Side-Band Ratio Correction for HIFI Data

Version 1 – 21/05/2013

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This note describes the general calibration problem associated with the side-band gain imbalance existing in double-side-band heterodyne systems such as HIFI, and provides some recipes and calibration tables applicable to the particular case of the HIFI mixers. It supersedes the information provided in the paper by Roelfsema et al. 2012.

1. Side-band gain ratio in heterodyne receivers

Heterodyne detectors are intrinsically simultaneously sensitive to two frequency ranges located on either side of the Local Oscillator (LO) frequencies, separated by twice the Intermediate Frequency (IF). They are called the lower and the upper side-bands (LSB and USB respectively), although some observatories use the nomenclature of Signal and Image side-band. Because heterodyne mixers usually have a non-flat response function, the signal received in each side-band is multiplied by a different gain (see Fig 1).

In Single-Side Band systems (SSB), the signal of one of the side-bands gets filtered out either electronically or optically, and the applicable gain is automatically calibrated by the band-pass calibration. In Double Side-Band systems (DSB) such as HIFI, both signals are folded onto each other and the band-pass calibration cannot disentangle the gain contribution from either of the side-bands. The proper calibration of line intensities resulting from the respective side-bands therefore requires the knowledge of the corresponding gains, expressed as the side-band gain ratio, often called *Side-Band Ratio* (SBR).

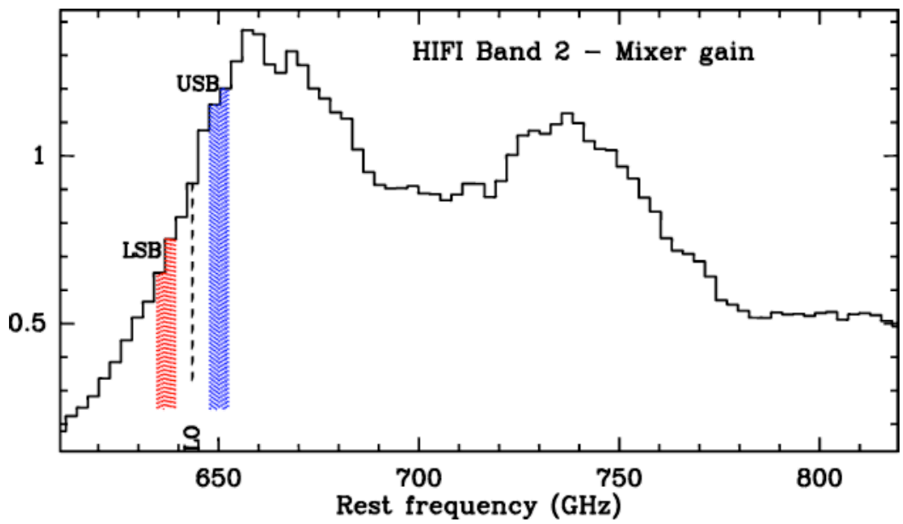

Fig 1.: Illustration of the gain response function of an un-pumped mixer as measured by an FTS (intensities are in arbitrary unit)

2. Measurement of the HIFI side-band gain ratio

The HIFI SBR was primarily measured pre-launch during the Instrument Level Test campaign. It used the same concept as that applied for the calibration of the SWAS satellite, namely measuring optically thick molecular emission through an absorption gas-cell (Teyssier et al. 2004, 2008, Higgins et al. 2010). The measurements included both saturated and non-saturated lines where estimate of the absolute line opacity was required to derive the

SBR. At the time of this campaign, the knowledge of the instrument was not fully mature and in retrospect some of the measurements in the least stable bands (e.g. bands 6 and 7) were probably not acquired in the most optimal fashion. Beside, several instrumental artifacts did affect the data-set and took some time to be understood (some of them are, as of today, still challenging to the calibration scientists). The overall picture of the SBR derived from this campaign is illustrated in the Fig. 2 and 3, resulting from R. Higgins' PhD thesis (see section 3 for the side-band ratio convention used). It forms the basis for the SBR correction applied in the HIFI pipeline and described in the following sections.

3. HIFI side-band ratio calibration strategy

3.1 Convention

The concepts used for the intensity calibration of HIFI are described in Ossenkopf 2003 (also available at http://herschel.esac.esa.int/twiki/pub/Public/HifiCalibrationWeb/calibframework.pdf). They assume a normalised convention for the side-band ratio, defined as:

$G_{ssb} = G_{usb}/(G_{usb}+G_{lsb})$ for the calibration of lines present from the USB (1)

and

$1 - G_{ssb} = G_{lsb}/(G_{usb}+G_{lsb})$ for the calibration of lines present from the LSB (2)

Where G_{usb} and G_{lsb} are the respective gains in the USB and LSB. The relationship between the HIFI convention and the "standard" definition of the side-band gain ratio is as follows:

$$R = G_{usb}/G_{lsb} = G_{ssb}/(1-G_{ssb}) \quad (3)$$

and

$$G_{ssb} = R/(1+R) \quad (4)$$

3.2 Side-band ratio correction in the pipeline and calibration tables

Following the above concepts, the overall calibration equation for HIFI writes (see Ossenkopf 2003 for details about the involved parameters):

$$J_S - J_{Ref} = \frac{\eta_c + \eta_h - 1}{\eta_{sf}(\eta_l G_{ssb} + \omega_{ssb})} \times \frac{c_S - c_R}{c_{hbb} - c_{cbb}} \times \left[J_{hbb} - J_{cbb} \right]$$

It means that the side-band gain correction basically corresponds to a division by the best-guess value for G_{ssb}, which takes values close to 0.5 when the side-band gains are balanced. This step occurs at the end of the HIFI level 2 pipeline and is performed by the tasks *mkSidebandGain* and *doSidebandGain*.

Currently, the side-band correction in the pipeline assumes that the side-band ratio is a smooth function of the LO frequency. As such, the side-band ratio assignment to a given observation is based on interpolation, and assumes a constant value over the 4 or 2.4 GHz of instantaneous IF bandwidth – we know that this is not always true but there is currently no automatic correction for it (see section 3.5). The concept of interpolation according to the frequency has made it complicated to turn the scarcely sampled measurement points from the ILT gas-cell campaign into a smooth calibration table valid at any frequency tuning. Currently, only two mixer bands feature tabulated side-band ratio entries in the calibration tree: band 2a between 624 and 654 GHz), and bands 5a and 5b, with a constant ratio, indicative of a constant gain slope (see Fig. 4).

