

## The Impact of Standing Waves in the LO path of a Heterodyne Receiver

O.Siebertz, C.Honingh, T.Tils, C.Gal, M.Olbrich, R.Bieber, F.Schmuelling, R.Schieder

KOSMA, I. Physikalisches Institut, Universität zu Köln, Germany

### Introduction

Many observations of molecular lines in interstellar space or planetary atmospheres are affected by serious problems with standing wave patterns in the spectra. This becomes particularly nasty when studying broad extragalactic or pressure broadened atmospheric lines. When observing at THz frequencies these problems become more and more prominent due to the increased required bandwidth. Mostly, such patterns are attributed to reflections in the telescope optics, particularly from the sub-reflector in a Cassegrain telescope. But there are many other sources of standing waves in the quasi-optics of a heterodyne receiver. In this paper we describe the effect of reflections between mixer and local oscillator (LO) inside of a receiver. Some portion of the signal radiation becomes reflected by the mixer, and propagates partly to the LO with reduced amplitude due to the generally small reflectivity of the beam combiner. Nevertheless, although the power in one roundtrip becomes significantly reduced, there is still enough amplitude left, so that interference with the incoming signal radiation becomes visible.

The situation is depicted in Fig.1. In the figure the local oscillator and mixer reflectivity is indicated by the power reflection coefficients  $r_L$  and  $r_M$  respectively. The beam splitter reflects and transmits the power with coefficients  $r$  and  $t$ . The field of the LO at the mixer is composed of the superposition of all partial beams which are reflected back and forth between the LO and the mixer. Consequently, after summing up all partial beams, the total LO power coupled to the mixer is:

$$P_L = r \cdot P_{L0} \cdot A(\nu_L) \quad \text{with} \quad A(\nu) = [(1-u)^2 + 4 \cdot u \cdot \sin^2(2\pi s / c \cdot \nu)]^{-1}$$

$P_{L0}$  is the power of the LO itself as is incident on the beam splitter, and  $\nu_L$  is the LO frequency.  $A(\nu)$  is the Airy-function as is well known for optical resonators.  $u = r \cdot \sqrt{r_M} \cdot \sqrt{r_L}$  is the roundtrip efficiency for the field amplitude within the cavity,  $s$  is the optical path length between mixer and LO, and  $c$  is the speed of light.

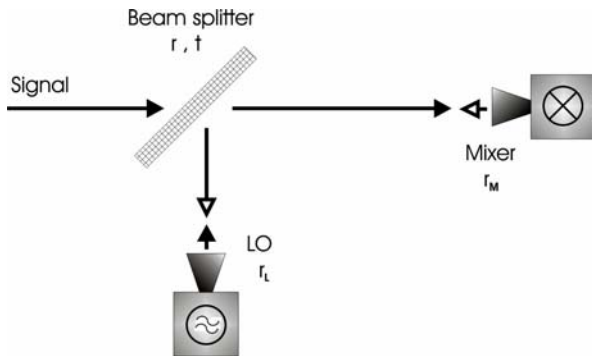


Fig.1

Beam path in a typical heterodyne setup

Due to the interference the LO power becomes periodically modulated as a function of frequency with a free spectral range  $FSR = c/(2 \cdot s)$ . The peak to valley ratio is given by:

$$PVR = (1+u)^2 / (1-u)^2$$

When assuming a LO-coupling of 10% and a reflection of 20% from mixer and LO, the resulting variation between peak and valley is 8%. This is a typical value one can easily verify by experiment when varying the distance between LO and mixer or the frequency of the LO.

The LO standing wave problem is a well known phenomenon, which confirms that there is usually an appreciable amount of reflection involved. But, what is mostly neglected, the consequences for the signal are as important. The signal power becomes also reflected within the mixer/LO cavity, and, similar as before, one finds for the signal power at the mixer:

$$P = t \cdot P_0 \cdot A(\nu_S)$$

with  $\nu_S$  the signal frequency ( $\nu_S = \nu_L \pm \nu_{IF}$ ) and  $P_0$  the signal input power as is incident on the beam splitter. Consequently, there is also modulation of the detected signal power with frequency, which is due to the

effective filter characteristics of the mixer/LO cavity. With the assumed reflectivities above the signal gain is also modulated by 8% peak to valley, which is a lot more than one can expect from feedback effects due to reflections from the telescope optics or the calibration loads.

