Atacama
Large
Millimeter
Array

Sideband Smear:
Sideband Separation with the ALMA 2SB and DSB Total Power Receivers

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Motivation: The motivation of this document is to assess and evaluate an effective routine for eliminating unwanted contaminating features in the image band of the total power antennae due to the finite sideband rejection ratio (or no rejection) of the 2SB and DSB receivers. This proposed calibration sequence involves a process of eliminating unwanted featured from the image band introduced by the amount of rejection imposed in the 2SB and DSB systems by imposing a “Sideband Smear” which will eliminate the ambiguities between features in the separate sidebands.

Abstract:

In mm-wave astronomy the most common receiver is a cooled low noise double sideband mixer, feeding a low noise i.f. amplifier. Although it is possible to obtain some rejection of the unwanted sideband by adjusting mixer backshorts or by using a wave-optic sideband filter in front of the receiver feed, this is often not possible. Depending on the choice of intermediate frequency, adjustable backshorts may give only a limited degree of unwanted sideband rejection, and the receiver tuning for best sideband ratio may not give the optimum noise performance. A filter before the receiver feed results in some degradation of system noise, and additional complexity in adjusting the receiver for optimum performance.

The technique of sideband discrimination described here, known as "Sideband Smear," requires that the first local oscillator (lo) and the second or later lo be under computer control; this is normally the case in modern radio telescopes. Beyond this, no extra hardware is required. The system can discriminate between narrow-band emission occurring in the upper and lower sidebands of the first mixer, giving a rejection ratio of up to ~100, although noise input from the unwanted sideband, e.g. atmospheric or spillover radiation - is not attenuated.

Introduction: Statement of the Problem:

Assessment of B7 ALMA science goals:

The highest level science requirements for ALMA are set forth in the Bilateral Agreement, Annex B. These requirements drive the technical specifications of ALMA. A highly simplified flow-down of science requirements into technical specifications is given in ALMA Scientific Specifications and Requirements ALMA-90.00.00.00-001-A- SPE.

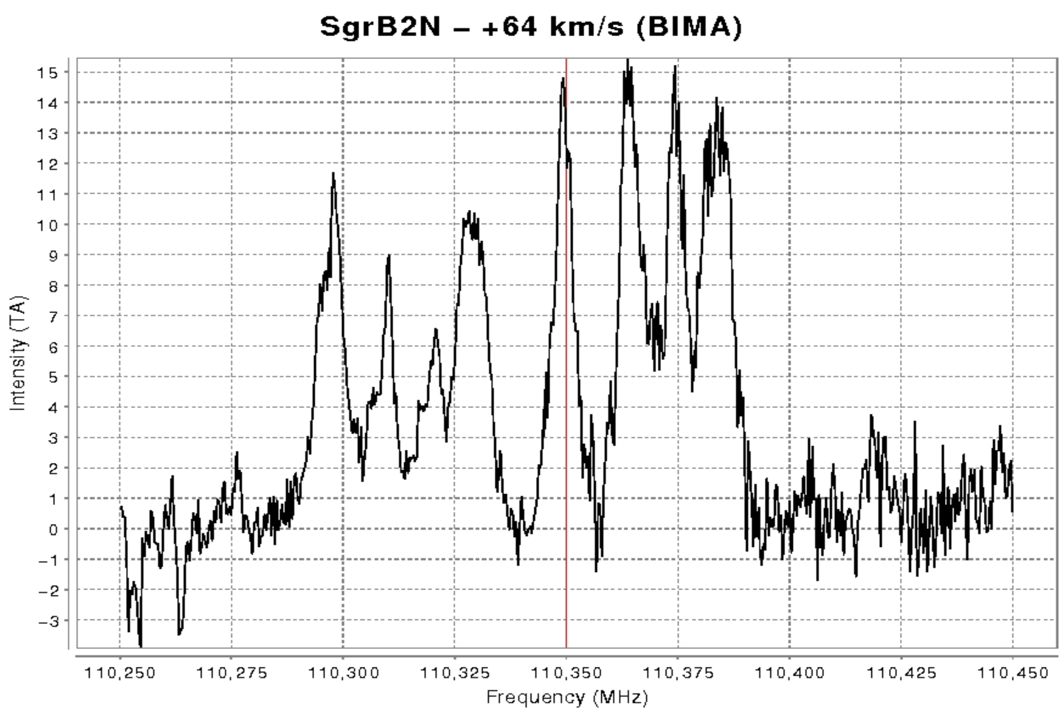
The third highest level science goal requires: *The ability to provide precise images at an angular resolution of 0.1". Here the term precise image means accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.*

