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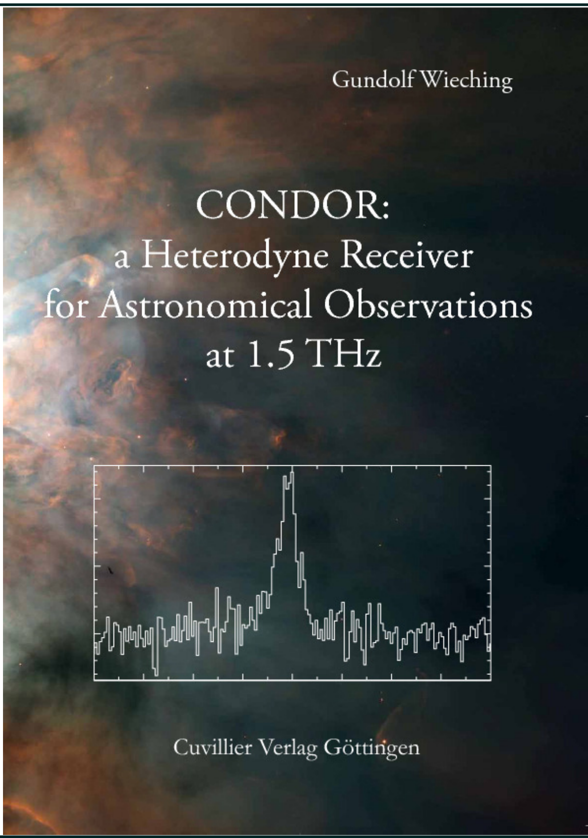
CONDOR: a Heterodyne Receiver for Astronomical Observations at 1.5 THz



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Chapter 1.

Introduction to Heterodyne Observations at THz-Frequencies

For thousands of years, astronomical observations were restricted to the visible light. This changed since the year 1931 with the first detection of radiation at 14.6 m wavelength by Jansky. Technological improvements since than extended the observable frequencies, thus in the last decades many observations could be performed below 1 THz, but also at infrared and higher energetic radiation, such as UV radiation. In these years, radio astronomy became a powerful tool to address astronomical questions related to star formation, the interstellar medium, active galaxies, our solar system, and the microwave background radiation.

Despite the technological improvements, the amount of astronomical observations decreases towards higher frequencies due to increasing technological difficulties and the poor transparency of the Earth's atmosphere. The opaqueness of the atmosphere is mostly due to water vapor in the troposphere and other molecules such as ozone and oxygen. This limits ground based observations at higher radio frequencies not only to some narrow atmospheric transmission windows, but also to very few high altitude locations. As an example for the atmospheric absorption in the mm and submm regime, the zenith transmission for Mauna Kea (USA) is calculated for very good weather (1 mm PWV [1] is available ∼20% of the time) conditions and plotted in figure 1.1. Mauna Kea is an excellent location for observations below 1 THz and since the 80's hosts a few of the important submm observatories, such as the 12 m CSO[2] or the 15 m JCMT[3]. Other sites equipped with telescopes suitable for high frequency observations are:

- Gornergrat near Zermatt (Switzerland) with the KOSMA[4] 3 m submillimeter observatory. It is operated by the I. Physikalisches Institut, Universität zu Köln (Germany) and the Argelander-Institut für Astronomie, University of Bonn (Germany).

[1]PWV = Precipitable Water Vapor
[2]CSO = Caltech Submillimeter Observatory
[3]JCMT = James Clerk Maxwell Telescope
[4]KOSMA = Kölner Observatorium für SubMillimeter Astronomie