The signal power of a single sideband system, as seen with the calibration loads, is now given by

$$P_{Hot,Cold} = P_{Sys} + t \cdot P_{H,C} \cdot A(\nu_S)$$

with  $P_H$  and  $P_C$  the thermal emission from the hot- and cold-load, and  $P_{Sys}$  the noise power of the system itself. This means that the y-factor, and the noise temperature accordingly, will depend on intermediate frequency like:

$$y(\nu_S) = P_{Hot}/P_{Cold} = [P_{Sys} + t \cdot P_H \cdot A(\nu_S)] / [P_{Sys} + t \cdot P_C \cdot A(\nu_S)] \approx 1 + t \cdot [P_H - P_C] / P_{Sys} \cdot A(\nu_L \pm \nu_{IF})$$

Consequently,  $y - 1$  varies also by 8%, when assuming the same reflectivities as above.

With a dual sideband mixer the input to the mixer is the sum of the signal inputs from both sidebands,  $P_l$  in the lower and  $P_u$  in the upper sideband. The total power is then equivalent to:

$$P = P_{Sys} + t \cdot [P_l + P_u] = P_{Sys} + t \cdot [P_{l0} \cdot A(\nu_l) + P_{u0} \cdot A(\nu_u)] \quad \nu_u = \nu_L + \nu_{IF}, \quad \nu_l = \nu_L - \nu_{IF}$$

The two Airy-functions give rise to different gain factors for each sideband, which depend on the two signal frequencies  $\nu_u$  and  $\nu_l$ . Their values vary with intermediate frequency, but in general differently for the two sidebands. If the cavity length  $s$  happens to be a multiple of a quarter of the LO wavelength, both Airy-functions have identical values at all intermediate frequencies  $\nu_{IF}$  so that both sidebands experience identical gain variations. (At this position the LO-power at the mixer is at minimum or maximum.) In this particular case the y-factor modulation is maximized. On the other hand, if the cavity length is an odd multiple of  $\lambda_{LO}/8$ , the ripples from both sidebands cancel each other nearly completely, and the y-factor modulation becomes minimized. This indicates that the appearance of the DSB-system noise temperature is strongly dependent on the actual LO tuning.

When observing spectra the problem is more intricate than it might appear, and this is due to the additional complication when calibrating a spectrum. A calibrated spectrum is usually evaluated from the ratio of two differences consisting of two measurements on sky (signal  $S$  and reference  $R$ ) and two load measurements (hot load  $H$  and cold load  $C$ ).

$$Signal \propto \frac{[S_l - R_l] \cdot A(\nu_l) + [S_u - R_u] \cdot A(\nu_u)}{[H_l - C_l] \cdot A(\nu_l) + [H_u - C_u] \cdot A(\nu_u)}$$

The problem is not visible, if a continuum signal is detected, which contributes equally in both sidebands, since the modulations  $A(\nu)$  in the numerator and denominator cancel each other. This is different when observing lines signals in one sideband only, or when measuring  $S$  and  $R$  from different emitters, as is typical during atmospheric studies, while switching between sky and an internal load. Since the power differences  $S-R$  are different in the two sidebands, the modulating Airy-functions can not cancel, unless they are identical in both sidebands. Thus, the expression becomes dependent on intermediate frequency. In effect, the derived sideband efficiencies become modulated, and consequently, the calibration becomes uncertain. One should note that this problem arises only due to the fact that the calibration signal originates from both sidebands, but the signal does not. Only, if the two Airy-functions  $A(\nu_l)$  and  $A(\nu_u)$  are identical at all IF-frequencies (or proportional, if the mixer itself has different responsivities in the two sidebands), the calibration is unaffected, as is the case for a cavity length equal to a multiple of  $\lambda_{LO}/4$ . This means that it is best to maximize the ripple on the noise temperature in order to minimize the calibration error! Without this precaution, the variation of the sideband sensitivities can make it particularly difficult to disentangle complex signals which come from both sidebands, or, in general, to compare the strength of different lines with high confidence.

