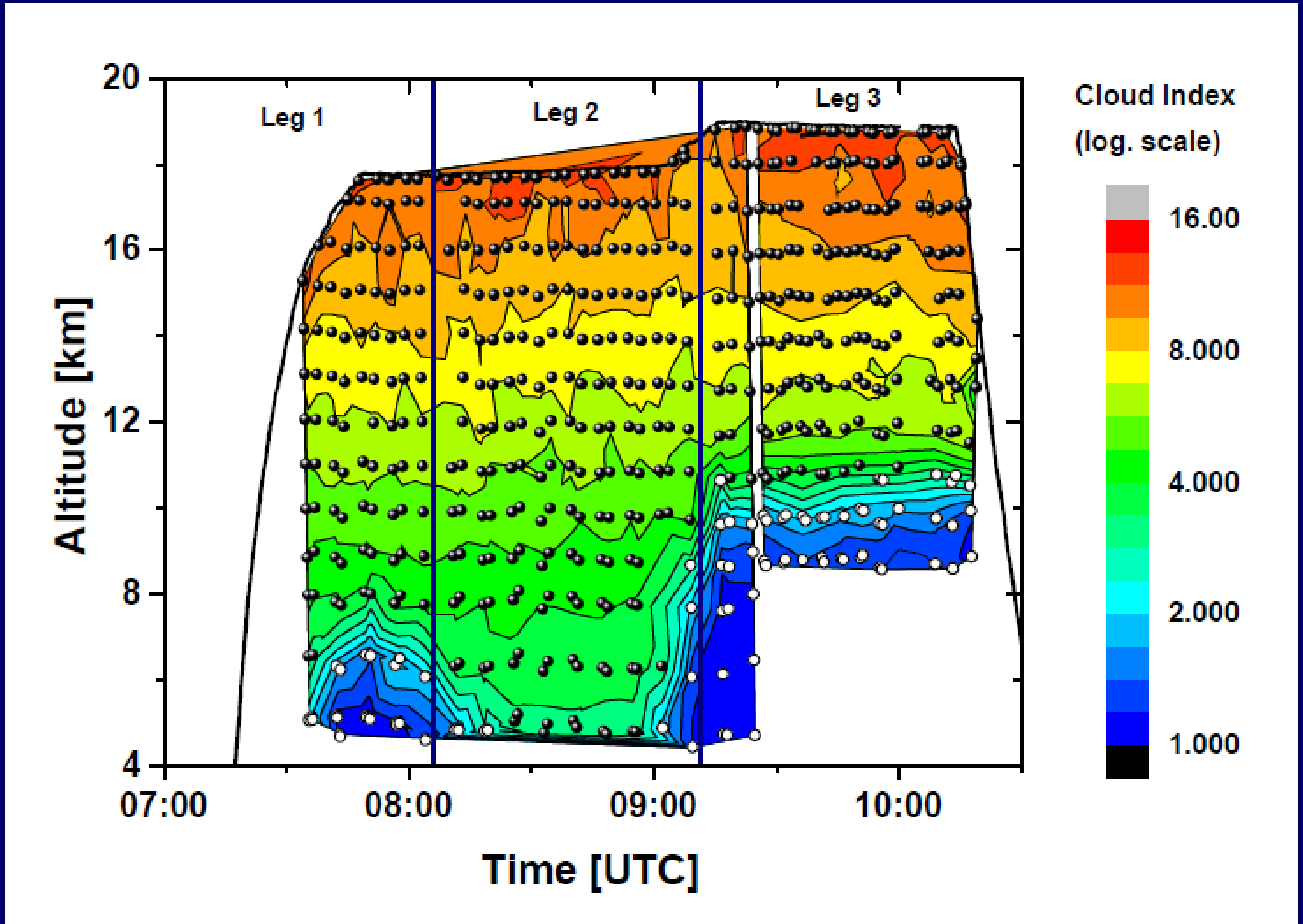
The noise-equivalent spectral radiance of channel 1 is $\sim 10 \times 10^{-9}$ W cm^{-2} sr^{-1} cm^{-1}.

The applied sampling programme during leg 1 and 2 of the PREMIEREX flight on 10th March 2010 included limb observations having tangent altitudes between ~**5** km and flight altitude and a vertical spacing of ~1 km (increased spacing below 8 km).

During the third flight leg, tangent altitudes below 9 km were excluded to avoid high tropospheric clouds.

MIPAS-STR includes an own GPS-supported inertial navigation system (Attitude and Heading Reference System), and the scan mirror is controlled via a fast control loop. The pointing accuracy is estimated to be within 0.8 arcmin.

MIPAS-STR tangent altitudes and Cloud Index



Flight altitude and vertical distribution of MIPAS-STR tangent points and interpolated Cloud Index.
White circles indicate MIPAS-STR observations showing CI values lower than the adopted cloud threshold value of 3.
Cloud index values close to 1 indicate opaque clouds.

MARSCHALS data processing

The MARC (Millimetre-wave Atmospheric Retrieval Code) retrieval code has been used to perform the PREMIER-Ex MARSCHALS data analysis.

MARC was developed under an ESA contract for the analysis of the MARSCHALS calibrated measurements. It was designed as a global fit, multi-target retrieval and it uses the Optimal Estimation approach along with the Levenberg-Marquardt algorithm.

MARC retrieves atmospheric profiles (temperature, H_2O, O_3, N_2O, HNO_3, CO, as well as a spectroscopic continuum) and scalar parameters (pointing bias, gain and offset, and frequency shift).

MARC uses the complete Variance Covariance Matrix (VCM) of the measurement. The VCM of the measurement is made of two components: the random component (measurement errors) and the systematic component (model parameters).

The VCM provides directly a retrieval error that contains both the random and systematic contributions and, therefore, corresponds to the total error.

MIPAS-STR data processing

Forward calculations were performed using KOPRA (Karlsruhe Optimized and Precise Radiative Transfer Algorithm) and inversion was performed utilizing KOPRAFIT. The profiles of the target parameters were inverted utilizing Gauss-Newton iterations subjected to first-order Tikhonov-Phillips regularisation.

The retrieval was performed sequentially: line-of-sight correction, temperature, HNO_3, O_3 and H_2O. Micro-windows were selected for low spectral interference with other species and sufficient radiance avoiding saturation of spectral lines.

The error budget for the retrieved parameters includes the spectral noise error, line-of-sight error and radiometric gain error.

For temperature, furthermore a defined bias in the CO2 profile was considered to estimate the effect of errors in the spectral line data and CO_2 profile.

In the retrievals of HNO_3, O_3 and H_2O, spectroscopic errors were taken into account, respectively, and a linear propagation of these errors into the retrieved profiles was assumed.

(L1+L2) data fusion

The (L1+L2) data fusion method consists in the inverse processing with optimal estimation of L1 data of one instrument using the L2 products of the other instrument as a priori information.

We have processed MARSCHALS L1 data using the L2 profiles obtained from MIPASSTR data analysis as a priori information with associated the covariance matrix containing both random and systematic error contributions.

MSS data fusion

The **MSS** (**Measurement Space Solution**) **method** provides the retrieved profile as the sum of a component belonging to the measurement space (the space generated by the rows of the Jacobian matrix of the forward model) and a component belonging to the null space (the orthogonal complement space to the measurement space).

The MSS is the component of the profile in the measurement space and is represented using an orthonormal basis of the measurement space, so that the components of the profile in this basis are uncorrelated with each other.

The MSS includes all the information coming from the observations without any a priori information.

When different independent measurements of the same profile are available, we can calculate the MSSs of these measurements on the same vertical grid so that all the measurement spaces are sub-spaces of the same complete space. The fusion of these measurements is obtained calculating the MSS in the sum space of the individual measurement spaces (that is the space including all vectors that are the sum of vectors of the individual measurement spaces). This new MSS (the MSS of the data fusion) includes all the information contained in the observations of the measurements to be fused without any bias due to a priori information.

Data Quality Quantifiers

A set of quantifiers was adopted to evaluate the quality of individual and synergistic data products and the efficiency of the synergistic effects:

- **Total Retrieval Error**
- **Degrees Of Freedom** (DOF)
- **Relative Information Distribution** (RID)
- **Synergy Factor** (SF)

Relative Information Distribution

The **Relative Information Distribution** (RID) is a quality quantifier for indirect measurements, derived from the diagonal of the Fisher Information matrix, that provides an absolute assessment (not relying on any a priori information) as a function of altitude of the information that the observations contain on the retrieved profile.

The Fisher information matrix $\mathbf{F}$ associated to the inverse problem of measurements of vertical atmospheric profiles is given by:

$$\mathbf{F} = \mathbf{K}^{T}\mathbf{S}_{y}^{-1}\mathbf{K}$$

where $\mathbf{K}$ is the Jacobian matrix of the forward model calculated in the minimum of the cost function minimized by the retrieval and $\mathbf{S}_y$ is the covariance matrix of the observations.
The trace of the Fisher information matrix is referred to as the **Measurement Quality Quantifier** (MQQ).

The RID is defined as equal to

$$F_{ii}\, x_i^2/\Delta z_i^2$$

where Δz_i is the altitude interval associated to the i^{th} level and x_i are the retrieved parameters.

Ref.: Ceccherini, S., et al., Quality quantifier of indirect measurements, Optics Express, 20, 5, 5151, 2012

Synergy Factor

The synergy factor of a retrieval scheme using N sources of information ($x_1, x_2, \ldots, x_N$) is defined as the ratio of the errors of the retrieval using the best single information, $\mathrm{Min}(E(x_i))(i = 1, \ldots, N)$, with the errors of the retrieval using all the sources of information $E(x_1, x_2, \ldots, x_N)$.

This synergy factor is > 1 when a synergy between the two individual datasets really exists

Ref.: Aires, F.: Measure and exploitation of multisensor and multiwavelength synergy for remote sensing: 1. Theoretical considerations, J. Geophys. Res., 116, D02301, 2011.