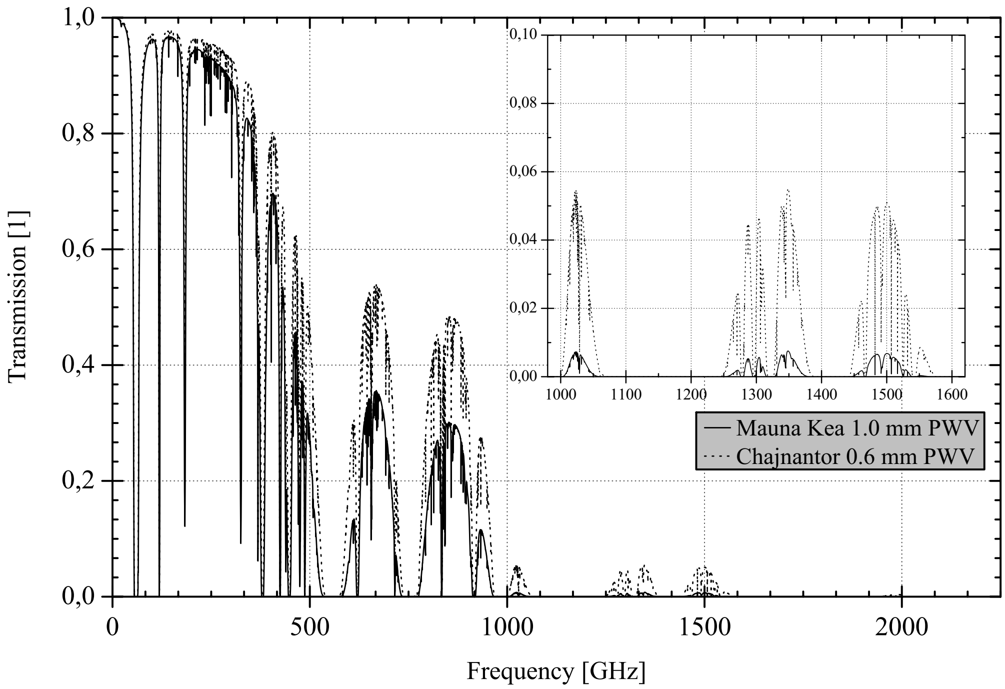

Figure 1.1.: Zenith transmission on Mauna Kea (USA) and at the Llano de Chajnantor (Chile) simulated with the *am* model [Paine, 2004]. The precipitable water vapor is ∼20% of the time below the plotted.

- South Pole (Antarctic) equipped with the 1.7 m AST/RO[5] (1995-2006).
- Llano de Chajnantor above the Atacama desert (Chile) hosting several observatories including the 12 m APEX[6] observatory (see chapter 6.1), the 4 m NANTEN2[7] observatory operated by Nagoya and Osaka University (Japan), Seoul National University (South Korea), KOSMA of the Universität zu Köln and the University Bonn (Germany), and in future ALMA[8].

To avoid most of the atmospheric absorption due to water vapor, especially at THz frequencies[9], airborne observatories were used since the late 70s. For example, the KAO[10], equipped with a 91 cm telescope, was operated from 1974 to 1996 and performed successful THz observations, e. g. [Boreiko et al., 1989] and [Metzger, 1990].

[5]AST/RO = Antarctic Submillimeter Telescope and Remote Observatory
[6]APEX = Atacama Pathfinder Experiment
[7]NANTEN = japanese for *southern sky*
[8]ALMA = Atacama Large Millimeter Array
[9]Even though there can be varying definitions of THz frequency found at the literature, in this thesis it describes the frequency rang between 1 and 3 THz.
[10]KAO = Kuiper Airborne Observatory

Currently a Boeing 747SP is modified and equipped with a 2.7 m telescope to operate as SOFIA[11]. It will be equipped with several incoherent and two coherent instruments, sensitive to radiation between 0.3 μm and 600 μm. One of the coherent receivers is GREAT[12], a modular dual-channel high-spectral resolution instrument [Güsten et al., 2000]. GREAT is a joint project of several German institutes. It will have observing capabilities at 1.5-1.9 THz, contributed by the KOSMA-Institute (Köln) [Graf et al., 2006], 2.6 THz by the Max-Planck-Institut für Radioastronomie (Bonn), and 4.7 THz by the DLR[13]-Institut für Weltraumsensorik & Planetenerkundung (Berlin).