## Experimental setup

The standing wave related effects were investigated using the development models of the WBS (**W**ide **B**and **S**pectrometer) and of the band-2 mixer of the HIFI instrument (**H**eterodyne **I**nstrument for the **F**ar-**I**nfrared) for the ESA cornerstone mission "Herschel" [1], which both have been fabricated at KOSMA. The spectrometer is an acousto-optical spectrometer (AOS), which is based on a recent development of a so called "Array-AOS" [2,3]. It provides 4 input bands between 1.6 and 2.6 GHz each at a resolution of approximately 1 MHz per pixel. The full coverage of the IF bandwidth of the mixer (4 to 8 GHz) is achieved by frequency converters in the IF processor which splits the input band into four identical AOS bands. The mixer is a fixed-tuned SIS Nb-AlO-NbTiN waveguide mixer for the range between 600 and 825 GHz (see e.g. [1]). Coupling of LO power to the mixer is provided by means of a tilted polarizing grid. A gas-cell, filled with Formaldehyde ( $H_2CO$ ) at a pressure of some ten mTorr, is positioned between

the mixer and two calibration loads (see Fig.2). The rotational molecular transitions are chosen for full saturation of the absorption in the center of the lines. Although H<sub>2</sub>CO has not a very dense rotational spectrum it has the advantage that the permanent dipole moment is very high and that it exhibits strong transitions over the full frequency range of the HIFI instrument between 500 GHz and 1.9 THz (see e.g. [5]).

The primary goal of the experiments was to analyze standing wave problems in a typical heterodyne receiver setup (see Fig.2). For this the spectrum is observed while detecting the emissions from the two calibration loads through the cell; a hot load at ambient temperature and a cold load at liquid Nitrogen temperature. A chopper wheel behind the cell switches between the loads at a rate of 0.8 Hz. The spectrometer is synchronized to the chopper, and for each measurement 100 such cycles are averaged in order to improve the signal to noise ratio. Before starting these integrations a "Zero-measurement" -  $Z(\nu)$  - is performed for an identification of the zero level of the spectrometer itself.

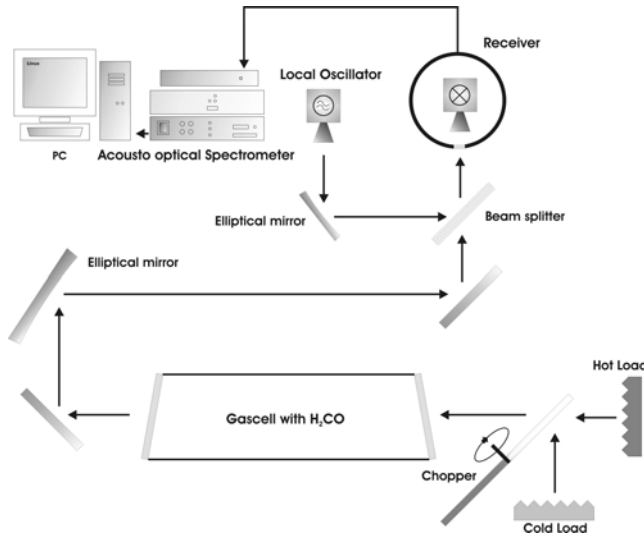


Fig.2 Lay-out of the gas-cell test set-up

Four data sets are taken: two with filled cell against hot and cold load, and another two with empty cell. When dividing the difference of the first two by the difference of the second one obtains a calibrated spectrum with

$$Q_{u,l}(\nu) = 1 - \gamma_{u,l} \cdot (1 - e^{-\tau(\nu)})$$

$\gamma_{u,l}$  are the two sideband efficiencies, and we have used:  $\gamma_u + \gamma_l + \gamma_0 = 1$ .  $\gamma_0$  stands for any other response like direct detection or harmonic response of the mixer.  $\tau(\nu)$  is the frequency dependent optical depth of the line signal. A too small value of  $\tau$  prohibits a precise determination of the sideband efficiency, since its exact value is usually unknown. Therefore, strong absorption lines (or long cells) are required so that the exponential vanishes. At the same time, there should be enough spectrometer bandwidth to cover some portion in the spectrum, which is free of molecular emission. The calibration accuracy can then be estimated from the resulting value of  $Q$ , which is supposed to be unity. Ideally, at sufficient optical depth, one obtains a precise value of the sideband efficiencies in the line centers:

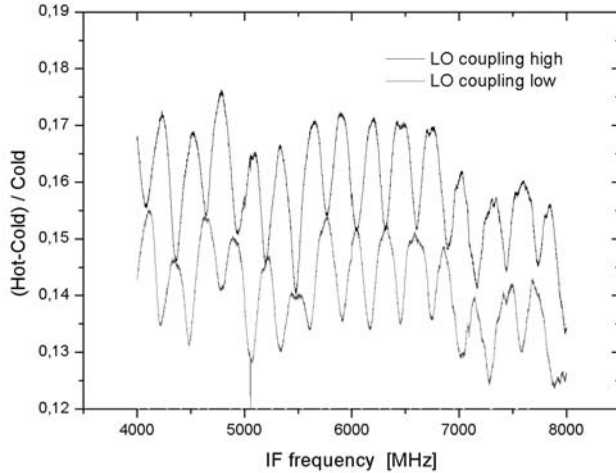
$$Q_{u,l} = 1 - \gamma_{u,l}$$

With two molecular lines one can determine now each of the sideband efficiencies, and it is clear that the sum of both,  $\gamma_u$  and  $\gamma_l$ , should be smaller than or equal to unity. How much it deviates depends on the amount of undesired response of the mixer. When positioning two saturated lines, one in the upper and the other in the lower sideband, at the same IF-frequency,  $Q$  should reach a value of 0, unless there is significant amount of direct detection. This is an excellent method to determine direct detection of HEBs for example.

### Experimental Results

The first goal during the experiments was to verify the existence of a signal standing wave between mixer and LO. For most of the following experimental results the LO coupling to the mixer was chosen fairly high ( $\approx 20\%$ ) in order to show the effects very clearly. Fig.3 indicates how significant the gain ripple can become. Depicted is the y-factor minus 1, which is derived from a cold and a hot load measurement with the empty gas-cell in the optical path. It is evident that a strong standing wave pattern with more than 10%

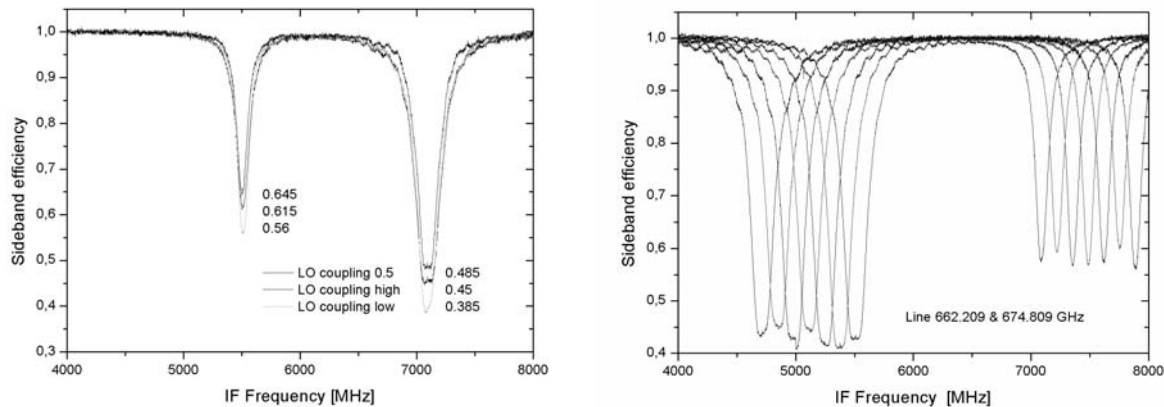
ripple is present. The period of the pattern corresponds exactly to the distance between mixer and LO (~ 27 cm). The two curves in the figure represent the outcome at two different LO positions separated by a quarter of a wavelength, which changes the phase of the pattern by  $\pi$ . This is a perfect confirmation that the signal standing wave originates from reflections at the local oscillator. The pattern is superimposed with the variation of the system noise temperature across the IF band, therefore there is additional structure in the spectrum.