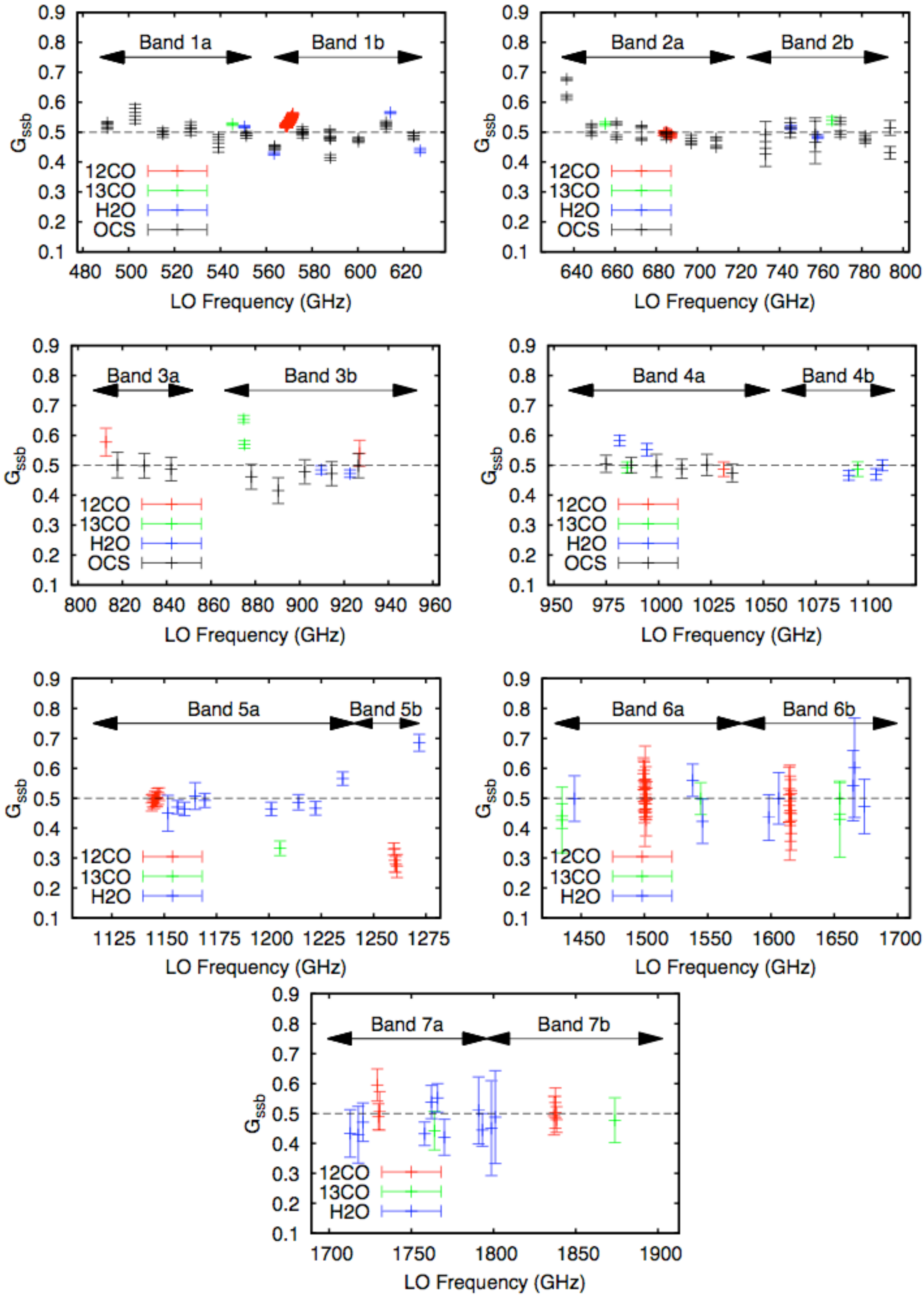

Fig 2.: Best estimate of the (normalised) HIFI side-band ratio in the USB for the H-polarisation mixers, using ^{12}CO, ^{13}CO, OCS and H_2O, from pre-flight data

