A Variable Reference Load for Advanced Millimeterwave Radiometry

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Abstract – A variable reference load which provides any necessary brightness temperature in the range from the cryogenic to the ambient temperature is presented. This reference is primarily intended for calibration of radiometric measurements with high temperature resolution. Experimental validation of the tuning characteristic as well as measurements of stratospheric trace gases are included.

Introduction

Measurements performed by millimeterwave radiometers require a calibration using well known reference loads. This is necessary in order to assign the measured intensities to absolute brightness temperatures. Typically the brightness temperatures of the references used form the edges of the measurement range; therefore there is a cold reference for the lowest and a hot reference for the highest temperatures to be measured. This method is called *hot-cold calibration*. Because of unavoidable instabilities and drifts in the system gain it is necessary to perform such calibrations frequently to minimize the influence of system fluctuations on the results.

In the hot-cold calibration procedure a linear dependency of the measured power M_{obj} on the brightness temperature of the observed object T_{obj} is assumed:

$$M_{obj} = GkB(T_{obj} + T_{rec}) \qquad (1)$$

where G is the total gain, k the Boltzmann-constant, B the bandwith and T_{rec} the receiver noise temperature.

Fig. 1 contains two spectra measured using the hot-cold calibration method. The upper plot shows the atmospheric spectrum with the ozone-line at 274.478 GHz whereas the lower spectrum is measured on a black body, for which the brightness temperature is chosen close to the atmospheric brightness temperature. Both curves have noise-like disturbances which remain even if the integration time is increased. The shape of these artifacts are very similar in both cases indicating systematic errors (see insert in Fig. 1). These are caused by slight nonlinearities in the system gain which differ from channel to channel of the spectrum. Taking the nonlinearities into account (1) should be rewritten as:

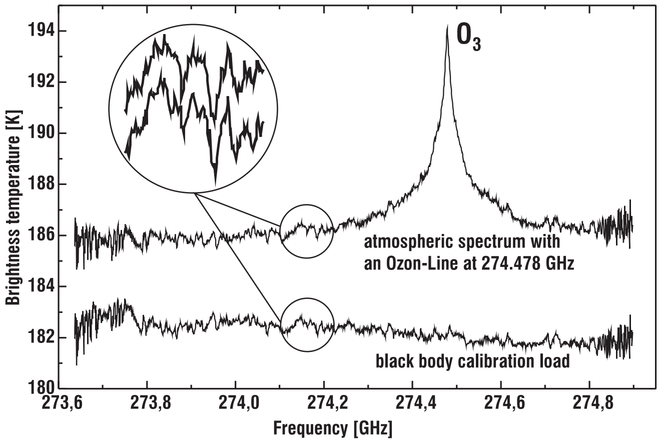

Figure 1: Effects of the nonlinearities on hot-cold calibrated spectra. The spectra are measured in succession within a 1000 s integration time

$$M_{obj} = kB\left\{G(T_{obj} + T_{rec})\right\}^{x}$$

where the exponent x indicates the degree of nonlinearity and is mostly very close to one. It typically differs from channel to channel by about one percent. As indicated in Fig. 2 the error made by neglecting the nonlinearities in the hot-cold calibration is most

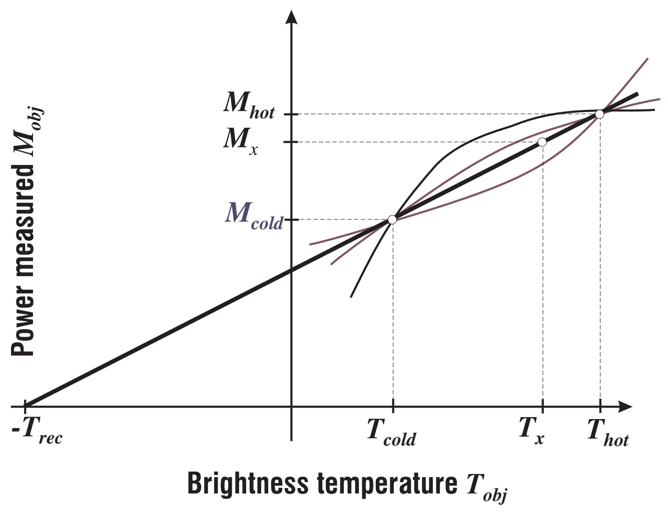

Figure 2: Nonlinearities in the system function.

