RETRIEVAL OF ATMOSPHERIC TEMPERATURE FROM AIRBORNE MICROWAVE RADIOMETER OBSERVATIONS

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ABSTRACT

Atmospheric temperature is a key geophysical parameter associated with fields such as meteorology, climatology, or photochemistry. There exist several techniques to measure temperature profiles. In the case of microwave remote sensing, the vertical temperature profile can be estimated from thermal emission lines of molecular oxygen. The MTP (Microwave Temperature Profiler) instrument is an airborne radiometer developed at the Jet Propulsion Laboratory (JPL), United States. The instrument passively measures natural thermal emission from oxygen lines at 3 frequencies and at a selection of 10 viewing angles (from near zenith to near nadir). MTP has participated in hundreds of flights, including on DLR's Falcon and HALO aircrafts. These flights have provided data of the vertical temperature distribution from the troposphere to the lower stratosphere with a good temporal and spatial resolution. In this work, we present temperature retrievals based on the Tikhonov-type regularized nonlinear least squares fitting method. In particular, Jacobians (i.e. temperature derivatives) are evaluated by means of automatic differentiation. The retrieval performance from the MTP measurements is analyzed by using synthetic data. Besides, the vertical sensitivity of the temperature retrieval is studied by weighting functions characterizing the sensitivity of the transmission at different frequencies with respect to changes of altitude levels.

Key words: inverse problems, temperature retrieval, microwave, airborne MTP.

1. INTRODUCTION

For infrared and microwave remote sensing, the vertical temperature profile can be derived from thermal emission lines such as CO or O_2. In the case of microwave radiation, a standard approach is to retrieve the temperature profile by analyzing spectra of oxygen molecules. On the one hand, oxygen molecules are highly absorptive and emissive between 50 GHz and 1 THz (see the left panel of Fig. 1). The lines at the lower frequencies are due to spin flip transitions at different rotational levels and almost all of these lines lie around 60 GHz. Because the molecular abundances of oxygen are well-known and constant, one can deduce the physical temperature of the molecules that generates this emission. On the other hand, microwave emission sounding techniques have the advantage that they are independent of the external source and are nearly unaffected by the presence of clouds and aerosols.

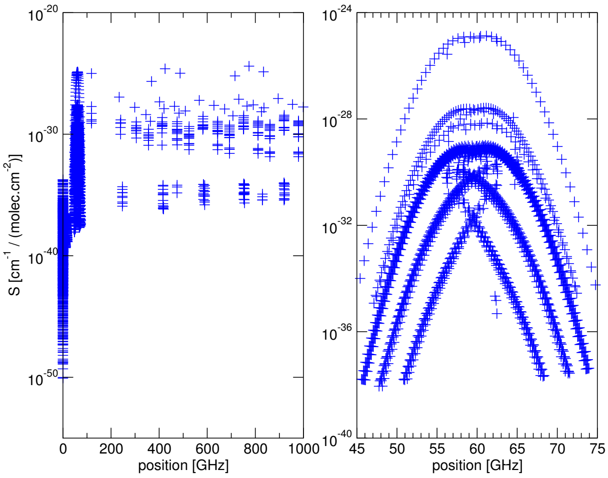

Figure 1. Oxygen lines in the spectral range of 0–1 THz *(left) and 45–75* GHz *(right).*

The MTP (Microwave Temperature Profiler) instrument [1] initially developed at the Jet Propulsion Laboratory (JPL) was designed to be a radiometer which passively detects natural thermal emission from O_2 lines at selected frequencies and at a range of viewing angles. The instrument has been utilized on hundreds of flights, including on DLR's Falcon and HALO aircrafts. MTP was designed to deliver altitude-dependent temperature profiles throughout an altitude range in the upper troposphere and lower stratosphere (UTLS) by measuring the thermal radiation emitted by oxygen molecules at frequencies ranging from 55 to 60 GHz.