**Fig.3** Standing wave pattern visible in the y-factor during gas-cell measurements with empty cell. The LO frequency is about 668.5 GHz. The two curves represent the results at two LO positions separated by a quarter of the LO wavelength.

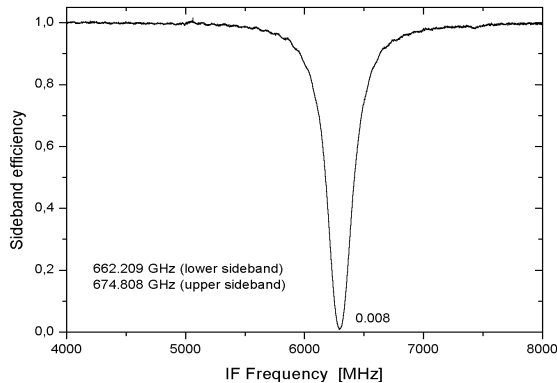
When calibrating the spectra, the ripple vanishes, since the same structure is present in both, the signal and the calibration measurements. Thus, a uniform baseline is the result (see figures below). But, any change of the LO position for example during the time needed for a complete observing cycle (signal, reference, hot, and cold load) will make parts of it visible. From this it becomes evident that the stability of the LO position and frequency is decisive for the appearance of ripple structures in the spectra. In consequence, the stability of the complete system as seen with Allan variance tests for example becomes negatively affected.

The strong variability of the sideband responses of the mixer is visible in Fig.4. There are two pressure broadened molecular lines, one in each sideband, which are rather different in amplitude indicating some significant differences in sideband sensitivity of the mixer itself. Plotted are the lines seen for three different lengths of the mixer/LO cavity, which has also direct consequences for the LO power coupled to the mixer. In order to compensate for the changes in noise power output the mixer bias is adjusted for similar operating conditions. The amplitude of the lines varies significantly while the sum of the two sideband efficiencies  $\gamma_u$  and  $\gamma_l$  is not even close to "1", as would be expected. The result is a clear proof that there is large uncertainty for the sideband response which is obviously caused by different influence of the standing wave on the two sideband efficiencies. In the presented case the amplitudes of the two lines vary by as much as 20%. Similar observations were made when tuning the LO-frequency.



**Fig.4 Left:** Line pair at 662.209 GHz – lower sideband (right line) – and 674.809 GHz – upper sideband (leftline) – observed at different LO positions. Note that the numbers provided in the plot represent the values of  $1-\gamma$ . **Right:** Same line pair (positions are reversed) at different LO frequencies. The line amplitudes appear dependent on LO tuning.

In order to verify that the setup is not responsible for the differences, we tuned the LO so that the two lines appear at exactly the same intermediate frequency. The result is shown in Fig.5. Since the value of  $\gamma_u + \gamma_l$  should be close to unity, a value near zero is expected at the peak of the combined lines. The deviation from this value is a good measure for the accuracy of the measurements. Part of the remaining 0.8 % signal at line center may be due to some minor amount of direct detection of the mixer, but a small contribution due to incomplete saturation is also possible (see Eq.(5)). In general one can conclude that the overall accuracy of the efficiency measurements is better than 1%, and that the effects on the calibration are definitely real.\*-



**Fig.5** Mixer response with the two lines of Fig.4 at identical intermediate frequency. The total response is 99.2%, which is very close to the theoretical value. This verifies that the lines seen in Fig.4 and 5 are fully saturated, and that the large difference in response between the sidebands is real and most likely caused by the mixer itself

## Conclusions

Our observations have confirmed that a major portion of baseline ripple in the spectra of heterodyne receivers can be attributed to standing waves in the mixer/LO cavity. The amplitude of the ripple structures depends directly on the coupling efficiency of the LO into the signal path. If one can afford to waste huge amounts of LO-power, minimum coupling should be used. Nevertheless, a coupling of 1% ( $r=0.01$ ) causes still ripples in the range of 1% peak to valley. The situation is slightly worse when using a grating as beam splitter, since the polarization effects increase the problems. Much more troublesome is a Martin-Puplett diplexer! Exactly in IF-band center, where the diplexer should have maximum signal transmission, is no reflection of signal to the LO. But at the band-edges, if one octave of IF-band is used, the uncertainty of the sideband calibration can exceed  $\pm 20\%$ , when using the same reflection coefficients for mixer and LO as above. This is due to the fact that a Martin-Puplett provides 25% reflectivity for the signal towards the LO at the band edges. The problem is rather difficult to handle, since the amplitude of the efficiency modulation is now dependent on IF-frequency, so that it is tricky to correct for during data analysis.

