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To: EDGES Group
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Subject: Local oscillator frequency cycling

1] 3 position switching

An ideal spectrometer has a perfectly flat frequency response. In the EDGES Acquiris spectrometer 3 position switching was used to remove the "bandpass". In this case:

$$p_0 = g\left(T_A + T_R\right) + c$$
$$p_1 = g\left(T_L + T_R\right) + c$$
$$p_2 = g\left(T_{cal} + T_L + T_R\right) + c$$

where T_A = antenna temperature
T_L = load temperature
T_R = receiver temperature
T_{cal} = calibration temperature
g = gain or bandpass function
c = constant receiver contribution

$$T_A = T_{cal}\left(p_0 - p_1\right) / \left(p_2 - p_1\right) + T_L$$

2] Frequency cycling

An alternate to 3 position switching in a spectrometer that employs a frequency shift mixing prior to the spectrum analysis is to cycle the frequency shift. So that

$$T_A\left(f\right) = \sum_{l=0}^{N-1} T_A\left(f\right) g\left(f + l\right) \Big/ \sum_{l=0}^{N-1} g\left(l\right)$$

where $g\left(l\right)$ is bandpass function which repeats module N. In this case the bandpass function is equally sampled through its entire domain for every frequency, if the local oscillator is cycled with a step size equal to the frequency spacing. In practice even a step size larger than the frequency spacing will decrease the bandpass variation by a large amount.

3] Effects of ADC defects

Analog to digital converters (ADC) are imperfect devices with non-linearities, subsampling harmonic mixing, variable bandpass ripple, in addition to high levels of spurious signals. As a result of these defects 3-position switching fails to produce uncorrupted spectra with noise that continues to average down in long integrations.

a. Non-linearieties
Non-linearities distort the spectrum. A perfectly white flat spectrum is only affected in amplitude but a sloping spectrum has its slope changed and distorted.
b. Subsampling harmonic mixing
Subharmonics in the sampling frequency mix with the noise and produce breaks in the spectrum at subharmonics of the sampling frequency.
c. Variable bandpass ripple
Delayed feedback from the sampler output into its input put ripple in the bandpass whose phase and amplitude is dependent on the spectrum.
d. Spurious signals
Subharmonics of the sampling frequency and harmonics of clocks in the digital circuitry following the ADC invariably show up in the spectrum.

These defects result in artifacts in the final spectra from the 3-position switched data unless the “signal” and “comparison” spectra are almost the same. To demonstrate the magnitude of these effects I took:

$$p_0 = \left(0.5 + \left(w/b\right)\right)/2$$
$$p_1 = 1.0$$

which simulates a flat bandpass for the reference and bandpass for the signal which starts at 0.25 at the D.C. edge and slopes up to start at 0.25 at the D.C. edge and slopes up to reach a value of 0.75 at the bandedge. In this case the total power for signal is half that of the comparison. The ADC defects result in a deviation in $\left(p_0 - p_1\right)$ from a linear slope. The following table lists the peak deviation from a slope for the following ADC defects

a. Non-linearity in the ADC amounting a peak deviation of 1 bit
b. Feedback from MSB of the ADC delayed by samples at a level of -70 dB below the ADC full scale
c. Sampling subharmonic at a level of -50 dBc
d. Spurs at a level of -90 dB below ADC full scale for resolution of 0.1% of the bandwidth.

ADC defect	#bits in ADC	Peak error (ppm)	Effect
Non-linearity 1 bit	7 8 9	500 100 30	Smooth distortion
Feedback -70 dB	Independent of # bits	50	Ripple
Sampling sub-harmonics -50 dBi	“	50	Distortion, and aliasing of bandedges into band
Spurs -90 dB	“	50	Spurs which don’t cancel

This table illustrates how critical the ADC performance is to a spectrometer performance for long integration at wide bandwidth. For example a level of 50 ppm should be reached in 30 minutes of integration with 1 MHz resolution. This is the level that EDGES needs to reach to measure a red shifted hydrogen line of 10 mK in a 200 K system. Firstly it looks like 8 bits is marginal even if the feedback and sampling subharmonics can be reduced to extremely low levels. The solution may be to use a narrower band digital spectrometer with a 12 or 16 bit ADC and then, in addition employ the frequency cycling techniques to smooth out the ADC bandpass and ADC defects.

Figure 1 shows an example of a effect of ADC defects on the Dicke switched difference spectrum. The ripples in the spectrum are the result of feedback from the sign bit of the output back to the input at a level of -80 dB relative to full scale. The 2.5 MHz spectral feature at 125 MHz and another at 375 MHz are the result of aliasing of the 2.5 MHz high pass filtering by the sample clock jitter at ¼ its rate at a level of -30 dBc.

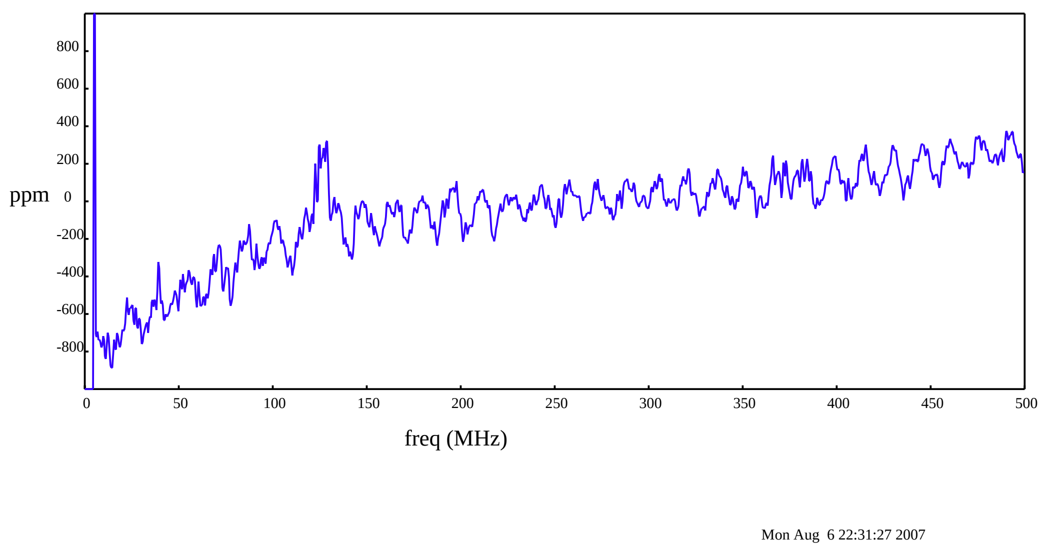

Figure 1. Example of the effects of ADC defects – see text for details.