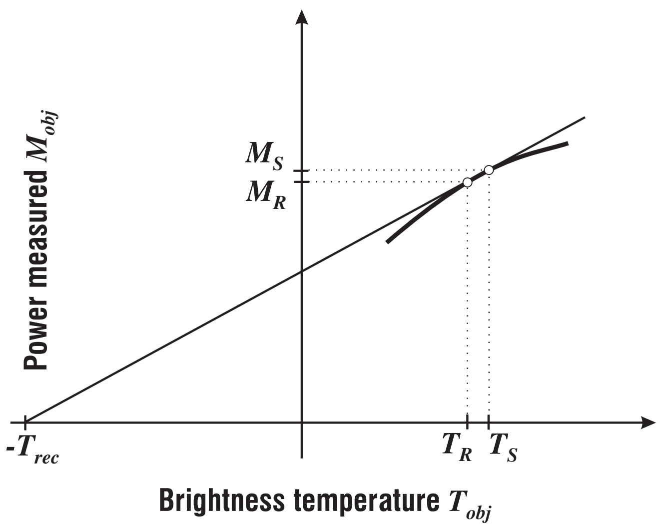

Figure 3: Calibration using a reference load with brightness temperature that is very close to the brightness temperature of the signal to be measured.

significant for intermediate brightness temperatures, far from the calibration points, whereas in the vicinity of the calibration points the errors vanish. In applications where high temperature resolution is needed, as in the case of vertical profile sounding of ClO, disturbances of this magnitude could not be tolerated and therefore a different calibration procedure is required. Fig. 2 suggests that the use of a reference load with brightness temperature very close to the measured brightness will reduce the kind of errors described above.

Balanced Calibration

If the brightness of the reference load is close to the signal brightness, as indicated in Fig. 3, their difference can be expressed as:

$$T_{dif} = T_S - T_R = \frac{M_S - M_R}{M_R}(T_R + T_{rec}). \qquad (2)$$

Assuming a signal coming from the atmosphere which contains the troposheric continuum and several spectral lines and a black body reference signal with a brightness temperature very close to that of the atmosphere, the difference T_{dif} includes all the spectral lines contained in the atmospheric signal whereas the tropospheric continuum is almost removed. Because of changing tropospheric conditions cousing changing atmospheric brightness temperature an adjustable reference load is required, which provides any necessary temperature in order to equalize both the signal and the reference levels.

A well established method using balanced calibration is based on a second path coming from the atmosphere seen through a dielectric lossy slab as described in [6]. The recently applied new method uses the quasioptical variable reference load described here.

Variable reference load

The load is based on the superposition of two signals coming from the cold and from the hot load on a rotatable polarizing wire grid as presented in Fig. 4. The plane 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. Since the receiver of the radiometer is sensitive only to a single polarization, it is possible to adjust the ratio of the contributions of the loads to the superimposed signal T_R by changing the angle α defined in the grid plane between a vertical axis and the direction of the wires.

The grid consists of tungsten wires 5 μm in radius spaced by 25 μm between the wire centers. The power reflexion coefficients $r_{||}$ and $r_{\perp}$ for the plane wave polarized parallel and perpendicular to the wire grids, respectively, can be calculated using the formulas de-

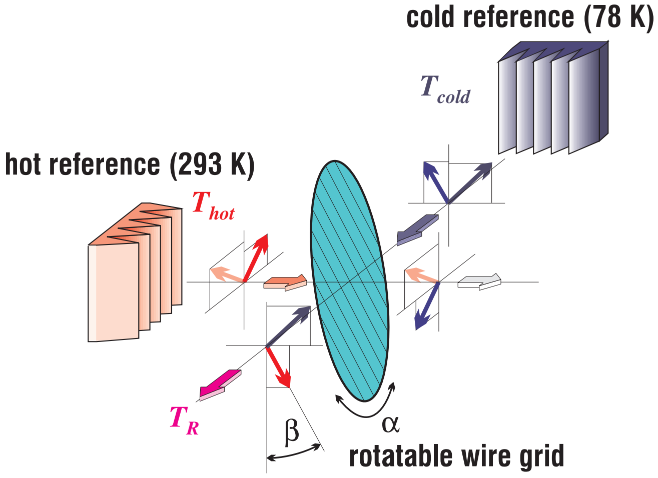

Figure 4: Setup of the variable reference load.

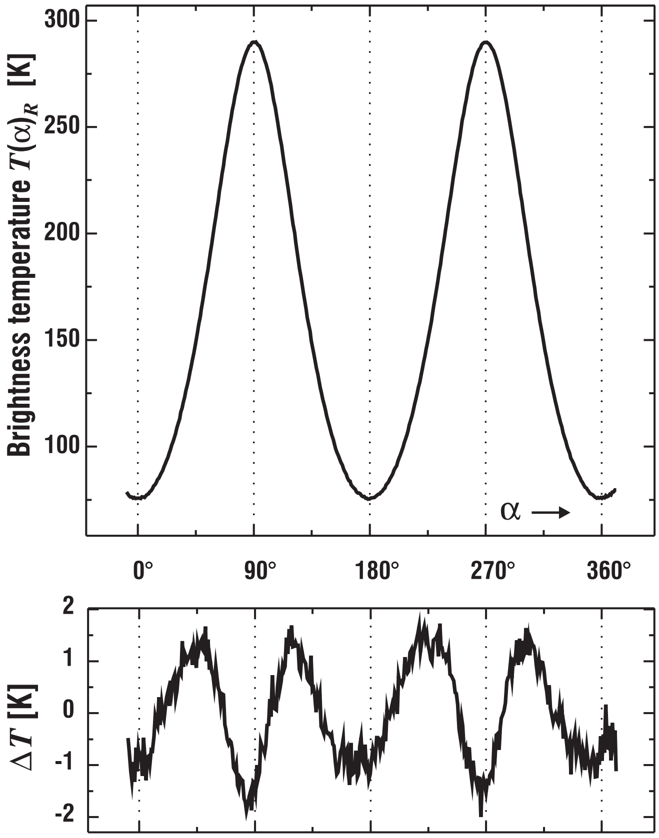

Figure 5: Dependency of the measured brightness temperature of the variable reference load on the grid angle α (upper plot); difference between the measured results an a fit using (4) (lower plot)