A ripple-free system would require that the calibration is also done with single sideband calibration loads. A single sideband filter helps, but it is important to implement a cold termination of the reflected sideband. This removes the ripple on the sideband efficiency because one calibrates now correctly with load signal from one sideband only, but the ripple on the system noise temperature remains. With a warm termination the situation deteriorates, because the radiation from a warm termination of the sideband filter co-adds to the signal of the calibration loads resulting in very different contributions from both sidebands. Good experience is made with sub-harmonically pumped mixers, because there is no possibility for the signal reaching the LO. Another and very practical way is to use a Fabry-Perot type diplexer, which does not allow any signal coupling to the LO (see e.g. [6]). But, similar as with a Martin-Puplett, the LO has maximum standing wave dependent on the coupling efficiency of the Fabry-Perot.

The LO standing wave itself is difficult to remove. A quarter-wave plate together with a linear polarizer can be useful, since it acts as an optical isolator for the reflected power. If it is placed in front of the LO, the signal and LO standing wave are both suppressed, but half of the LO power is wasted. Unfortunately, with simple quarter-wave plates or an equivalent grid/mirror arrangement the isolation is frequency dependent. One therefore has no full isolation at all signal frequencies. But isolation in the range of at least 15 dB is always possible (see e.g. [7]). It might be a bit tedious to tune the isolator for each new LO frequency, but it is probably worthwhile. An alternative method is to use a path-length modulator in front of the mixer or LO. If the modulation is fast enough and has sufficient amplitude, the ripple is effectively averaged out. The introduced LO-power modulation might be nasty, but, when synchronizing sampling time with modulation frequency, it should be possible to remove those effects. If a polarizing grid or a Martin-Puplett is used for LO-coupling, one has to be careful when using polarizing components for isolation. It requires some additional analysis to do it properly.

**References**

- [1] Th.de Graauw, F.P.Helmich; Proc. of 'The Promise of the Herschel Space Observatory', symposium held 12-15 December 2000 in Toledo, Spain, eds. G.L.Pilbratt, J.Cernicharo, A.M.Heras, T.Prusti, R.Harris, ESA SP-460, pp. 45-51, 2001
- [2] J.Horn, O.Siebertz, F.Schmülling, C.Kunz, R.Schieder, G.Winnewisser; *Exper.Astron.* **9**, 17-38 (1999)
- [3] R.Schieder, O.Siebertz, F.Schloeder, C.Gal, J.Stutzki, P.Hartogh, V.Natale, Proc. of "UV, Optical, and IR Space Telescopes and Instruments", J.B.Breckinridge, P.Jakobsen Eds., SPIE 4013, 313-324, (2000)
- [4] I. López-Fernández, J.D. Gallego, C. Diez, A. Barcia, J.M. Pintado, Proc. of "Astronomical Telescopes and Instrumentation" Conference: "Millimeter and Submillimeter detectors", Waikoloa (Hawaii, USA) on August 22-28 2002 SPIE 4855 (2002)
- [5] The Cologne Database for Molecular Spectroscopy CDMSH; S. P. Müller, S. Thorwirth, D. A. Roth, and G. Winnewisser, *Astronomy and Astrophysics* **370**, L49–L52 (2001)
- [6] F.Schmuelling, B.Klumb, M.Harter, R.Schieder, B.Vowinkel, G.Winnewisser; *Appl.Opt.* **37**, 5771 (1998)
- [7] K.Eigler, R.Schieder, B.Vowinkel; 16th Int. Conference on Infrared and Millimeter Waves, Conf.Digest, Lausanne, SPIE 1576 (1991)