Results of MSS data fusion

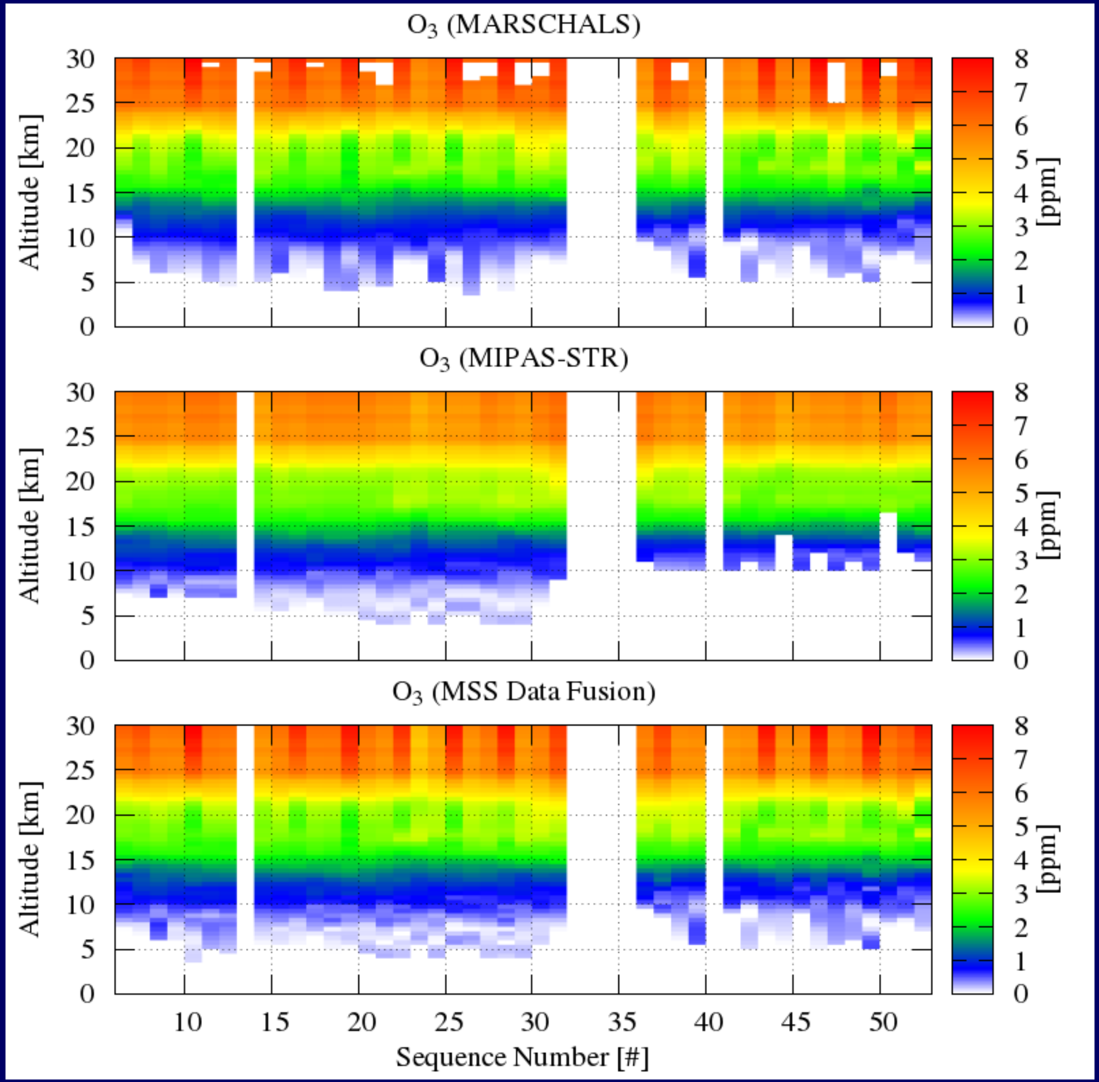
The MSS data fusion approach was applied to four atmospheric targets simultaneously measured by MIPAS-STR and MARSCHALS during the PREMIEREX flight on March 10^{th}, 2010:

- **Ozone**
- **Nitric Acid**
- **Water Vapor**
- **Temperature**

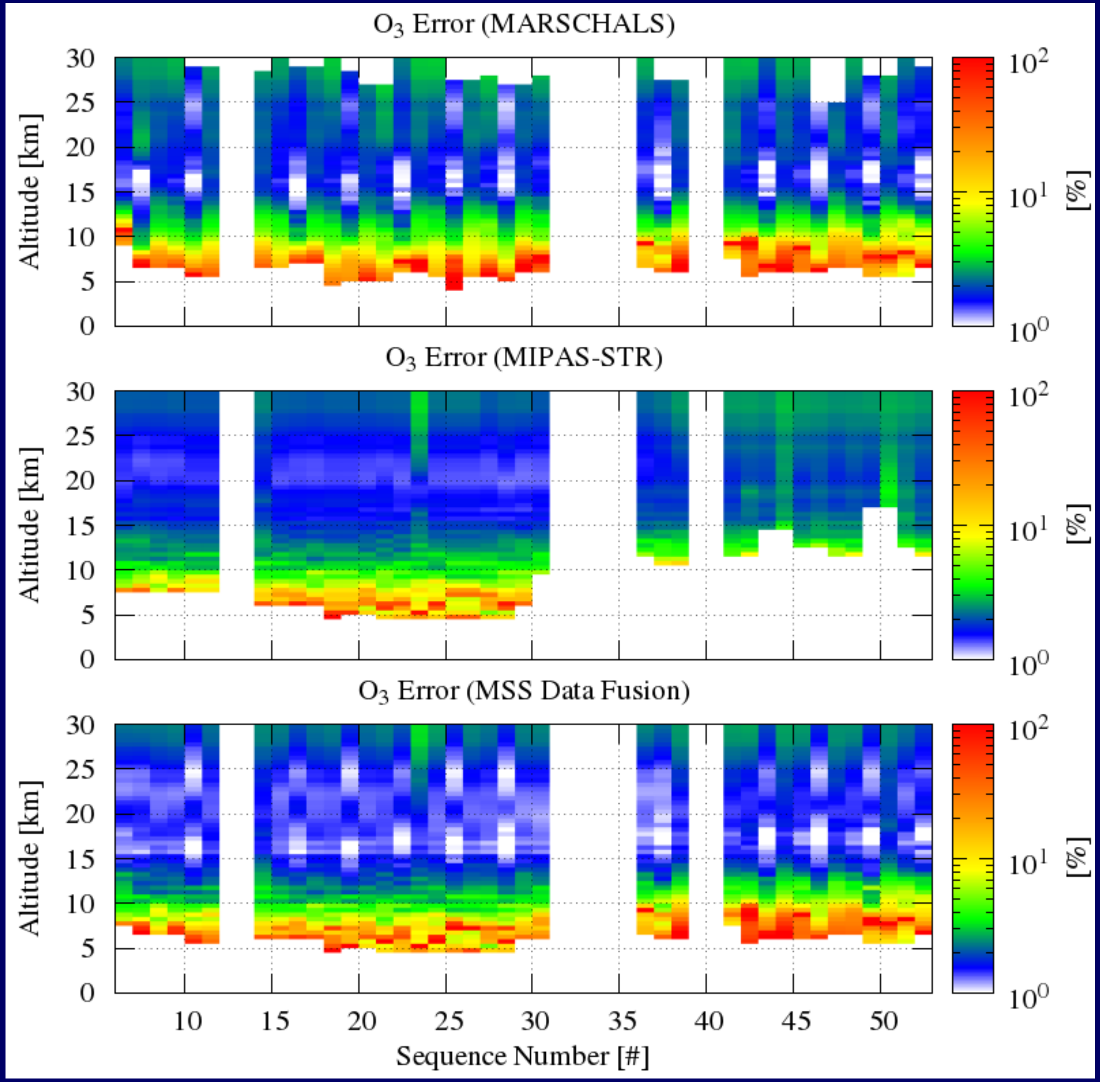
In this study, for the first time, we use the representation of the vertical profile that is obtained using the Tikhonov-Philips regularization for the purpose of MSS data fusion.