Annex B proceeds to state: *The requirement for high fidelity imaging constrains the number of antennas in the array, since a sufficient number of baselines to cover adequately the uv plane (i.e., the time/frequency domain plane in which the data are sampled) is required. Detailed studies of the imaging performance of aperture synthesis arrays have shown that the requisite imaging performance implies a minimum number of antennas, 40 or above, and accurate measurements of the shortest baselines, as well as of the large scale emission measured by total power from the antennas.*

Thus quantitative imaging of flux on all spatial scales is required. This requires proper assignment of flux in single-dish images to the correct sideband on all appropriate scales.

Comparison between an Interferometer vs. Single Dish Single Pointing Spectrum

Spectral features measured with an interferometer will not have the same spatial frequencies as those measured in single dish mode, and their intensities may vary by large factors for short spatial frequencies. For example, the spectra shown in figure 1 are for the same spectral passband containing the CH_3CN line at 3mm, observed with BIMA (which has very good low spatial frequency response) and with the NRAO 12m (twice the diameter of the BIMA antennas). It is immediately apparent that one could not difference these spectra and do quantitative science with the result which is consistent with the third top-level science requirement.



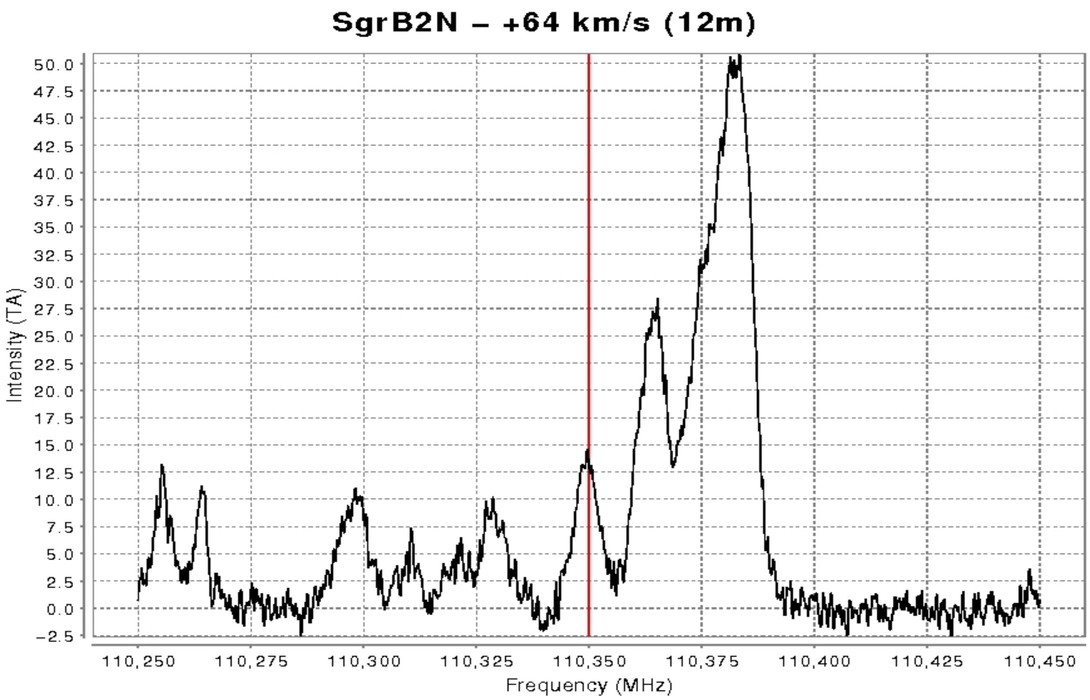


Figure 1.

In order to show the effects of sideband contamination in a 2SB system, we used archival SMA data taken at ~345 GHz and performed simulations based on these passbands covering ~2 GHz of bandwidth with a spectral resolution of ~3.5 MHz/channel. Figure 2 shows these passbands near 338 and 348 GHz, respectively.