The goal of this paper is to discuss retrieval feasibility of vertical temperature profiles from synthetic airborne MTP data and to investigate potential instrument capabilities. An overview of the MTP measurement and the theoretical background of the retrieval algorithm are also given.

2. MTP OVERVIEW

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. The atmosphere is probed by the airborne instrument from near zenith to near nadir in the flight direction by using a scanning mirror to change the viewing angle.

The right panel of Fig. 1 shows the thermal O_2 emission lines which are considered by MTP. As can be seen from the figure, O_2 transitions are dominant over this spectral range and there is no significant contributions from other interfering molecules, which makes it easy for retrieving temperature profile.

3. RETRIEVAL METHODOLOGY

3.1. Methodology

TIRAMISU (Temperature InveRsion Algorithm for MIcrowave SoUnding) has been developed at the Remote Sensing Technology Institute of DLR and will be applied to analysis of the MTP measurements. The retrieval code is adapted from PILS (Profile Inversion for Limb Sounding) [2] and consists of a forward model based on GARLIC [3] and a regularized nonlinear least squares inversion framework.

The forward model $\boldsymbol{F}$ manages to simulate atmospheric radiative transfer by means of Schwarzschild equation in an efficient manner. The exact Jacobians $\mathbf{K}$ are delivered by means of automatic differentiation (AD) [4, 5]. [6] claimed that AD Jacobians are advantageous in terms of algorithmic efficiency, ease of implementation, and accuracy as compared to finite difference Jacobians.

The inversion algorithm relies on Tikhonov-type regularization methods for reconstruction of vertical temperature profile $\boldsymbol{x}$ from noisy MTP measurement $\boldsymbol{y}^\delta$. The iterative solution can be evaluated by the iteratively regularized Gauss–Newton method:

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

where $\mathbf{K}^\dagger_\lambda = (\mathbf{K}^T\mathbf{K} + \lambda\mathbf{L}^T\mathbf{L})^{-1}\mathbf{K}^T$ is the regularized generalized inverse. $\boldsymbol{x}_\mathrm{a}$ is the a priori state vector which is essentially composed of climatology knowledge. In this method, the regularization parameter λ is defined as a monotonically decreasing sequence, and therefore, the regularization strength is gradually decreased during the iteration. One main advantage of this iterative regularization method is that the computational effort on determining the proper λ is reduced.

3.2. Weighting function

Weighting functions are used as a quantitative measure which describes how different altitude regimes contribute to the measured signal.

$$W(z,f) = -\frac{\partial \mathcal{T}}{\partial z} \tag{2}$$

In the context of temperature sounding, weighting functions have been widely used in order to study the retrieval sensitivity. In Fig. 2, the weighting functions for these three LO frequencies with respect to the viewing angles are plotted. The maximum lies at the bottom of the atmosphere when the instrument detects the atmosphere downwards, whereas the maximum lies between the upper troposphere and lower stratosphere when the instrument looks upwards.

4. RETRIEVAL RESULTS

To investigate the numerical performance of temperature retrievals, we have carried out the test retrievals based on different types of measurement. The test retrievals are performed using synthetic MTP data and real TELIS data.

4.1. TELIS test

TELIS (TErahertz and submillimeter LImb Sounder) [7] is a cryogenic multi-channel heterodyne spectrometer designed to investigate atmospheric chemistry and dynamics with an emphasis on the stratosphere (10–40 km). The instrument measures vertical distribution of temperature by measuring O_2 transitions around far infrared and submillimeter spectral range. The TELIS data used in this study are taken from the TELIS submillimeter channel. In the upper panel of Fig. 3, a retrieval from the synthetic TELIS data is presented. Apart from small discrepancies at lower altitudes due to regularization, an overall good agreement is reached between the retrieved and the true profiles. In the bottom panel of Fig. 3, the temperature profile retrieved from one limb sequence which was measured on 24 January 2010, is compared against the MIPAS-B retrieval. Likewise, the major difference between both profiles is found at lower altitudes.

