TOWARDS THE TEMPERATURE RETRIEVAL BY USING AIRBORNE MICROWAVE RADIOMETER DATA

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ABSTRACT

Atmospheric temperature is a key geophysical parameter when dealing with the atmosphere in areas such as climatology and meteorology. In general, thermal emissions of molecular lines (e.g. oxygen, carbon dioxide) can be used for the determination of the temperature profile. The superheterodyne radiometer MTP (Microwave Temperature Profiler) passively detects thermal emission from oxygen lines at a selection of frequencies between 55–60 GHz by scanning the atmosphere from near zenith to near nadir in the flight direction. The MTP instrument was designed to observe the vertical temperature distribution over the upper troposphere and lower stratosphere (UTLS) with a good temporal and spatial resolution. The instrument was originally developed at NASA's JPL and has been recently flown on DLR's HALO research aircraft.

To estimate the temperature profile from microwave measurements (e.g. provided by MTP), the retrieval algorithm TIRAMISU (Temperature Inversion Algorithm for Microwave Sounding) has been developed at DLR and is currently used to conduct the data processing of the MTP measurements. This study performs the retrievals from the MTP data with a focus on the ML-CIRRUS mission. The corresponding retrieval performance is investigated by associated error characterization and external comparisons with other ground-based and satellite observations. These observations are important to resolve a variety of phenomena in the UTLS region and to potentially improve the temperature spaceborne soundings.

Key words: ill-posed inverse problem, atmospheric retrieval, MTP.

1. INTRODUCTION

Atmospheric temperature is a key geophysical parameter when dealing with the atmosphere in areas such as climatology and meteorology. In general, thermal emissions of molecular lines (e.g. oxygen, carbon dioxide) can be used for the determination of the temperature profile. The airborne radiometer MTP (Microwave Temperature Profiler) [1, 2], originally designed by NASA's JPL, passively detects thermal emission from oxygen lines at a selection of frequencies between 55–60 GHz by scanning the atmosphere from near zenith to near nadir in the flight direction. The objective of the MTP instrument was to observe the vertical temperature distribution over the upper troposphere and lower stratosphere (UTLS) with a good temporal and spatial resolution. The instrument has been involved in hundreds of campaigns and been recently flown on the HALO research aircraft operated by DLR.

A typical MTP measurement cycle consists of 30 brightness temperature measurements with respect to 3 frequencies and 10 viewing angles. The HALO-MTP instrument uses local oscillator (LO) frequencies of 56.363, 57.612, and 58.363 GHz.

In this work, the retrieval algorithm dedicated to MTP is introduced in Sect. 2. In particular, the corresponding retrieval performance using various regularization schemes is investigated. In Sect. 3, we present the recent retrievals from the ML-CIRRUS campaign which took place in Spring, 2014.

2. METHODOLOGY

The reconstruction of vertically distributed temperature profile $\boldsymbol{x} \in \mathbb{R}^n$ from noise-contaminated MTP observations $\boldsymbol{y}^\delta = \boldsymbol{y} + \boldsymbol{\delta} \in \mathbb{R}^m$ is a nonlinear ill-posed inverse problem and can be solved by minimizing the following objective function

$$\mathcal{F}(\boldsymbol{x}) = \left\|\boldsymbol{F}(\boldsymbol{x}) - \boldsymbol{y}^\delta\right\|^2 + \lambda \left\|\mathbf{L}(\boldsymbol{x} - \boldsymbol{x}_\mathrm{a})\right\|^2 , \quad (1)$$

where $\mathbf{L}$ and λ are the regularization matrix and the regularization parameter, respectively, $\boldsymbol{x}_\mathrm{a}$ is the a priori state vector, and the mapping $\boldsymbol{F} : \mathbb{R}^n \to \mathbb{R}^m$ is the forward model. The residual term $\left\|\boldsymbol{F}(\boldsymbol{x}) - \boldsymbol{y}^\delta\right\|^2$ quantifies the goodness of fit, whereas the penalty term $\|\mathbf{L}(\boldsymbol{x} - \boldsymbol{x}_\mathrm{a})\|^2$ measures the regularity of the solution.

