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ALMA Use of LO Offsetting for Spurious Signal Suppression and Sideband Rejection

P. Napier, 16 January, 2006

Summary

Loss of Walsh function synchronization will result in reduced spurious signal suppression as correlator spectral resolution is increased. It is proposed that LO offsetting be used in place of Walsh function phase switching in this case. Additionally, it is proposed that LO offsetting be used to improve the suppression of the undesired sideband for observations made using ALMA's single sideband receivers. The advantages and disadvantages of LO offsetting are discussed as are the methods for implementing it on both the ALMA-B and ALMA-J correlators. Some rules for the use of phase switching and LO offsetting for ALMA's various observing modes are proposed.

1. Introduction

In a previous note (Napier, 2006) it was pointed out that when ALMA is observing in its high spectral resolution modes the 180^{o} Walsh function switching used to remove DC offsets and other undesired signals will not work well. It was proposed that in these cases LO offsetting on the first LO be used for spurious signal suppression instead of 180^{o} phase switching. Since this initial study the use of LO offsetting to increase the rejection of an unwanted frontend sideband has also been studied further. Also, a spurious response in the ALMA IF system has been discovered which requires LO offset on the second LO for suppression. The purpose of this report is to provide a plan for how ALMA will use LO offsetting for these various purposes. We begin by reviewing the problem with 180^{o} Walsh function phase switching.

2. Synchronization Loss in Walsh Function Phase Switching

The original plan (D'Addario, 2000) for ALMA has been to remove spurious responses and DC offsets due to quantization by using 180 degree phase switching using a Walsh function switching sequence imposed on the first LO and removed after digitization in the Digital Transmission System Transmitter (DTX) module. When the phase switching is removed in the DTX module it is removed from the desired signal which had it imposed at the first LO but it is imposed onto spurious signals and DC offsets which did not undergo the correct first frequency conversion. Each antenna is assigned a different Walsh function and all Walsh functions complete at least one full period during the correlator shortest integration time of 16 ms. Since Walsh functions are orthogonal, provided that the Walsh functions are synchronized in time at the input to the correlator multiplier, the undesired spurious signals and DC offsets will average to zero after a 16 ms integration period. If the Walsh functions are not synchronized in time at the multiplier input then the suppression of the undesired signals will be reduced (Emerson, 2005), with the amount of suppression loss being dependent on which particular pair of

Walsh functions are involved. In an XF correlator such as the ALMA baseline 64 antenna correlator, a problem arises due to the time offsets that are introduced between antennas during the formation of the lag function. The introduction of these time offsets necessarily de-synchronizes the Walsh functions between the two antennas causing reduced suppression of the undesired signals.

The example shown in Figure 1 will help to illustrate the problem. Consider two antennas, one with phase switching according to the Walsh function WAL(7,t) and the other using WAL (23,t) (see Emerson (2005) for definitions of this nomenclature for Walsh functions). For lag zero, in which no time offset is inserted between the antennas, the product of the DC offsets from the two antennas varies as WAL(7,t)*WAL(23,t) which, as seen in Figure 1c, is a signal with zero mean and so the DC offset is suppressed.