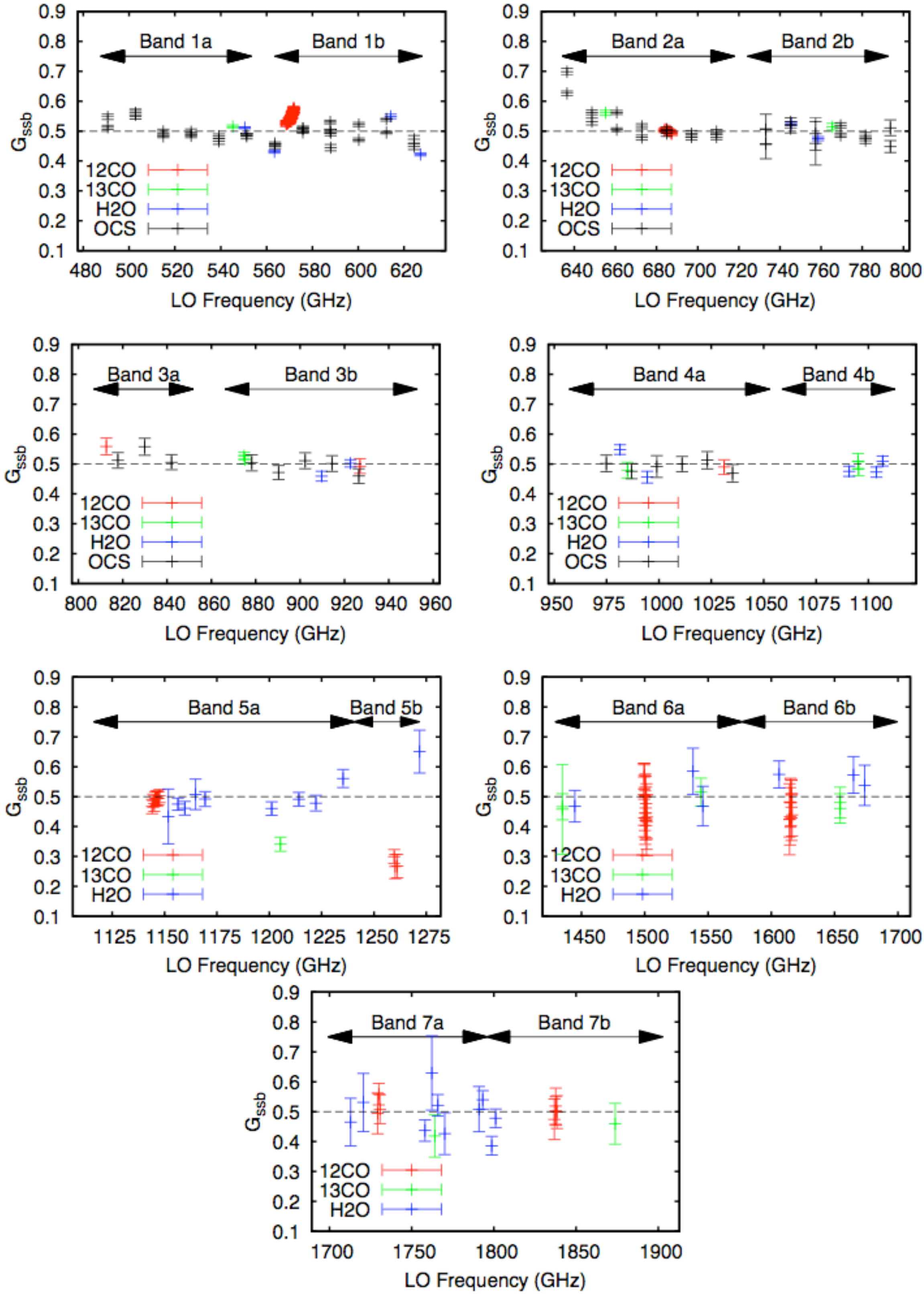

Fig 3.: Same as Fig. 2 for the V-polarisation mixers

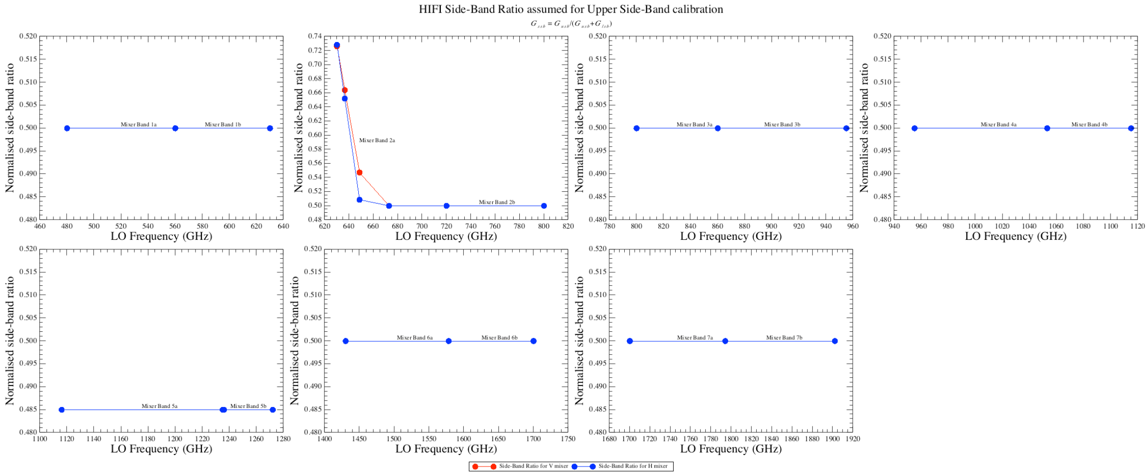

Fig 4.: Side-band ratio currently in use in the HIFI pipeline as of HIFI_CAL_11_0 (as of January 2013), and applied in the bulk reprocessing with HIPE 10

For the remaining of the HIFI range, we are currently working on extending the calibration table of side-band ratio function over the other bands, but individual values for particular lines of interest can be found in section 4.

It is worth adding that, due to the usually poorer/noisier quality of both pre-launch and in-orbit data in the bands 6 and 7, the prospect of deriving high accuracy side-band ratio tables in those bands is less promising. On the other hand, there is strong indication, both from the theoretical and experimental viewpoints, that the detector technology used in these mixers (Hot Electron Bolometer) implies very smooth response functions that result is side-band ratio close to unity at nearly any location of the operational range. In that sense, the current assumption of a perfectly balanced mixer in those two bands should be taken with much more confidence than what the pre-launch measurement uncertainty numbers would suggest a face value.

3.3 Side-band ratio and deconvolution

HIFI data obtained in spectral scan mode can use the redundancy of lines observed at different LO tunings in order to reconstruct the single-side band signal (Comito el al 2002). Since the deconvolution algorithm applies the side band ratio to the data, the level2 sideband ratio conversion must be removed, hence the data fed into the deconvolution algorithm should **NOT** be a priori corrected from the side-band ratio. Since the deconvolution is usually applied post-level2, a dedicated step has been introduced into its algorithm in order to undo the default side-band ratio correction applied by the pipeline as described in section 3.2. Note that this operation is not yet available in the CLASS/GILDAS version of the deconvolution but we expect it to be implemented around April 2013. Also note that you can undo the side-band ratio correction yourself if needed, either by using the task *undoSidebandGain* in HIPE, or by multiplying the spectra by the meta-data stored as *Gim* in the Class header of each individual level2-exported spectrum.

In principle, the deconvolution algorithm offers the option to automatically fit the side-band gains applying to the individual frequency tunings. Our experience is that this approach does not work very well and needs in any case a high line density. Therefore we strongly **discourage** to activate this option (both on the HIPE and the Gildas/CLASS deconvolution codes) in its present form. Instead we recommend to select the "GAIN_FIT_OFF_USE_PRESET" option, which uses the tabulated ratios as input, see figure 4 for an overview of the preset side band ratios (note: this is currently the default option in the *doDeconvolution* task).

3.4 Side-band ratio and continuum calibration

The side-band ratio correction is only valid for the line intensity calibration and alters the continuum calibration at level2. This is because the continuum contribution from a black body is nearly equal in both side-bands, both from the source and from the internal calibrators used to compute the band-pass correction. Since the sum of the respective normalised side-band ratios for USB and LSB contribution is 1, the continuum is already correctly calibrated at level1 prior to the side-band ratio correction. At level2, the continuum is therefore approximately twice its real value (exactly twice for a perfectly balanced receiver), and this is why for example saturated absorption lines will have their dip at about half the continuum level in level2 products (see e.g. Fig. 5 from Neufeld et al. 2010).

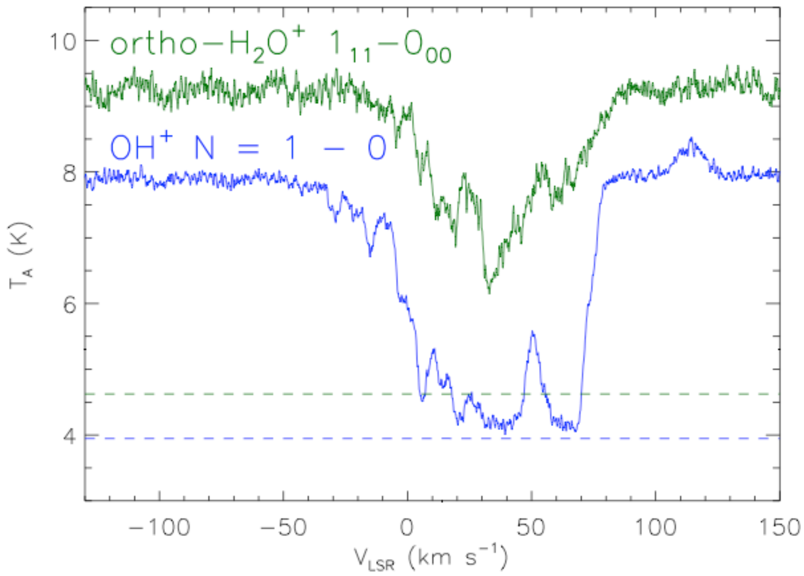

Fig 5.: Example of absorption lines in the HIFI band 5a (from Neufeld et al. 2010). The dashed lines correspond to the expected saturation level in case of a perfectly balanced mixer

When the user is interested in the exact continuum level, the most accurate way consists in undoing the side-band ratio correction on level2 data, either by using the task *undoSidebandGain* in HIPE, or by multiplying the spectra by the meta-data stored as *Gim* in the CLASS header of each individual level2-exported spectrum. By doing this bear in mind that you are invalidating any line intensity calibration.