Beside airborne telescopes, observations using satellite based observatories are used for THz observations without the negative impact of the earth's atmosphere. Examples for space telescopes are:

- the 57 cm telescope on IRAS[14] operated for almost one year in 1983,
- the COBE[15] operated in 1990,
- the ISO[16] operated between 1995 and 1998,
- and with SWAS[17] in 1999 the first heterodyne receiver operated in space.

In the near future, the Herschel Space Observatory will provide beside observations with incoherent detectors, also heterodyne observations at frequencies between 480–1250 GHz and 1410–1910 GHz with a 3.5 m telescope. Contributions to this satellite from KOSMA are a spectrometer and the 640 to 800 GHz mixing devices for HIFI[18], the heterodyne instrument on Herschel.

Even though there is a lot of effort to observe at THz frequencies, data at these frequencies are rare and were mostly gathered with space- or air-borne observatories. Intensive site explorations, however, showed in the last decade that ground based observations are feasible at certain frequencies between 1 and 1.5 THz. Figure 1.1 shows the simulated zenith transmission for 20 % of the best weather at Mauna Kea in comparison to the Llano de Chajnator at 5100 m altitude in northern Chile. The very dry conditions on Chajnator allows astronomical observations in three atmospheric windows above 1 THz. Beside sites at the high Andes in northern Chile [Pardo et al., 2001], also places in the Antarctica, such as the south pole [Peterson et al., 2003], or Dome C [Valenziano and dall'Oglio, 1999], showed

[11]SOFIA = Stratospheric Observatory for Infrared Astronomy
[12]GREAT = German Receiver for Astronomy at Terahertz Frequencies
[13]DLR = Deutsches Zentrum für Luft- und Raumfahrt
[14]IRAS = Infrared Astronomical Satellite
[15]COBE = Cosmic Background Explorer
[16]Infrared Space Observatory
[17]SWAS = Submillimeter Wave Astronomy Satellite
[18]HIFI = Heterodyne Instrument for the Far Infrared

the potential for THz observations. This discovery showed, that ground based THz observations are possible and a few astronomical institutes started the development of THz receivers for ground based observations in these frequency windows. Successful ground based observations in the two higher transmission windows were published from the RLT [19] at a site (altitude 5500 m) in northern Chile close to Cerro Sairecabur [Marrone et al., 2005], the AST/RO at the South Pole using SPIFI[20] [Stacey et al., 2005], [Oberst et al., 2006], and from CONDOR at the APEX telescope described as part of this thesis work in chapter 6 [Wiedner et al., 2006].

In section 1.1, a selection of the possible astronomical observations that can be performed with CONDOR is presented. The different THz receiver technologies are described in section 1.2. The choice for the CONDOR technology is explained in section 1.2.3.

1.1. THz-Astronomy

CONDOR is designed as an astronomical THz receiver for the airborne observatory SOFIA as well as for the ground based APEX observatory. The poor atmospheric transmission for ground based observations at THz frequencies limits the observable frequencies to two windows centered at 1.32 THz and 1.5 THz. Nevertheless, several astronomically interesting lines can be found in this frequency range [Siegel, 2002] of which the following promise to be astronomically very interesting as well as bright and thus observable with CONDOR. At the time SOFIA is put in operation the observable frequency range for CONDOR will increases, because of the low atmospheric absorbtion.