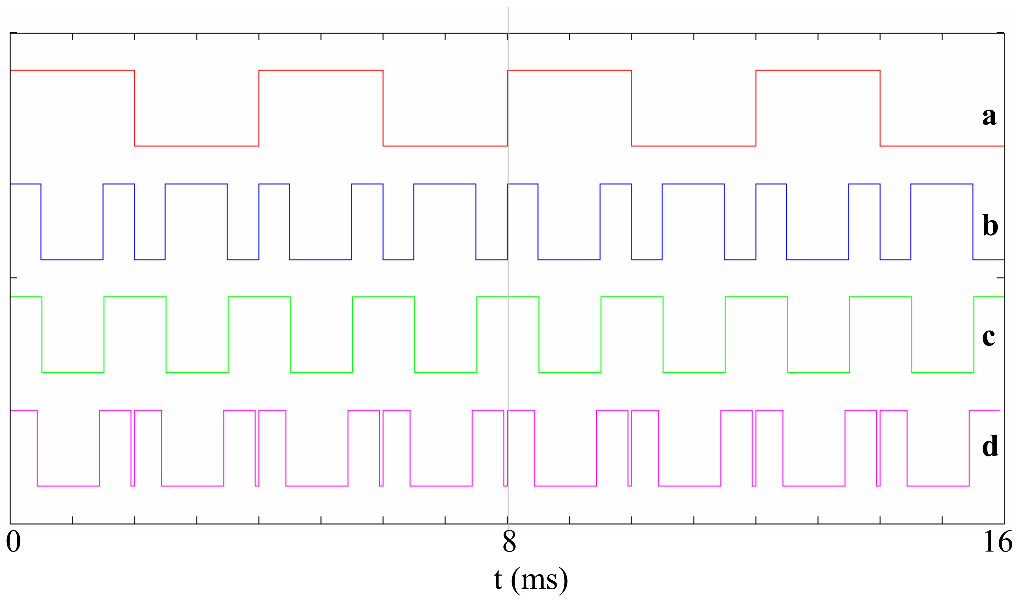

Figure 1. An example of loss of Walsh function orthogonality due to loss of synchronism. The horizontal time scale is 16 ms, a full period of the slowest Walsh function. All waveforms switch between ± 1 and are shown vertically displaced to allow comparison. The example waveforms shown are (a) WAL (7,t), (b) WAL(23,t), (c) WAL(7,t)*WAL(23,t), (d) WAL(7,t)*WAL(23,t+62.5µs).

Now suppose that the correlator is being used to provide a spectral resolution of 8 KHz. This implies maximum lags (time offsets) between the two antennas of ± 62.5 µs. With a 62.5 µs time offset the product of the DC offsets from the two antennas varies as WAL(7,t)*WAL(23,t+62.5µs) which, as shown in Figure 1 (d) is no longer a zero mean signal and in this case the DC offset is suppressed by only -12 dB. For ease of illustration this example has used a relatively high spectral resolution, and therefore a rather large time offset, but similar losses of spurious signal reduction can occur for much lower spectral resolution if one considers pairs of higher sequency Walsh functions. The ALMA system level requirement for synchronization of the Walsh functions is 0.1 µs (Requirement 444 of (Sramek and Haupt, 2006)) which implies that Walsh function synchronization will become an issue when spectral channels are narrower than approximately 5 MHz.

The discussion above in this section explains how Walsh function desychronization occurs in an XF correlator due to the time offsets that are required for calculation of the lag function. An equivalent effect occurs in an FX correlator and, for completeness, we will now provide this point of view since the ALMA-J correlator is an FX correlator. This explanation was originally provided by Harp (2006). If we define wal(N,f) to be the Fourier transform of WAL(N,t), then wal(N,f) is the complex voltage spectrum of WAL(N,t). Figure 2 shows the voltage amplitude of wal(7,f) and wal(23,f), corresponding to the Walsh functions shown in the time domain in Figure 1. Remember that these spectra correspond to the spectrum of the DC offsets of the two antennas as a result of the DC offsets being modulated by the Walsh function switching in the DTX. Now, in an FX correlator, if the spectral resolution is, for example, 30 KHz, then channel zero contains all signals in the range 0-30 KHz, which contains all the significant harmonics present in both wal(7,f) and wal(32,f). In this case the product of the channel zeros from the two antennas will average to zero because of the orthogonality of the two Walsh functions. As a different example, now suppose that the spectral resolution is 8 KHz, corresponding to example (d) in Figure 1. In this case Figure 2 shows that significant harmonics exist in the Walsh functions above 8 KHz so the product of the channel zeros will no longer average to zero because of the missing higher frequency harmonics. In fact the attenuation of the DC offset in channel zero is only -12 dB as was found for the example of Figure 1d.