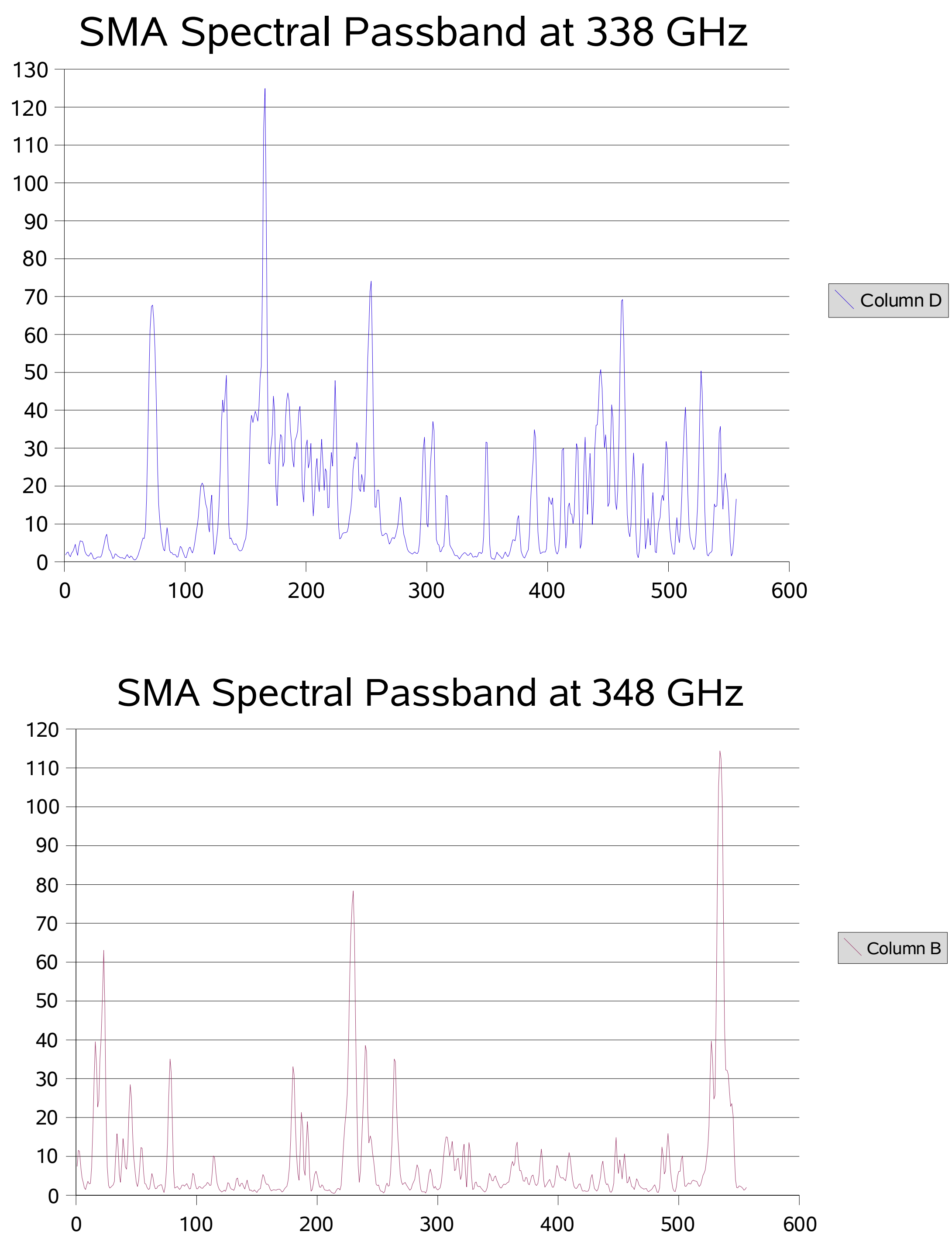

SMA Spectral Passband at 338 GHz
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
Column D
SMA Spectral Passband at 348 GHz
120
110
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
Column B

Figure 2.