CO Rotational Transitions

CO has a rotational transition lines every 115 GHz and is the most important tracer for molecular gas. Intensive studies were performed mostly at rotational transmission lines below 1 THz, e. g., the first astronomical $CO 1 \rightarrow 0$ detection [Wilson et al., 1970], the galactic $CO 1 \rightarrow 0$ survey [Dame et al., 2001], or the ^{13}CO Galactic Ring Survey [Simon et al., 2004]. Several mid-J CO lines in dense warm molecular clouds were observed, such as $^{13}CO 6 \rightarrow 5$ in the Orion core [Graf et al., 1990], $^{13}CO 6 \rightarrow 5$ in M17 W [Stutzki et al., 1988], or in DR21 [Jakob et al., 2006]. To probe hot molecular gas (several hundred Kelvin), for example in high mass star forming regions, the higher rotational transitions of *CO* at approximately 1.5 THz are most suitable (see table 1.1). Several high-J *CO* transitions were observed at the KAO with FIFI between $J=14 \rightarrow 13$ and $J=17 \rightarrow 16$ at a variable but low spectral resolution [Geis et al., 1995]. Furthermore, a few observations of PDRs[21]

[19] RLT = Receiver Lab Telescope
[20] SPIFI = The South Pole Imaging Fabry-Perot Interferometer
[21] PDR = Photon Dominated Region

were performed with a high spectral 3.2 MHz resolution receiver onboard KAO [Boreiko and Betz, 1997]. Observations with ISO of several class 0 sources were done at up to 13 different *CO* transitions in the frequency range between 1.25 and 3 THz ([Nisini et al., 1999], [Giannini et al., 2001]), at a spectral resolution of $\geq$ 0.1 % and a spatial resolution of 80" [de Graauw et al., 1996]. As an example, the obtained fluxes of NGC 1333-IRAS 4 are plotted for the different rotational transitions in figure 1.2. By fitting a model of the *CO* emission to the data, Giannini *et al.* were able to determine the temperature of the warm molecule gas to lie between 200 K and 2000 K [Giannini et al., 2001]. This is a typical source to be observed with CONDOR. By observing the peak emission, it is possible to determine the temperature of the warm gas. In addition, CONDORs high spectral resolution capability will also yield information on the dynamics inside the sources. This allows to restrict the models for star formation.

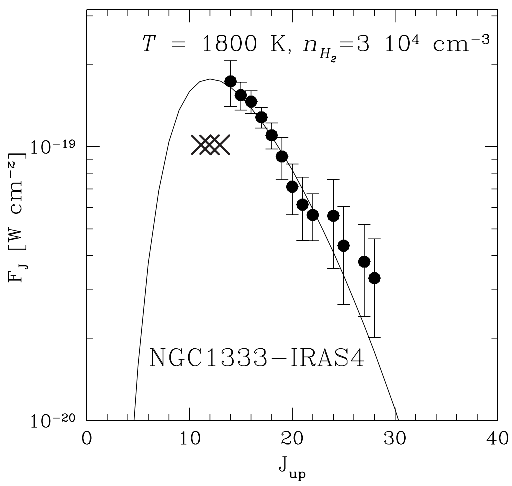

Figure 1.2.: CO line flux measured toward NGS 1333-IRAS 4 as a function of the rotational quantum number J_{up} [Giannini et al., 2001]. The crosses point out the CO transitions observable with CONDOR.

The N^+ Fine Structure Line

The emission of N^+ traces the low density ionized medium. With the ratio of the fine structure lines $^3P_1 \rightarrow ^3P_0$ (1.46 THz) and $^3P_2 \rightarrow ^3P_1$ (2.46 THz), the electron density can be obtained. Observations of both lines were performed with the KAO [Petuchowski et al., 1994].

The first detection of $^3P_1 \rightarrow ^3P_0$ N^+ was done with the COBE satellite using the FIRAS[22] at an observing wavelength of 1 cm to 100 μm, a spatial resolution

[22]FIRAS = FAR Infrared Absolute Spectrophotometer

of 7°, and a spectral resolution ≥ 5 % [Wright et al., 1991], [Mather et al., 1993]. By reprocessing the data with a improved calibration Fixsen *et al.* created a large scale map of the N^+ emission at 1.38 THz, see figure 1.3 [Fixsen et al., 1999]. They showed that the $^3P_1 \rightarrow ^3P_0$ N^+ emission is the third strongest emission line observable with COBE in our Galaxy. Even though this map has a poor spectral and spatial resolution, it shows the high astronomical importance of this line for the cooling of the warm, low density ionized medium.