For absorption line studies, it is fundamental to have both line and continuum intensity consistently calibrated. Some recipe has been provided e.g. in the user-provided data release note from the PRISMAS project (which will be available at https://astro.ens.fr/index.cgi?exe=217263 in the near future – please contact M. Gerin in the meantime – *gerin@lra.ens.fr*) but the principles are reminded here. The bottom line is as follows: the user needs to estimate the continuum in the level 2 spectrum undone from the side-band correction as explained above (e.g. via an zero order polynomial fit to the spectrum or a simple average over a range free from line), then subtract this value from the uncorrected level2 spectrum that holds the proper line intensity calibration.

3.5 Side-band ratio and IF frequency slope

When the gain response of a DSB heterodyne mixer is not equal in its respective upper and lower side bands, the side- band ratio (R = G_{usb}/G_{lsb}) deviates from unity. Since gain responses are usually smooth functions of the LO frequency, one can assume to first order that this gain function is approximated to a nearly constant slope over a frequency range extending typically from ($f_{LO} - f_{IF}$) to ($f_{LO} + f_{IF}$), where f_{LO} and f_{IF} are the LO and IF frequencies, respectively. In this assumption, one can demonstrate that IF frequency points farther away from the LO frequency (higher IF frequencies) will have a more unbalanced sideband gain than those closer to the LO frequency. This is illustrated in Fig. 6. In this model, a gain ratio of e.g. $R = 1.16$ is assumed at $f_{LO} = 570$ GHz and $f_{IF} = 6$ GHz. One can see that the gain ratio would then vary between 1.1 and 1.22 from one end of the IF to the other. Based on this rationale one can also assume that this effect should be ignored in HEB bands as the side-band ratio is expected to be very close to unity on broad ranges.

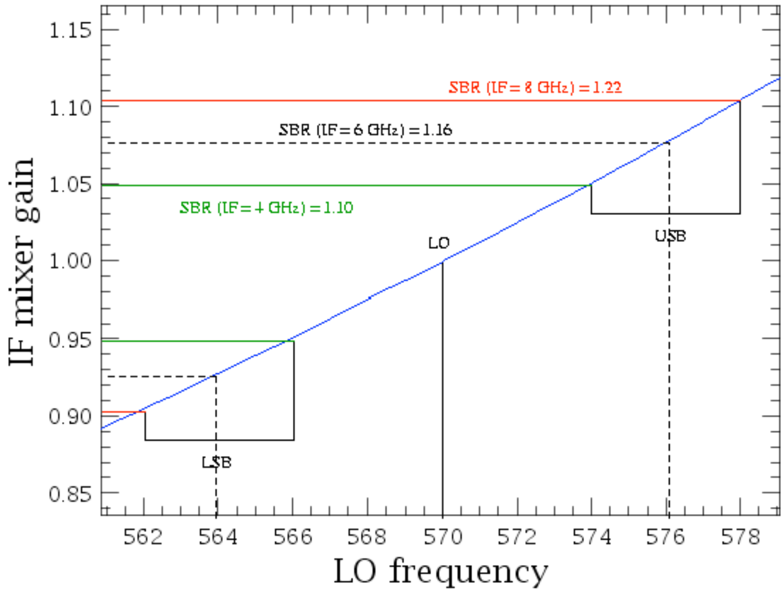

Fig 6.: Illustration of the deviations in sideband ratio with large sideband separation (from Roelfsema et al. 2012)

In this formalism, one can demonstrate that the IF variation of the gain ratio can be described as

$$R(f) = R(f_{IF})^{(f/f_{IF})} \qquad (6)$$

where f is the frequency in the IF scale (between 4 and 8 GHz for bands 1 to 5, and 2.4 to 4.8 GHz in bands 6 and 7), and $R(f_{IF})$ is the gain ratio at f_{IF} (i.e. in the middle of the IF band). Figure 7 shows the typical error that would affect the gain ratio over the IF band if one assumed that the ratio value at the IF center applies over the whole IF bandwidth.

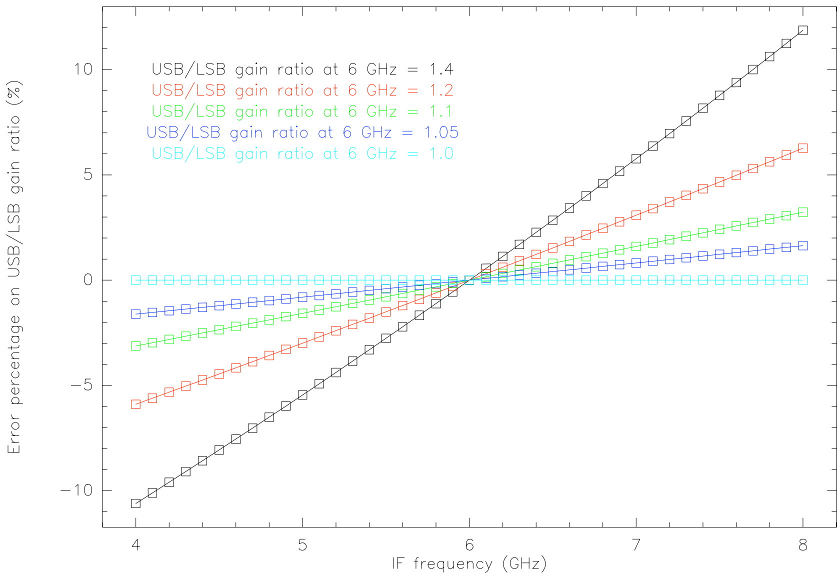

Fig 7.: Errors resulting from deviations in sideband ratio with large sideband separation (from Roelfsema et al. 2012)

Of course, such intrinsic correction should be applied with extreme care, since the assumption of a smooth and constant slope response over a large section of the mixer frequency range is not always guaranteed. For instance, inflexion points in the gain function can lead to a similar situation with a mixer response that is far from a straight line over, e.g., twice the IF. For the case of HIFI, we have observed that this formalism was accurate at least in the lower end of band 2a (Fig. 8).