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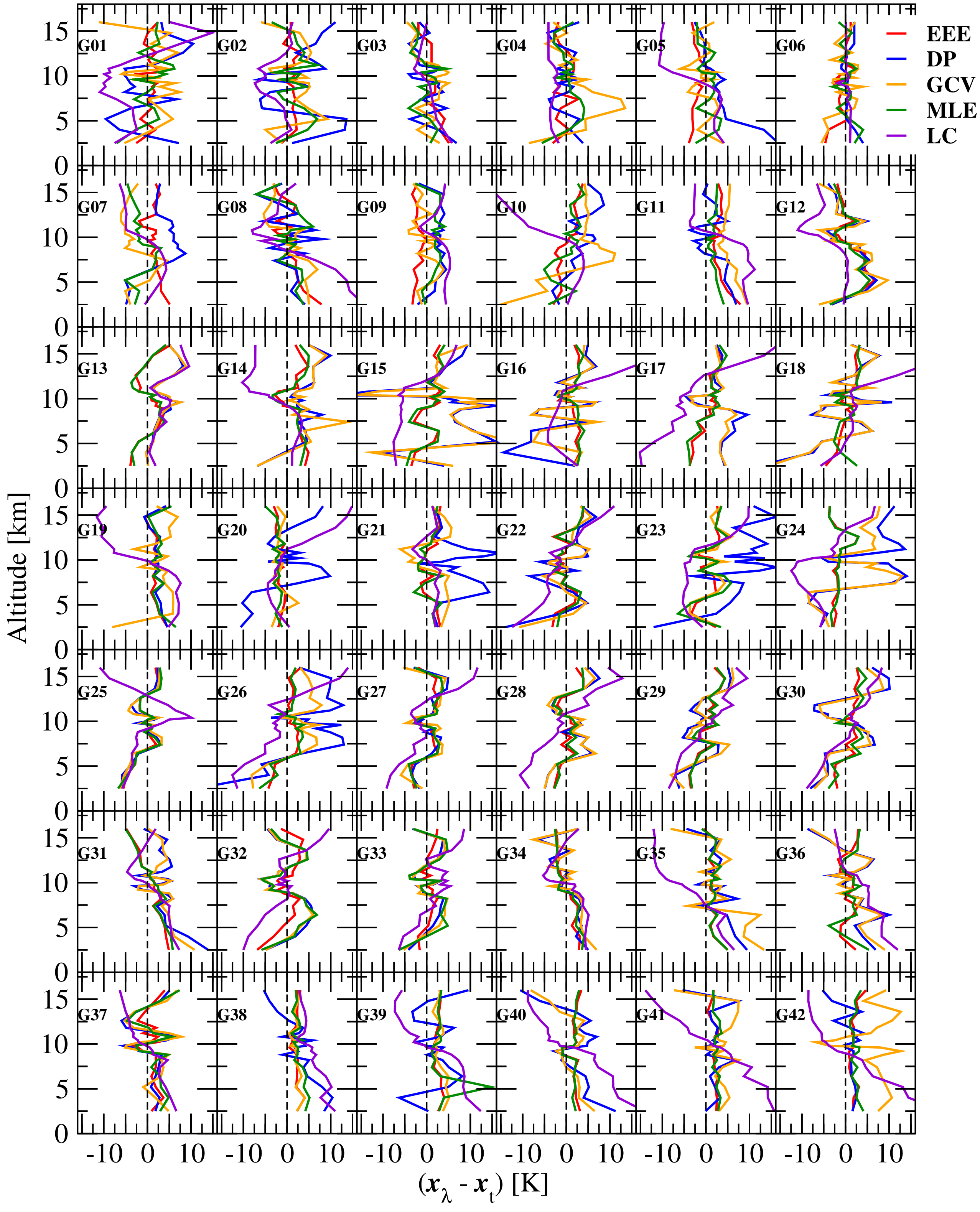

Figure 1. Comparison of retrieved temperature profiles with exact profiles as a function of altitude for five regularization parameter selection methods. Synthetic MTP data were generated with 42 Garand atmospheres [3] and the noise standard deviation $\sigma = 0.1$. The plotted altitude range of 2.5–16 km *is the altitude range which can be observed by MTP with confidence. The retrieval beyond this altitude range has little physical meaning.*