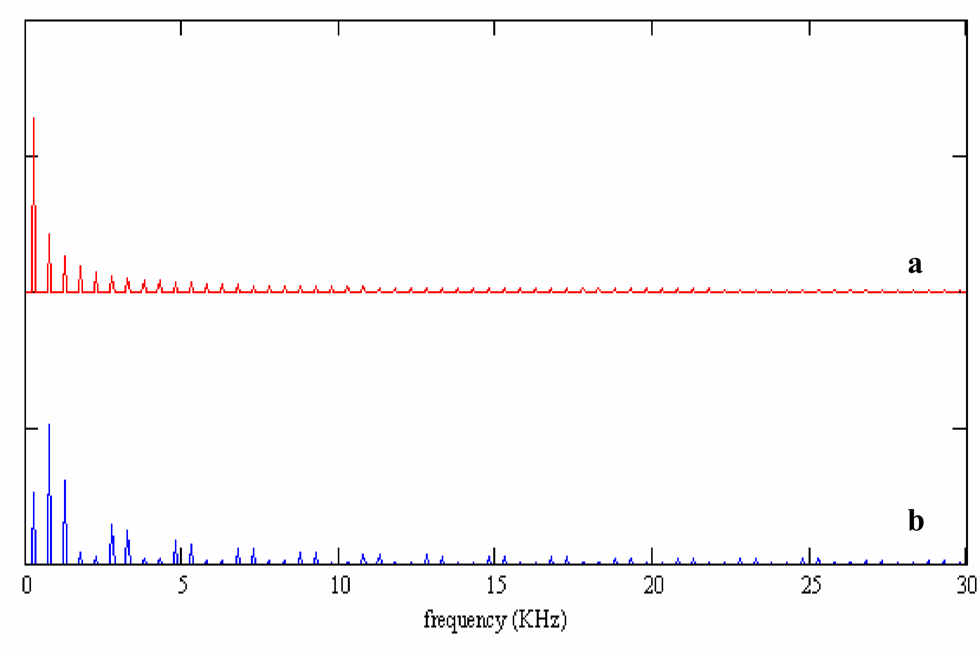

Figure 2 Voltage amplitudes for the functions (a) wal(7,f) and (b) wal(32,f). The vertical scale is arbitrary and is proportional to the voltage amplitude of the spectrum.

So we see that in an FX correlator orthogonality of the Walsh functions begins to be lost as the spectral resolution becomes fine enough so that the spectrum of the Walsh function begins to be resolved. The example given here has used low sequency Walsh functions for ease of computation but loss of orthogonality of the highest sequency Walsh functions will occur with much coarser spectral resolution. Also, these example have used the DC offset as the example spurious signal. In practice it is likely that suppression of spurious responses other than the DC offset will be more important but we currently have little information concerning any of the spurious responses associated with the first frequency conversion.

3. Use of LO Offsets to Remove Spurious Signals

As explained in Section 2 above, use of ALMA in higher spectral resolution observing modes will reduce the effectiveness of suppression of DC offsets and other spurious signals by 180 degree Walsh Function phase switching. In the previous note (Napier, 2006) is was suggested that 180 degree phase switching could be replaced by an LO offsetting scheme in which an LO offset is applied on the first local oscillator at the antenna and removed in the digital LO in the Tunable Filter Bank (TFB) in the correlator. We now consider some of the details of such a scheme.

3.1 LO Offset Requirements

First let us determine how large an LO offset is required to provide adequate spurious signal rejection for ALMA. We will start by considering how much offset is required to attenuate the quantizer DC offsets to an acceptable level. Note that the magnitude of the DC offset, in Janskys, that was mentioned in Napier (2006) is too large by a factor of about 100. This resulted from an assumption that the DC offsets would produce a correlated signal of strength 1% in power, whereas in fact the DC offsets in the ALMA quantizers are of order 1% in voltage. In the Appendix below we assume a worst-case DC offset of 5% of the digitizer rms voltage. In the Appendix we show that to attenuate such a DC offset to the thermal noise the LO offset between two antennas must be greater than 350 Hz. In addition to the DC offsets we wish to suppress other spurious signals. There is not yet much information concerning the spurious signal levels present in the ALMA electronics system but at least one significant spurious signal has been identified in the IF Downconverter that has a level -14 dB below the desired response (see Section 3.2.3 below). To achieve the system requirement of keeping spurious responses below -40 dB (Requirement 295 of Sramek and Haupt (2006)) this spurious response would have to be attenuated by an additional -26 dB which, from equation (5) in the Appendix, for an integration time of 16 ms would require an LO offset of at least 8 KHz.