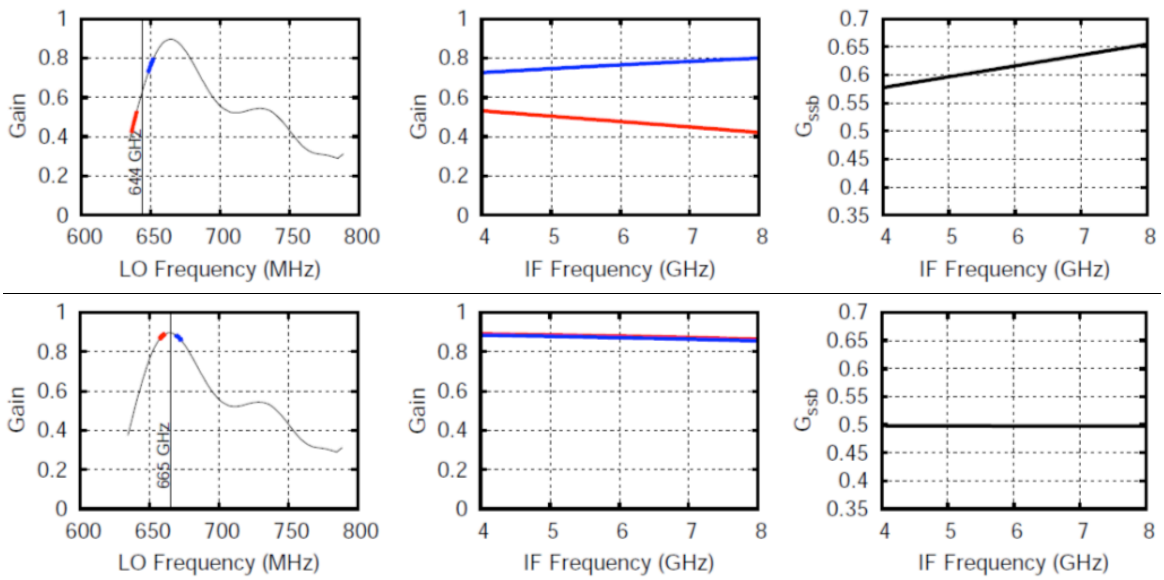

Fig 8.: Illustration of the IF slope of the side-band ratio in two different locations of a mixer range similar to that of the HIFI band 2. *Upper panel*: close to a band border, *Lower panel*: close to an inflexion point (from R. Higgins' thesis)

It can also be demonstrated on a simple case measured with the gas-cell during the pre-flight campaign. Figure 9 shows an OCS measurement taken at an LO frequency of 636.444 GHz in the WBS-H. Because OCS has transitions regularly spaced every 12 GHz, a clever tuning allows to systematically observe one line from the USB (at high IF frequency, here 7.4 GHz) and one line from the LSB (at low IF, here 4.7 GHz). The imbalance between the two sidebands is striking, showing the strong mixer gain slope at the bottom end of band 2a. The side-band ratio in the middle of the IF (IF = 6 GHz) is tabulated as $\boldsymbol{G_{ssb}}$ **= 0.652**, or R = 1.87, however the side-band ratio inferred from the respective transitions differs a lot (**0.615** from the line in the LSB *vs* **0.681** for the line in the USB). According to the equation (6) above, the following ratio apply at other IF frequencies:

- R(IF=7.4 GHz) = 2.19, or G_{ssb} = 0.685. This is indeed very close to the value derived for the transition seen in the USB (Fig. 9)

- R(IF=4.7 GHz) = 1.63, or G_{ssb} = 0.620. Again this very close to the value derived for the transition seen in the LSB (Fig. 9)

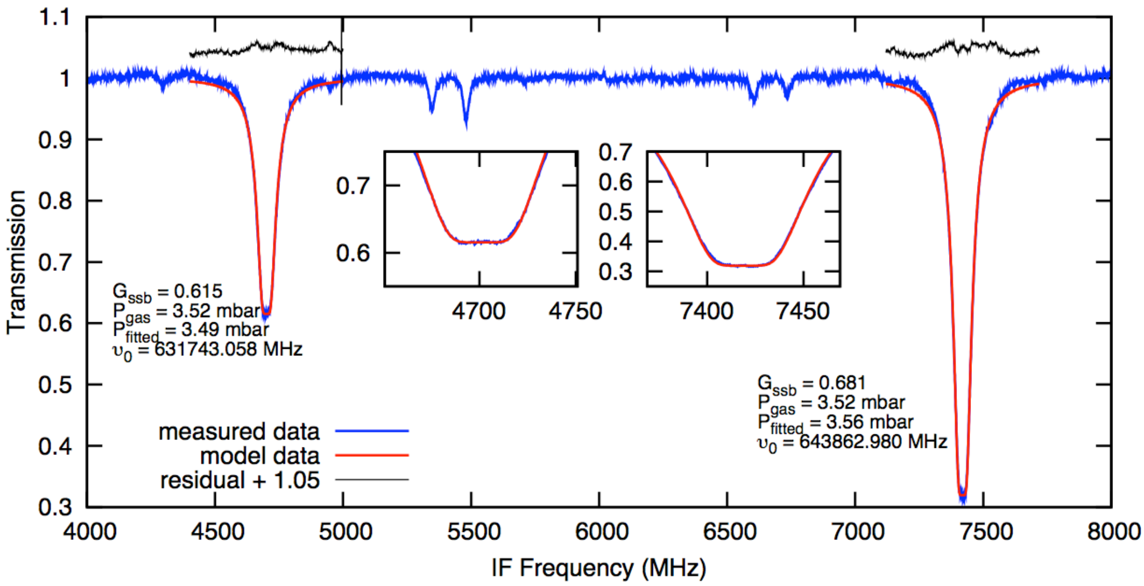

Fig 9.: Gas-cell observation of the J=52-51 and J=53-52 transitions of OCS in the WBS-H at LO = 636.444 GHz. The red profiles correspond to the best LTE fits – note that both lines are predicted to be saturated (from R. Higgins' thesis)

The same can be illustrated on real data. The following plot shows isolated lines observed in the Orion KL spectral survey from band 2a. The lines shown here have been chosen so that they appear at various IF locations with negligible line contamination due to blending. The annotations on the plot indicate the side-band ratio correction applied to each individual LO frequency setting, corresponding to a line that would be located at IF = 6 GHz. The corrected ratio taking into account the IF slope is consistent with LSB line intensities being over-estimated at low IF (blue curve) and under-estimated at high IF (green curve), and LSB line intensities being over-estimated at high IF (blue curve) and under-estimated at low IF (green curve). At IF close to 6 GHz (red curve) the line intensity is comparable to that from the deconvolved product (thick black curve), where the IF slope effect basically averages out.

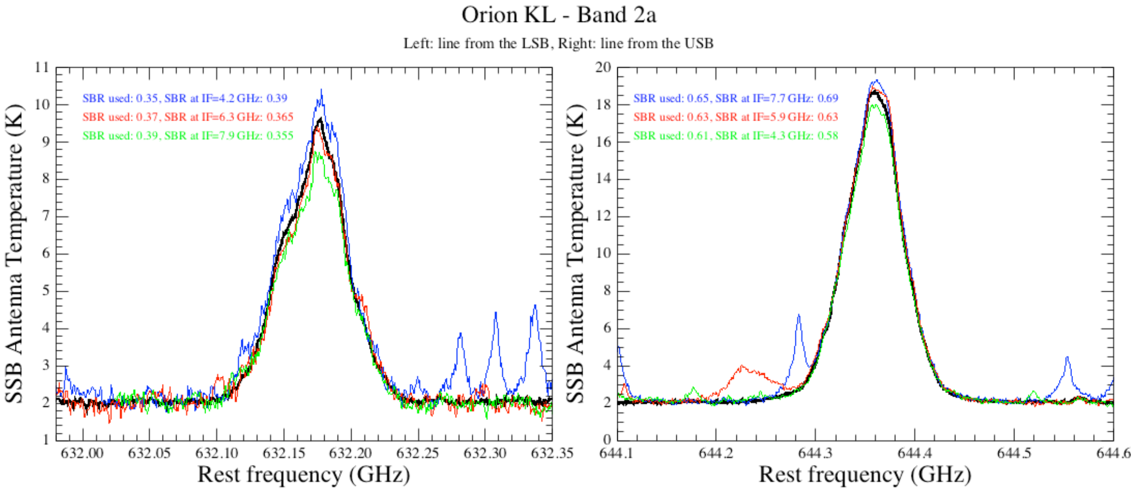

Fig 10.: Orion KL spectra observed in band 2a between LO = 636.3 GHz and LO = 640 GHz. See text for details

