EVLA Memo 169
Spectral artifacts from phase serialization

R.J. Sault, Ken Sowinski

August 26, 2013

Introduction

This memo investigates some artifacts seen in high dynamic range spectral observations. It is shown to be a consequence of phase model decimation when using either recirculation or baseline board stacking in WIDAR. The magnitude of the effect goes quadratically with the $f_{\rm shift}$ frequencies. By appropriate choice of these frequencies, the artifacts can be reduced to an acceptable level.

The artifact

Figure 1 shows an example of some artifacts seen in some very high dynamic range EVLA spectra. This is an observation of a strong source (∼500 Jy) which is spatially a point and spectrally very narrow. In this observation the true line peaks at channel 588, and "ghost" lines are seen at offsets of plus and minus a quarter and half the bandwidth (channels 332, 844 and 76 respectively). The line shape of the artifacts follows that of the true line. The true line in this observation was not set at the phase center (Fig. 1 results after shifting the data in post-processing), yet spatially the artifacts appear to be near point sources at the same spatial location as the true line. The artifacts do not change significantly over the course of the ∼65 minute observation. They are the same in the RR and LL channels. Thus, apart from an attenuation by a factor of ∼5000 and a spectral shift, the artifacts are spectrally and spatially good copies of the true line.

One aspect where the artifacts and true line differ is variation between baselines. Whereas the true line is spatially unresolved, and so constant with baseline, the artifacts were noted to vary between baselines. In particular it was noted that the artefacts varied as a function of the "number" assigned to the antennas of a baseline. The magnitude of the artifact tended to be larger on baselines involving small-numbered antennas than those involving large-numbered antennas. For example, baselines involving antenna 1 tended to had larger artefacts than baselines involving antenna 27.

Artifacts from phase serialization

An important part of WIDARs architecture is that a phase model accompanies the astronomy data through the correlator. This phase model is used for phase correction in the correlator cells that form a lag spectrum.