The digital LO available in the TFB is tunable with a resolution of 30.5 KHz (4 GHz/2^{17}) (Baudry, 2006a) so it is easily capable of meeting the requirements in the previous paragraph. From equation (5) of the Appendix an LO offset of 30.5 KHz will provide spurious signal suppression of -32 dB in 16 ms which is comparable to the suppression expected using phase switching for low spectral resolution observations. The question arises as to whether there are any disadvantages in having the LO offset steps be as large as 30.5 KHz and here the issue is loss of baseband bandwidth due to the presence of the LO offset. The range of baseband frequencies input to the digitizer is determined by a 2 GHz wide anti-aliasing filter with steep attenuation skirts. The range of sky frequencies available within this baseband is offset on each antenna by the amount of the LO offset on the antenna. Therefore, if a sub-band in the TFB is selected to be at the very edge of the baseband then an amount of bandwidth equal to the LO offset could be lost. As proposed in Section 6.2.2 below, for 64 antennas the largest LO offset seen by the TFB would be of order 3*64*30.5 KHz = 5.9 MHz so in the worst case 5.9 MHz of bandwidth could be lost in a 64 MHz wide sub-band located at the edge of the 2 GHz baseband. However, due to the need to overlap sub-bands in order to "stitch" adjacent sub-bands together, an amount of bandwidth much larger than 5.9 MHz (approximately 125 MHz) is already lost at the edge of the 2 GHz bandpass (see Section 5.3 of Baudry (2006a). So LO offsets quantized to 30.5 KHZ will not result in any additional loss of bandwidth. Another reason to keep the LO offset quantized at 30.5 KHz is that this makes the LO offset commensurate with the spectral channel width available in the ALMA-J FX correlator and therefore enables LO offset removal in the ALMA-J correlator by simple channel shifting (see section 5 below). Therefore we plan to use LO offsets that are quantized to 30.5 KHz as currently provided by the TFB.

It is worth noting that whereas timing errors in the electronics system will cause a reduction in the spurious signal reduction provided by 180 degree phase switching, this is not the case with LO offsetting. Provided that the minimum offset frequency is chosen to be high enough so that there are a sufficient number of cycles in an integration period to provide the suppression required (equation (5) of the Appendix), then this suppression will not be reduced by a change in phase of the LO offset on an antenna. Therefore, we should use LO offsetting rather than phase switching for spurious signal reduction so long as there is no other disadvantage of using LO offsetting.

3.2 Limitations of LO Offsetting

There are a number of limitations associated with using LO offsetting in place of 180^{o} phase switching:

3.2.1 Correlator Bypass Mode

In high-time-resolution bypass mode the baseline ALMA 64 antenna correlator (hereafter called ALMA-B) does not use the TFB and so removal of an LO offset after the digitizer is not possible. In this case the currently planned Walsh function phase switching will still be required. The highest spectral resolution possible in bypass mode is 7.8 MHz (256 spectral channels over 2 GHz) which requires lag delays up to ±.06 microsec. This is less than the ALMA System Technical Requirement (Requirement # 444) for synchronizing the Walsh functions between antennas to 0.1 microsec, so there should be no problems with phase switching when the correlator is in bypass mode.

3.2.2 Loss of Sideband Separation Ability

If the LO offset is applied on the first LO (LO1) then its removal using a digital LO in the TFB can only be done correctly for either the upper (USB) or lower (LSB) sideband of the receiver. This is because the USB and LSB require opposite signs for the LO offset removal. So, when LO offsetting is in use, it will not be possible to do sideband separation after correlation using 90 degree phase switching which was planned (D'Addario, 2000) for the two double sideband receivers (Bands 9 and 10). However, since each of the 32 sub-bands available for a given 2 GHz baseband in the TFB has its own digital LO, it will be possible to share the sub-bands between USB and LSB. So simultaneous observations in both the USB and LSB within a given 2 GHz baseband will still be possible, but only by sacrificing the bandwidth available in any one sideband. 2 GHz of total bandwidth is available for USB and LSB together. This observing mode, in which the sub-bands are shared between USB and LSB will be useful if there are particular molecular species, some in USB and some in LSB, which are desired to be observed simultaneously. If the desire for both USB and LSB is spectral surveying where the full 2 GHz of bandwidth is needed in both sidebands, then such observations will not benefit by sharing the sub-bands between USB and LSB and instead the observer will have to assign a second 2 GHz baseband channel to the same range of sky frequencies or use time sharing between the two sidebands