3.6 Side-band ratio modulation over the IF

On top of IF dependence purely due to the sub-GHz intrinsic mixer gain response function, there are other instrumental artifacts that may create an small scale gain ratio variation, which typically manifests as modulation of the side-band ratio over the IF due to resonance between the mixer and the LO feed horns. The situation can become more complex when a diplexer is involved in the LO signal injection as diplexers have an IF frequency-dependent transmission response (see e.g. R. Higgins' PhD thesis). The IF band edges are more sensitive to these effects. The details of how this alters the side-band ratio and its magnitude is however relatively poorly known at the moment but the HIFI team is currently building a full optical model and conducting dedicated measurements on the flight hardware to improve the understanding of these effects (work of B. Delforge, SRON-G/JPL).

As can be seen in the overall calibration equation in section 3.1, this term, called ω_{ssb} in our data model, is not considered in the tabulated entries for the side-band ratio G_{ssb}.

3.7 Side-band ratio and spectral purity

It has been demonstrated that some frequency domains over the HIFI operational range do suffer from spectral impurity. What this means is that the DSB spectrum obtained from the mixing process may hold signal arising from frequency ranges not belonging to the intended ones. In this situation, the detector gain cannot be described with only 2 components (LSB and USB) but has to take into account an additional component (the Outer Side Band contribution, OSB). In practice this implies that the total system gain is altered by that of the unwanted regions and the line calibration becomes erroneous as it assumes a side-band correction relying on only two side-bands.

One can extend the formalism introduced in equations (1) and (2) (section 3.1) as follows. Assuming that the OSB contributes to the total gain as G_{osb}, the new side-band gain ratio correction to apply to lines from the USB writes:

$$G_{ssb}^{impure} = G_{usb} / (G_{usb} + G_{lsb} + G_{osb}) \qquad (7)$$

Since we calibrate against continuum sources (internal loads) this will manifest in a decrease of the side-band gain ratio by a factor F_{corr} (<1) such that $G_{ssb}^{impure} = G_{ssb} \times F_{corr}$.

Consequently, one can see that $(G_{usb} + G_{lsb} + G_{osb}) = (G_{usb} + G_{lsb})/F_{corr}$, so that the new side-band ration correction for lines in the LSB will now write:

$$G_{lsb} / (G_{usb} + G_{lsb} + G_{osb}) = (1 - G_{ssb}) \times F_{corr} \qquad (8)$$

i.e. the correction factor applies similarly for lines in either side-band.

A description of the known impure regions can be found in the HIFI release notes (http://herschel.esac.esa.int/twiki/pub/Public/HifiCalibrationWeb/HifiObservingModesPerformance_110926a.pdf). The most severe one was the band 5b, which was in fact only released to the community after most of its purity issues got resolved. Evidence of the side band ratio imbalance in this situation can be see the gas-cell results shown in figures 2 and 3. In this example on can see that depending on which side band the line is observed in the intensity can be greatly over or underestimated. There are however remaining slightly impure regions, e.g. in band 3b (LO = 951-953 GHz) and 5a (LO=1231-1236 GHz for data taken before OD-595). We provide here correction factor that can be applied to the data in those ranges.

- For band 5a, observations taken in the range f_{LO} = 1231-1236 GHz prior to OD-595 can be corrected by dividing by the following factor:
  $\boldsymbol{F_{corr} = 0.9873 - 0.1047 \times [f_{LO} - 1231]\ (GHz)}$ for the H polarization
  $\boldsymbol{F_{corr} = 0.9294 - 0.1006 \times [f_{LO} - 1231]\ (GHz)}$ for the V polarization

- For band 3b, observations taken in the range LOF = 951-953 GHz prior to OD-1393 (i.e. basically all the mission) can be corrected by dividing by the following factor:

$$\boldsymbol{F_{corr} = TBD}$$

3.8 Side-band ratio accuracy

The following table, taken from Roelfsema et al. 2012, provides a conservative accuracy estimate for the side-band ratio. In this table, the error applies to the assumption of a unity ratio (i.e. G_{ssb} = 0.5 in the HIFI convention) applied at any frequency. At this stage it does not yet take into account the ranges where non-unity ratio have been tabulated based on pre-launch and in-orbit data, and where better accuracy should be applied as the ratio is better constrained. No IF dependence (intrinsic gain slope or standing wave modulation) is considered in this budget. Finally, as explained above the numbers applying to the HEB bands may be pessimistic if one considers the expected flat response function of these detectors.

	HIFI mixer band			
	1 & 2	**3 & 4**	**5**	**6 & 7**
Side-band ratio error (%)	3-4	4-6	4	5-8

4. HIFI side-band ratio tables for dedicated tunings

The current calibration tables for the side-band ratio do only reflect a small fraction of the ratio estimated in the course of the pre-launch gas-cell campaign. As explained above, this is due to the necessity of ensuring a continuous representation of the ratio even in ranges poorly covered in these tests. We are currently filling those gaps by using data measured in orbit, tracking high SNR line intensities over various LO settings, and bootstrapping their relative variation to absolute measurement points from the pre-launch campaign. This process is long and may not be complete before the end of the archive phase. In the meantime, we are providing the following side-band ratio values as measured at spot frequencies, which corresponds to ranges covering the most relevant ^{12}CO, ^{13}CO and water lines. **The side-band ratio is given for lines from the USB**. Correction for lines in the LSB can simply be obtained by taking ($1 - G_{ssb}$). Bear in mind that frequency interpolation between those numbers can be very risky, the worst range being probably in the band 1b (see also Fig. 1 and 2) where quick variation and gain slope inversion can occur on small frequency scale. For any further recommendation please contact the Herschel Helpdesk (http://herschel.esac.esa.int/esupport/).

4.1 Side-band ratio table

In the following, emphasis is given to line transition for which non-unity side-band ratio need to be involved. Other transitions were also measured but confirmed the adequacy in applying side-band ratio of 1 (i.e. $G_{ssb} = 0.5$). When several frequencies are given for the same line transition, interpolation can be applied. Otherwise, side-band ratios for lines located at other IF frequency may suffer from the uncertainty described in section 3.5 due to IF slope effects. In the near future, we will try to update the table below with the necessary information to allow extrapolation at other IF. Section 4.2 describes a typical use-case to apply entries from the table, while section 4.3 illustrates a particular outlier we have observed next to the CO *J*=5-4 line, where particular care is needed.

