# Microwave-Radiometer

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## Preliminary remarks

The preparation and execution of this experiment should give the students a basic insight in the main terms and specifications of a heterodyne radiometer. The experiment contains all main components of a heterodyne receiver system as it is used in remote sensing of ground, sea surface, atmosphere, plasma diagnostics (fusion research) and radio astronomy. The experiment is thematically connected to major projects of the institute (!) and should create interest for a bachelor work or dissertation in one of our work groups.

## Hints for the preparation of the experiment

**Bold terms** as well as all formulas should be explained respectively deduced in the written report. The items in section "Hints for the written report" should be followed. Supporting documents can be downloaded from the institute web page: http://www.astro.uni-koeln.de/node/189. It is necessary to read them carefully in order to be prepared for the experiment.

## Introduction

A main task of modern astrophysics is the understanding of the formation of stars and planets. Therefore spectral and spatial high resolved observations of star formation regions with their associated molecule clouds are important. Especially the electromagnetic radiation of molecules in the frequency region from 100 GHz to some 1000 GHz are of interest. From the observed spatial distribution of the gas, the excited states and the shape of the line profiles of different molecule species and molecule transitions, the physical and dynamic state of the matter can be determined and compared with model predictions.

For the necessary high resolution spectroscopy, radio telescopes with **heterodyne radiometers** as receivers are used (depending on the observed wavelength one talks about millimetre-wave resp. submillimeter-wave receivers). In the **heterodyne principle** the received signal is mixed with a fixed frequency of a **local oscillator** (LO) and down converted to a significant lower **intermediate frequency** (IF). This method is necessary by the following facts:

a) Above about 100 GHz there are at present no amplifiers available that are able to amplify the extreme weak extraterrestrial signals with sufficient sensitivity. By converting the signal to a lower frequency (typically 1 – 10 GHz) with a mixer of low conversion loss, the signal can be amplified at this lower frequency with low noise amplifiers and than fed to a spectrometer for spectral analysis.

b) The extreme high spectral resolution (order of $10^{-7}$), that is necessary for spectroscopy cannot be reached with filters at the original high frequency of the signals.

In radio astronomy nowadays **SIS-mixers** (SIS = **s**uperconductor-**i**solator-**s**uperconductor) are successfully used. They have replaced the commonly used **Schottky-diode-mixers** used in older receiver systems and for other applications. Because of the superconducting material properties, SIS-mixers show a nearly ideal nonlinear **current-voltage-characteristic** and offer as **quantum-mixers** the best possible **mixing efficiency**.

Because of the mixing process, signals from both **sidebands** are reaching the IF amplifier chain. To obtain an unambiguous identification of the spectra, one sideband has to be suppressed by a filter (single-sideband operation **SSB** versus double-sideband operation **DSB**).

## 1. Passive microwave radiometry

A radiometer for passive microwave radiometry must be able to detect extremely small signal powers, especially when used for radio astronomy. After the **Nyquist-theorem** the electromagnetic thermal noise power P is proportional to the physical temperature T of an equivalent **black body** and the receiving bandwidth $\Delta\nu$:

$$P = k_B T \Delta\nu \quad (1)$$

The antenna is the first component of a radiometer. Although it does not emit a significant amount of noise power, there is a noise power available at the output that is caused by the received electromagnetic radiation. After equation (1) this power can be assigned to a **noise temperature**. This temperature is called antenna temperature $T_A$. As the receiving bandwidth is technically fixed, one can say after equation (1) that the receiver should be able to detect as small as possible changes of the antenna temperature.

Receivers consist of components that generate noise power by their own (**thermal noise**, **shot noise**, etc.). This noise power cannot be distinguished in general from the received signal noise power. The total measured noise power $P_{sys}$ therefore consists of the noise power from the receiver $P_R$ and the noise power from the antenna $P_A$:

$$P_{sys} = P_R + P_A \quad (2)$$

resp. with (1)

$$T_{sys} = T_R + T_A \quad (3)$$

The quantity $T_{sys}$ is called system noise temperature, $T_R$ is the receiver noise temperature and $T_A$ the antenna temperature.

