Balanced Calibration Technique with an Internal Reference Load for Ground Based Millimeter Wave Radiometry

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Abstract – A new balanced calibration technique for ground based radiometric detection of millimeter wave atmospheric spectra with very high intensity resolution is presented. It is based on an internal adjustable reference load. The working principle of this load will be explained and proved by the verification results. Main advantages of this new technique such as a significantly enhanced signal to noise ratio as compared with the reference beam method are discussed in some detail.

INTRODUCTION

By evaluation of pressure broadened atmospheric emission spectra in the millimeter wave range it is possible to determine the vertical volume mixing ratio profiles of several trace gases including, among others, water vapor, ozone and chlorine monoxide. For the detection of these spectra sensitive millimeter wave radiometers are needed which provide sufficiently high resolution for both frequency and amplitude.

The demand for high amplitude resolution entails a frequent calibration, which serves the suppression of fluctuations in the system gain. The use of a two point calibration method, like the hot-cold calibration, leads to noiselike artifacts in the measured spectra, due to nonlinear effects in the system gain, which commonly differs from one spectral channel to another. This obstructs the detection of weak spectral lines. To avoid the influence of such systematic effects, balanced calibration techniques are applied. In opposite to the hot-cold calibration, which uses reference loads with fixed brightness temperatures, the balanced method uses a variable load, which brightness temperature is permanently adjusted to equate the intensity received from the atmosphere.

Up to now the most established technique for balanced calibration was the reference beam method as described in [4], which uses a second observation path in the atmosphere seen through a lossy dielectric slab. The technique presented in this paper is based on a internal reference load first presented in [1].

INTERNAL REFERENCE LOAD

The variable reference load uses a quasioptical polarizing beam splitter with an adjustable splitting ratio. The radiation coming from a cold and a hot load is superimposed on a rotatable wire grid as shown in Fig. 1. The plane

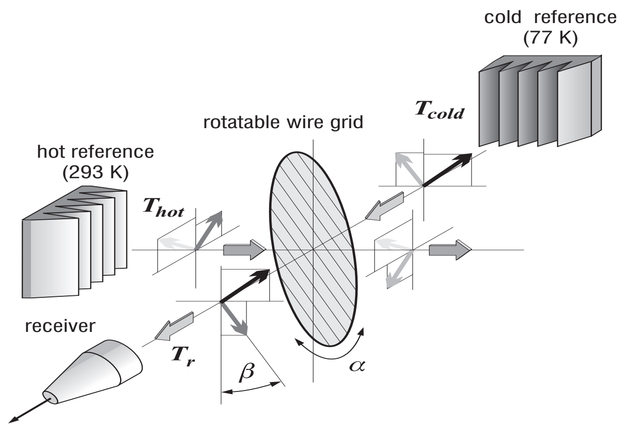

Fig. 1: Setup of the variable reference load.

of the grid is arranged at 45° with respect to the optical axis, therefore it acts as a reflector for the radiation coming from the hot load whereas the cold load is seen in transmission through the wire grid. The brightness temperature as seen in a single polarization thus depends on the angle α the wires close with the vertical axis.

Assuming a lossless wire grid ($r_{\parallel} \approx 1$, $t_{\parallel} \approx 0$, $r_{\perp} \approx 0$, $t_{\perp} \approx 1$), which is still a good approximation for the used grid, one yields for the superimposed brightness temperature T_r (in vertical polarization) from elementary geometrical considerations

$$T_r = T_{cold} \sin^2 \beta + T_{hot} \cos^2 \beta \quad (1)$$

$$T_r = \frac{1}{1+\tan^2 \alpha} \left(2T_{hot} + T_{cold} \tan^2 \alpha\right) \quad (2)$$

where β is the projection of the angle α in the direction of the signal propagation along the optical axis.

The experimental validation of the dependency of the brightness temperature T_r on α shows a very good agreement between the model given by (2) and the measurements, as indicated in Fig. 2. The values for T_r in the upper plot are averages of hot-cold calibrated spectra measured with a 278 GHz radiometer for different angles α. The residuum shown in the lower plot results primarily from nonlinearities, which are not taken into consideration by the hot-cold calibration and from slight inaccuracies in the position of the rotatable wire grid. Nevertheless