OZONE

O_3 VMR Vertical Profile

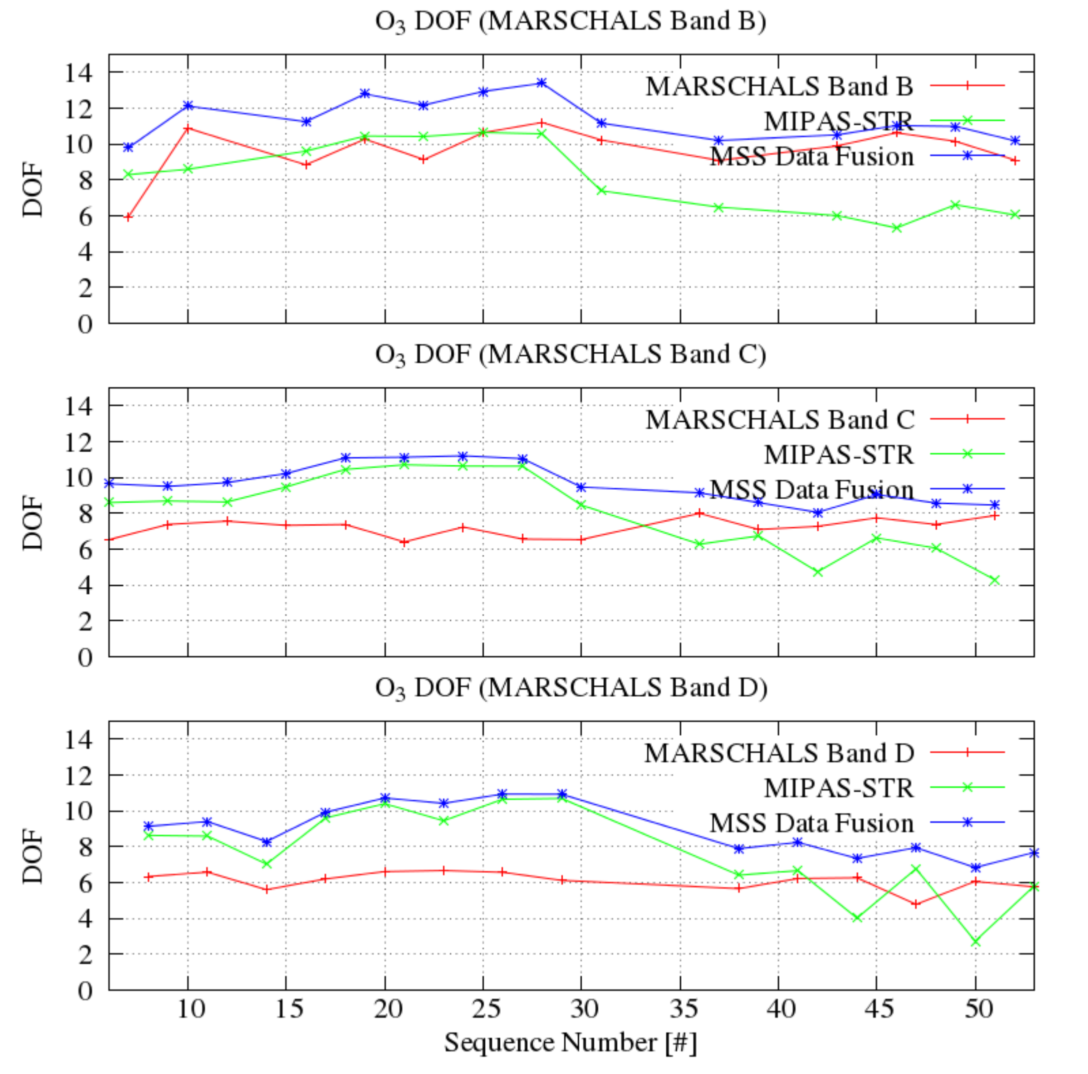


O_3 VMR Total Relative Error

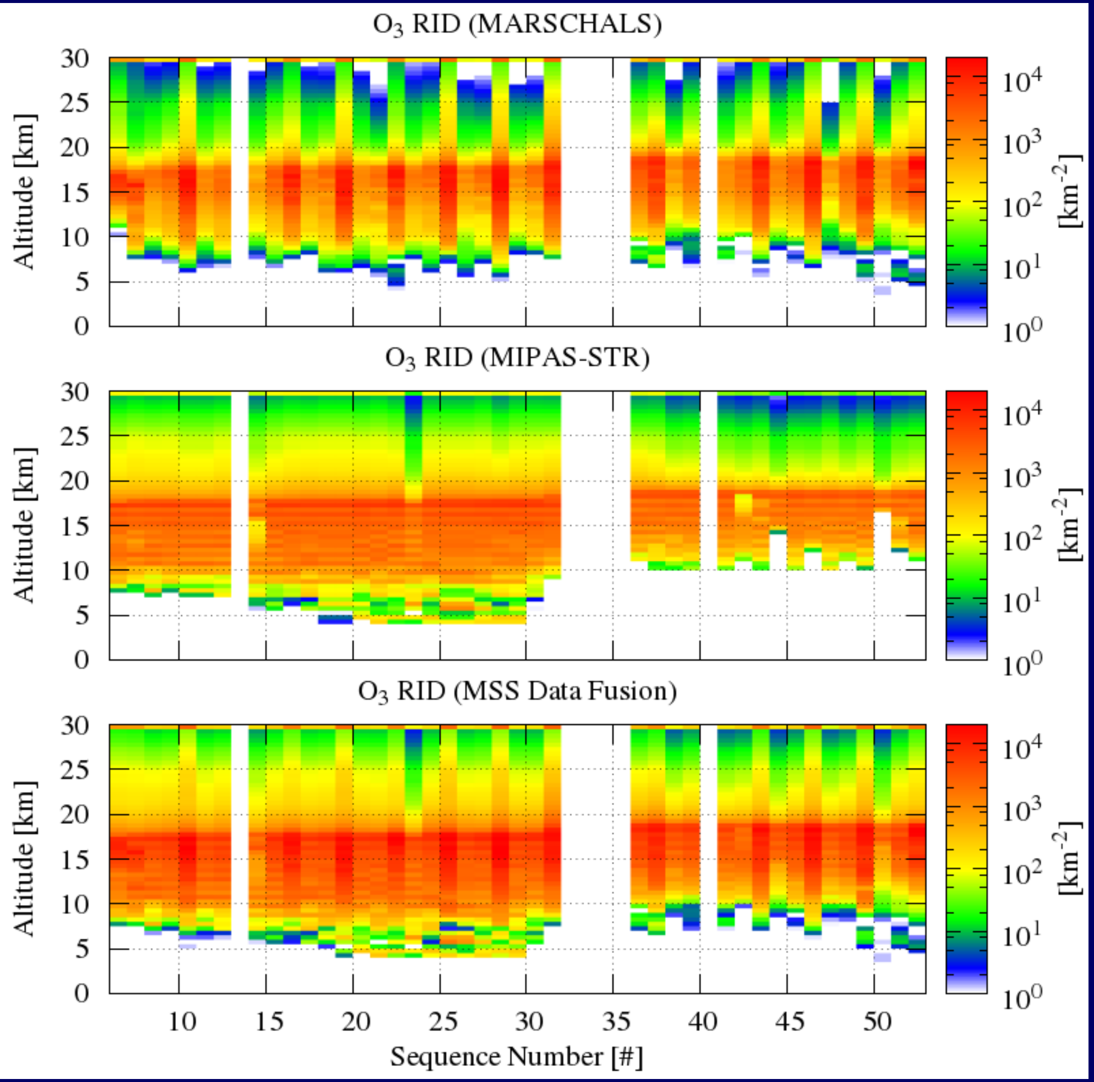


OZONE

O_3 Degrees Of Freedom

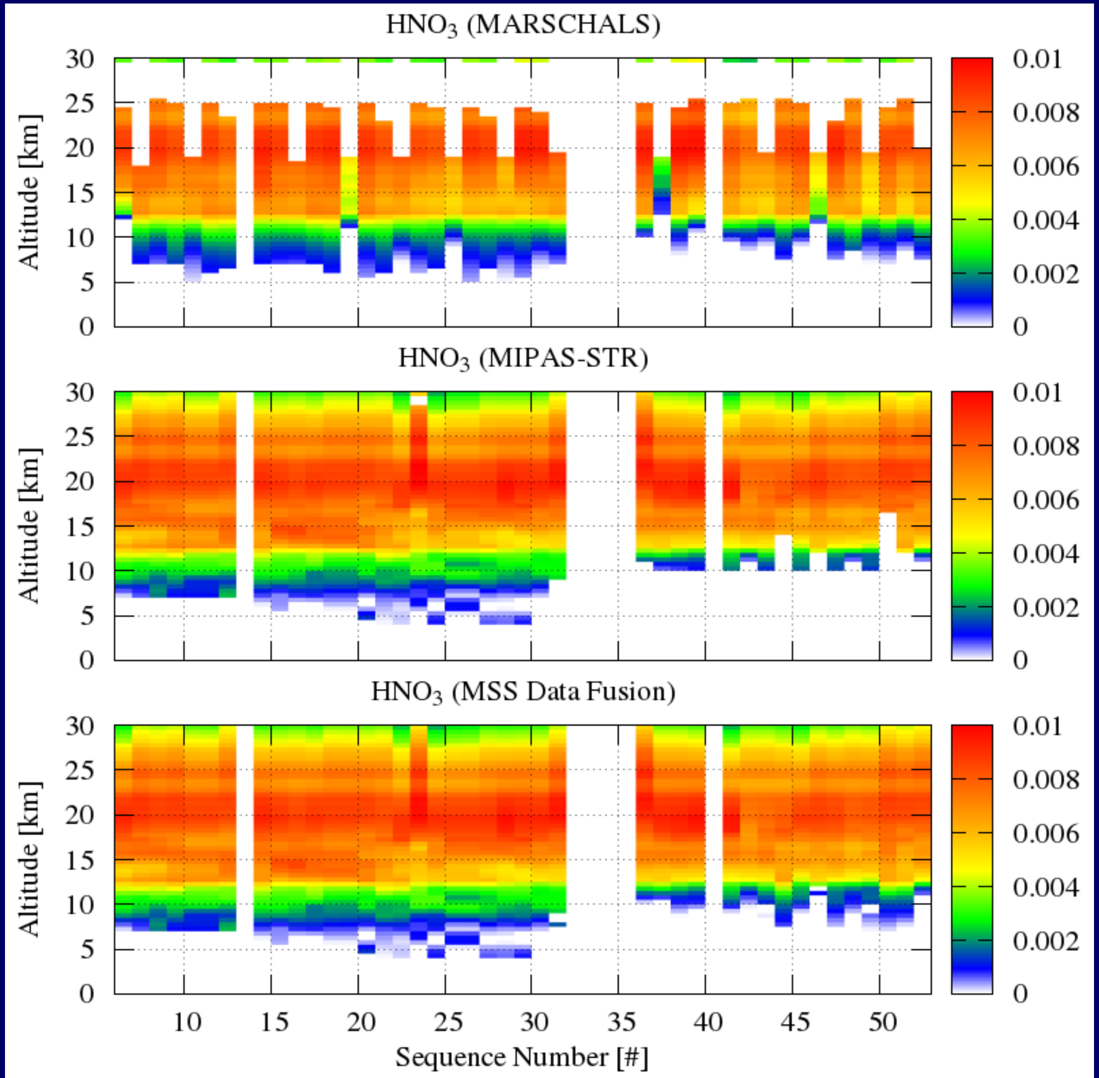