It is clear that the detection limit gets worse with increasing receiver noise temperature. This correlation is described more precisely by the **radiometer equation**:

$$\Delta T = \frac{T_{sys}}{\sqrt{\tau \cdot \Delta \nu}} \tag{4}$$

where $\tau$ is the integration time and $\Delta T$ the detection limit

## 2. Noise contribution by single components of a radiometer

An important question for the optimum design of a receiver is: which components contribute most to the total receiver noise temperature? If one imagines the receiver as a ladder network of single stages (e.g. amplifier stages), where each stage is characterized by the power gain $G_X$ and its noise temperature $T_X$ (Fig. 1), we get for the equivalent **total noise temperature** related to the input of the network:

$$T = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots + \frac{T_N}{G_1 G_2 \cdots G_{N-1}} \tag{5}$$

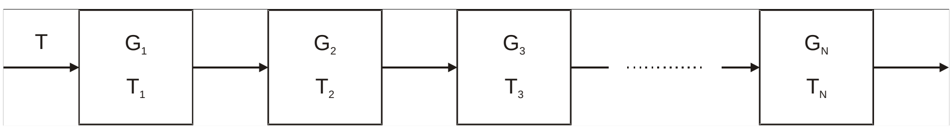


**Fig 1. ladder network of the receiver**

From eq. (5) one can see that the main contribution to the total noise temperature comes in general from the first amplifier stages and lossy components in front of them. Therefore special care has to be taken of the noise temperatures of these stages.

In a heterodyne radiometer the first component is normally the mixer. If one adds up the IF-amplifier chain to a single stage that has a noise temperature of $T_{IF}$, then equation (5) changes to:

$$T_R = T_M + L \cdot T_{IF} \tag{6}$$

Where $T_M$ is the noise temperature of the mixer and L is the so called **conversion loss** (reciprocal of the gain) of the mixer.

The next question is, how we can determine the detection limit of a specific radiometer by practical measurements. The bandwidth $\Delta\nu$ is fixed by a bandpass filter or the frequency response of the amplifiers and therefore known. The same applies for the integration time $\tau$, that is determined by the circuit elements of the integrator. What remains is the determination of the system noise temperature $T_{sys}$, respectively the receiver noise temperature $T_R$.

For this purpose one has to measure the total noise power for different, well known antenna temperatures $T_A$ (**hot-cold method**). After (2) and (3) we get:

$$T_{sys} = T_R + T_A = c \cdot P_{HF} \tag{7}$$

with an unknown constant c.

If we first produce a high antenna temperature $T_H$ and then a low antenna temperature $T_C$, the corresponding noise powers are:

$$P_H = (T_H + T_R) \cdot c \tag{8}$$

$$P_C = (T_C + T_R) \cdot c \tag{9}$$

From the measured power relation $P_H / P_C = Y$ one can determine the receiver noise temperature by:

$$T_R = \frac{T_H - Y \cdot T_C}{Y\text{-}1} \tag{10}$$

For the realisation of a high antenna temperature absorbing material at room temperature is usually used that is placed in front of the antenna (see task 5A), whereas the low antenna temperature is produced by cooling the absorber material with liquid nitrogen (77K). Of course the equivalent noise temperatures of single components (e.g. amplifiers) can be determined by the same method (task 3 and 4). Instead of an antenna, a **matched load** resistor (50 $\Omega$) can also be used, by applying the hot-cold method (task 5B).

## 3. Setup of the experiment

The radiometer consists of a Schottky-diode mixer, a transistor oscillator and two IF-amplifiers. For the adjustment of the oscillator power fixed attenuators are used. Furthermore an additional bandpass filter can be inserted in the IF part.

The measurement of the oscillator power and the output power of the IF-amplifiers is done with a power meter (HP 436A). In task 2, 3 and 4 a noise diode (HP 346B) is applied as noise source. The diode noise temperature that is needed for the analysis of the measurement can be calculated from the given (see table attached to the noise diode) **ENR** (excess noise ratio = ratio of the diode noise temperature to the room temperature in dB, see supplement).

