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Enhanced Image Rejection in Receivers with Sideband-Separating Mixers

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ABSTRACT: The finite image rejection of a spectrometer using a sideband-separating mixer receiver can be enhanced by subtracting a fraction of each output from the other output. The correction factors are determined by a simple measurement of the ratio of the two IF output powers when an RF test signal is injected first in one sideband then in the other. The relative power levels of the test signals need not be known. Changes in the upper- and/or lower-sideband signal path attenuation ahead of the receiver (*e.g.*, due to the atmosphere) do not affect the correction. This image enhancement procedure is not applicable to the more common double-sideband mixer reciever, but only to receivers with a sideband-separating mixer which has at least some degree of image rejection.

INTRODUCTION

For terrestrial observations of astronomical spectral lines, cryogenic receivers using sideband-separating mixers can have greater sensitivity than those with double-sideband mixers. This is because the sideband-separating mixer eliminates the down-converted atmospheric noise from the image sideband which otherwise adds to the system noise. Another advantage of sideband-separating mixer receivers is that spectral lines in one sideband are not overlaid with spectral features present in the image band, but this separation is only as good as the image rejection of the sideband-separating mixer. For the sideband-separating receivers developed for ALMA, which have wide frequency coverage and wide IF bandwidth, it has been possible to obtain an image rejection of > 10 dB at most frequencies, which is sufficient to suppress the atmospheric noise from the image band adequately. However, observers on single-dish telescopes would like greater image rejection to eliminate confusion caused by strong sources in the image band[1]. One approach to suppressing image frequency lines on double-sideband mixer receivers was explored on the NRAO 12-m telescope *ca.* 1991. The first and second local oscillators were swept during the observation so as to smear out spectral features from the image band. However, this approach has several drawbacks as described in [1][2].

This note describes a post-processing procedure for enhancing the image rejection of a sideband-separating mixer receiver. It requires a simple measurement of the image rejection as a function of frequency using an RF test signal whose power level need not be known. Spectra given by filterbanks on the nominal upper- and lower-sideband outputs of the receiver can then be corrected to remove the image components. This procedure is only possible with a receiver using a sideband-separating mixer with separate IF outputs nominally for the upper and lower sidebands. It cannot be used with a double-sideband receiver to remove downconverted image signals.

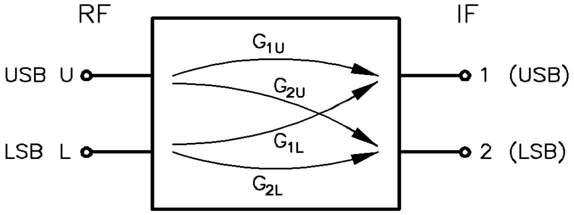

Fig. 1. Power gains of an imperfect sideband-separating receiver. The RF upper and lower sideband ports are normally the same waveguide or transmission line, but are shown separately for clarity.

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[1] On an interferometer, such as ALMA, the different fringe rates in the upper and lower sidebands automatically result in high image rejection, although atmospheric noise in the image band is not reduced in this way because it is not correlated from one interferometer element to the next.

The conversion gains of a sideband separating receiver are depicted in Fig. 1. The notation used here is the same as in ALMA Memo 357 [3]. The image rejection ratios are:

$$R_1 = \frac{G_{1U}}{G_{1L}} \quad \text{at IF port 1, and} \quad R_2 = \frac{G_{2L}}{G_{2U}} \quad \text{at IF port 2.} \tag{1}$$

In principle, R_1 and R_2 could be measured by injecting CW signals of known relative amplitudes into the upper and lower sidebands and measuring the IF response to each. At millimeter wavelengths, however, it is difficult to determine with sufficient accuracy the relative amplitudes of two low level RF signals separated in frequency by twice the IF ($2f_{IF}$ = 8–24 GHz in the case of ALMA receivers). However, two quantities which are easily measured without any knowledge of the RF test signal levels are the ratios M_U and M_L of the output powers at IF ports 1 and 2 with a CW test signal (of unknown amplitude) in each RF sideband:

$$M_U = \frac{G_{1U}}{G_{2U}} \quad \text{and} \quad M_L = \frac{G_{2L}}{G_{1L}}. \tag{2}$$

The IF powers at ports 1 and 2 are:

$$P_1 = G_{1U} P_U + G_{1L} P_L + P'_{R_1} \tag{3a}$$

and

$$P_2 = G_{2U} P_U + G_{2U} P_L + P'_{R_2}, \tag{3b}$$

where P_U and P_L are the upper- and lower sideband signals incident on the receiver and P'_{R1} and P'_{R2} are the noise powers engendered at ports 1 and 2 by the receiver itself.