rived by Lamb [3]:

$$r_{\|} = \frac{1}{1 + \left(\frac{2d}{\lambda} \ln \frac{d}{2\pi a}\right)^2}$$

and

$$r_{\perp} = \frac{\left(\frac{2\pi^2 a^2}{\lambda d}\right)^2}{1 + \left(\frac{2\pi^2 a^2}{\lambda d}\right)^2},$$

where a denotes the radius and d the spacing of the wires. Inserting the grid parameters and the operating frequency of 280 GHz yields:

$$r_{\|} = 99.9889\% \qquad \text{and} \qquad r_{\perp} = 0.0329\%.$$

This justifies the approximation of $r_{\|}$ by 1 and $r_{\perp}$ by 0 in the further treatment. With some geometrical considerations one finds the dependency of the superimposed brightness temperature T_R on β or α:

$$T_R(\beta) = T_{cold} \cos^2 \beta + T_{hot} \sin^2 \beta \tag{3}$$

$$T_R(\alpha) = \frac{1}{2 + \tan^2 \alpha} \left(2T_{cold} + T_{hot} \tan^2 \alpha\right), \tag{4}$$

where β is the angle of the wires with respect to a vertical axis as seen in the direction of signal propagation along the optical axis.

Experimental validation

To test the validity of this dependency of the superimposed brightness temperature T_R, several series of hot-cold calibrated measurements on the variable reference load are performed at 278 GHz with an instantaneous bandwidth of 1 GHz for different values of angle α. The collected spectra are averaged over all channels (1800) yielding a single value for given α. The results are presented in Fig. 5. In the upper plot the measured brightness temperature is given as a function of α. The lower plot shows the residuum between the measured values and a fitted function given by (4). The difference of about ± 1 K results mainly from the slight frequency dependency of the measured spectra as well as from neglecting the non-linearities by the hot-cold calibration especially at intermediate brightness temperatures. Nevertheless a very good agreement between expected values and measured data is obtained.

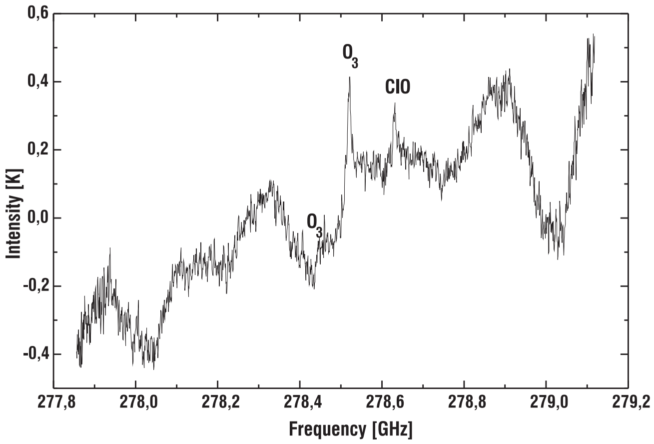

Figure 6: Atmospheric spectrum containing the 278.631 GHz ClO signature taken over 2000 s integration time at Kiruna on March 23, 1996.

Radiometric Measurements

A new radiometer system using this variable reference load was extensively tested under realistic circumstances during the arctic measurement kampaign at Kiruna (68° N) in the winter of 1996. The receiver was a single sideband system with 1200 K noise temperature (SSB) based on a cryogenic cooled single ended Schottky mixer manufactured by Radiometer Physics. The spectrum was measured using an acousto-optical spectrometer operating at 2.1 GHz with a spectral resolution of 1 MHz over an instantaneous IF bandwith of 1 GHz, which has been developed and manufactured at the University of Cologne.

As an example of stratospheric gas measurements Fig. 6 shows a raw atmospheric spectrum calibrated using the variable load containing the very weak ClO signature at 278.631 GHz as well as minor ozone lines. The spectrum is affected by residual baseline ripples due to standing waves in the receiver. Nevertheless the weak lines can be detected because artifacts as typical for hot-cold calibrated data (see Fig. 1) are avoided applying the balanced calibration. Even under conditions of increased chlorine monoxide concentration, the peak intensity of the ClO signature is below 100 mK, and could thus not be detected using hot-cold calibration procedure.

Conclusions

Using the variable reference load and the balanced calibration method, the weak lines of stratospheric trace gases have been measured successfully in spite of imperfections of the new radiometer system. Additional effort will be spent to the further improvement of the variable load especially the spectral flatness and the elaboration of the inherent advantages of this new calibration technique.

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