O_3 Relative Information Distribution

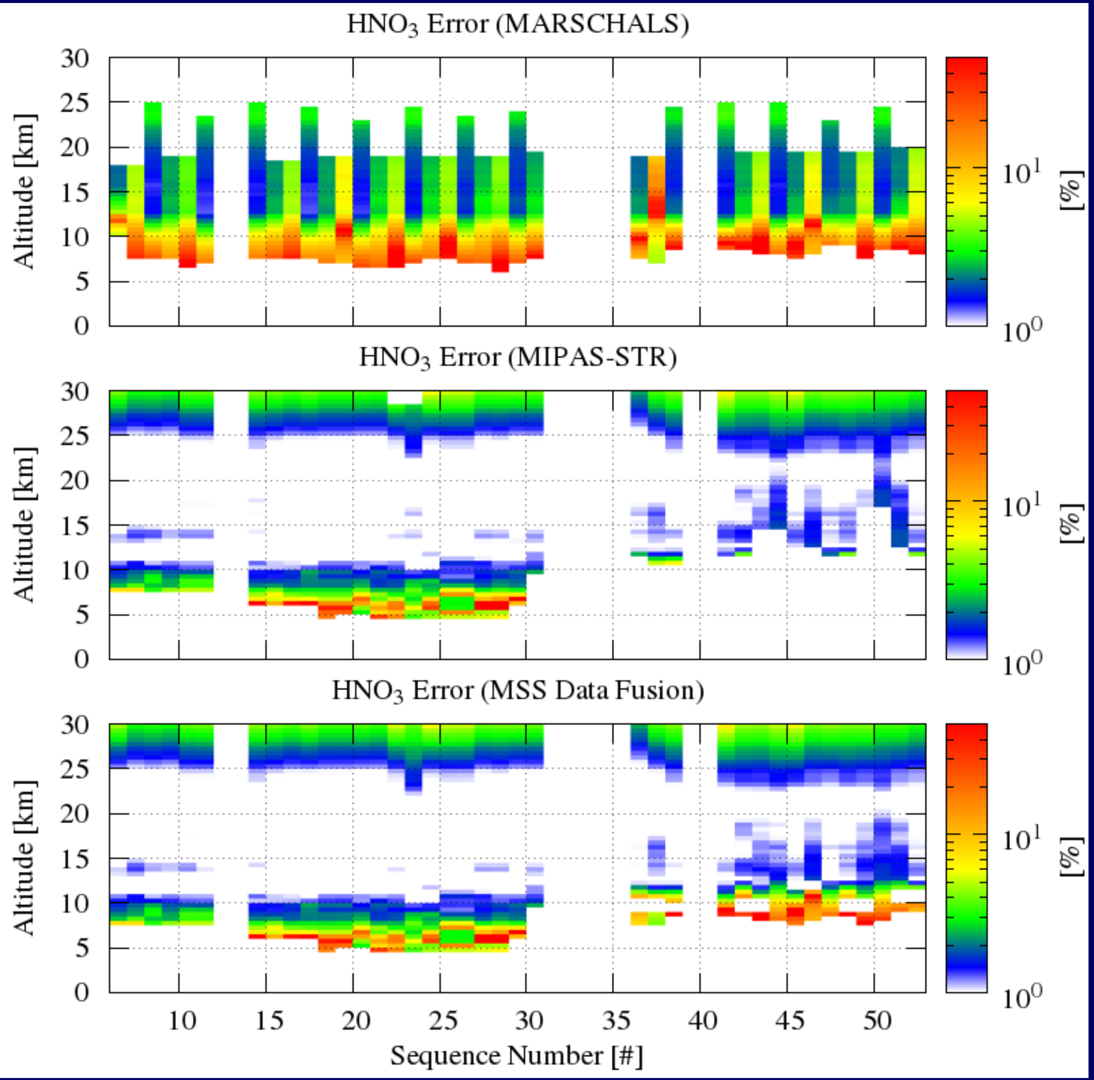


NITRIC ACID

HNO_3 VMR Vertical Profile

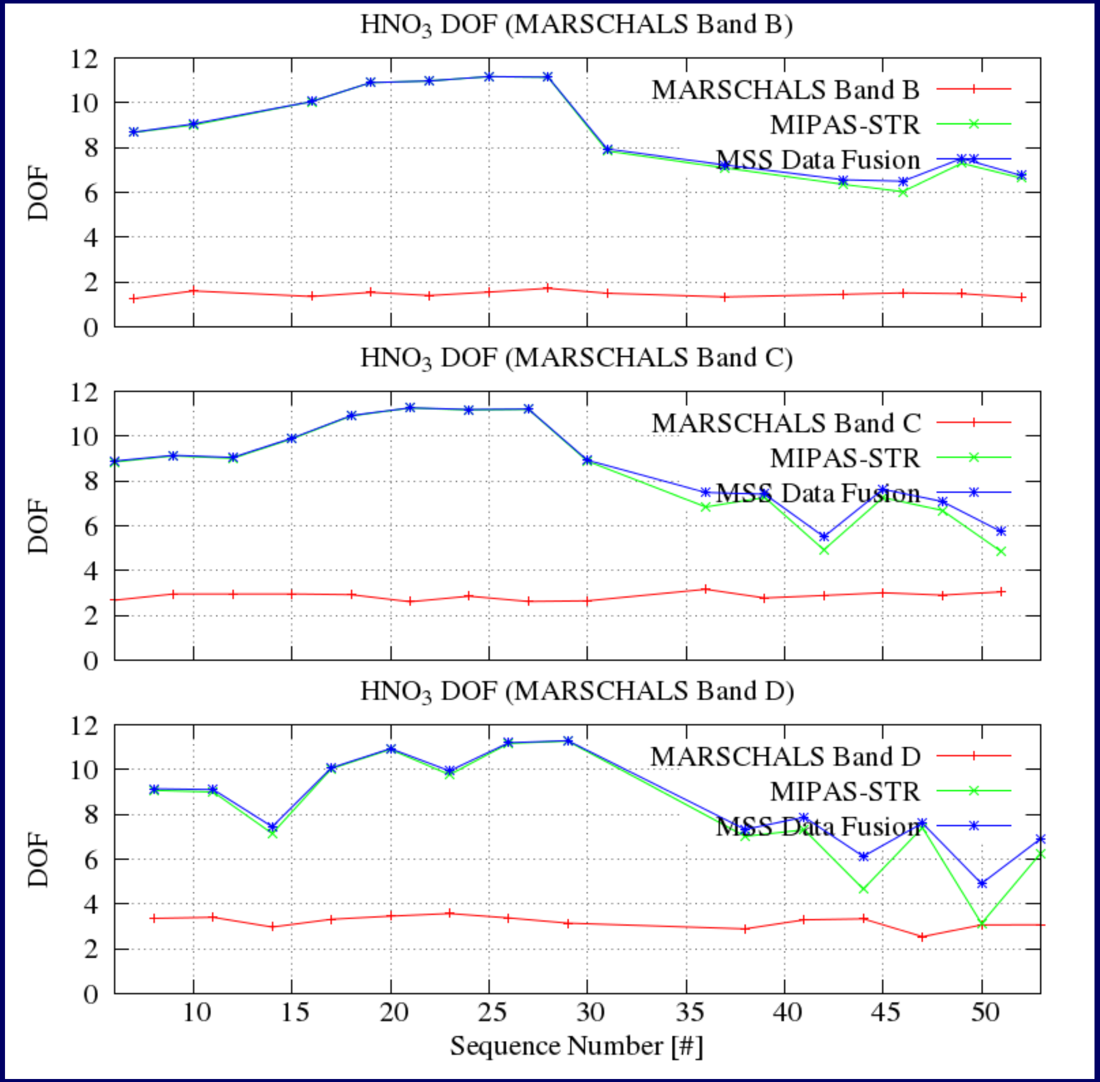


HNO_3 VMR Total Relative Error

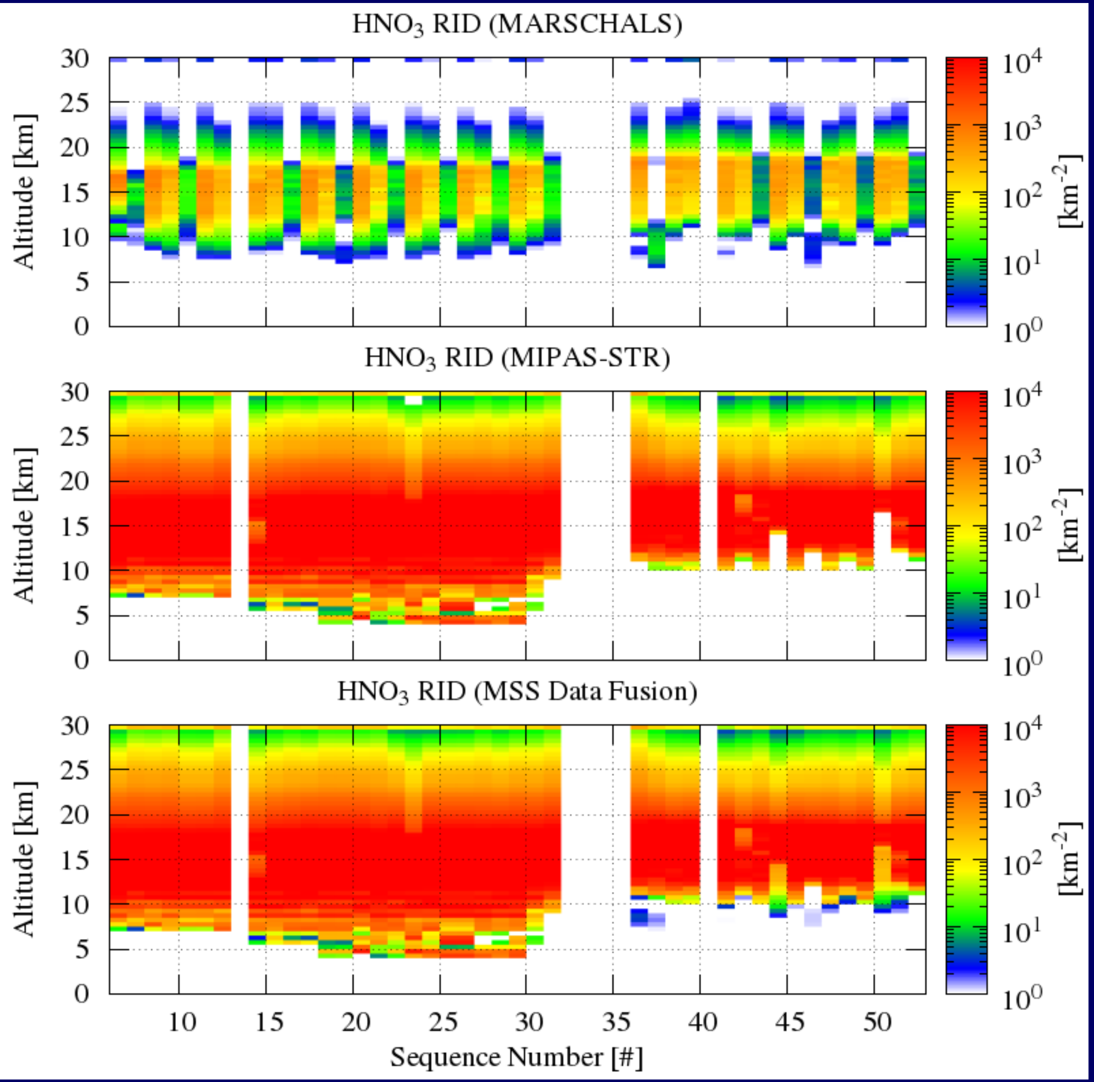