When observations are done using Dicke switching, the quantities of interest are the switched power at IF ports 1 and 2, $\Delta P_1 = P_1|_{\text{on source}} - P_1|_{\text{off source}}$ and $\Delta P_2 = P_2|_{\text{on source}} - P_2|_{\text{off source}}$. From (3),

$$\Delta P_1 = G_{1U} \Delta P_U + G_{1L} \Delta P_L \tag{4a}$$

and

$$\Delta P_2 = G_{2U} \Delta P_U + G_{2L} \Delta P_L. \tag{4b}$$

From (2) and (4),

$$G_{1U} \Delta P_U = \frac{\Delta P_1 - \Delta P_2 / M_L}{1 - \dfrac{1}{M_U M_L}} \tag{5a}$$

and

$$G_{2L} \Delta P_L = \frac{\Delta P_2 - \Delta P_1 / M_U}{1 - \dfrac{1}{M_U M_L}}. \tag{5b}$$

Equations (5a) and (5b) give the IF output powers from the upper- and lower-sideband signals, corrected for the imperfect image rejection.

CORRECTING OBSERVATIONS MADE WITH A FILTERBANK

In spectral line observations using a sideband-separating mixer receiver with filter banks on the two IF outputs, equation (5) can be used to remove image contamination of the switched-power outputs. If *i* denotes the channel of each filterbank which responds to an intermediate frequency f_i, generated by upper- and lower-sideband signals P_{Ui} and P_{Li} at frequencies $f_{LO} + f_i$ and $f_{LO} - f_i$, then the measured switched ((on source) - (off source)) powers ΔP_{1i} and ΔP_{2i} at IF ports 1 and 2, are from (4),

$$\Delta P_{1i} = G_{1Ui} \Delta P_{Ui} + G_{1Li} \Delta P_{Li} \tag{6a}$$

and

$$\Delta P_{2i} = G_{2Ui} \Delta P_{Ui} + G_{2Ui} \Delta P_{Li}. \tag{6b}$$

The sideband calibration data are taken as follows:

(i) With the receiver looking at a background of constant temperature, a CW test signal (of arbitrary amplitude) at frequency $f_{LO} + f_i$ is injected in the upper sideband. The corresponding filerbank outputs from IF ports 1 and 2, P_{1calUi} and P_{2calUi} are measured.

(ii) With the receiver looking at the same background, a CW test signal (of arbitrary amplitude) at frequency $f_{LO} - f_i$ is injected in the lower sideband. The corresponding filerbank outputs from IF ports 1 and 2, P_{1calLi} and P_{2calLi} are measured.

(iii) With the receiver looking at the same background, but with the CW test signal switched off, the filerbank outputs from IF ports 1 and 2, P_{1offUi} and P_{2offUi} are measured.

The quantities M_{Ui} and M_{Li} for filterbank channels *i* are then calculated from equation (2):

$$M_{Ui} = \frac{P_{1calUi} - P_{1offUi}}{P_{2calUi} - P_{2offUi}} = \frac{G_{1Ui}}{G_{2Ui}} \tag{7a}$$

and

$$M_{Li} = \frac{P_{2calLi} - P_{2offLi}}{P_{1calLi} - P_{1offLi}} = \frac{G_{2Li}}{G_{1Li}} \quad . \tag{7b}$$

The corrected filterbank channel *i* outputs are then, using (5) and (6),

$$G_{1Ui}\Delta P_{Ui} = \frac{\Delta P_{1i} - \Delta P_{2i} / M_{Li}}{1 - \dfrac{1}{M_{Ui} M_{Li}}} \tag{8a}$$

and

$$G_{2Li}\Delta P_{Li} = \frac{\Delta P_{2i} - \Delta P_{1i} / M_{Ui}}{1 - \dfrac{1}{M_{Ui} M_{Li}}} \quad , \tag{8b}$$

which can be evaluated using the measured quantities.

DISCUSSION

The accuracy of the corrected filterbank outputs given by (8) depends on the accuracy with which M_U and M_L are measured, and also on the intrinsic image rejection of the sideband-separating mixer. This is demonstrated in the following example.