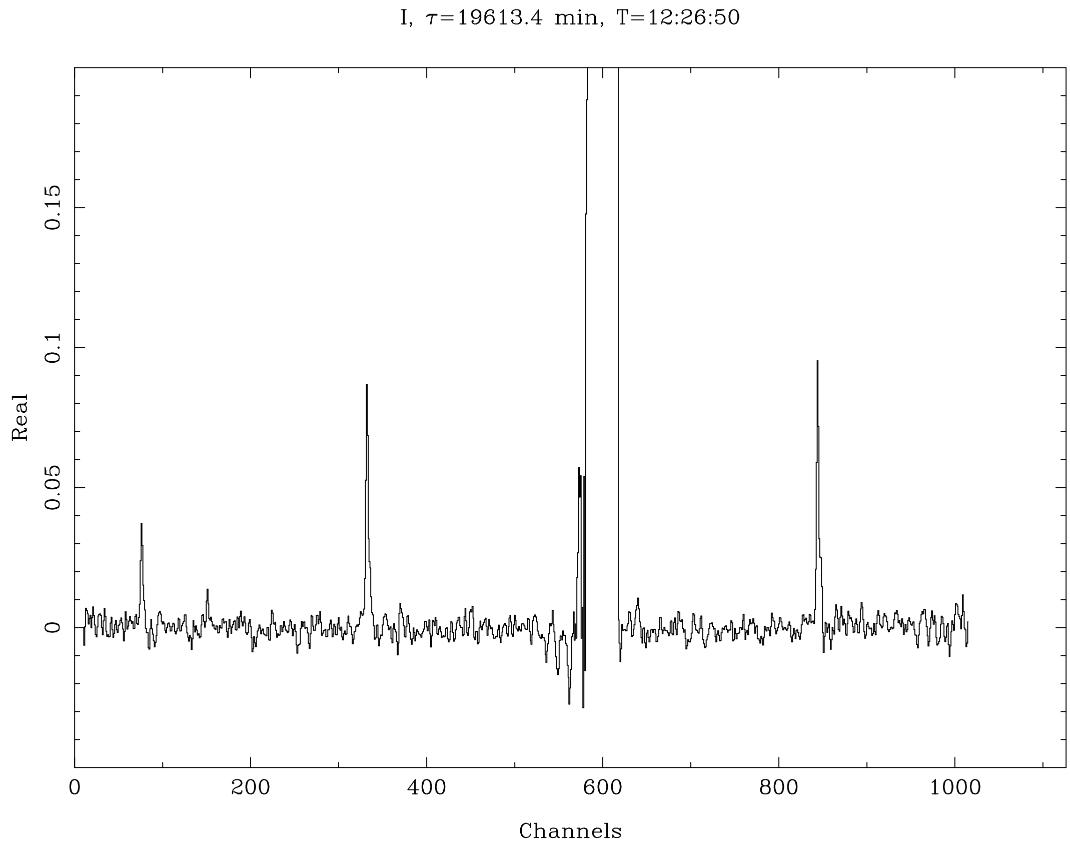

Figure 1: Spectrum of a 6.7 GHz methanol maser, which peaks at channel 588. Artifacts are seen at channels 76, 332 and 884.

When performing either recirculation or baseline board stacking in WIDAR, the phase model is by default decimated by a factor of 8 to conserve some resources. This phase model decimation can be thought of as a source of phase noise, which in turn will lead to some amplitude decorrelation. This decorrelation is described in the WIDAR document "Requirements and functional specification: Recirculation controller FPGA" (hereafter called the Recirculation RFS) (see page 50). EVLA Memo 163 measured the decorrelation in some real continuum observations and verified that it broadly agreed with the analysis of the Recirculation RFS.

If all lags experienced the same amount of decorrelation, no spectral signature would be expected. However this appears not to be the case. In EVLA Memo 163 it was noted that the amount of decorrelation did vary with lag – see Fig. 3 in that memo. To understand this, consider that the error in the phase model caused by decimation: the error will go through a sawtooth wave cycle over 8 sample times. The error will initially be zero, then build up at the antenna phase rate to a maximum after 8 sample steps, and then the error will fall back to 0.

For any given lag correlator cell, it appears that the offset between the sawtooth sequence of the phase errors of the two antennas remains constant with time. However this offset differs between different lag cells. This is a consequence of the ladder of cells used to build up a lag spectrum. As an example, consider one lag correlator cell which sees the error in the phase model of both its inputs start together at 0, then build up to their maximum error on the 8th sample, and then fall back to 0. An adjacent lag cell will see an offset of one step in the error of the phase models between the two inputs: e.g. one stream will be at step 1 in the sequence when the other stream would be at step 0. Once the two sequences are differenced, it is apparent this lag cell will experience different phase noise from its neighboring cell.

The mean phase noise will be the same for all cells[1]. However as the decorrelation is proportional to the square of the phase noise (assuming small errors), the decorrelation will vary between lag cells. This results in a real-valued decorrelation pattern that repeats every eight lags across the lag spectrum. A multiplicative pattern that repeats every eight lags transforms to a convolutional function with impulses offset from the origin by quarter and half the visibility spectrum width. Thus the effect of the lag decorrelation pattern is to generate ghost lines offset from the true line by quarter and half the visibility spectrum. For the data of Fig. 1, this corresponds to 256 and 512 channels.

The magnitude of the artifact on a given baseline is dependent on the phase rates on the two antennas. For typical EVLA observing (particularly at 6.7 GHz in C array corresponding to the above observation), the phase rates are dominated by the f_{shift} frequencies used. In the current observing system, the f_{shift} frequency of a particular antenna i is approximately

$$f_{\mathrm{shift}} \approx (32 - i) \times f_0,$$

where f_0 is the so-called f_{shift} fundamental. As the smaller-numbered antennas will have larger phase rates, greater decorrelation (and larger spectral artifacts) would be expected for baselines formed with them.