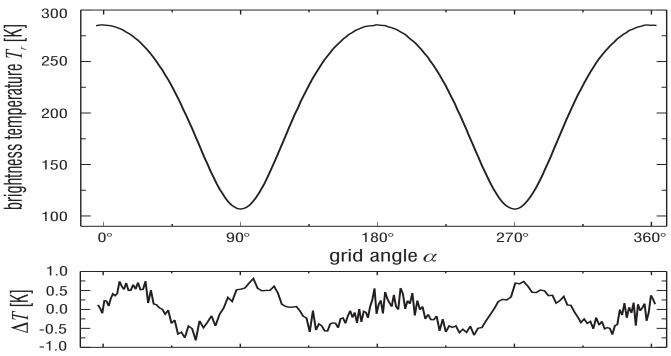

Fig. 2: Verification of the resulting brightness temperature T_r as a function of the grid angle α. Spectral mean values of hot-cold calibrated measurements taken with different grid angles (upper plot); residuum obtained with (2) (lower plot).

the accuracy achieved is still enough for the application as balanced reference load.

BALANCED CALIBRATION

In order to suppress the radiometer gain fluctuations the atmospheric spectra have to be calibrated on the spectra of the reference load every few seconds. The length of the time interval between calibrations depends mainly on the stability of the measurement system and can be determined by measuring the modified Allan-Variance as discussed in [5].

Building the normalized difference ΔM_{sr} between the spectrum M_s measured in the atmosphere and the reference spectrum M_r eliminates the influence of the gain term

$$\Delta M_{sr} = \frac{M_s - M_r}{M_r} \quad . \tag{3}$$

For the absolute assignment between the measured values and the brightness temperature of the atmosphere the hot-cold calibration is still used. Since the gain fluctuations are already suppressed by the balanced calibration the hot-cold calibration is required only in longer time intervals in the order of ten minutes.

The true atmospheric spectrum T_{atm} will be determined from

$$T_{atm} = \Delta M_{sr} \left(\overline{T_r} + T_{rec}\right) + \overline{T_r} \quad , \tag{4}$$

where T_r denotes the reference spectrum and T_{rec} the spectrum of the system noise temperature. The reference load should behave like an perfect black body, thus in the observation bandwidth of 1 GHz its spectrum is assumed independent of the frequency and averaged values can be used. The vertical profiles of the volume mixing ratio of the emitting gases are retrieved from T_{atm} by the treatment as described in detail in [3].

At first sight still using the hot-cold method for the absolute calibration is in contradiction to the intention of the balanced calibration namely to avoid the systematic errors due to nonlinearities in the system gain. Careful analysis, however, shows that residual nonlinearity errors appearing by the balanced calibration and errors arising by the determination of T_{rec} and T_r by means of hot-cold calibration are opposite in their sign and compensate partial one another [2]. Thus the resulting error became very weak.

As shown in [2] the new technique is also suitable for observations of stronger signatures. Even though the balance between the signal and reference spectrum near the line center is not given, the resulting error is still better then using the hot-cold method only.

PROPERTIES OF THE INTERNAL LOAD METHOD

The use of a black body based adjustable load as balanced reference allows the relatively simple evaluation of measured data, as shown in the previous section, and has several advantages. A comparison with the treatment needed by the method based on an additional observation path in the atmosphere gives a good reference for it.

Supposed is a single signature to be measured. Because of the residual spectral line in the reference spectrum, which is an attenuated atmospheric spectrum with an additional amount contributed by the thermal emission of the dielectric slab, the normalized difference ΔM_{sr} contains a net spectral line. The net line has first to be properly scaled to achieve the true spectral line. This is performed using the corresponding air-mass factors as follows

$$T_{lz} = \Delta M_{sr} \left(T_r + T_{rec}\right) \frac{1}{A_{ss} \mathrm{e}^{-A_{ts}\tau_z} - A_{sr} \mathrm{e}^{-A_{tr}\tau_z} \mathrm{e}^{-\tau_d}} \tag{5}$$

where T_{lz} is the spectral line as would be seen in zenith direction without the presence of the troposphere, A_{ss} and A_{ts} are the air-mass factors of the stratosphere (index s) and the troposphere (index t) respectively seen in the real observation path, A_{sr} and A_{tr} are the corresponding air-mass factors for the reference observation path, τ_z is the tropospheric opacity in zenith direction and τ_d the opacity of the dielectric slab used in the reference path. The difficulty of the evaluation lie by the air-mass factors, which in general are dependent of the height in the atmosphere. In (5) the dependency on the height is not considered, thus proper chosen values, especially for A_{ss}, have to be used. This of course give rise to some systematic errors.

