EVLA Memo No. 192

Evaluation of Hittite 3-bit Samplers.

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ABSTRACT

Tests of the EVLA wideband 3-bit samplers are summarized, comparing the SNR performance of the new modules based on Hittite chips, with the older Teledyne chips. The news is generally good, but some discussion of the kinky details of sampler behavior is unavoidable. Fortunately most of these can be calibrated.

1 Background

The samplers (digitizers) convert the analog voltage received by the antennas to digital data for transmission by fiber to the correlator. Each EVLA antenna has 2 polarization pairs of 1 GHz bandwidth 8-bit samplers, and 4 pairs of 2 GHz 3-bit samplers.

Prototype Teledyne sampler chips were purchased early in the EVLA project, and found to be less than ideal in performance when eventually tested. Nevertheless they were deployed, as there were no other options at the time. The bulk of them work adequately, but the performance distribution has a long tail, and about 15 to 20% (15-20 modules, each with 2 samplers) could stand to be replaced. But there were insufficient chips.

The 8-bit samplers are stable and well behaved, and provide good benchmarks for comparison. In the intervening 3 years, another sampler chip from Hittite Microwave had become available. A new board was designed, a batch of 5 Hittite sampler pairs were tested, and seen to be closer to ideal 3-bit devices. Replacement of the entire set of samplers was too expensive, so in late 2013 an estimate was made of the benefits of replacing just the worst Teledyne samplers with the new Hittite modules (Butler, Dhawan, & Durand 2013 - attached).

Starting in October 2014, a second batch of 13 Hittite sampler boards was built and deployed on the array by May 2015. In this memo the whole ensemble of samplers is evaluated on various metrics, including the relative signal-to-noise (SNR) of the Hittites vs. Teledynes.

The engineering evaluation (bench tests) of the Hittite samplers showed them to be tamer devices, easier to setup and stabilize at power-on, and free of the RF resonances of the Teledyne devices. All of these points were borne out by the observational tests described here.

2 Summary of Conclusions

Evaluation criteria and main results are listed here. For zealots there is more detail in subsequent sections and slides.

1. **RMS noise:** This is the main point of interest for most users. In short, the Hittite samplers live up to their expectations, with 85% of them good or excellent.

2. **The pre-game prediction was 7%** improvement in SNR across the ensemble, if 15 sampler modules were replaced. The outcome was 5% improvement after 13 replacements. The very few spares that were available have now been augmented by a dozen.

3. **Bandpass Stability & Polarization Cross-Talk** are very good, comparable to the excellent 8-bit samplers. The ripple in the 2 GHz sampler band (typically 5dB) from upstream electronics affects both types of 3-bit sampler, for about $2 \pm 2\%$ loss in SNR.

4. **Stability over time:** Over durations of 10's of minutes in these tests, no instabilities were seen in either type of sampler, once they warmed up.

5. **SNR improvement with integration time:** Images made by scientific users, accumulating tens of hours, produce near-theoretical rms, down to a few micro-Jansky, with the wideband receivers at Ka and Q bands. These results are from Teledyne samplers. The Hittites have not been in use long enough, but are expected to be as good or better. A future action item.

6. **Birdies:** There is a ubiquitous 13 GHz resonance in Teledyne chips. Nothing resembling it is seen on any Hittite sampler.

7. **Flux Calibration & Switched-Power Calibration:** There is no significant difference between two types.

8. **State Counts:** a minor point, but Hittites are clearly better than Teledynes, probably indicating better stability of the internal threshold levels.

9. **Long-Term Reliability:** There is a possible issue with how well the Teledyne samplers hold their performance - the SNR of the ensemble shows signs of slowly degrading over 3 years. For Hittite samplers it is still too early to tell. Both types will need to be re-asessed periodically.

3 Results in More Detail

The main result pertains to the rms noise and is contained in slide 3.