What is simulated below in Figure 3 is the amount of the 338 GHz passband (blue) that is leaked into the 348 GHz spectrum assuming -8dB of rejection between the 338 and 348 GHz passbands:

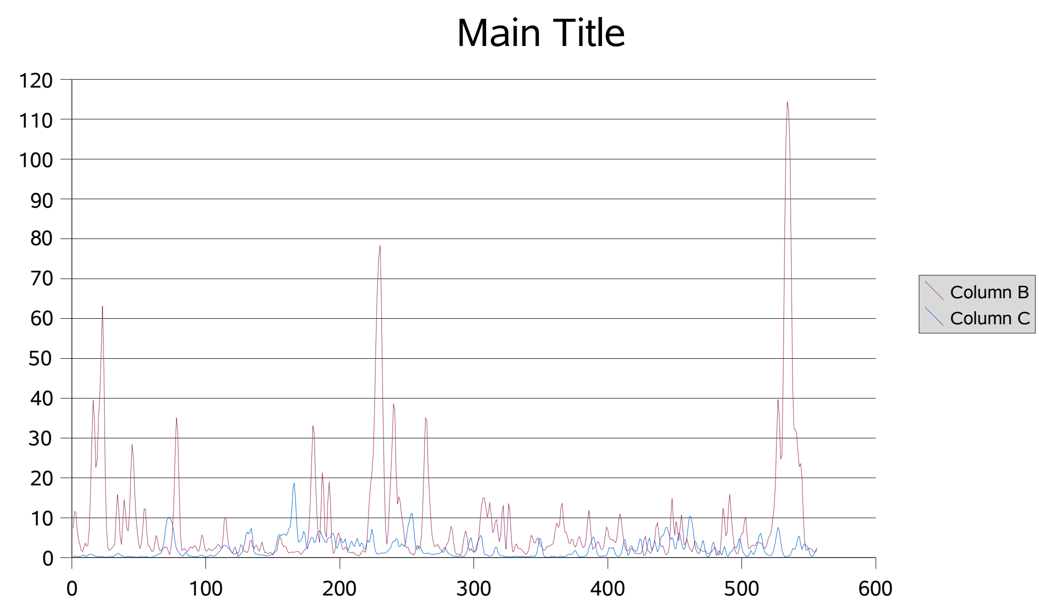


Figure 3.

Figure 4 shows the resultant spectrum that one would observe assuming only the -8dB of rejection between the 2 passbands:

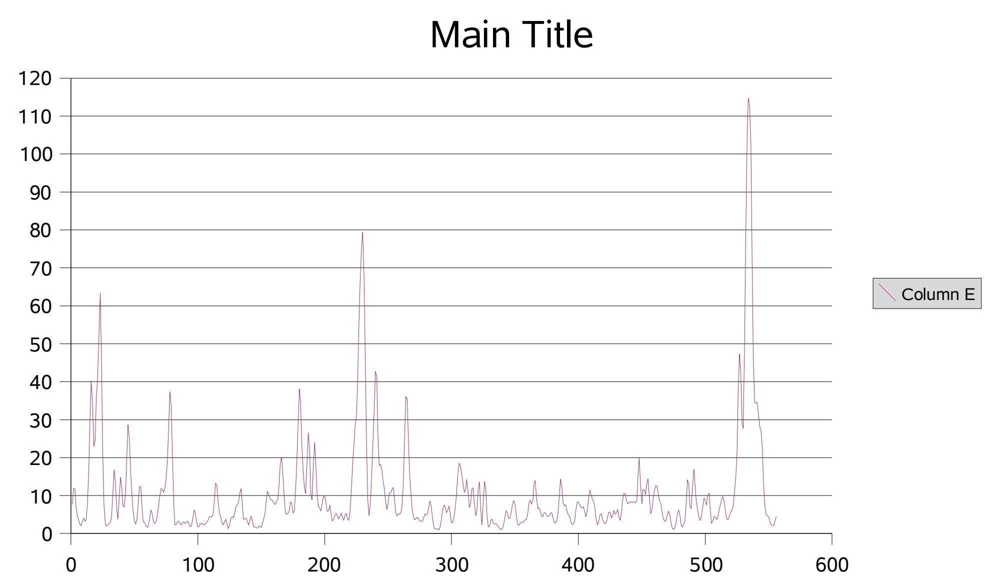


Figure 4.