Nevertheless, $^3P_1 \rightarrow ^3P_0$ N^+ observations are rare, a detection was achieved with the KAO [Colgan et al., 1993] and up to date the only published ground based detection of this line was performed by Stacey *et al.* with the SPIFI instrument on the AST/RO at low spectral resolution [Stacey et al., 2005], [Oberst et al., 2006].

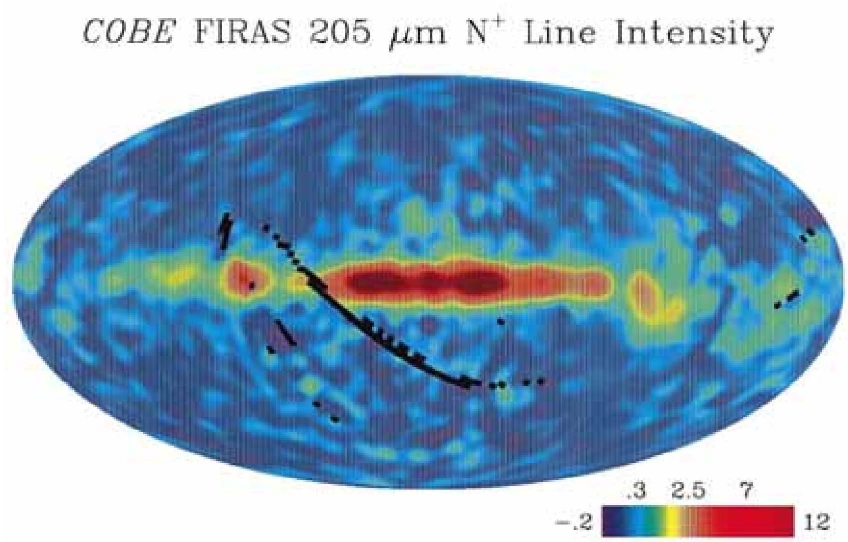

Figure 1.3.: A full sky map of 205.3 μm N^+ emission from the COBE FIRAS experiment. The maps are projections of the full sky in Galactic coordinates. The plane of the Milky Way is horizontal in the middle of the map with the Galactic center at the center. Galactic longitude l = 90° is to the left of the center. The maps are smoothed to 10° resolution. Color bars indicate emission intensity in units of nW m^{-2} sr^{-1} [Fixsen et al., 1999].

Ground Transition of Para H_2D^+

The second molecule presented in the this short overview is H_2D^+, which exists as para H_2D^+ and ortho H_2D^+ with ground state transitions at 1.37 THz and 372 GHz, respectively. Chemical models were developed in recent years describing the formation of deuterated species, showing that H_2D^+ plays a key role at cold

Table 1.1.: A selection of astronomically interesting transitions falling into the CONDOR RF band. Beside the transition frequency the wavelength and the energy of the upper level is given.

Molecule	Transition	Frequency [THz]	Wavelength [μm]	Energy [K]
CO	$11 \rightarrow 10$	1.267	237	431
CO	$12 \rightarrow 11$	1.382	217	503
CO	$13 \rightarrow 12$	1.496	200	580
N^+	$^3P_1 \rightarrow ^3P_0$	1.461	205	70
H_2D^+	$1_{01} \rightarrow 0_{00}$	1.370	219	65

temperatures ($\leq$10 K). Furthermore, H_2D^+ is probably the last observable molecule in cold, dense cloud cores, where nearly all other molecules freeze out onto dust grains [Walmsley et al., 2004]. Observations of the $1_{01} - 0_{00}$ transition of para H_2D^+ in combination with ortho H_2D^+ can be used to test the chemical model predictions and hence confirm or falsify models.

Nevertheless this shows the importance of H_2D^+, only a marginal detection in absorption of the $1_{01} - 0_{00}$ transition of para H_2D^+ was obtained with the KAO [Boreiko and Betz, 1993], and only a few detections of the ground state transitions of ortho H_2D^+ are reported, for example [Stark et al., 1999], [Caselli et al., 2003], [Ceccarelli et al., 2004], [Hogerheijde et al., 2006].