The supplementary slides are single examples to illustrate the measurements that make up the rest of the memo. All data have been examined, but it is impractical to record every plot. The original data are saved in AIPS, to be queried as necessary.

3.1 RMS Noise

Referring to the histograms in **Slide # 3:**

1. Measurement setup and processing: All 3-bit and 8-bit samplers are tuned to the same center frequency on the sky. Observations follow the standard data path used for astronomical observations from antenna to correlator to post-processing in the AIPS package. The full capacity of the WIDAR correlator is used to process upto 8 data paths in parallel.

   The off-source rms noise of each 3-bit sampler is ratio'd to an 8-bit one from the same antenna and polarization, after calibrating on source. This corrects for Tsys, antenna efficiency, pointing errors, and sky opacity. The passband of the last downconverter before the sampler is unique to that unit and is calibrated in post-processing.

2. The expected ratio of noise for ideal 3bit/8bit is 1.04, i.e. 3-bit 4% worse. In practice, the 3-bit is more sensitive to bandpass ripple, which is hard to control over the 2 GHz bandwidth, and is typically 5 dB. This results in a further loss of to 2±2%.

3. About 40% of the Teledyne samplers (black line, 2014 April) performed better than 1.1.

4. Whereas 85% of the 34[*] Hittite chips (red line) do better than 1.1. The green line shows the combined set on the array at present. The Hittites are clearly at the upper end of the green distribution, all measured simultaneously in 2015. [*] One more pair was deployed after these measurements.]

5. The black curve (April 2014) was truncated at 1.4. There were 6 pairs off the chart, upto 1.8. They were the first to be replaced.

6. Finally, there are now zero samplers worse than 1.3 in the green plot. There are still about a dozen worse than 1.2, it would be nice to replace some of these, but we are out of cash and chips. The removed Teledynes will be re-worked into spares as far as possible.

3.2 Improvement of SNR with Integration Time

The tests reported here span tens of minutes. The SNR has been verified to improve with bandwidth and integration time as $\sqrt{B\tau}$. Deep exposures show that the noise continues to integrate down. Indeed, scientific projects accumulating tens of hours have produced near-theoretical rms down to a few micro-Jansky, using the wideband receivers at Ka and Q bands. (e.g. Isella et al. 2014, Ap.J. 788:129, achieve 3.6μJy, vs. 3μJy theoretical noise, in 21 hours of on-source integration, over 68 hours of observations, spread over many weeks. And Wagg et al.

2014 Ap.J. 783:71, achieve 6μJy vs. 5μJy theoretical, from 8 hours on-source.) These examples, and others, validate the samplers and the entire telecsope.

The results quoted are using Teledyne samplers, Hittites have not been in use long enough, but are expected to be as good or better. To asses the differences between sampler types in this regard, one would have to make images with subsets of baselines using the two types of samplers, and and measure the rms (normallized by the number of baselines). This has not been addressed in the present effort.

3.3 Polarization Cross-Talk

SLIDE # 4:

The 2 samplers in a module (one board) process the R & L polarizations for a given chunk of sky signal, and leakage between the 2 sides affects the polarization purity of the signals.

Slide 4 shows the RL and LR cross-talk vs. frequency, after calibrating the individual R,L bandpasses on each sampler. The result is the vector sum of contributions from the source, the front-end polarization impurity, and any added by the downstream electronics. This can be corrected in post-processing, if the instrument is stable, to yield an accurate measurement of astronomical polarization.

In this particular setup, the plot should be identical for every sampler that is fed the same signal from the front end. In fact each color differs only a little from the others. The full-scale is 10% cross-talk (-20dB power). The measured cross-talk within the sampler modules is, on average, well below 1% fringe amplitude (-40 dB power). At some frequencies in the passband it can be as high as a few% (-30 dB). Further investigation shows that the cross-talk is stable in time at all frequencies (the variations are within the noise), for both Teledyne and Hittite boards. This permits their use in wideband polarimetry.