Example: A sideband-separating mixer receiver with 10 dB image rejection, which is sufficient to remove most of the atmospheric image frequency noise. Assume $G_{1U} = G_{2L} = 1$, and $G_{2U} = G_{1L} = 0.1$, consistent with 10 dB image rejection. Then the measured M_U and M_L should be 10 dB. Consider three cases:

(i) The measured value of M_U (or M_L) is in error by E %.

(ii) The measured values of M_U and M_L are both in error by E % in the same sense.

(iii) The measured values of M_U and M_L are both in error by E % in opposite senses.

For each case, the image rejection obtained after correction of the filterbank outputs using equations (5) (or (8)) are as shown in Fig.2. An error in measuring M_U and/or M_L also causes a small error in corrected value of the desired signal. The magnitude of the this error is different for the three cases (i)-(iii) as shown in Fig. 3.

During a practical astronomical measurement atmospheric variation (*e.g.*, due to clouds) may cause the attenuation in the two sidebands to vary. However, the enhanced image rejection obtained using (5) or (8) should be immune to gain changes due to the atmospheric fluctuations because the measured quantities M_U and M_L (equation (2)) are ratios of gains from one sideband to one IF output and from the *same* sideband to the other IF output.

Changes in attenuation ahead of the receiver do not affect M_U and M_L.

In a practical sideband-separating mixer, M_U and M_L depend to some degree on the local oscillator frequency. During an astronomical observation, the LO frequency is adjusted continuously to track the Doppler shift of the desired source caused by rotation of the earth. However, the total change of LO frequency during an observing session is of the order of one part in 10^6, and over such a small range M_U and M_L should not change significantly. The sensitivity of M_U and M_L to LO frequency is determined entirely by the internal circuit of the mixer which would not normally contain any strongly frequency-dependent elements.

The power levels of the CW test signals must be chosen to allow M_U and M_L to be measured with sufficient accuracy while avoiding saturating the receiver. Note that saturation in SIS receivers [4][5] is a very gradual process and may not be obvious.

A Note on Power Measurements in the Presence of Noise

If, in determining M_U and M_L, a spectrum analyzer is used to measure the output powers at IF ports 1 and 2 with the CW test signal on and off, care must be taken to correct readings for the fact that the envelope detector in most modern spectrum analyzers does not indicate the sum of the CW signal power and the system noise power but gives a reading closer to the CW power alone [1][6][7]. This is not the case with most power meters and other square-law detectors, which require no such correction.

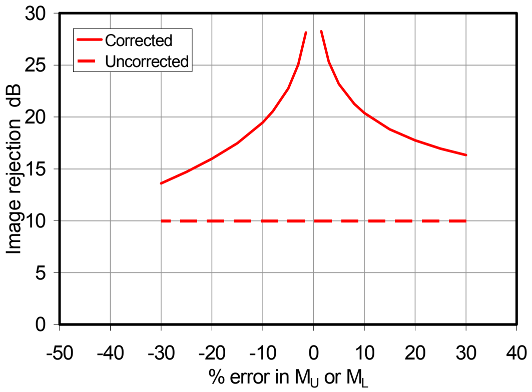

Fig. 2. Degraded image rejection caused by an error in measuring M_U and/or M_L
For the example, $G_{1U} = G_{2L} = 1$, and $G_{2U} = G_{1L} = 0.1$.

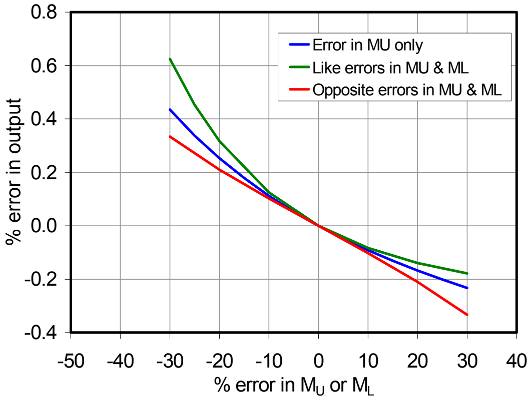

Fig. 3. Error in the measured signal caused by an error in measuring M_U and/or M_L
For the example, $G_{1U} = G_{2L} = 1$, and $G_{2U} = G_{1L} = 0.1$.

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