3.2.3 IF Leakage Suppression

180 degree phase switching and lo offsetting are used to remove spurious signals that are generated in the signal path between the points where the phase switching or LO offset are inserted and removed. Spurious responses associated with the first frequency conversion in the receiver have not yet been measured but we now have good data concerning the spurious responses caused by the second frequency conversion, the conversion which takes place in the IF Down Converter (IFDC). Figure 3 shows a simple block diagram of the measurement procedure used to measure these spurious responses. A swept signal generator was used as the input signal source for an IFDC and the output power was measured by the total power detector after the 2-4 GHz anti-aliasing filter. The output power level as a function of the input frequency is shown in Figure 4 for an LO2 frequency of 14.0 GHz. The desired response, LO2 –IF is seen as expected for input frequencies in the range 10-12 GHz. Spurious responses of LO2-2*IF and 2*IF-LO2 are seen at 5-6 GHz and 8-9 GHz input frequency respectively. These spurious responses will be removed by either 180 degree phase switching or LO offsetting on the first LO. The large spurious response, only -14 dB below the desired response, seen at 3-4 GHz input frequency is direct leakage of IF signal from the input to the output of the IFDC. It is difficult to attenuate because any increase in attenuation of the 4-12 GHz input filter below 4 GHz will also cause increased attenuation in the desired frequency range just above 4 GHz. This spurious response will not be suppressed by either phase switching or LO offsetting on the first LO. It is suppressed by any fringe rotation applied to LO2 but there are always places in the sky

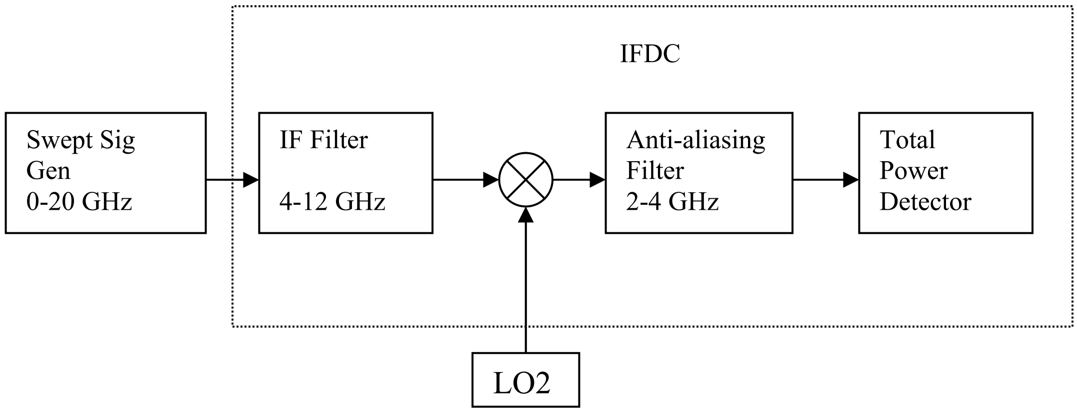

Figure 3 Test setup for measurement of the spurious responses in the IFDC.