Even though the above described astronomical lines (table 1.1) show the astronomical importance of CONDOR, there are more astronomically interesting lines observable in the CONDOR frequency range. Furthermore, CONDOR will provide a high spectral and (at APEX) unique spatial resolution (see chapter 2). This will allow to measure the kinematics and distribution of the observed species with great detail.

1.2. THz Receivers

At THz feasible detectors can be classified into coherent and incoherent (direct) detectors. In section 1.2.1 the heterodyne (also super-heterodyne) principle will be described, which is used for coherent detectors at higher frequencies. This technic is originally used at radio frequencies. The incoherent detectors originally used at the infrared range are briefly described in section 1.2.2. The differences between the coherent and incoherent detector classes will be pointed out in section 1.2.3 and the decision of designing CONDOR as a heterodyne receiver is motevated.

1.2.1. Description of a Heterodyne System

The heterodyne principle was patented by Lucien Lévy (1917) and Edwin Howard Armstrong (1918), enhancing the frequency selectivity of the early radio systems. Instead of filtering and amplifying the incoming radio frequency (RF) signal as such, it is down-converted to a lower Intermediate Frequency (IF).

This down conversion has three mainly advantages. First the final resolution of the RF signal $\Delta\nu/\nu$ is the resolution obtained in the analysis of the IF, times the down conversion ratio RF/IF. This factor is 10^3 for the CONDOR receiver. Secondly this significant lower IF signal can be handled and processed, e. g. digitalized (see section 2.5.1), with substantially less technological effort. And finally, the phase of the signal is preserved during the conversion, this makes interferometric observations with several baselines possible, e. g. with ALMA.

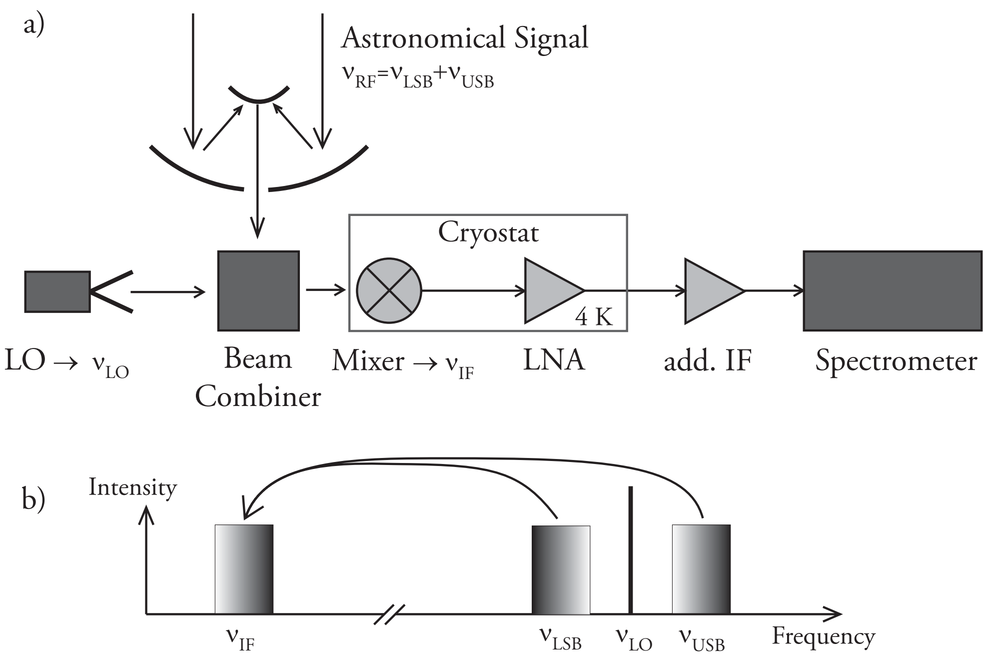

Figure 1.4.: a) Block diagram of a basic astronomical heterodyne receiver setup. The astronomical signal is collected with the telescope antenna, combined with the LO signal, and then directed to a mixing element, which creates the beat frequency. This frequency (IF) is amplified, sometimes converted, filtered and spectrally analyzed.
b) Schematic of a frequency mixer. The signal from two sidebands ν_{LSB} and ν_{USB} centered on the LO frequency ν_{LO} is converted to the lower frequency IF ν_{IF} signal.