The goal of the minimization is to reach an compromise between the penalty term and the residual term. Thus, the selection of the regularization parameter λ is important in the Tikhonov-type regularization framework and can be conducted by various selection methods, e.g. the expected error estimation (EEE), the discrepancy principle (DP), the generalized cross-validation (GCV), the maximum likelihood estimation (MLE), and the L-curve (LC). In Fig. 1, we compare the retrieval performance of these five regularization parameter selection methods using synthetic MTP data. EEE and MLE surpass the other methods in terms of the inversion accuracy.

Since the estimation of a proper λ in direct regularization methods is not a trivial task which may require considerable computational effort, iterative regularization methods can be considered as a promising alternative as it simplifies the λ-selection and still obtains reasonable solution regardless of overestimations of initial λ. In the so-called iteratively regularized Gauss–Newton method, the iterative solution can be computed as

$$\boldsymbol{x}_{\lambda,i+1} = \boldsymbol{x}_{\mathrm{a}} + \mathbf{K}_{\lambda,i}^{\dagger} \left(\boldsymbol{y}^{\delta} - \boldsymbol{F}(\boldsymbol{x}_{\lambda,i}) + \mathbf{K}_i(\boldsymbol{x}_{\lambda,i} - \boldsymbol{x}_{\mathrm{a}}) \right), \tag{2}$$

where $\mathbf{K}_{\lambda}^{\dagger} = (\mathbf{K}^T\mathbf{K} + \lambda\mathbf{L}^T\mathbf{L})^{-1}\mathbf{K}^T$ is the regularized generalized inverse based on the Jacobian matrix $\mathbf{K}$.

A new retrieval code TIRAMISU (Temperature InveRsion Algorithm for MIcrowave SoUnding) has been developed at the Remote Sensing Technology Institute of DLR and is currently being applied to analysis of the MTP measurements. The retrieval algorithm is adapted from GARLIC (Generic Atmospheric Radiation Line-by-line Infrared Code) [4] and PILS (Profile Inversion for Limb Sounding) [5]. Additionally, the evaluation of Jacobians is conducted by an automatic differentiation tool [6].

3. RESULTS AND DISCUSSIONS

This study placed an emphasis on the ML-CIRRUS campaign that took place between 26 March and 15 April 2014. The objective area was cirrus and contrail cirrus in the mid latitude tropopause region in Europe and the North Atlantic. The corresponding results are important to resolve a variety of phenomena in the UTLS region and to potentially improve the spaceborne temperature soundings.

The state vector $\boldsymbol{x}$ comprises the temperature profile and a polynomial for baseline offset. The a priori information was taken from the US standard profile. Since the aircraft height was changing during the whole flight, the retrieval grid was also dynamically configured and was discretized densely close to the instrument and coarsely far from the instrument.

Fig. 2 depicts first retrieval results from a morning flight which took place on 11 April 2014 over Great Britain. As the aircraft was ascending gradually, we obtained more