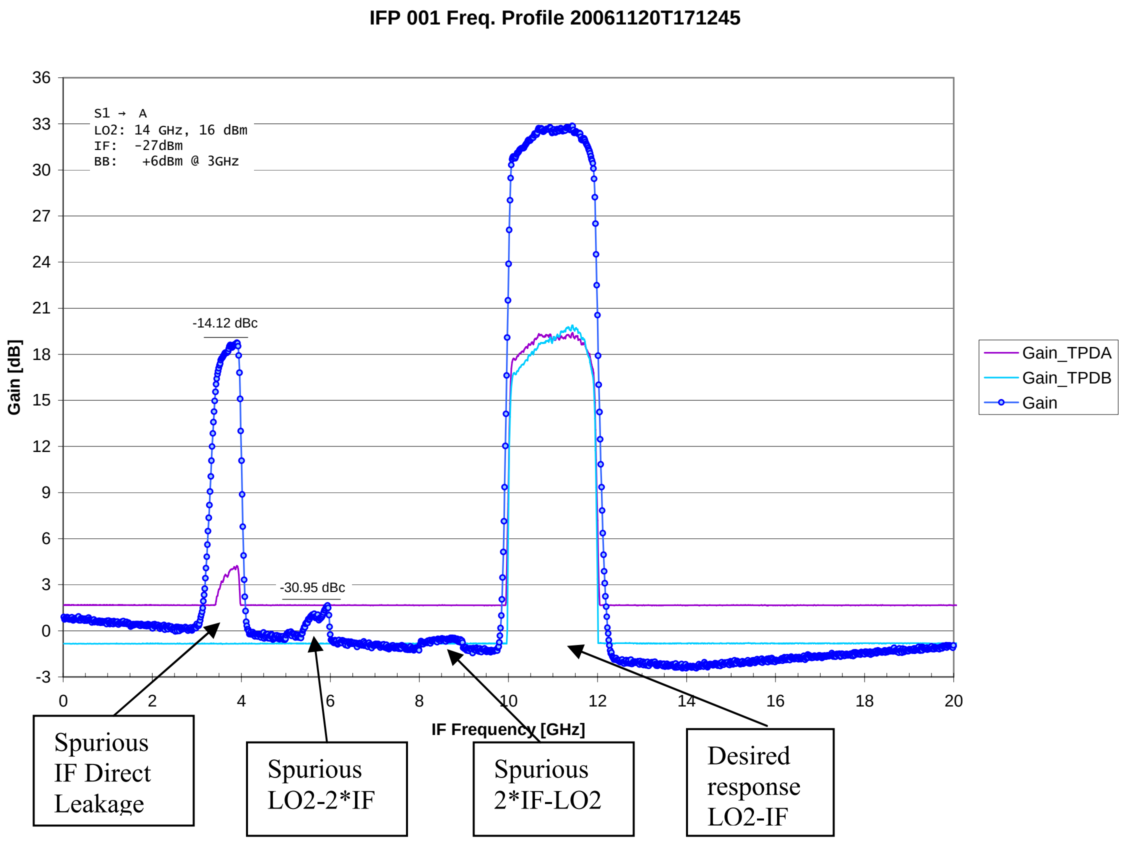

Figure 4 Output power as a function of input frequency for an IFDC with LO2=14.0 GHz

where the fringe rate drops to zero so this cannot be relied on to remove this spurious response. It would be suppressed by LO offset applied to LO2 so for this reason it is advisable to have LO offsets on both LO1 and LO2.

4 Use of LO Offsets For Sideband Suppression

So far we have been considering the use of LO offsets for suppression of DC offsets and other spurious responses. Another important use is to improve the suppression of an undesired sideband. The ALMA specification for the suppression of the undesired sideband in the dual sideband (2SB) receivers (Bands 3-8) is only -10 dB (Requirement 231 of Sramek and Haupt (2006)). This is not adequate for many science requirements and will need to be improved either by 90 degree phase switching or LO offsetting on LO1. As a general principle sideband suppression by LO offsetting will be superior to 90 degree phase switching due to the rather long switching cycle times required for the 90 degree phase switching. An LO1 offset used for sideband suppression can be removed at either LO2 (where it also suppresses IF leakage as explained in Section 3.2.3) or at the digital LO in the TFB (where it also suppresses the DC offsets as explained in Section 3.1).

5. Impact on ALMA-J FX Correlator

As explained in Section 2 above the effectiveness of the 180 degree Walsh function phase switching will be degraded in the ALMA-J correlator in an analogous way to the ALMA-B correlator, when the spectral resolution is high. In this case LO offsetting on LO1 will be used instead, as explained above. The ALMA-J correlator does not have an equivalent of the TFB at its input and so cannot remove the LO offset using a digitally synthesized LO on the sub-bands. Instead, the LO offset will be removed in the correlator at the output of the FFT stage by simply shifting the spectrum by the appropriate number of spectral channels (Kamazaki et. al. 2006). Since the LO offsets will be quantized to multiples of 4GHz/2^{17} (30.5 KHz), and 4GHz/2^{17} corresponds to exactly 8 spectral channels in the ACA FFT, the LO offset will be removed completely in this way. Since the spectral shift required is in opposite directions for USB and LSB, for a given 2 GHz baseband processing in the ACA correlator will be limited to either USB or LSB. Mixed observations in both USB and LSB within a single 2 GHz baseband, as is possible with the TFB (Section 3.2.2 above), will not be possible when LO offsetting is in use.