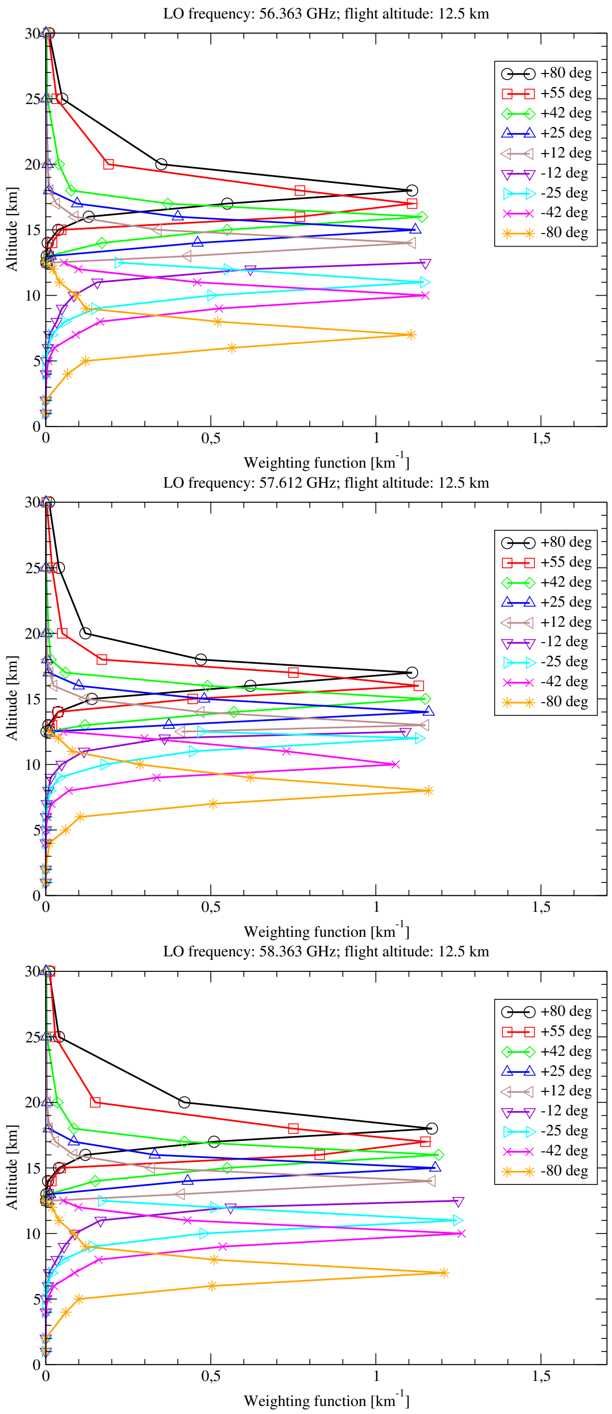

Figure 2. Weighting functions for LO frequency of 56.363, 57.612, and 58.363 GHz

4.2. MTP test

The MTP test considers the temperature retrieval from synthetic MTP data based on actual configuration. The altitude grid is non-equidistant and the altitude steps close to the aircraft are 500 m whereas the others far from the aircraft are 1 km. A denser step size is used for altitude levels that are close to the aircraft where the MTP measurements comprise most useful information. To examine the effect of the a priori information on the retrieval product, we use two different a priori knowledge setup. The results show that the retrieval quality is promising despite some oscillations around the denser grid part. Even with the constant a priori, the retrieval is reasonable. The oscillations can be due to insufficient number of measurements, leading to a underdetermined inverse problem.