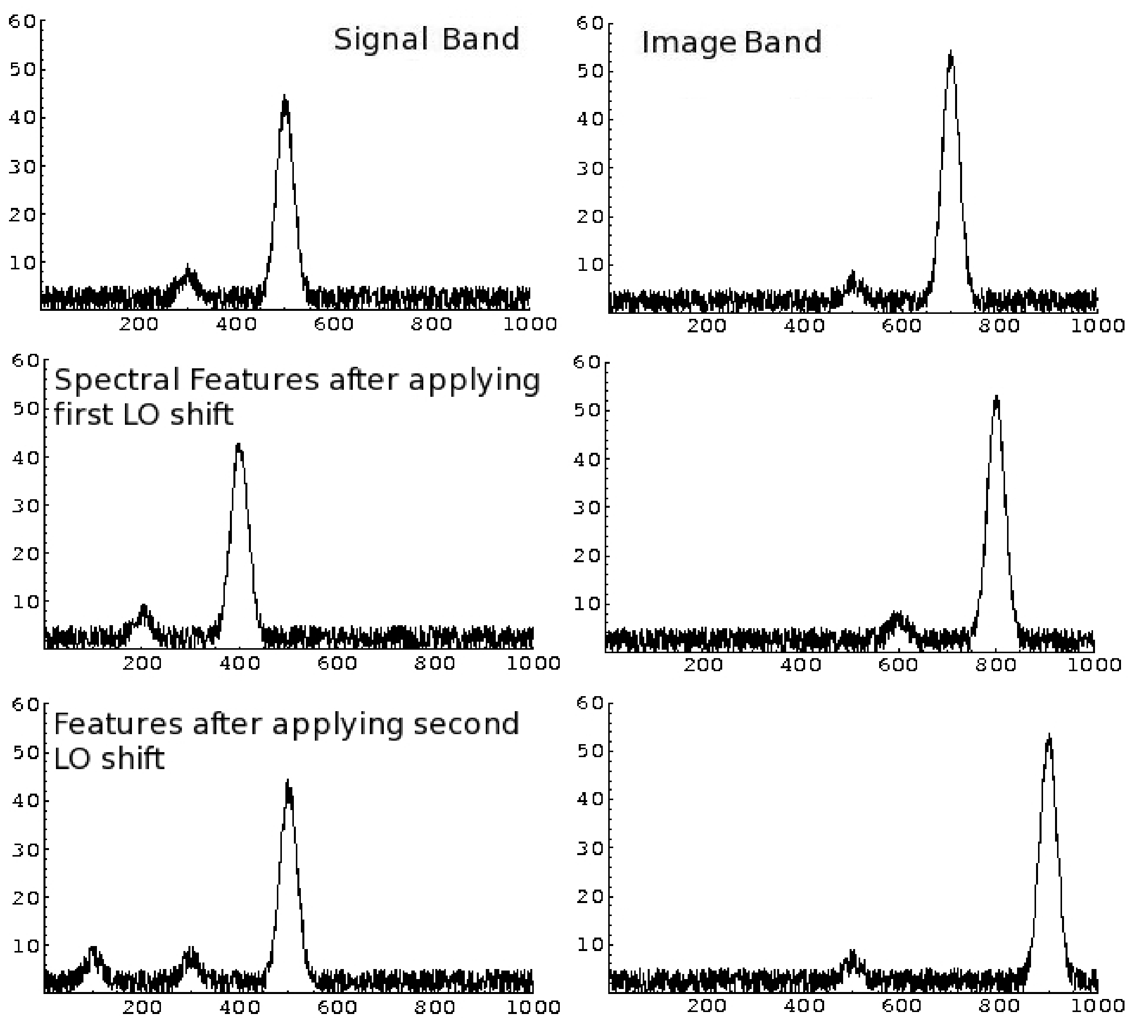
Comparing Figure 4 with the the 348 GHz spectrum in Figure 1, it is apparent that there are several contaminating features present in the Figure 4 spectra from the 338 GHz passband. Furthermore, there are several low lying features that are not apparent in the Figure 4 passband where neither a visual inspection nor an automated “interloper” routine would be able to identify. The question that needs to be addressed is how does one eliminate those contaminating features without losing the ambiguities concerning which spectral features are from which sideband?