Band	Transition	LO (GHz)	IF (GHz)	G_{ssb} H	Error H	G_{ssb} V	Error V
			^{12}CO				
1b/USB	*J*=5-4	568.5	7.77	0.522	0.007	0.528	0.008
1b/USB	*J*=5-4	569.6	6.66	0.532	0.005	0.531	0.004
1b/USB	*J*=5-4	570.5	5.77	0.539	0.004	0.534	0.003
1b/USB	*J*=5-4	571.7	4.57	0.560	0.003	0.560	0.004
			^{13}CO				
1a/USB	*J*=5-4	545.25	5.68	0.526	0.004	0.516	0.005
2a/USB	*J*=6-5	655.25	5.82	0.528	0.007	0.561	0.008
2b/USB	*J*=7-6	765.50	5.68	0.539	0.013	0.515	0.011
			H_2O				
1a/USB	110-101	550.436	6.5	0.518	0.004	0.511	0.003
1b/LSB	110-101	563.436	-6.5	0.428	0.005	0.431	0.005
1b/USB	532-441	614.200	6.5	0.565	0.003	0.549	0.008
1b/LSB	532-441	627.201	-6.5	0.438	0.008	0.422	0.005
2b/USB	211-202	745.533	6.5	0.515	0.007	0.525	0.006
2b/LSB	211-202	758.532	-6.5	0.485	0.006	0.475	0.007

4.2 How to apply the ratios from the table

Section 4.1 provided of table of known side band ratio imbalances in the HIFI frequency coverage. This section describes how a non-unity SBR can be applied to level 2 data. We use a water line observation from the CHESS key program. This line is observed in the upper side band using the 1a LO chain and observed in the lower side band using the 1b LO chain. Fortunately this line was also observed in the upper and lower side band during the gas-cell test campaign so complimentary data is available.

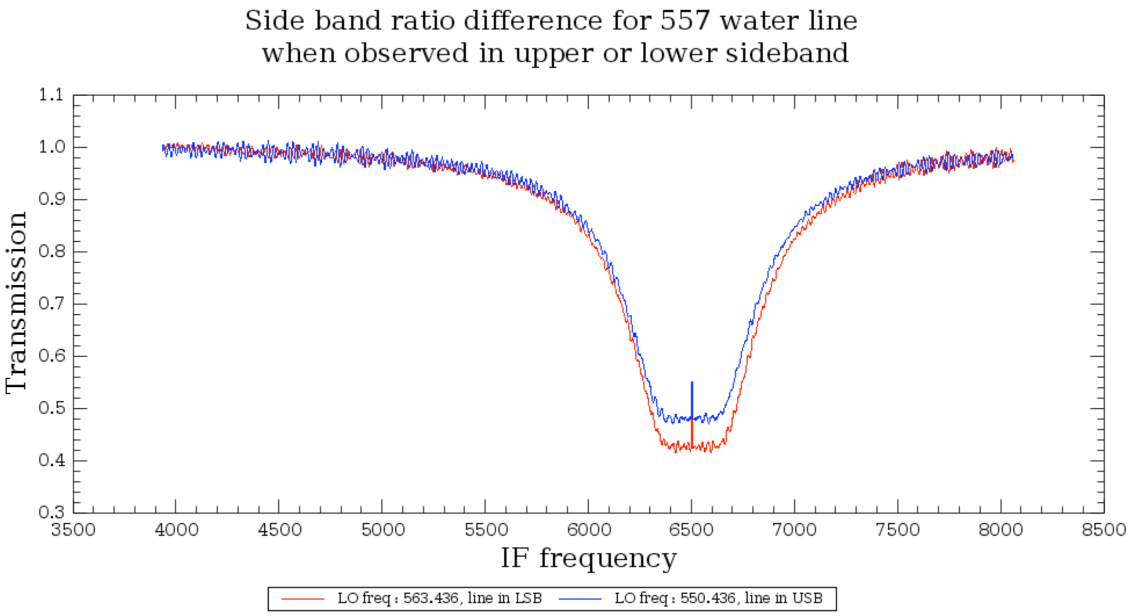

Fig 11.: Gascell data from H mixer showing side band ratio difference between upper lower sideband

Figure 11 shows the 557 water line measured at an LO frequency of 563.436 (band 1b) and 550.436 (band 1a) GHz during the ground test campaign. In an ideal mixer with equal gain in the upper and lower side band the saturated absorbed line would reach 0.5. In this example this is not the case. The red line shows a spectral line measured in the LSB. Here the upper side band is dominant ($G_{ssb} > 0.5$) and hence the water line measured in this side band would be over estimated if an equal gain in both side bands were assumed. Interestingly when the line is measured in the lower side bands shown with the blue line profile the absorbed line is also below 0.5 indicating that at this frequency the lower side band gain is dominant ($G_{ssb} < 0.5$).

Figure 12 shows a 557 GHz Water line observed toward OMC2 (CHESS GTKP) in the upper and lower side band. The left hand figure shows the line observed and calibrated assuming a side band ratio of 0.5. The red line shows the LSB observed line and the blue the USB observed line. When the actual side band ratio, extracted from the gas-cell data shown in figure 9, is applied there is a excellent match between the upper and lower side band ratio. In both cases, the line intensity as calibrated with unity side-band ratio was over-estimated, and more prominently in the LSB.

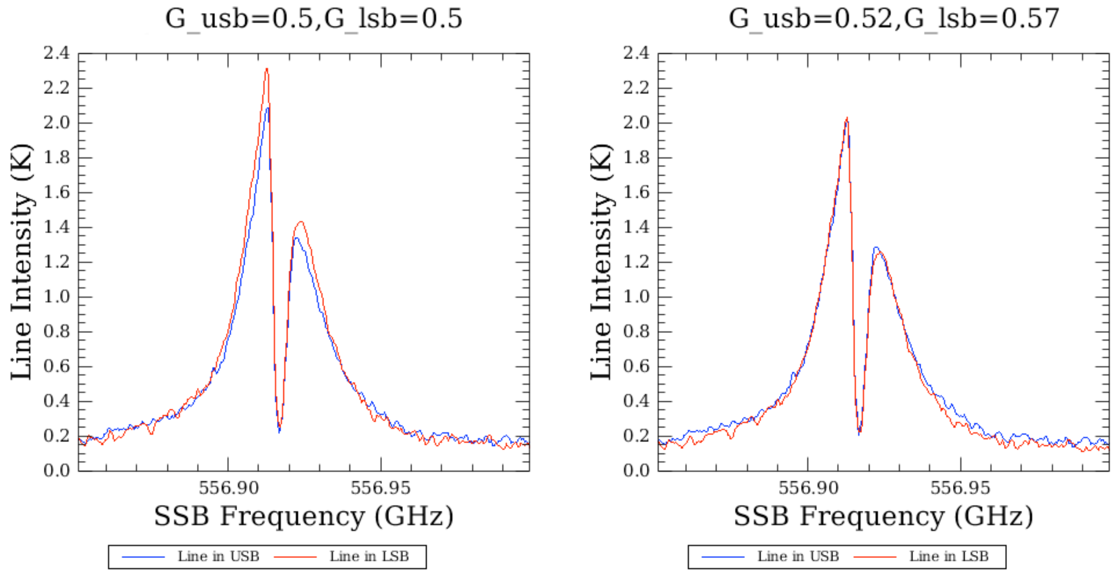

Fig 12.: Comparison of water line measured in upper and lower side band before and after side band ratio correction