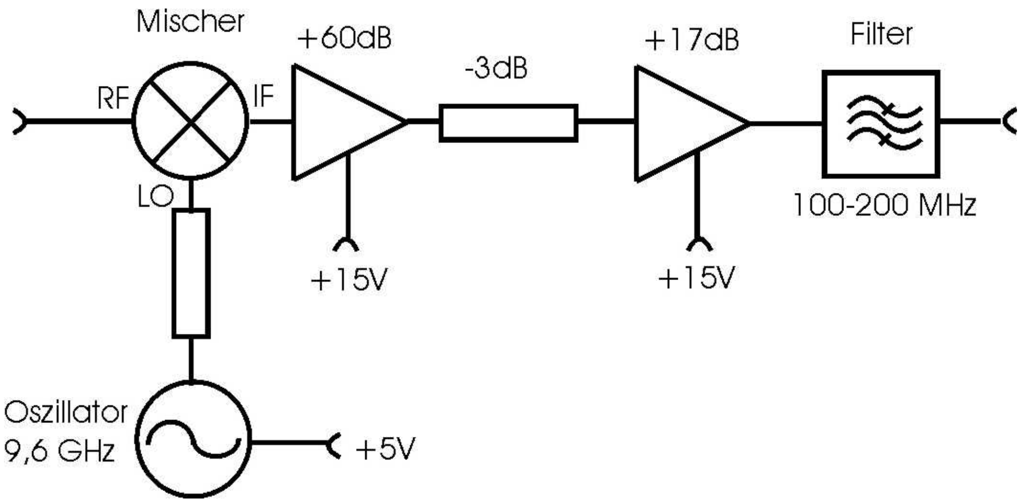


Fig.2: schematic layout of the experiment

## 4. Important hints for the execution of the experiment

The components of the heterodyne radiometer und the power meter may not look very impressive but they work properly and they are expensive when purchased (power meter HP 436A more than 2000 €). Some other components are single piece productions of our institute. So don't play around with them.

- As it is more practicable, the components are not fixed together but rather in loose condition, which requires careful handling.
- The components oscillator, mixer and amplifier chain are sensitive to electrostatic discharges. Therefore the complete experiment is placed on an electrical conducting mat. Before screwing the SMA connectors together, be sure that they have been grounded and discharged (supervisor will show you).
- Don't screw the SMA screw nuts too tight together with the wrench! Screwing by hand is normally sufficient for a RF-sealed connection.
- Make sure that the polarity of the power supplies for the oscillator (+5 V) and the amplifier chain (+12 V) is correct. See colour codes!
- Let the components warm up (monitor the power indication at the power meter, the gain of the amplifiers will drift to lower values during warm up and settles after some time)
- Don't measure all hot and then all cold values, but rather measure pairs of hot-cold values. As the power meter has a certain temperature drift, check the zero offset of the power meter from time to time and adjust it. For the same reason one should measure pairs of hot-cold values within short time distances.

- Include simple schematic diagrams of the different tasks of the experiment in the report.
- Record errors of the instruments and the different measurements.

## 5. Tasks

### Task 1: Calibration of the fixed attenuators

Calibrate the fixed attenuators by using the oscillator as power source and the power meter as detector. Take care that especially at low power levels the zero point of the power meter has no offset and adjust it if necessary (advisor shows how).

### Task 2: Determination of the total receiver noise temperature in dependence on the LO power $T_R(P_{LO})$

Determine the total receiver noise temperature (mixer + IF-chain) in dependence on the oscillator power (1dB steps until max. 10dB by combination of fixed attenuators) using the noise diode (on-off relates to hot-cold). In the switched-off condition, a noise temperature of room temperature (293 K) can be assumed for the noise diode. Avoid corner adapters and other unnecessary plug connections. For the following measurements the attenuation of the oscillator power should be fixed (using adequate attenuators) to the optimal value (lowest noise temperature).

### Task 3: Determination of the IF-noise temperature

Determine the noise temperature of the IF-amplifier chain using the noise diode. Repeat the measurement by placing the bandpass filter in front and behind the IF-amplifier chain. Which position is the better one? By leaving the filter in the optimal position, repeat the determination of the IF-noise temperature using the load resistor at room temperature (hot) and at liquid Nitrogen temperature (cold).

### Task 4: Determination of the mixer conversion loss L

Determine the conversion loss of the mixer by systematically increasing the IF-noise temperature with fixed attenuators between mixer and IF-amplifier chain (attenuation in 1dB steps up to 6dB) and measuring the total receiver noise temperature $T_R$ and the relating IF-noise temperature $T_{IF}$. If one plots $T_R$ versus $T_{IF}$, a straight line will result, from which (after equation (6)) $T_M$ and L can be determined (diagram with computed fit of the straight line, including error consideration).