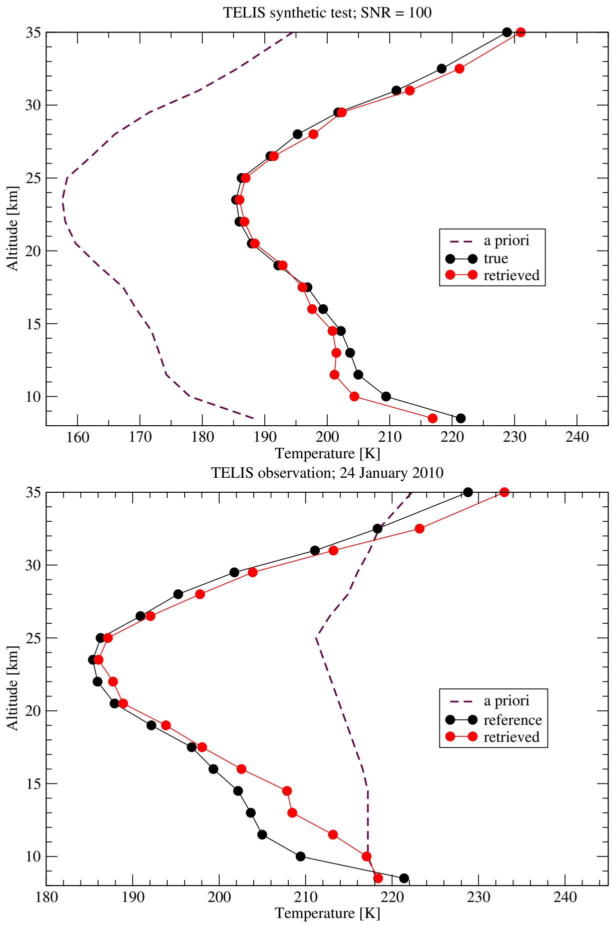

Figure 3. Temperature retrievals from TELIS data.

5. CONCLUSIONS

Theoretical and practical aspects of temperature retrievals from synthetic MTP data have been discussed. The inversion algorithm is built on a line-by-line forward model and regularized nonlinear least squares fitting. The iterative regularization scheme has been implemented to avoid much computational burden for estimating the proper regularization parameter.

According to the retrieval tests using TELIS and MTP measurements, the inversion performance is reasonable and the study will be further investigated based on real MTP measurements.

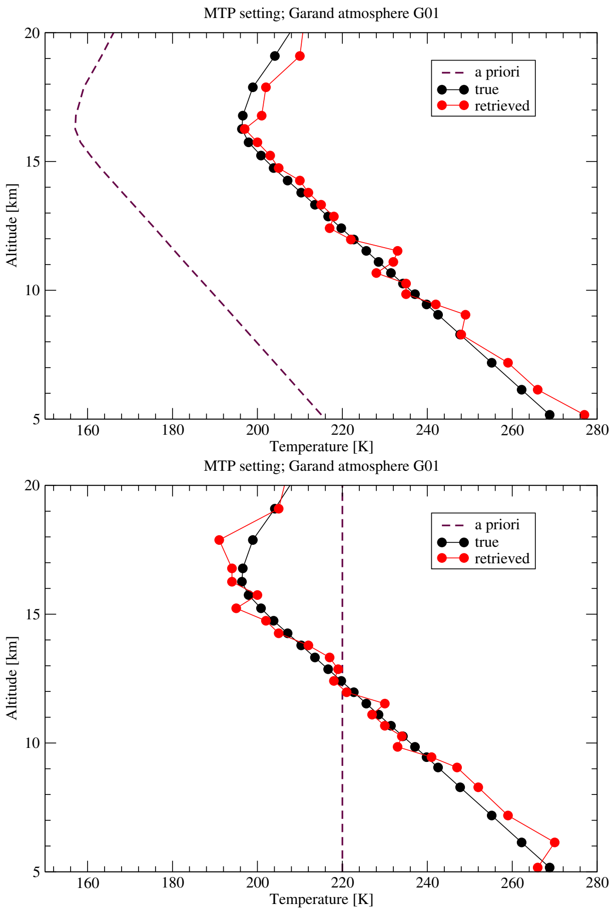

Figure 4. Temperature retrievals from synthetic MTP data.

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