6. Summary of Phase Switching and LO Offsetting "Rules".

In this section, based on the considerations outlined above, we provide some proposed "rules" for the use of phase switching and LO offsetting in ALMA. The rules are complicated by the differing requirements for SSB and DSB receivers and by the two modes, bypass or TFB, of the ALMA-B correlator.

The guiding principles for these rules are as follows:

(a) In general, LO offsetting will provide better suppression of spurious signals than will phase switching, so use LO offsetting unless there is some other clear disadvantage in doing so.

(b) For the single sideband receivers, or for the double sideband receivers when only one sideband is required, there should always be LO offset on LO1 to provide increased suppression of the undesired sideband.

(c) For the double sideband receivers, in order to preserve the capability of sideband separation using 90 degree phase switching, use LO offsetting only when phase switching will not work.

(d) Unless there is a clear disadvantage in doing so, apply some LO offset to LO2 in order to suppress IF leakage.

(e) LO offsets will be quantized in units of $\Delta = 4\text{GHz}/2^{17}$ (approximately 30.5 KHz). The offset for a particular antenna will be determined by the antenna identification number N, a unique integer assigned to each antenna. For the ACA antennas N will be in the range 1-16. If no ACA antennas are correlated in the ALMA-B correlator N will be in the range 1-50 for the 12 m antennas. If ACA antennas are correlated in the ALMA-B correlator N will be in the range 17-66 for the 12 m antennas.

There are two rules for each of the two receiver types:

6.1 Receiver Bands 1-8

6.1.1 Receiver Bands 1-8, ALMA-B Correlator in Bypass Mode

Apply 180 degree Walsh function phase switching and an LO offset of $N\Delta$ on LO1. Remove LO offset of $N\Delta$ on LO2 with sign appropriate for the desired sideband.

6.1.2 Receiver Bands 1-8, ALMA-B Correlator in TFB Mode

Apply an LO offset of $2N\Delta$ on LO1. Apply no phase switching on LO1.
Remove LO offset of $N\Delta$ on LO2 with sign appropriate for desired sideband.
Remove LO offset of $N\Delta$ using the TFB LOs or ACA spectrum shift after FFT, with sign appropriate for the desired sideband.

6.2. Receiver Bands 9-10

6.2.1 Receiver Bands 9-10, Low Spectral Resolution

"Low spectral resolution" means that the spectral resolution is sufficiently coarse so that the 180 degree Walsh function phase switching provides adequate spurious signal suppression.
Apply 180 degree and 90 degree phase switching on LO1. Apply no LO offset on LO1. Perform sideband separation after correlation using the 90 degree phase switching. (Note: if the observer requires only USB or LSB, but not both, then the observation should be made according to rule 6.1.1 or 6.1.2, depending on the correlator mode.)

6.2.2 Receiver Bands 9-10, High Spectral Resolution

"High spectral resolution" means that the spectral channels are sufficiently narrow so that 180 degree Walsh function phase switching provides inadequate spurious signal suppression.
Apply an LO offset of $2N\Delta$ on LO1. Apply no phase switching on LO1.

Remove LO offset of NΔ on LO2 with sign appropriate for USB.
For ALMA-B correlator assign the 32 TFB sub-bands to USB or LSB as desired and remove LO offset of NΔ for USB sub-bands or 3NΔ for LSB sub-bands using the TFB LOs.
For ACA correlator only one sideband can be processed so remove LO offset of NΔ for USB or 3NΔ for LSB using spectrum shift after FFT.
(Note: if the observer requires only USB or LSB, but not both, then the observation should be made according to rule 6.1.1 or 6.1.2, depending on the correlator mode.)

7. Total Power Considerations

As a concluding remark we should remember that ALMA, unlike most previous interferometers, is intended to provide total power as well as interferometric data. None of the phase switching or LO offsetting techniques discussed in this memo serve to remove spurious signals, improve undesired sideband rejection or enable sideband separation for autocorrelation spectra. With respect to undesired sideband rejection LO1 offsetting will cause the spectrum of the undesired sideband to be frequency shifted by a different amount in each antenna's autocorrelation spectrum so it is possible that an averaging of autocorrelation spectra from all the antennas will provide some suppression of the undesired sideband. Simulations are needed to determine to what extent the -10 dB sideband suppression ratio can be improved for autocorrelation spectra by spectrum averaging.