The weighty consequence resulting from the residual spectral line in the reference beam is a degradation in the signal to noise ratio because the net spectral line is still weaker than the real spectral line as it is observed in the signal path. To quantify this effect a contrast factor γ is defined

$$\gamma = \frac{T_s - T_r}{T_{lz}} \quad , \tag{6}$$

where T_s denotes the atmosphreic spectrum as could be measured in the signal path. The division by T_{lz} makes γ

independent of the intensity of the observed line. Applied for the reference beam method yields

$$\gamma_{bs} = A_{ss} e^{-A_{ts}\tau_z} - A_{sr} e^{-A_{tr}\tau_z} e^{-\tau_d} \tag{7}$$

and for the new technique with a variable load

$$\gamma_{vl} = A_{ss} e^{-A_{ts}\tau_z} \quad . \tag{8}$$

In Fig. 3 the contrast factors for both methods are computed for different observation conditions represented by the different water vapor column amounts, which affects strongly the line intensities observed on the ground. The amount of 100 percent is corresponding to the standard winter atmosphere for mid altitudes. By the computation of the contrast factor for the reference beam method a zenith elevation angle of 90° and an optimal dielectric slab was still assumed for the balance. This results in slight higher values for the contrast factor γ_{bs} as would be encountered by practical measurements, where the balance is adjusted by the modification of the signal path observation angle.

It is evident that the new technique offers still a better contrast values in particular under less favorable atmospheric conditions. This extends the available period for measurements of gases with weak spectral signatures, which until now could only be measured under excellent atmospheric conditions. Also the dependency on the elevation angle is stronger by the reference beam method, thus the angle for observation have to be chosen more carefully to achieve good contrast values.

It has be mentioned that an important consideration for the application of the reference beam method is no significant difference existing between the composition and the state of the atmospheric volumes seen in the signal and in the reference path. Any deviations from this consideration give rise to additional systematic errors.

The most important consideration for the new technique is the excellent spectral quality of the applied adjustable load. As could be seen from (4) each deviation from the black body behavior is transferred as systematic error into the final result namely T_{atm}. Thus a very careful design and realization of the applied load is advisable.

CONCLUDING REMARKS

The new balanced calibration technique is already successful used by two polar measurement campaigns in Kiruna (1996, 67.8°N, 20.4°E) and in Ny-Ålesund (1997, 78.9°N, 11.9°E) where primarily spectra of chlorine monoxide near 278 GHz are measured. The excellent results obtained supply the evidence for the effectiveness of this technique.

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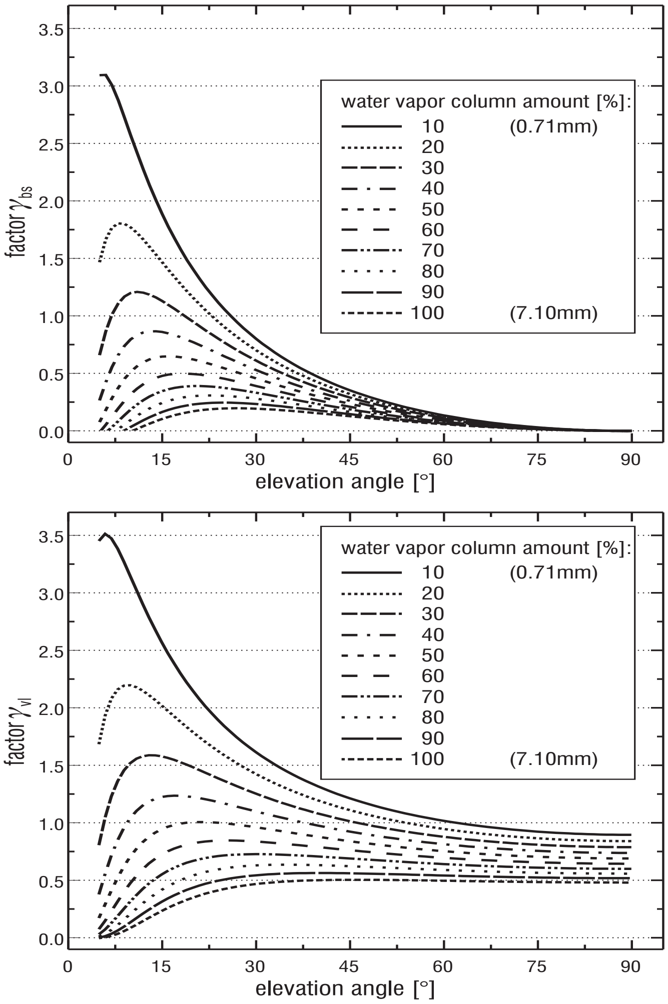

Fig. 3: Comparison of the contrast factors for the reference beam method (upper plot) and internal reference method (lower plot) computed for different water vapor column amounts.

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