NITRIC ACID

HNO_3 Degrees Of Freedom

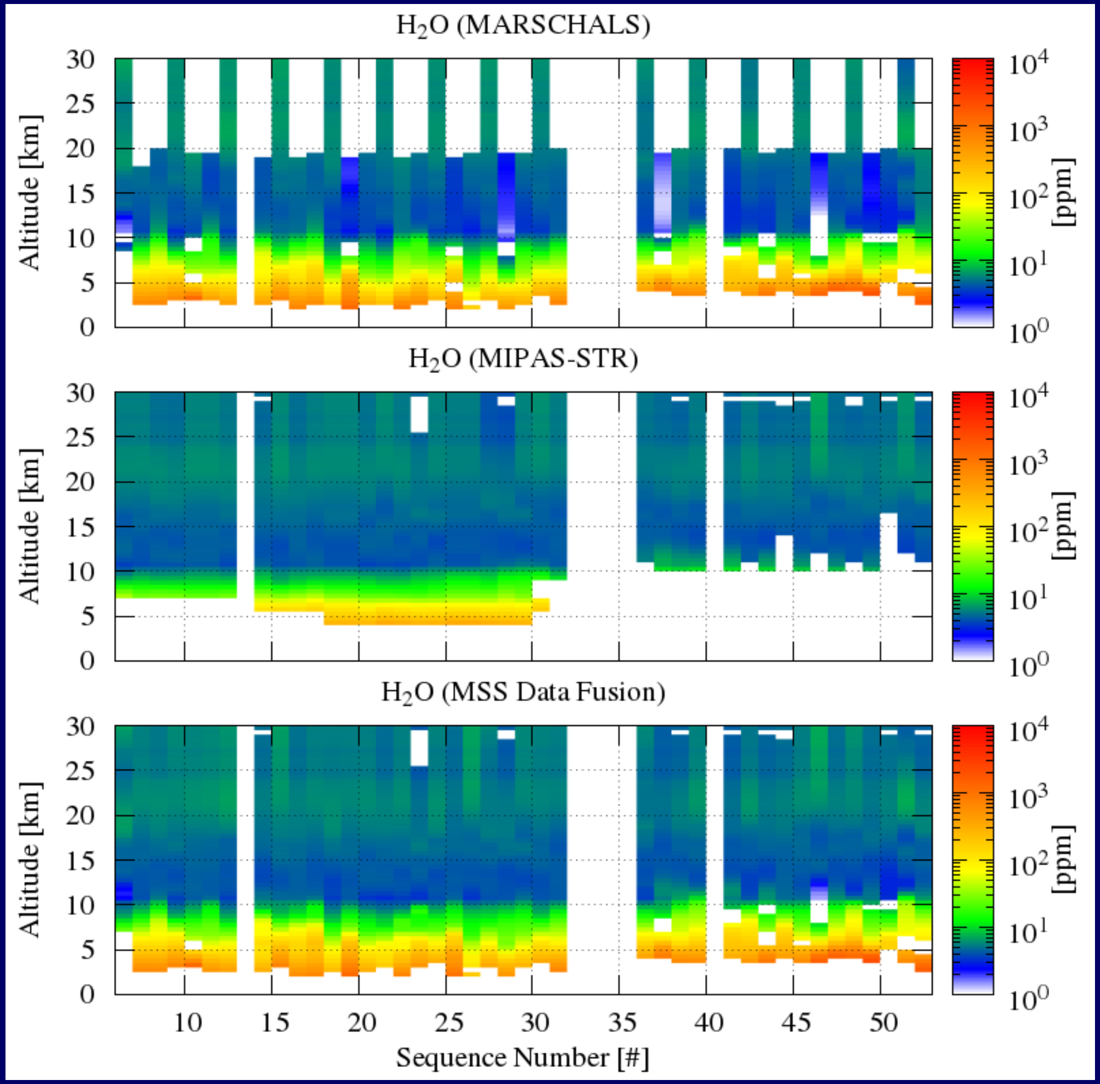


HNO_3 Relative Information Distribution

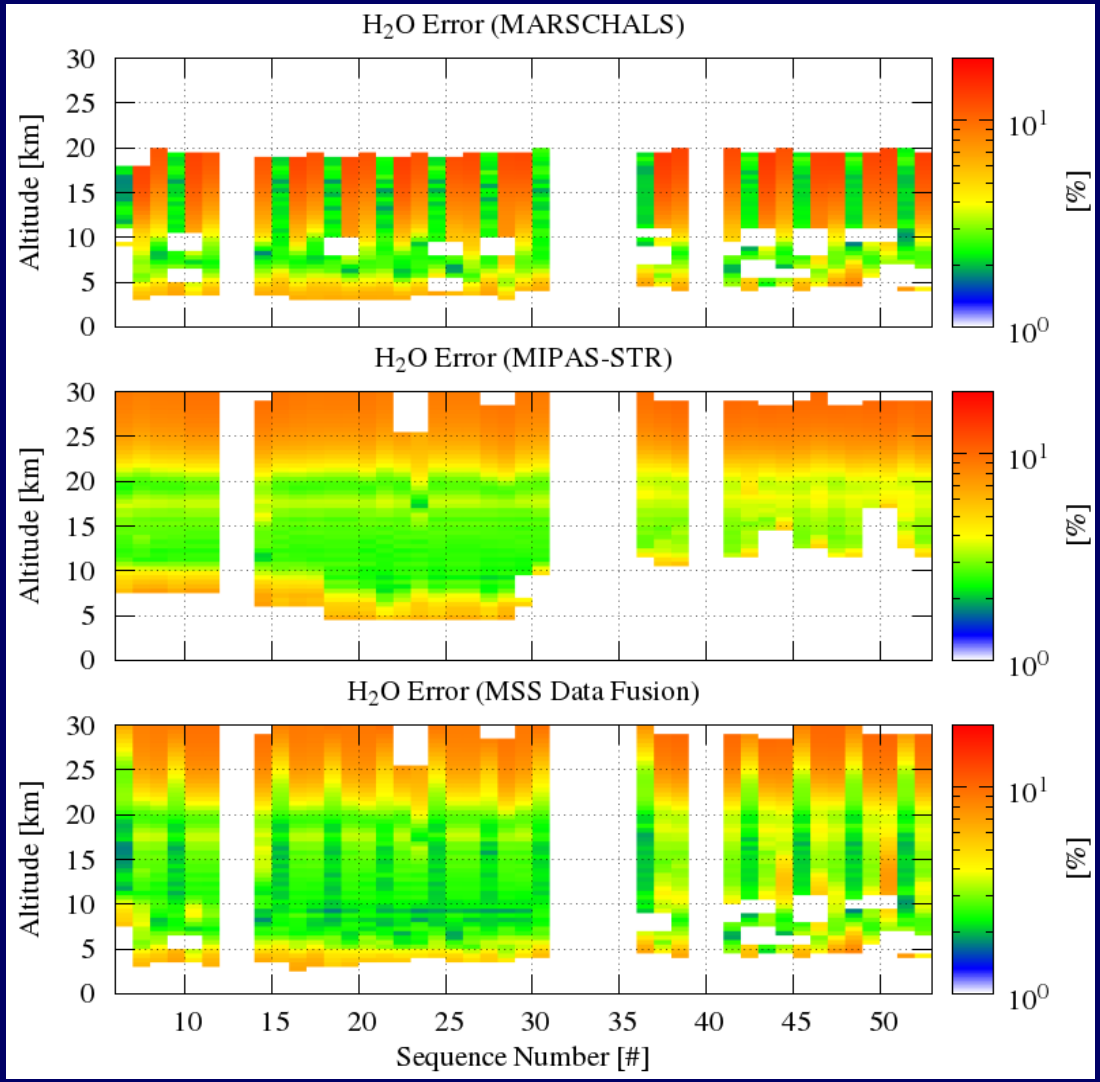


WATER VAPOR

Water Vapor VMR Vertical Profile