Acknowledgements
A number of valuable comments were received from A. Baudry, B. Carlson, Y. Chikada, D. Emerson, G. Harp, S. Iguchi, R.Lucas, S. Okumura and D. Sramek. Thanks to W. Holmes and H. Malagon for the IFDC measurements discussed in Section 3.2.3.

Appendix:

Amount of LO offset required to suppress digitizer DC offsets

In this section we determine the amount of LO offset required to reduce the correlated signal caused by the digitizer DC offsets down to the level of the rms fluctuations in the correlator caused by thermal noise.

The formula (Baudry, 2006b) used to determine the magnitude of the DC offset from an ALMA digitizer expresses the DC offset voltage as a fraction of the rms voltage into the digitizer. Let D be the ratio of the DC offset voltage to the rms voltage. If two antennas both have DC offsets D and identical system temperatures, T_{sys}, after correlation the DC offsets will produce a correlated signal of strength $D^2 * T_{sys}$. ^oK. This relationship follows because the rms voltage into the digitizer is the rms voltage equivalent to the system temperature.

Let S_{DC} be the point source flux equivalent to the correlated signal resulting from the DC offset. Then , from TMS (eqn 6.46)

$$S_{DC} = \frac{D^2 * T_{sys} * k_B}{0.5 * A} \qquad (1)$$

Where k_B is Boltzman's constant and A is the effective area of an interferometer antenna (assumed identical for both antennas).

Let ΔS be the rms noise level at the output of the correlator. From TMS (eqn 6.50, but note typo in TMS in location of the $\sqrt{(\Delta\nu * \tau)}$)

$$\Delta S = \frac{\sqrt{2} * k_B * T_{sys}}{A * \eta_Q * \sqrt{\Delta\nu * \tau}} \qquad (2)$$

Where η_Q is the correlation efficiency, Δν is the IF bandwidth and τ is the integration time. From (1) and (2) the ratio of DC offset flux to correlator noise is then

$$\frac{S_{DC}}{\Delta S} = \sqrt{2} * \eta_Q * D^2 * \sqrt{\Delta\nu * \tau} \qquad (3)$$

If different LO offsets are applied to the two antennas at a point in the receiver system before the DC offset is created, and these LO offsets are removed at a point after the DC offsets are created, then the residual frequency offset between the two antennas will attenuate the correlated output due to the DC offsets. The amount of this attenuation is given by the factor f (TMS, eqn 15.5)

$$f = \frac{\sin(\pi * \nu_o * \tau)}{\pi * \nu_o * \tau} \qquad (4)$$

where ν_o is the residual offset frequency between the two antennas. (4) shows that if there are an integral number of cycles of ν_o in an integration time then f=0 and the DC offsets are removed completely. In practice this condition may be difficult to achieve because of various blanking periods in the correlator so we will assume the more conservative case that the attenuation is given by the envelope of the lobes of the sinc function in (4). If f_e is the attenuation provided by the envelope then

$$f_e = \frac{1}{\pi * \nu_o * \tau} \qquad (5)$$

If we require this attenuation to be sufficient to reduce the DC offset down to the thermal noise then f_e must equal $\Delta S/S_{DC}$. From (3) and (5) we then have

$$\nu_o = \frac{\sqrt{2}}{\pi} * \eta_Q * D^2 * \sqrt{\frac{\Delta\nu}{\tau}} \qquad (6)$$

The goal for D is .01 but in long term testing of the digitizers in the prototype test racks (DuVall and Napier, 2006) we occasionally see the DC offsets drifting as high as D=.05 so we will take this as a worst case and ensure sufficient LO offset to attenuate DC offsets as large as .05. Then using η_Q=0.88 for the 4 level correlation performed in the correlator, D =.05, $\Delta\upsilon$ =2 GHz for the maximum IF bandwidth and τ = 16 msec for the basic integration time in the correlator, we calculate from (6) that ν_o = 350 Hz. For integration times longer than 16 ms, which will be achieved by adding together a number of individual 16 ms integrations, the amount of suppression provided by the LO offset depends on how the phase of the LO offset changes between 16 ms integrations. It is reasonable to assume that the suppression will improve at least as fast as the square root of the total integration time, which is the same rate as the reduction in the thermal noise. So 350 Hz is also adequate for integration times longer than 16 ms.

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