While a number of frequency switching procedures are in place that may account for several of the strong features present in Figure 4 and be able to effectively eliminate these contaminating features, ***at present, there is no procedure set up by ALMA or any other 2SB or DSB systems that will effectively and unambiguously eliminate all unwanted features from the passband of interest.***

The “Sideband Smear” technique, that was first tested at the NRAO 12m in the early 90s, will effectively separate the contamination of the unwanted sideband at the expense of losing imaging the contaminating sideband without adding an additional LO.

Sideband “Smear” Procedure for Eliminating “ghost” Features from the Signal Sideband:

The technique of shifting the first local oscillator to identify which features belong to which sideband is a special case of a more general technique. Once again, we utilize the 338 and 348 GHz spectra from the SMA in our simulation and we wish to resolve the 348 GHz spectrum shown in Figure 1 by eliminating the contamination from the unwanted sideband, in this case from the 338 GHz spectrum that has been attenuated by -8dB. However, before this is applied to the SMA data, we first present a simple illustration of how features move based on shifting the first and second LOs. In the first image of Figure 5 shows a simple illustration of 2 strong spectral features and their associated contaminating features in a passband that is 1000 channels wide. ***Note***: for illustration purposes, no averaging was applied after the shifting so the contaminating features remain at their initial intensities after the shift and arbitrary noise is applied after the shift.



In the next set of spectra, a **first local oscillator** shift of ~100 channels has been applied, shifting the USB contaminating feature to the left, and the LSB contaminating feature to the right. Then, an offset of 100 channels has been applied to the **second local oscillator**, shifting the LSB main feature back to its original position, but putting the USB feature even further from its original position in the LSB of the spectrometer. If the observation simulated is repeated, but with many (=N) different frequency shifts, the energy from the unwanted (USB) feature will be spread into the N different positions, each reduced in amplitude by (1/N). The wanted, LSB feature is unaffected, while the unwanted, USB feature has effectively been convolved with the frequency-step function, in this case consisting of N equal delta functions. By varying the number of coupled frequency steps of the first and second local oscillators, and adjusting the integration time spent at each frequency offset, the features in the unwanted sideband may be convolved with almost any chosen, positive, convolution function. An obvious example is obtained by using a large number of offset steps, each closely spaced with equal integration times; this becomes equivalent to a gradual, synchronized linear shift of frequency with time of the two local oscillators. This would be equivalent to convolving the unwanted sideband signals with a top hat function, of width equal to the total offset frequency excursion. Any feature from the unwanted sideband appearing in the resultant spectrum will have been smeared by the width of this function, and will appear as a slightly raised baseline to the features from the wanted sideband. Other functions are possible and may be advantageous in a given set of circumstances, such as a Gaussian or a sinusoidal smear function.

We now apply this procedure to the 338 and 348 GHz SMA data. In this case, we shifted the 338 GHz data by 40 channels (~140 MHz) until we effectively covered the entire 2 GHz passband. This was done in 28 independent steps after the initial measurement was taken. Figure 6 shows the result of how the data presented in the blue trace of Figure 3 is "smeared" using the above procedure.