The following steps should be followed when converting from level 2 side band spectra with the nominal side band ratio applied to a side band ratio quoted in the table in section 4. The side band ratio given in the table is for the Upper Side Band. The factor that you apply to the data depends on which side band your line was observed in. For the example shown in figure 12, the data is first multiplied by 0.5 to remove the pipeline nominal applied side band ratio and then divided by the appropriate side band ratio. For the USB observed line (blue line) shown in figure 12, the line is divided by the side band ratio (G_{ssb} = 0.52) given in section 4.1. For the LSB observed line (red line), the tabulated side band ratio must be converted to the LSB value ($1 - G_{ssb} = 0.57$) and the spectrum divided by this value.

4.3 Side-band ratio around the ^{12}CO J=5-4 line

We have noted a particularly marked slope in the side-band gain ratio at LO frequencies covering the ^{12}CO *J*=5-4 line. Figure 13 illustrates the original data derived from the gas-cell campaign with the line observed in the USB. This relative trend was confirmed on high signal-to-noise data taken in-orbit for various sources (see e.g. Fig. 14). The particularity of this IF trend is that it goes opposite to the simple IF slope model described in section 3.5. Indeed, the side-band ratio is observed to be higher at lower IF than at higher IF – this basically means that the mixer gain profile in this area does not follow the simple model introduced in 3.5 and that the most accurate correction consists in using the entries provided at various IF in the table of section 4.1 and interpolate. At this stage, extrapolation outside this range is risky and should not be done.

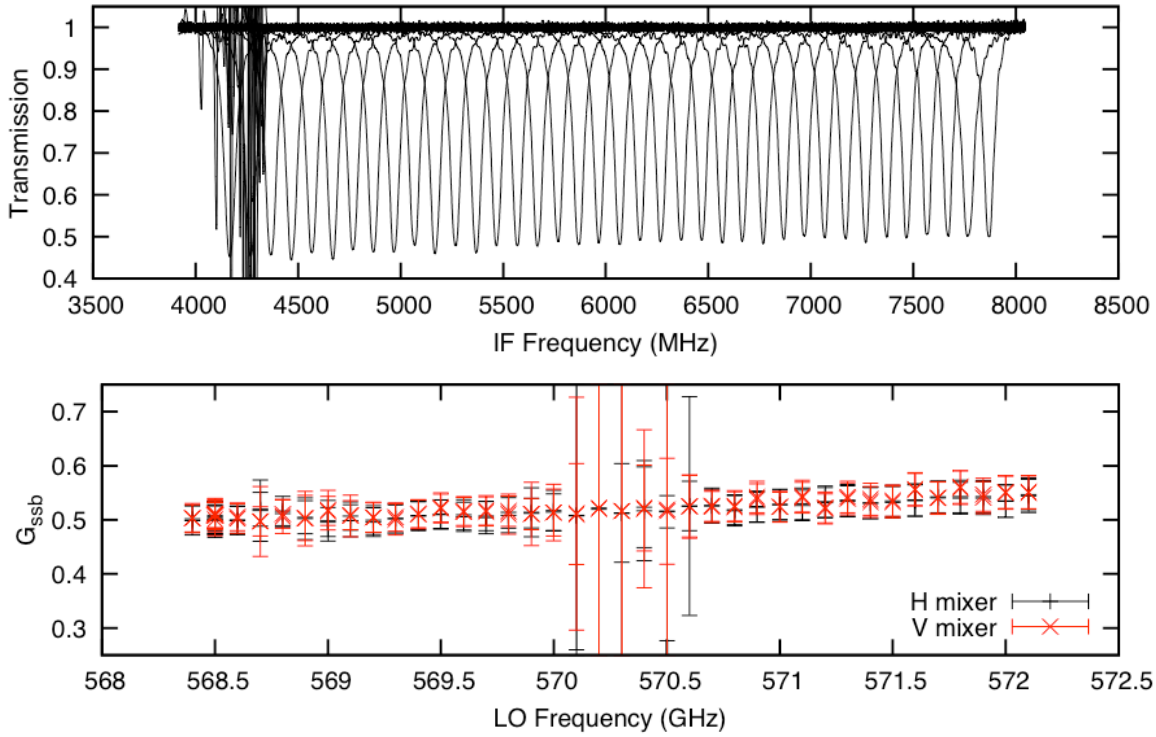

Fig. 13: *Up*: ^{12}CO J=5-4 spectra taken with the gas-cell during a spectral scan of LO steps 100 MHz between 568.4 and 572.1 GHz. *Bottom*: corresponding side-band gain ratio derived from the data. Error bars are calculated from scatter in continuum – the large error bars in the centre are due to spurious emission. From R. Higgins' thesis

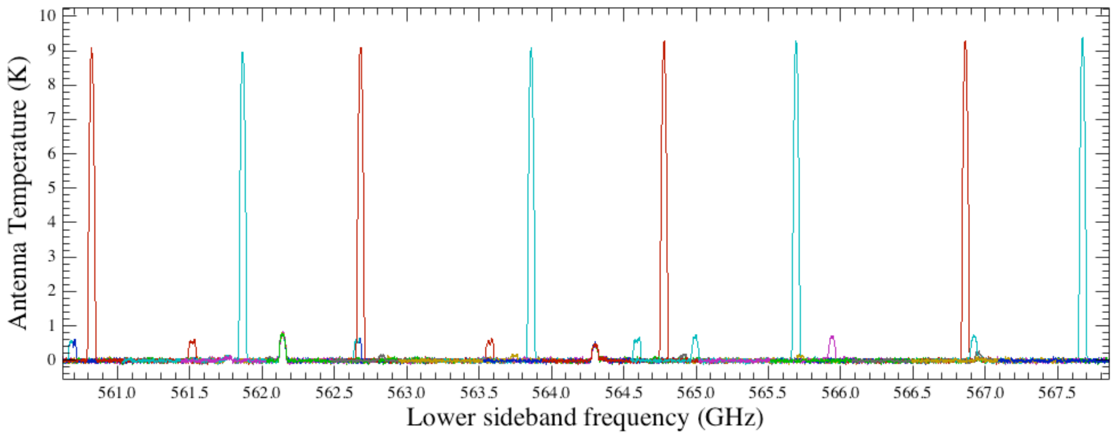

Fig. 14: Uncorrected ^{12}CO J=5-4 spectra observed in the USB on IRC+10216 at LO frequencies between 568.6 GHz (left line) and 572 GHz (right line) – note that the spectra are shown on an LSB frequency scale to separate each line tuning

5. References

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