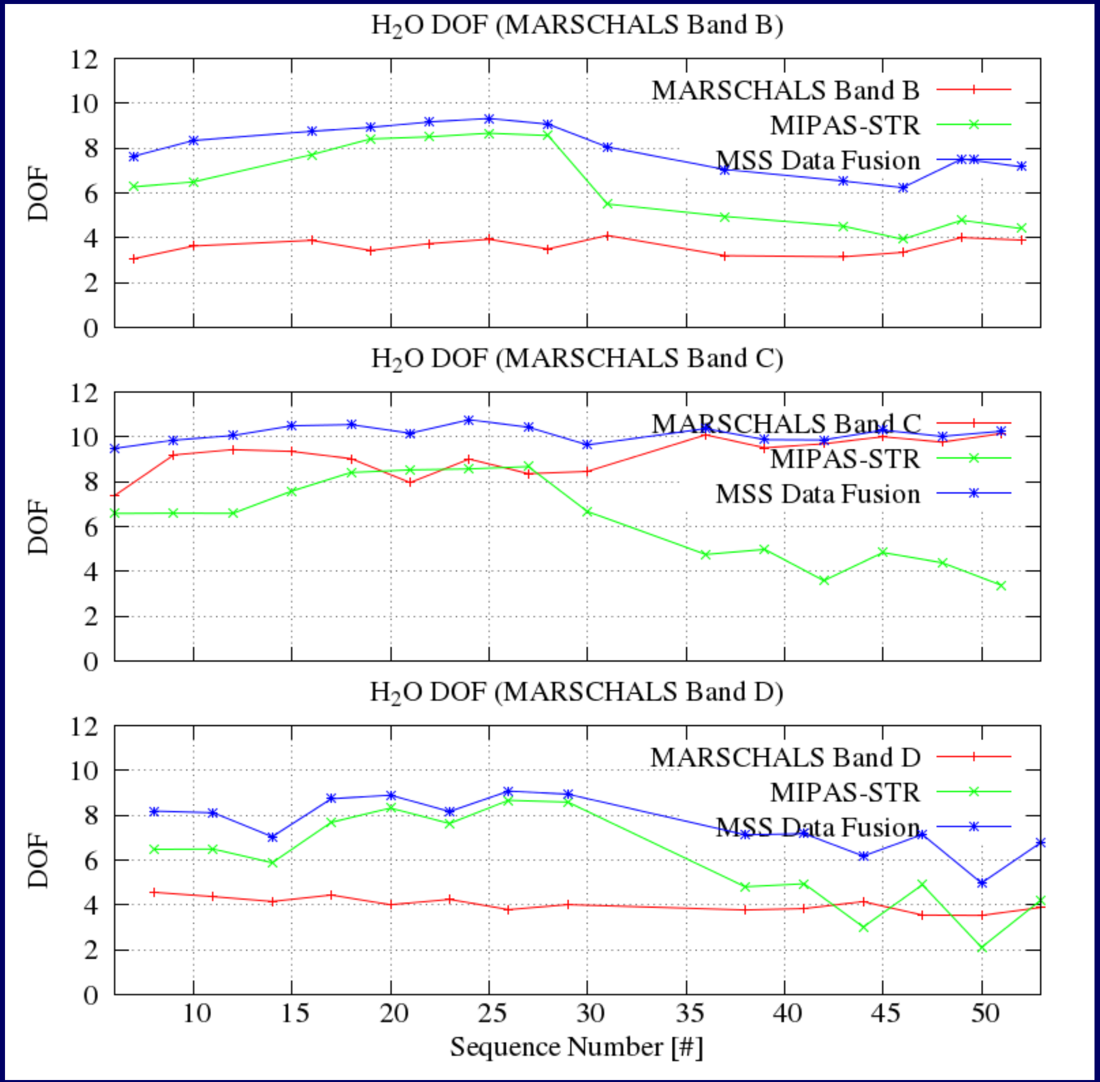


Water Vapor VMR Total Relative Error

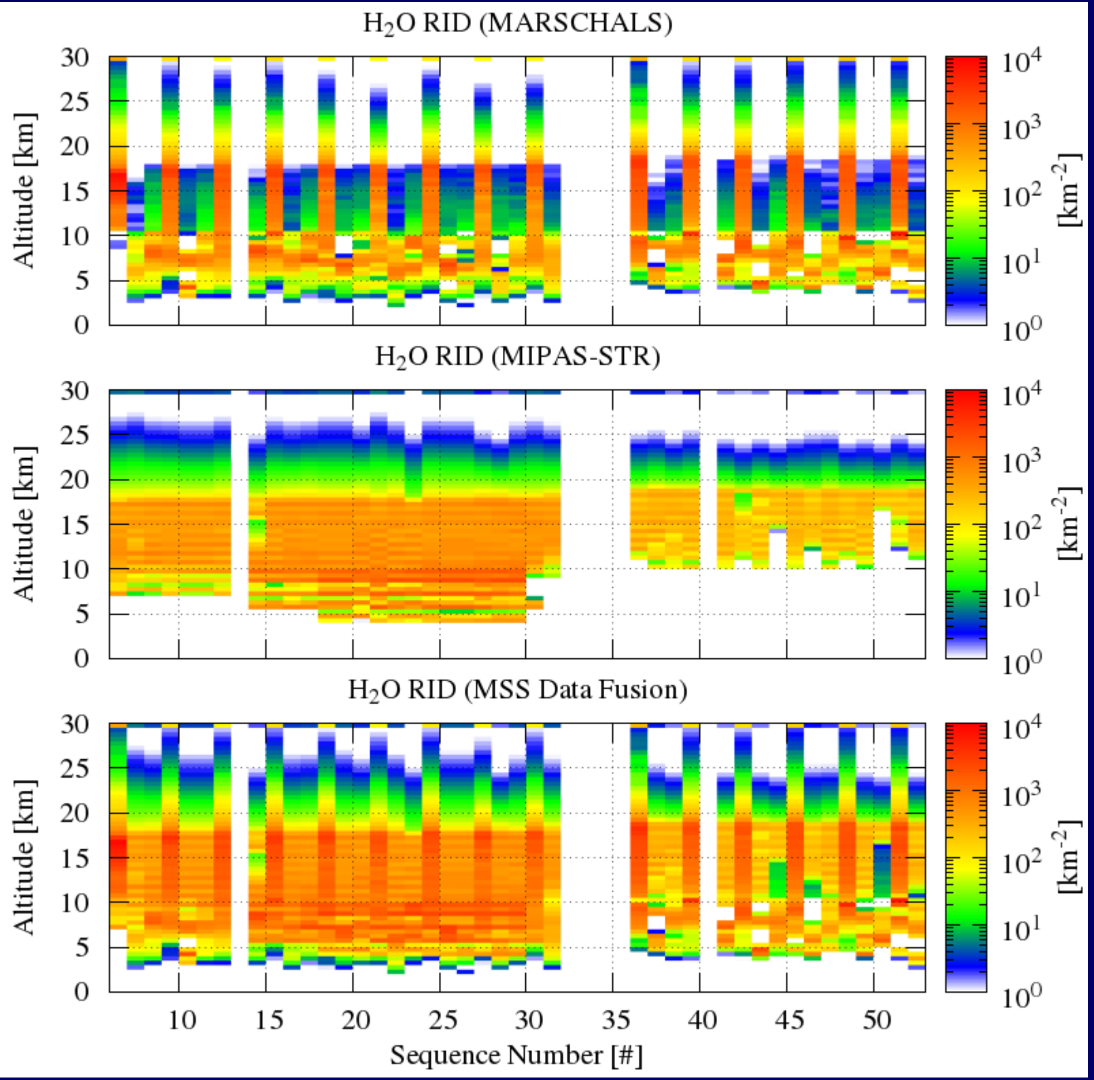


WATER VAPOR

Water Vapor Degrees Of Freedom

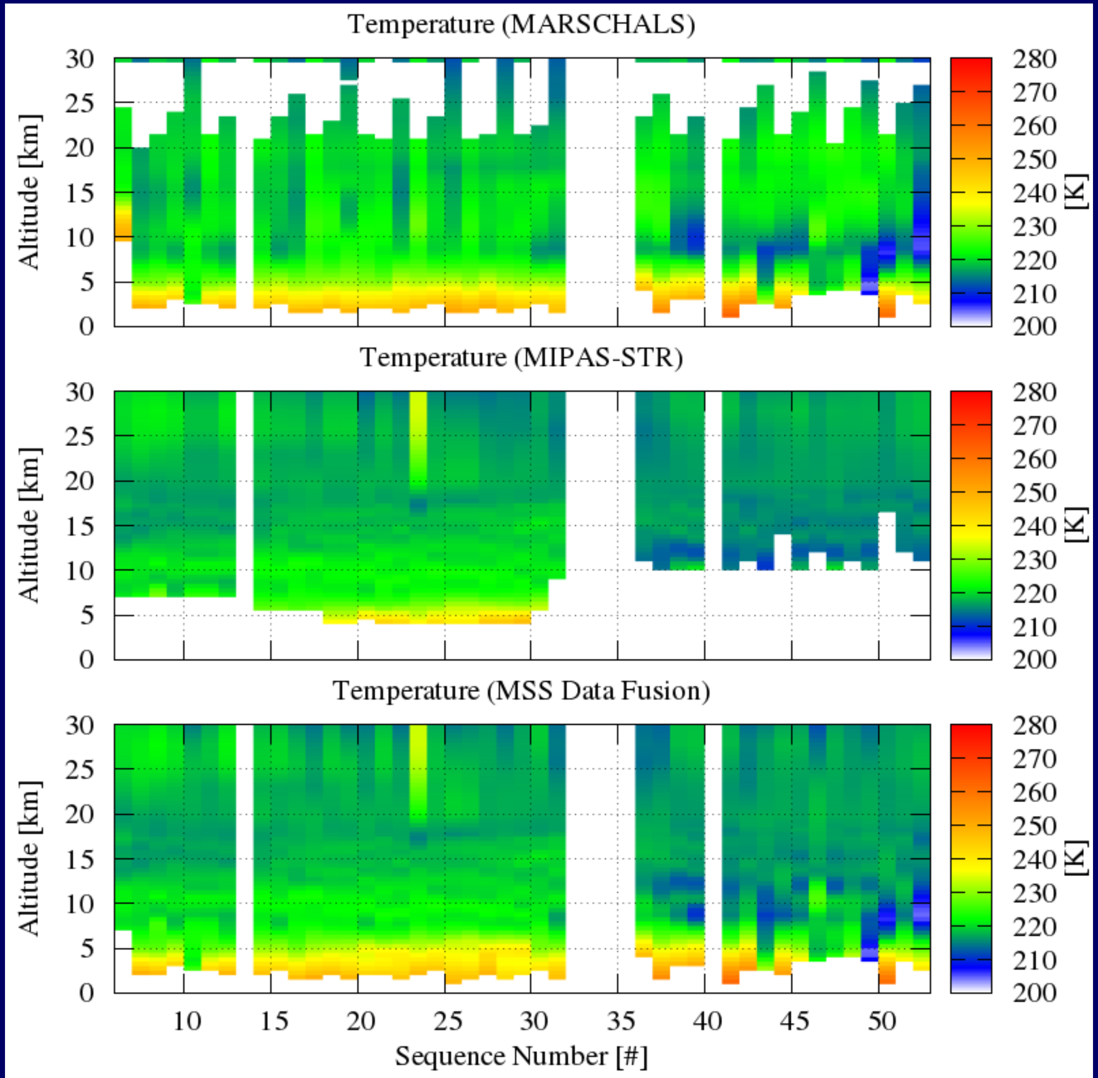


Water Vapor Relative Information Distr.