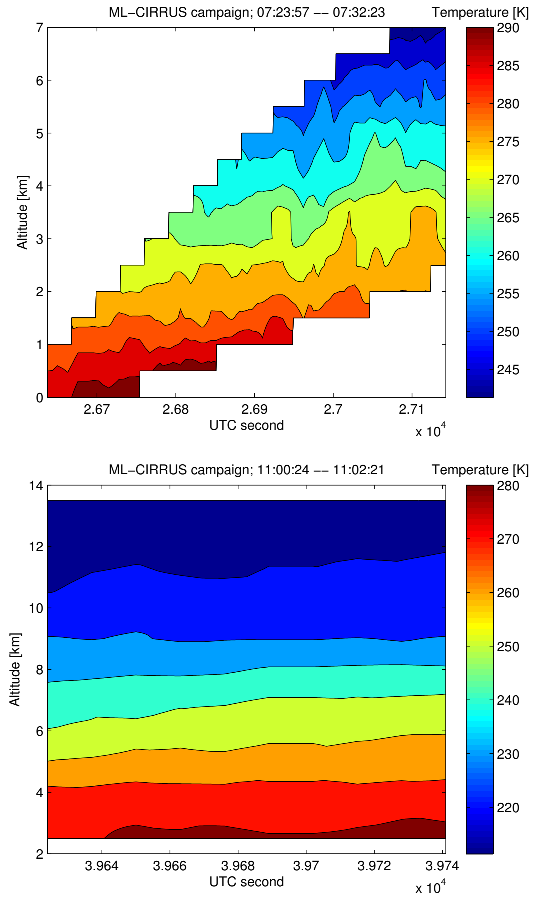

Figure 2. Retrieved atmospheric temperature with respect to altitude and measuring time (UTC second). The retrievals were done for the morning data from the ML-CIRRUS flight on 11 April 2014.

vertical information accordingly, as inferred from the left panel of Fig. 2. The variations between each temperature profile may be due to the fact that the instrument was in a warming-up stage and had not been fully stable. The right panel of Fig. 2 shows that these variations turn out to be much smaller as the instrument was in a stable status.

Fig. 3 compares the modeled intensities after convergence with the observed ones for a cycle of the MTP data. Overall, both intensities reach an agreement except a few discrepancies at 55°. It can be seen that the retrieval achieves a reasonable fit to the measured data.

Fig. 4 shows a comparison of the retrieved temperature profile from the MTP data by TIRAMISU and JPL. The JPL retrieval was carried out by an approach based on the Bayesian statistical method [7]. Additionally, two climatological profiles from ECMWF and NCEP datasets are included. As the JPL retrieval depends highly on the ECMWF profile and other ground-based observations, the retrieved JPL profile looks almost identical to the ECMWF profile. The retrieval processed by TIMIRASU shows oscillations around 10 km and large deviations from the other profiles below 5 km. This can