3.4 Birdies

SLIDE # 5:

The Teledyne chips exhibit a resonance around 13$\pm$0.5 GHz which appears aliased as a spectral feature in the 2 GHz passband. See the right panels in slide 5 for an example. Each chip is unique, the features are narrow and corrupt $<$ 1% of the bandwidth, and the birdies from different antennas do not overlap or correlate, so they are not a hinderance to continuum observations. They are a potential nuisance to spectral-line observing and are completely absent in the Hittite chips, (top left panel in slide 5.)

3.5 Bandpass Ripple

SLIDE # 5:

The 2 GHz sampler band is not flat, as a result of front-end, downconverter, and internal sampler gain variations and impedance mismatches. The loss of SNR is estimated at 2-4% from the typical 5 dB ripple. Slide 5 shows examples. Re-working of the analog antenna electronics is not contemplated, therefore this factor affect both type of samplers.

3.6 Calibration

SLIDE # 6:

Non-linearity of the switched-power response is a consequence of using a few-bits sampler with a variable drive level. The theoretical curve is unfortunately **not** followed by either type of sampler, so a generic correction is inadequate. We would need a calibration lookup-table specific to every sampler at each RF band, to enable 'blind' amplitude calibration. Currently, we bypass this problem by requiring every schedule block to observe a known flux-calibration source, at some loss of observing efficiency.

In slide 6, the horizontal axes are input power, the vertical is output power. The light brown curves are theoretical, the coloured points are 4 different samplers per antenna, each follows a different non-ideal calibration curve.

3.7 Histogram of State-Counts

SLIDE # 7:

Early tests with Teledyne showed the population statistics for the seven equally spaced sampler levels to be surprisingly non-Gaussian. It may indicate unequal levels within the chip. Hittites are much better in this regard, it may be a clue to their more consistent performance. But many Teledyne samplers have good SNR in spite of wonky histograms, so the utility of this simple test is unclear.

3.8 Stability etc:

Each sampler at power-on needs to go through a startup calibration sequence. This procedure is simpler for the Hittite modules (from discussions with the designer, M.Revnell). The sequence occasionally fails, requiring a manual reset after which the performance is stable. Hittite samplers do this rarely, but that could be just their smaller numbers in the array. I note that in some cases a re-calibration on the bench can improve the Teledyne modules considerably. We do not yet have sufficient experience with the failure and recovery of the Hittites. In any case the increased number of spares is a relief.

3.9 Long-Term Reliability

SLIDE # 8 Older histogram

There is a possible issue with how well the Teledyne samplers hold their performance. Compare the black histograms in slides from October 2012, to April 2014 or May 2015.

The samplers are not expected to behave identically long term, since the input RF drive levels are re-adjusted, the upstream electronics gets re-shuffled, samplers get power cycled and moved between antennas. Still, the average performance should be stable. Therefore, it is of some concern that the ensemble shows signs of slowly spreading to lower SNR over 3 years. For Hittite samplers it is still too early to tell. Both types will need to be re-assessed periodically.