## Task 5: Determination of $T_R$ by using the horn antenna and the load resistor

Repeat the determination of the total receiver noise temperature at the optimum adjustment of the LO power and for the optimal position of the IF filter by the following methods:

A. With the horn antenna connected to the input of the radiometer, directed first at the absorbing material at room temperature (293K) and afterwards cooled with liquid Nitrogen (77 K). When cooling the absorber material, be sure that the material is completely covered with liquid Nitrogen. The measurement with cooled absorber material should be done once without and once with reflecting metal sheet underneath the absorber vessel. How do you explain the resulting differences of the noise temperature?

B. With the load resistor at the input of the radiometer (also at room temperature and at 77K).

## 6. Important hints for the written report

- Include the records of your measurements
- Include a schematic diagram of the experimental setup for each task
- Include a complete error calculation
- Discuss the results!
- Note your e-mail adresses

## 7. Literature

Hachenberg, O., Vowinkel, B.: Technische Grundlagen der Radioastronomie. BI, 1982

(extracts can be downloaded from the web page of the experiment)

K. Rohlfs, T. Wilson: Tools of Radio Astronomy. 3rd Edition, Springer-Verlag 2000

Literature from the library of the physics institutes (Categories EE und EXP)

The basic principle of a SIS-mixer can also be downloaded from the following web page of the institute: http://www.ph1.uni-koeln.de/micro/deutsch/sdm_d.html (SFB 494, workgroup *Superconducting Devices and Mixers*).

## Supplement A: Equations

In microwave technology the commonly used logarithmic power ratio in decibel (dB) of the output power $P_2$ to the input power $P_1$ of a device is defined as:

$$dB \equiv 10 \log (P_2/P_1)$$

Absolute power levels are expressed in the logarithmic unit dBm:

$$dBm \equiv 10 \log (P/1mW) \qquad \text{with P in [mW]}$$

For instance we have: $0\ dBm \equiv 1mW$

The noise measure F [dB] is often used instead of the noise temperature T [K]. The definition is:

$$F = 10 \log \left(1 + \frac{T}{T_0}\right) \text{ in [dB]}$$

Here T is the noise temperature of the device under test and $T_0$ (293 K) is the room temperature.

The excess noise ratio (ENR) [dB] of a noise source is given by:

$$ENR = 10 \log \left(\frac{T_E}{T_0}\right) \text{ in [dB]}$$

where $T_E$ is the noise temperature of the source and $T_0$ (293 K) is the room temperature.

## Supplement B: List of all components and devices

| cmponent / device | specifications | | description, comments |
|---|---|---|---|
| mixer<br>Mini-Circuits ZMX-10G | $\nu_{RF}$<br>$\nu_{IF}$<br>max. $P_{LO}$ | 3.7 – 10 GHz<br>DC – 2 GHz<br>+7 dBm | |

| | | | |
|---|---|---|---|
| | max. $P_{RF}$ | +1 dBm | |
| oscillator<br>(transistor-based) | ν<br>P | 9.6 GHz<br>4.34 mW | supply voltage: +5 V, |
| power meter<br>HP 436A | P | 1 μW – 100 mW | |
| power head<br>HP 8481 A | ν<br>P | 0.01 – 18 GHz<br>1 μW – 100 mW | |
| noise diode<br>HP 346 B | ν<br>ENR | 0.01 – 18 GHz<br>+15.1 dB<br>(@ 10 GHz) | supply voltage: + 28 V |
| IF-amplifier chain | ν<br>$G_{total}$(ZF)<br>G(V1)<br>G(V2) | 5 – 400 MHz<br>+74 dB<br>+60 dB<br>+17 dB | supply voltage: +15 V<br>-3dB fixed attenuator between stages |
| bandpass filter<br>Telemeter Electronic GmbH | $\Delta\nu$ | 100 – 200 MHz<br>(100MHz bandwidth) | |
| fixed attenuators | -1 dB<br>-2 dB<br>-3 dB<br>-5 dB | 2×<br>1×<br>2×<br>1× | |
| power supply 1 | | +5 V, +15 V | colour coded |
| power supply 2 | | ±15 V | for noise diode |

In addition there is a horn antenna, a 50 Ω load resistor (including extension), a styrofoam vessel, a 5/16 inch wrench and absorbing material (used as load for the measurements with antenna).