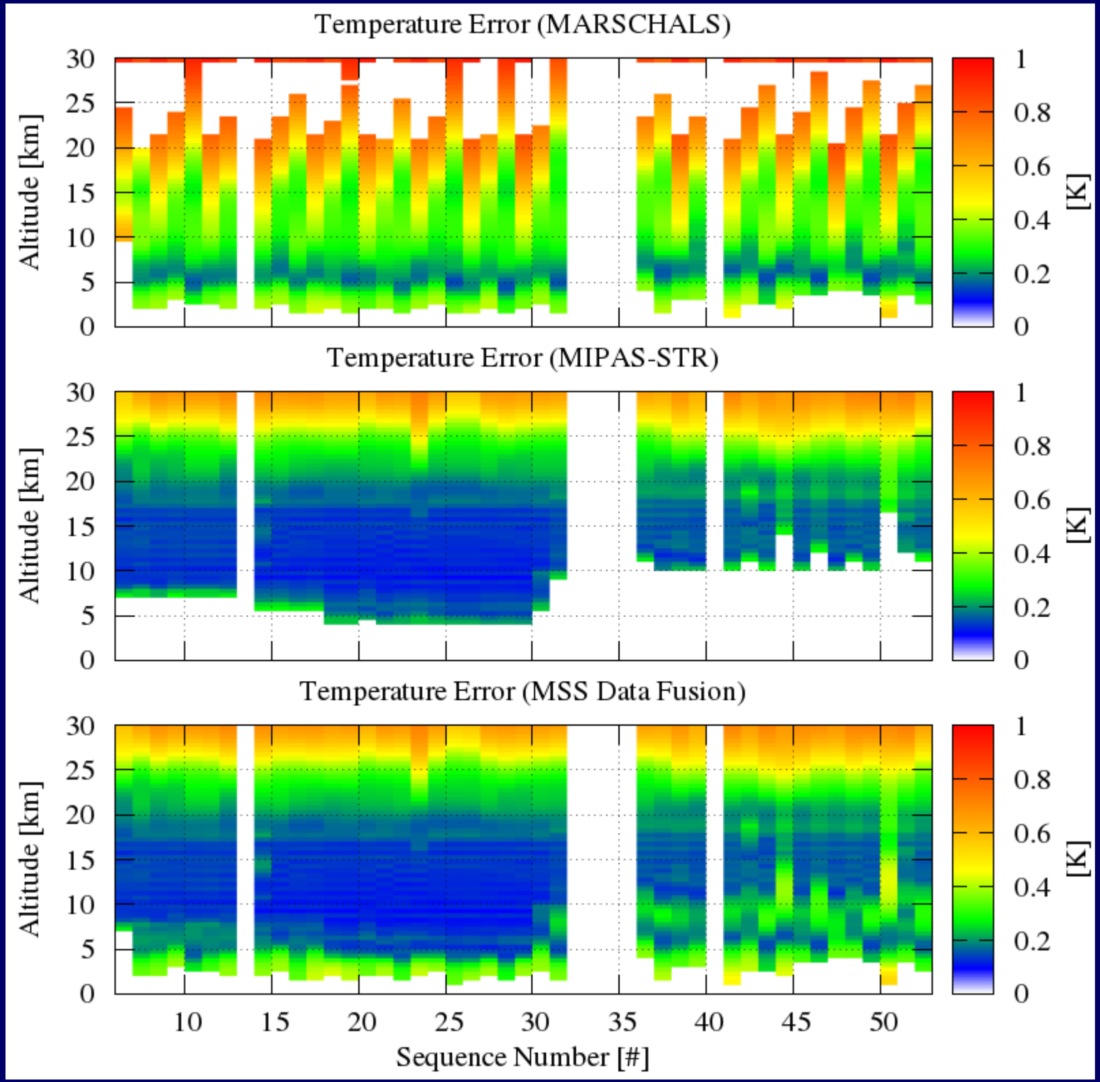


TEMPERATURE

Temperature Vertical Profile

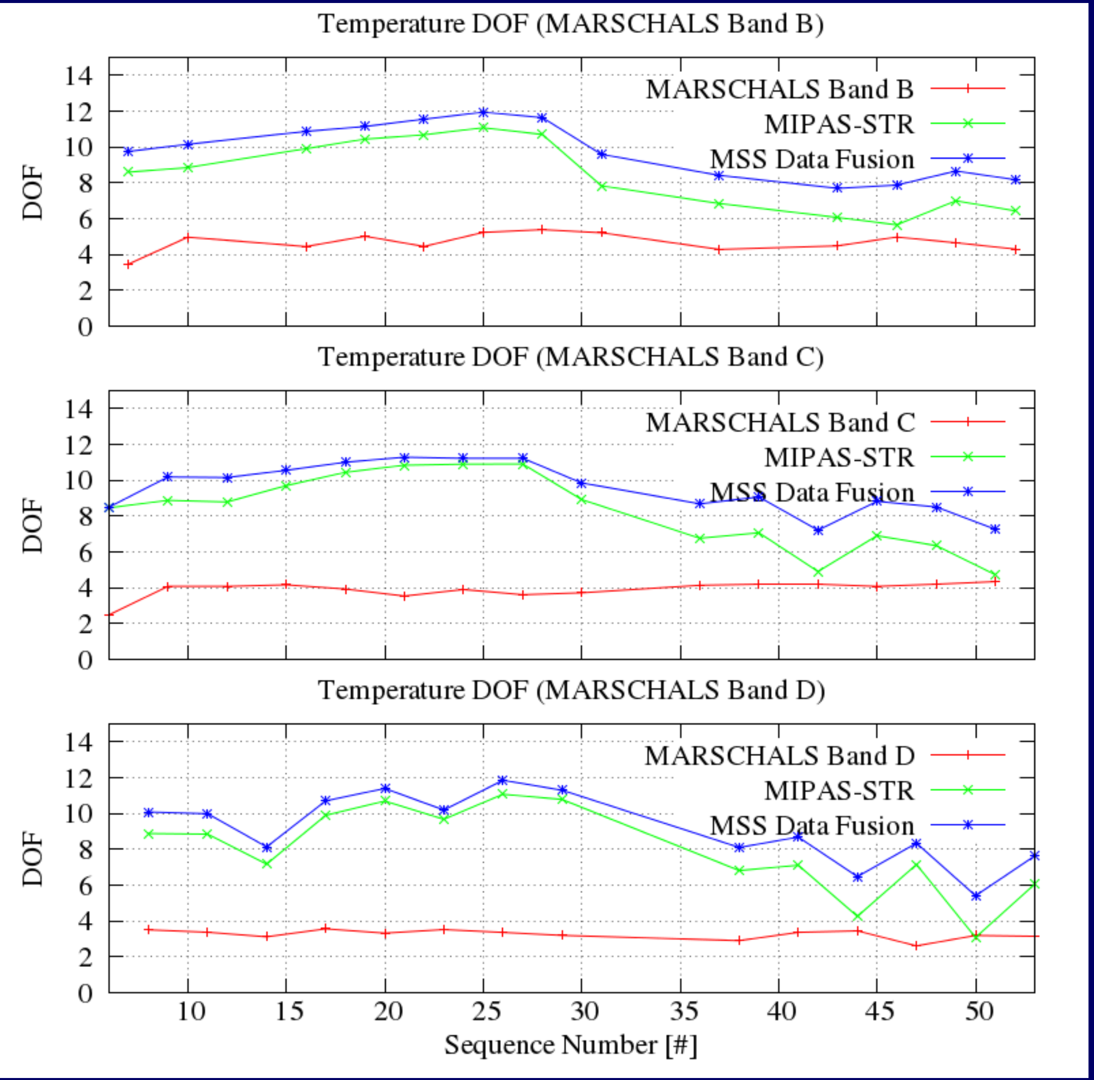


Temperature Total Error

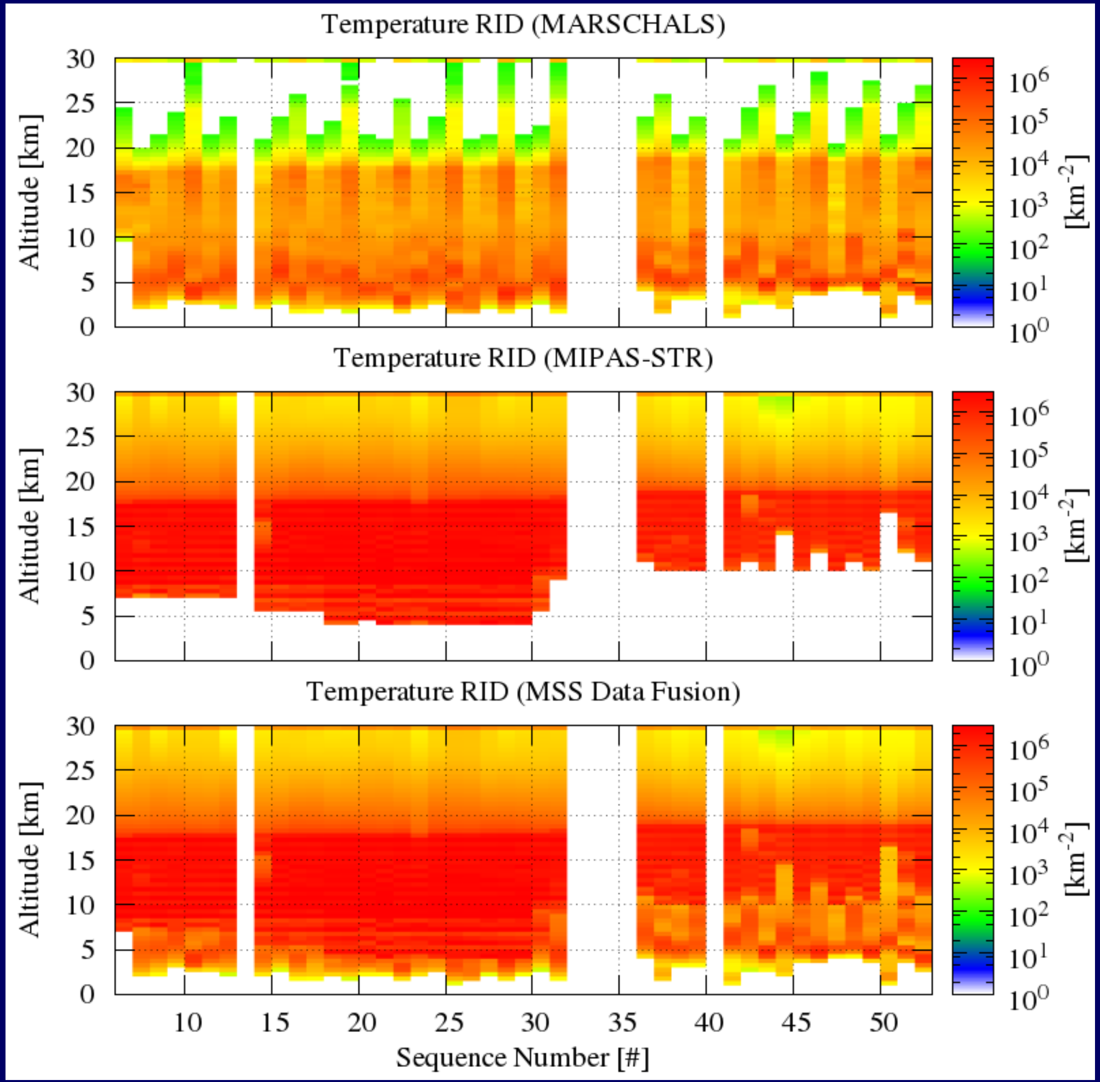


TEMPERATURE

Temperature Degrees of Freedom

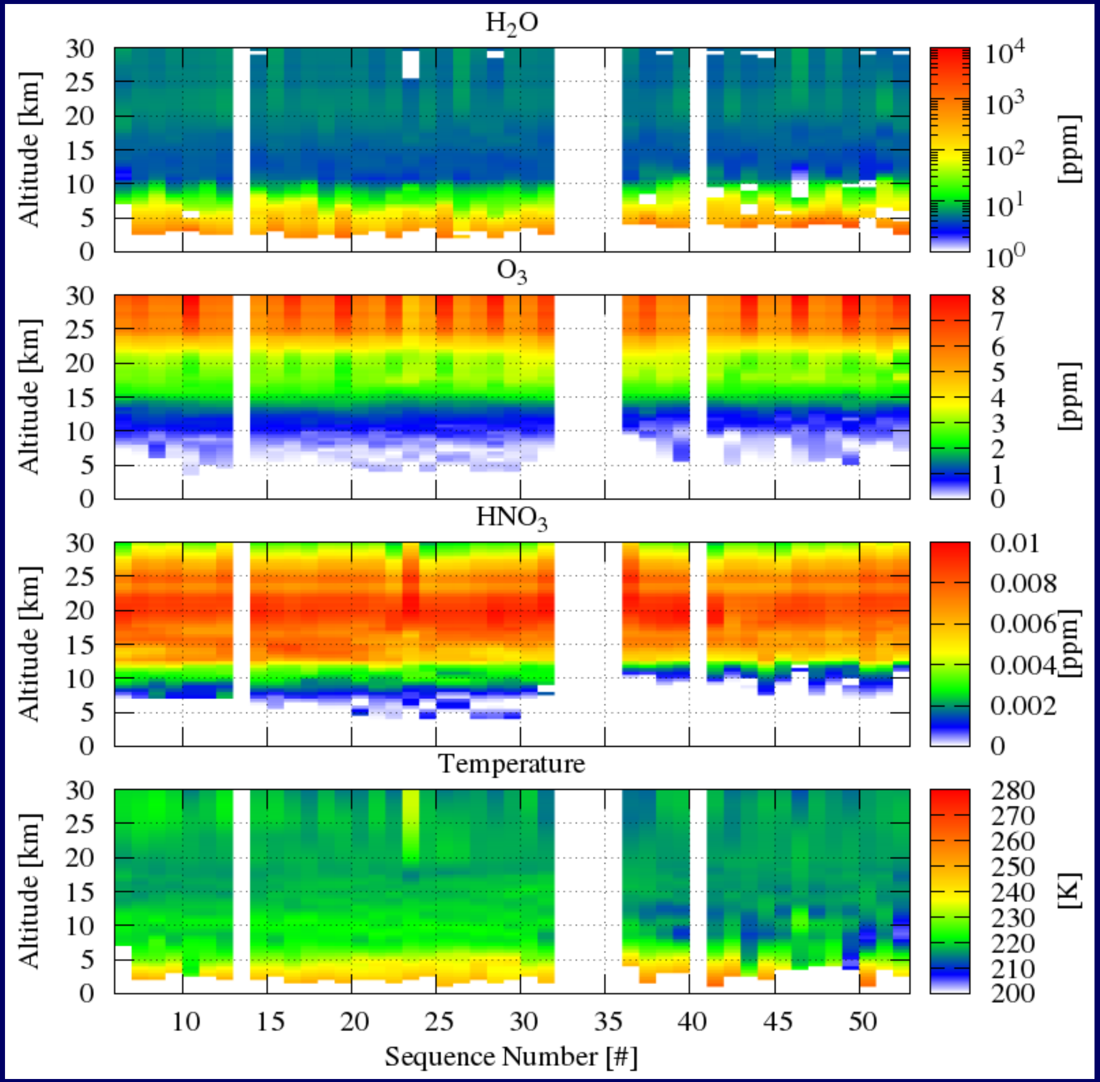


Temperature Relative Information Distr.

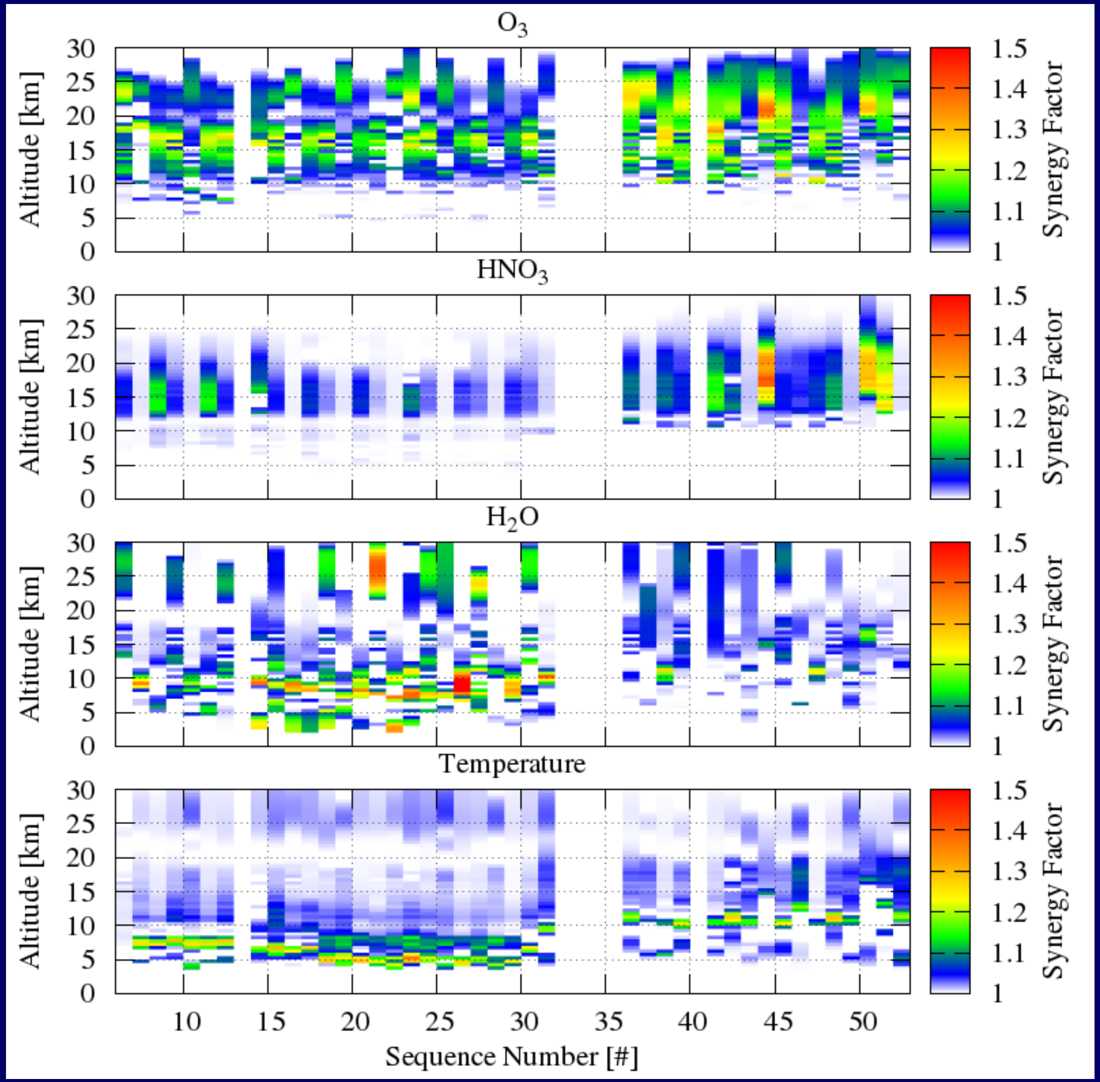


SYNERGY FACTOR

MSS data fusion products



Synergy Factor



Comparison with the results of (L1+L2) data fusion

The (L1+L2) data fusion was applied to the same atmospheric targets (O_3, HNO_3, H_2O, T) as the MSS. We focused on the O_3 results only, because representative for the problem associated with the (L1+L2) method.

- The total error on O_3 is reduced, compared to total errors of O_3 retrieved from MIPAS-STR data.
- The number of DOFs calculated for the MIPAS-STR retrieval of O_3 is significantly increased by the combination with MARSCHALS data.
- The RID is independent from the used retrieval approach and from the external constraint.
- The SF provides not comparable values in the (L1+L2) and MSS cases due to the different retrieval approaches and external constraints used for MIPAS-STR and MARSCHALS data analysis.

(L1+L2) applied to different retrieval methods qualitatively demonstrates the synergy between the different techniques; quantitative comparisons are difficult since the characteristics of the different retrieval methods are not fully compatible.

MSS allows for a more clear comparison of the individual and synergistic results: the measured components from the different techniques are treated in a similar way and the results are subject to the same external constraint.

CONCLUSIONS

We performed a thorough and comprehensive analysis of the potential synergy between middle infrared and millimetre-wave limb sounding measurements of UTLS temperature and minor constituents by using the (L1+L2) method of data fusion and the innovative approach based on the MSS.

We showed in a quantitative manner (total retrrieval error, DOF, RID, SF) the effects of the combination of measurements of O_3, HNO_3 Water Vapor and Temperature acquired by MIPAS-STR and MARSCHALS in the Arctic UTLS during the PREMIEREX flight from Kiruna, Sweden on March 10^{th}, 2010.

We demonstrated the applicability of the MSS data fusion method to combine two sets of individual products by using Tikhonov-Phillips regularization.

We demonstrated the better performance of the MSS method compared to the (L1+L2) method of data fusion.

A paper reporting the results of the study is currently being finalised for submission to AMTD.