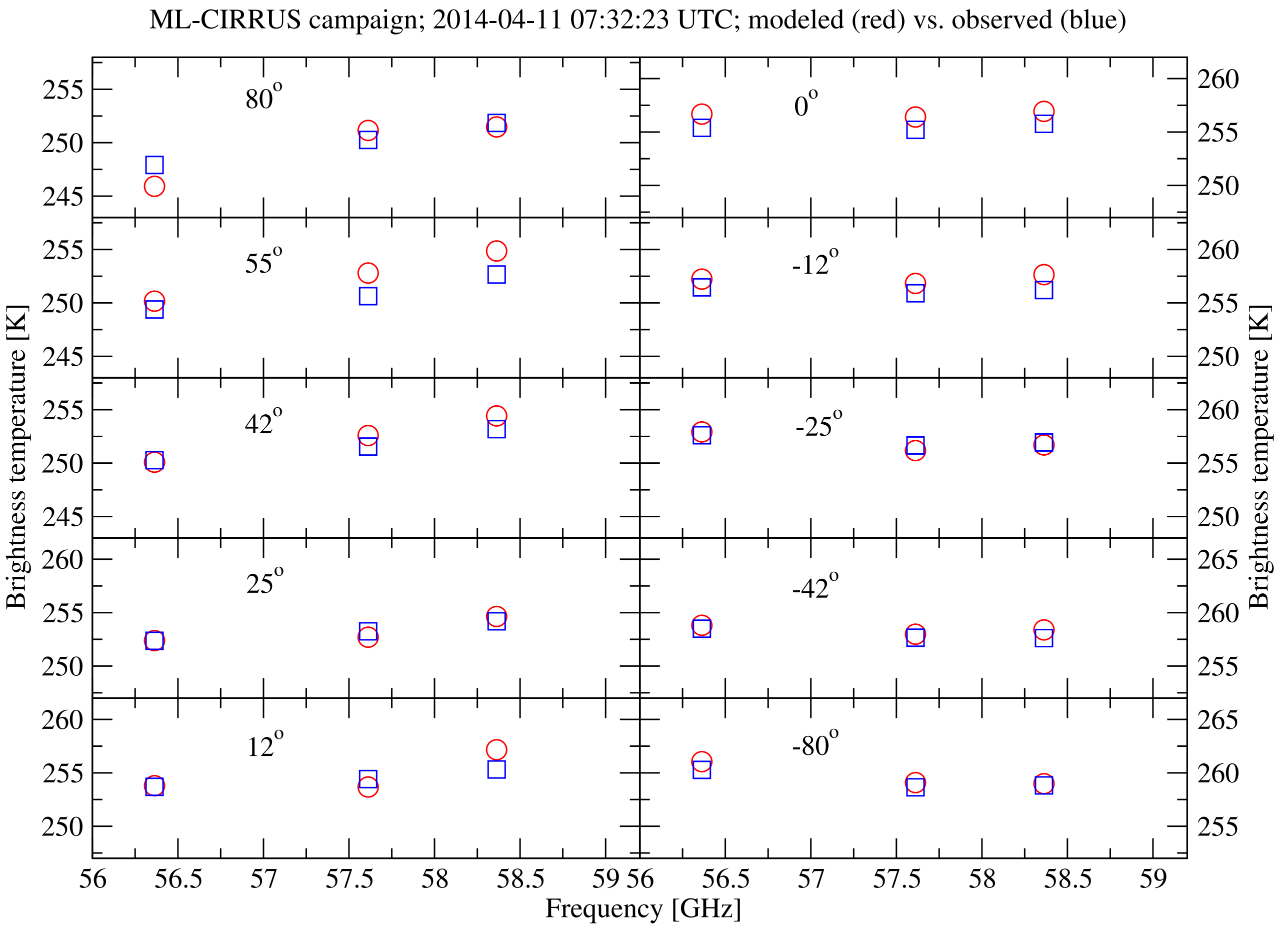

Figure 3. Comparison of the modeled intensities after convergence with the observed intensities for one cycle of the MTP data which was measured in the ML-CIRRUS campaign. 10 viewing angles related to the horizon are indicated in each subfigure.

be due to the configuration of the retrieval grid used by TIRAMISU and lack of useful information at lower altitudes. We may conclude that the TIRAMISU retrieval reaches an agreement with the other profiles, although the corresponding error analysis could be helpful in understanding the above-mentioned discrepancies.

4. CONCLUSIONS

We have presented a retrieval code TIRAMISU dedicated to the Level-2 processing of the MTP measurements. The algorithm is based on a nonlinear least squares fitting framework constrained by Tikhonov-type regularization.

First retrieval results from a ML-CIRRUS campaign in Spring 2014 have been shown, revealing that the MTP instrument is capable of detecting the temperature variations in the troposphere over a local region. The residual after convergence indicates that the current retrieval achieves a good fit and the retrieved profile seems reasonable.

The corresponding error characterization will be the next work focus. Ongoing efforts to improve the MTP retrievals are currently focusing on modernizing/optimizing the retrieval software. Furthermore, an intercomparison of the inversion performance between TIRAMISU and the Bayesian statistical method will be conducted. Ground-based observations and in-situ profiles using dropsondes will be used to validate the MTP results.

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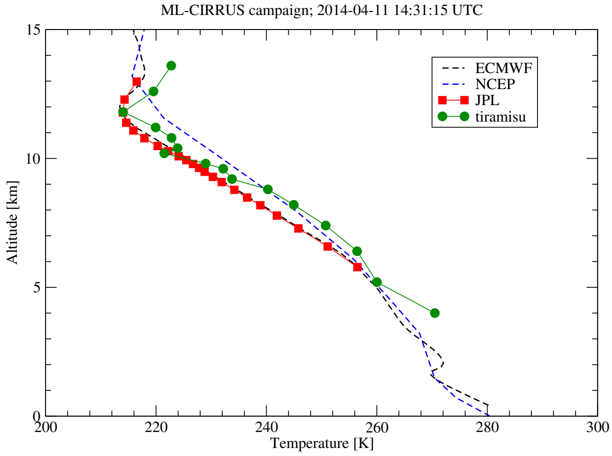

Figure 4. Comparison of retrieved temperature profile with the JPL retrieval and other two climatological profiles. The comparison was done for an example of the afternoon data from the ML-CIRRUS flight on 11 April 2014.

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