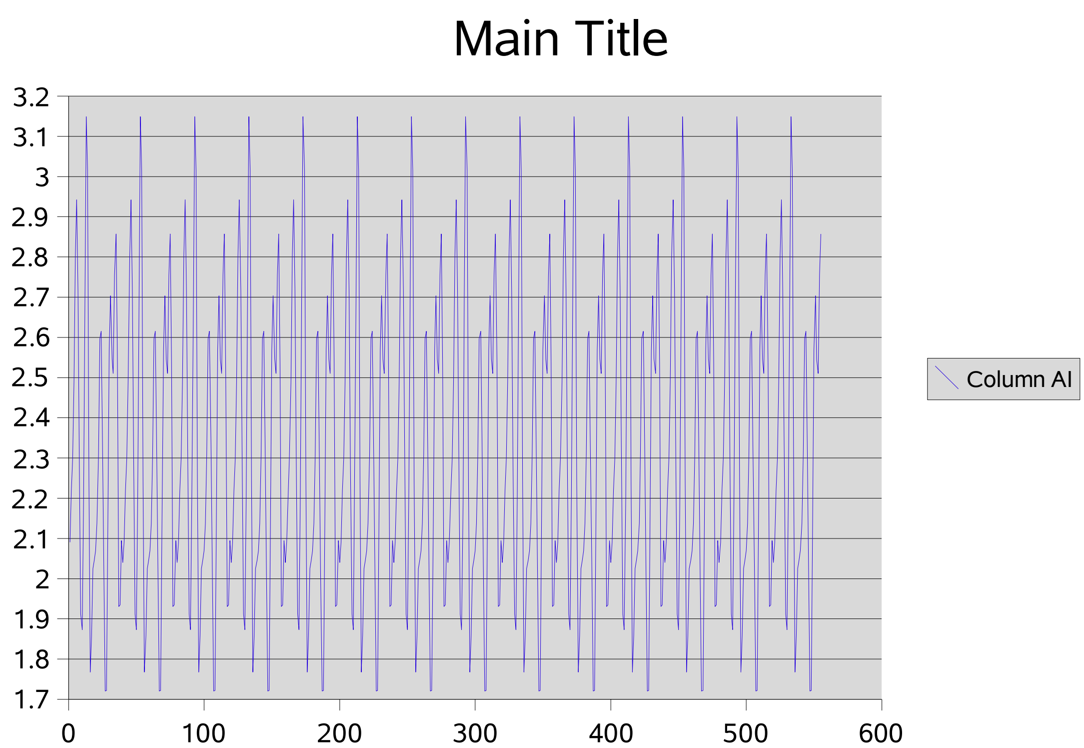


Figure 6.

In arbitrary intensity units, the peak to peak variation of the spectrum shown in Figure 6 is 1.3 units and will effectively add ~2.4 units to the continuum of the 348 GHz spectrum shown in Figure 1. Figure 7 shows the result of the smeared data convolved with the 348 GHz data in Figure 1. ***As you can see, every spectral feature is identified unambiguously with no contaminating features present as their were in Figure 4***. The overall continuum is higher by about 2.4 units as predicted by the smearing routine.

Thus, not only will this procedure be essential to the unambiguous identification of spectral features present in the ALMA 2SB passbands but will be the only procedure that will effectively eliminate unwanted sideband features in the DSB systems.

As with any algorithm of this sort, there are caveats associated with its success. We outline several of these issues below.

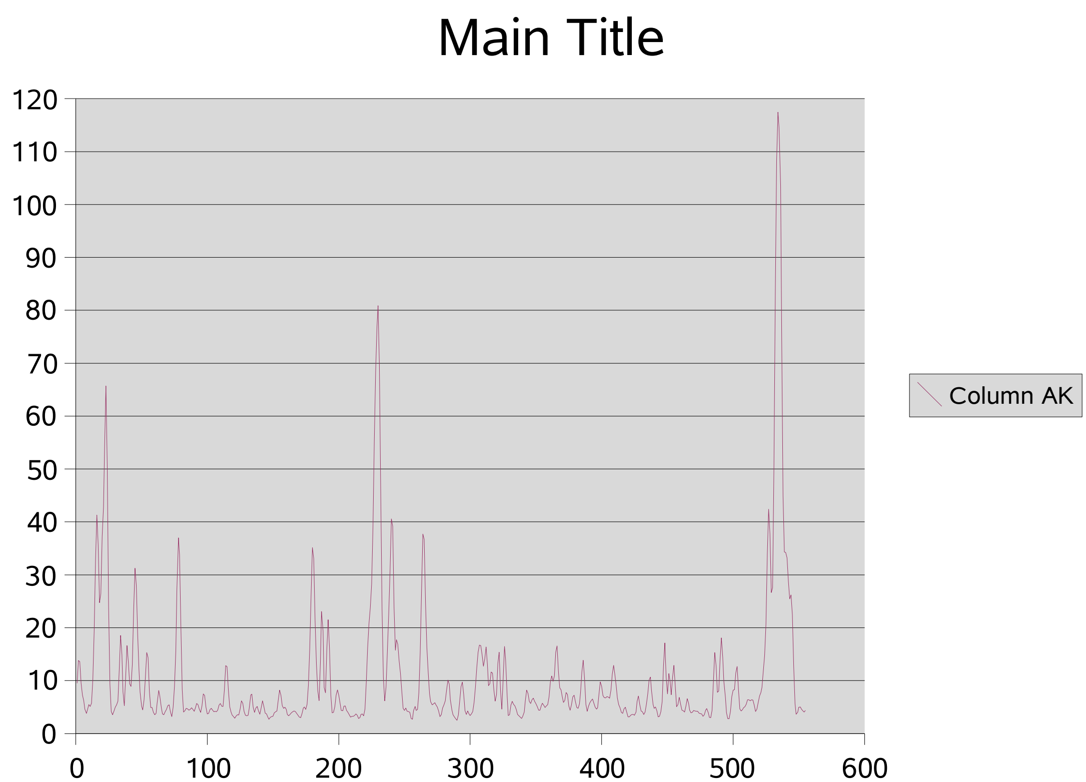


Figure 7.