We have performed a simple simulation to compare this understanding of the artifacts with the observation shown in Fig. 1. The resultant simulated spectrum is a good match to that given in Fig. 1. As f_{shift}, the phase rates, and thus the effect are a function of baseline, we have also simulated the expected artifact peak (at channel 332 in Fig. 1) as a function of baseline. Figure 2 shows the simulation results along with the the actual measured data. For each baseline, we plot the simulation prediction against the observed data. Agreement is quite good. For the observation given in Fig. 1, the bandwidth was 8 MHz (i.e. the sampling rate was 16 MHz) and the f_{shift} fundamental was 1.6 kHz.

[1] As noted in Memo 163, the current system leaves a mean phase error as a residual in the data. This phase offset is simply correctable and closing, and is of little consequence.

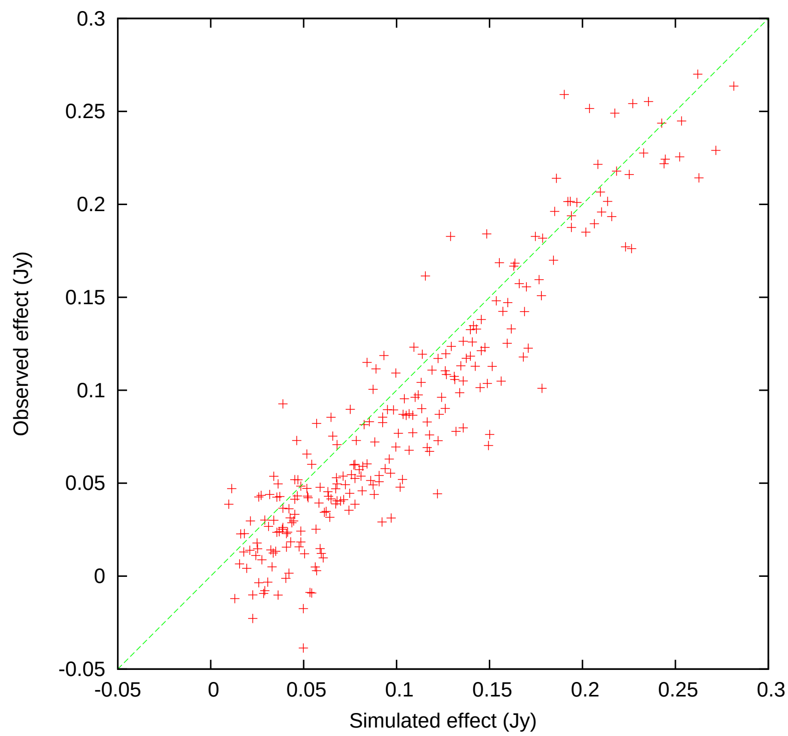

Figure 2: Comparison of simulated and observed artifact peak at channel 332. A $y = x$ line (i.e. the expected relationship) is shown as an aid.

Concluding remarks

Some aspects of this artifact are mentioned in the Recirculation RFS (page 50). Indeed this gives an equation giving the approximate magnitude of the effect. It recommends that to ensure that artifacts are 50 dB down, the $f_{\rm shift}$ frequencies should be

$$f_{\rm shift} < 5 \times 10^{-4} f_s$$

(where f_s is the sampling rate), or stating this in terms of the $f_{\rm shift}$ fundamental f_0,

$$f_0 < 5 \times 10^{-4}/32 f_s$$

For the observation of Fig. 1, this suggests $f_{\rm shift}$ fundamental of no more than 250 Hz, whereas the observation used 1.6 kHz.

The magnitude of the artifacts will go as the square of $f_{\rm shift}$ values (phase noise is proportional to $f_{\rm shift}$, and decorrelation is proportional to the square of phase noise). Clearly it is wise to ensure $f_{\rm shift}$ is sufficiently small to achieve the dynamic range needed in an observations. However there are other constraints on appropriate values of $f_{\rm shift}$. Care is needed.