Figure 1.4 a) shows a block diagram of a heterodyne setup adapted to the requirement of an astronomical receiver. In figure 1.4 b) the frequency conversion is illustrated. The local oscillator signal at frequency ν_{LO} and the weak astronomical signals ν_{RF} are combined and then mixed to give an output at the IF frequency of $\nu_{IF} = |\nu_{RF} - \nu_{LO}|$. In general, for mixing a device with a nonlinear current voltage characteristic is used, e. g. Schottky-diode. In such a device the current I(t) can be written as a Taylor series of voltage V(t). A Hot Electron Bolometer (HEB) device, as used in CONDOR, mixes, because a bolometer responds to the incoming power and is thus a square low detector. The dependence of voltage $V(t)$ and current $I(t)$ is given by the square law for $V(t) \geq 0$ with $I(t) \sim V^2(t)$. Considering an RF voltage $V_{RF}(t) = V_{RF}\cos(\omega_{RF}t)$[23] and a LO voltage $V_{LO}(t) = V_{LO}\cos(\omega_{LO}t)$ the square law detector leads to:

$$\begin{aligned} I(t) \sim & V^2(t) \\ = & \left[V_{RF}(t) + V_{LO}(t)\right]^2 \\ = & \frac{1}{2}\left[V_{LO}^2 + V_{RF}^2 + V_{RF}^2\cos(2\omega_{RF}t) + V_{LO}^2\cos(2\omega_{LO}t)\right] \\ & + V_{LO}V_{RF}\cos\left((\omega_{RF} - \omega_{LO})t\right) + V_{LO}V_{RF}\cos\left((\omega_{RF} + \omega_{LO})t\right) \end{aligned} \tag{1.1}$$

According to equation 1.1 the resulting current has high frequencies components at $2\omega_{RF}$, $2\omega_{LO}$, $\omega_{RF}+\omega_{LO}$ and the desired low frequency components $|\omega_{RF}-\omega_{LO}| = \omega_{IF}$. Equation 1.1 can be reduced to:

$$I(t) \sim \frac{V_{LO}^2 + V_{RF}^2}{2} + V_{LO}V_{RF}\cos\left((\omega_{RF} - \omega_{LO})t\right), \tag{1.2}$$

because a HEB is a slow device which cannot follow the oscillations at frequencies above a few GHz. But not only the RF spectrum higher than the LO signal, the Upper Side Band (USB) $(\nu_{RF} > \nu_{LO}) \equiv \nu_{USB}$, is transformed towards the IF band. The frequencies below the LO frequency, the Lower Side Band (LSB) $(\nu_{RF} < \nu_{LO}) \equiv \nu_{LSB}$, are also mirrored into the IF band. The averaged current change of the mixer caused by $V_{LO}^2/2$ and $V_{RF}^2/2$ can be used for direct detection.

Most of the astronomical heterodyne receivers in use are sensitive to both the upper and the lower side band and are called therefore Double Side Band (DSB) receivers. Receivers that intrinsically suppress one side band are named Signal Side Band (SSB) receiver. Depending on the astronomical purpose one or both sidebands of a DSB receiver are utilized for detection. For observations of a broad band source, covering both sidebands, the sensitivity is improved due to the additional signal power of the second sideband. If only one side band is used for detection, because for example of a narrow band signal, the noise of the unwanted side band is unavoidably added to the IF signal.

[23] $\omega_x = 2\pi\nu_x$