Practical implementation of Sideband Smear

Although a very simple technique, there are some practical points that deserve attention:

1. *Total range of offset frequency sweep.* If the total IF bandwidth is not sufficient, there is the risk of putting part of the spectrometer beyond the IF response. Thus, there is a chance

the the entire 4 GHz range cannot be used in band 7 if this procedure is utilized. If the width of spectrum of interest is B, the total bandwidth of the IF amplifier BI, then the total range of Sideband Smear frequency offset S should be:

$$S < (BI - B)$$

There may also be other constraints,- e.g. the first local oscillator is normally phaselocked in some way to a signal derived from a computer controlled frequency synthesizer of much lower frequency. The total range of frequency swing may be limited by the performance of the phase lock circuity and the high frequency oscillating device.

Subject to the above constraints, the larger the total frequency sweep, the bigger the discrimination, in terms of spectral width and amplitude, between the wanted and unwanted sideband.

2. *Step size.* If a series of small frequency offset steps is used, rather than a continuous sweep in frequency, then the offset frequency step should be small enough. In the case of ALMA, for a spectrometer that fully samples the spectrum, an offset step equal to the spectrometer frequency sampling interval, or less, is appropriate. To cover 4 GHz of bandwidth effectively will take 56 individual steps assuming a step size of ~140 MHz per step (~3.5 MHz spectral resolution). Of course, the number of steps can be reduced even further at the expense of resolution.

3. *Step timing*. In general, the faster the offset frequency is stepped, the better. The total frequency sweep (see (1) above) has to be covered within the total integration time of a given observation on the sky. However, there may be limitations due to computer overhead and frequency synthesizer or phase lock settling time. For ALMA, a reasonable compromise might be to re-tune the first and second LO's every ½ second. I this case, an entire 4 GHz passband can be effectively imaged assuming the step criteria presented in 2) in ~0.5 hrs of observing time.

In order to estimate the noise level reached during this time for a single 12 m ALMA telescope, we used the APEX online sensitivity calculator to estimate these values. In 1 hr "ON" source at 345 GHz, T_{atm}=260 K, el=45 degrees and T_{rec}=77 K at a resolution of 3.0 km/s, τ=0.2, the 1σ rms=0.004 K or 4mK. At 0.1 km/s resolution, this becomes ~20 mK and a smaller step size should be considered to effectively cover the entire band at high enough resolution.

4. *Signal and Reference matching.* Most observing techniques involve switching in some sequence between the wanted "signal" position on the sky, and a blank region known as the "reference" position. It is most important that the sequence of Sideband Smear offset frequency steps match in the signal and reference observations. That is, the pre-programmed frequency offset step sequence should restart at the same point for signal and

reference observations. If this is not done, then bad spectral baselines, due to the inevitable frequency structure in the telescope optics, receiver frontend and IF passband, are likely to appear in the spectrum. However, because of the high constraints on the spectral passbands set up by the Front End IPT, this should not affect the procedure greatly. Testing of this procedure is essential to the success of the routine.

A possible alternative to this carefully synchronized switching sequence would be a very rapid, asynchronous frequency sweep control. The first and second local oscillators would have swept the entire smear range many times - ideally many hundred times - synchronously with each other, but asynchronous to the start of data acquisition, within the total integration time. This procedure could be written into the telescope control software for single dish (total power) observations.

A Possible extension?

It is possible to recover both sidebands with sufficient rejection if the signal is split before heading to the second LO. Both sidebands are retrieved independently, but at the cost of duplicating the second mixer and using more of the spectrometer. Upper and lower sideband signals are retrieved independently, with the opposite sideband being smeared in each spectrum.