3-bit samplers - update

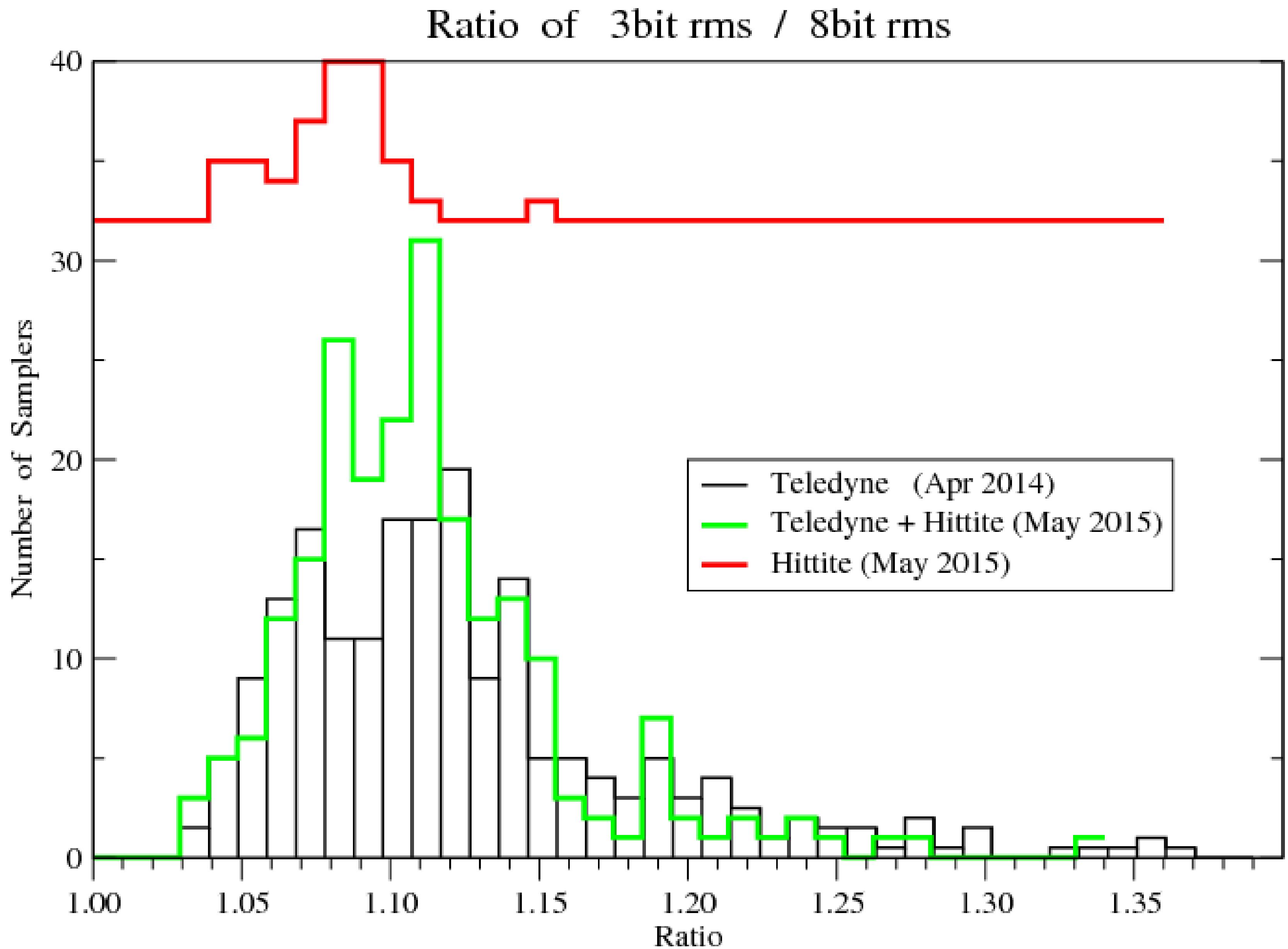
2015 Jun 27

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

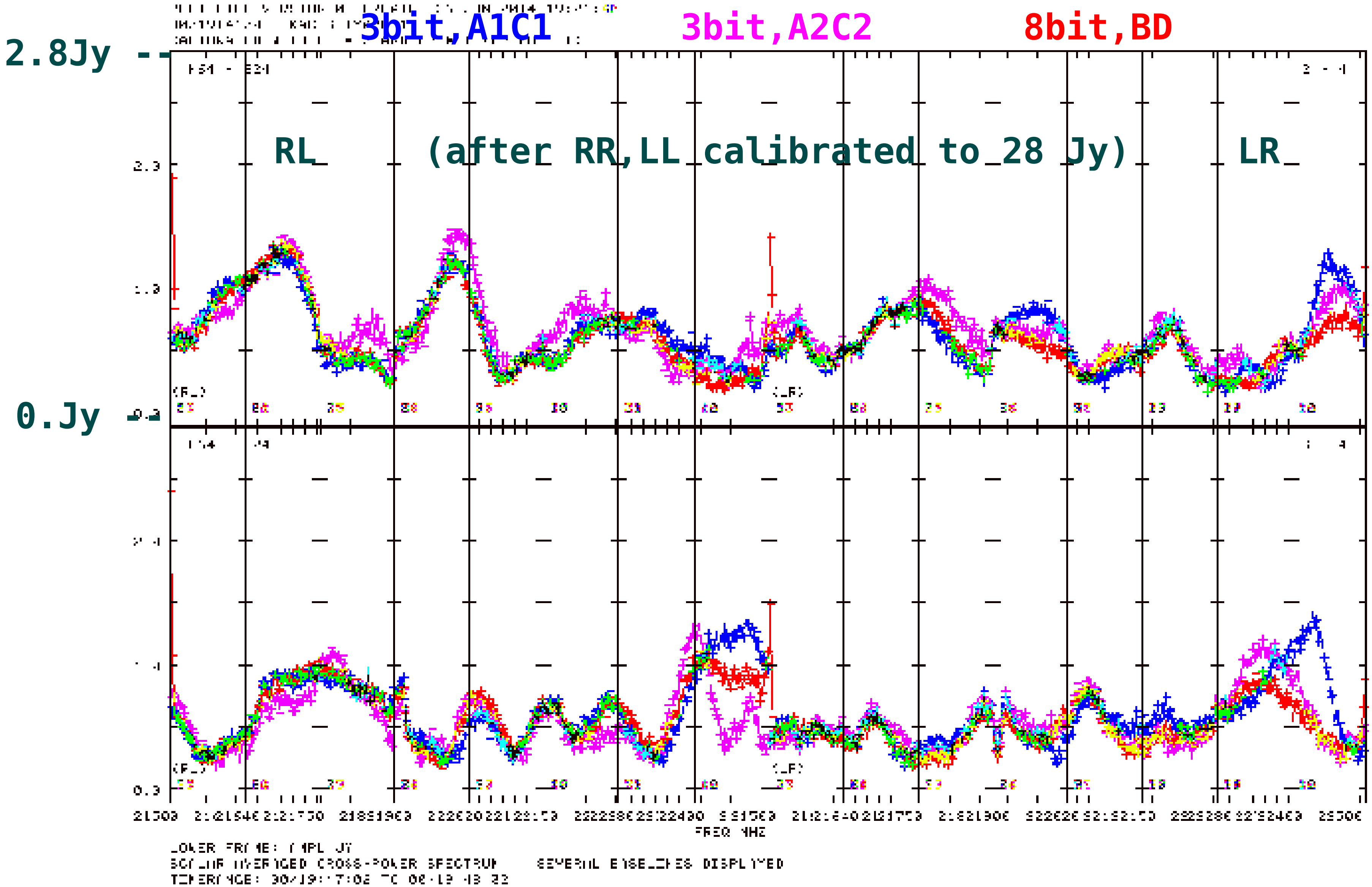
Summary, 2015 June: 13 new Hittite boards installed.

- Cost to replace Teledynes with Hittites: $10K / board.
- Replaced out-of-stock chips, built up spares.
- SNR improved ~5% (?) on array. Pregame estimate was 7% if 15 boards replaced (Butler et al. Dec 2013).
- NO birdies (internal 13 GHz resonance) with Hittites.
- Poln. X-talk – same as Teledyne, <1% = -40dB, stable.
- Calibration (switched power) non linearity – same as Tel.
- Loss from BP ripple (FE + T304): 2+-2%. same as Teledyne.
- Stability on setup, repeatability, etc. same as Teled.
- State count histogram – Hittites better (so what?)
- Long-Term Reliability: Possible slow changes in SNR?

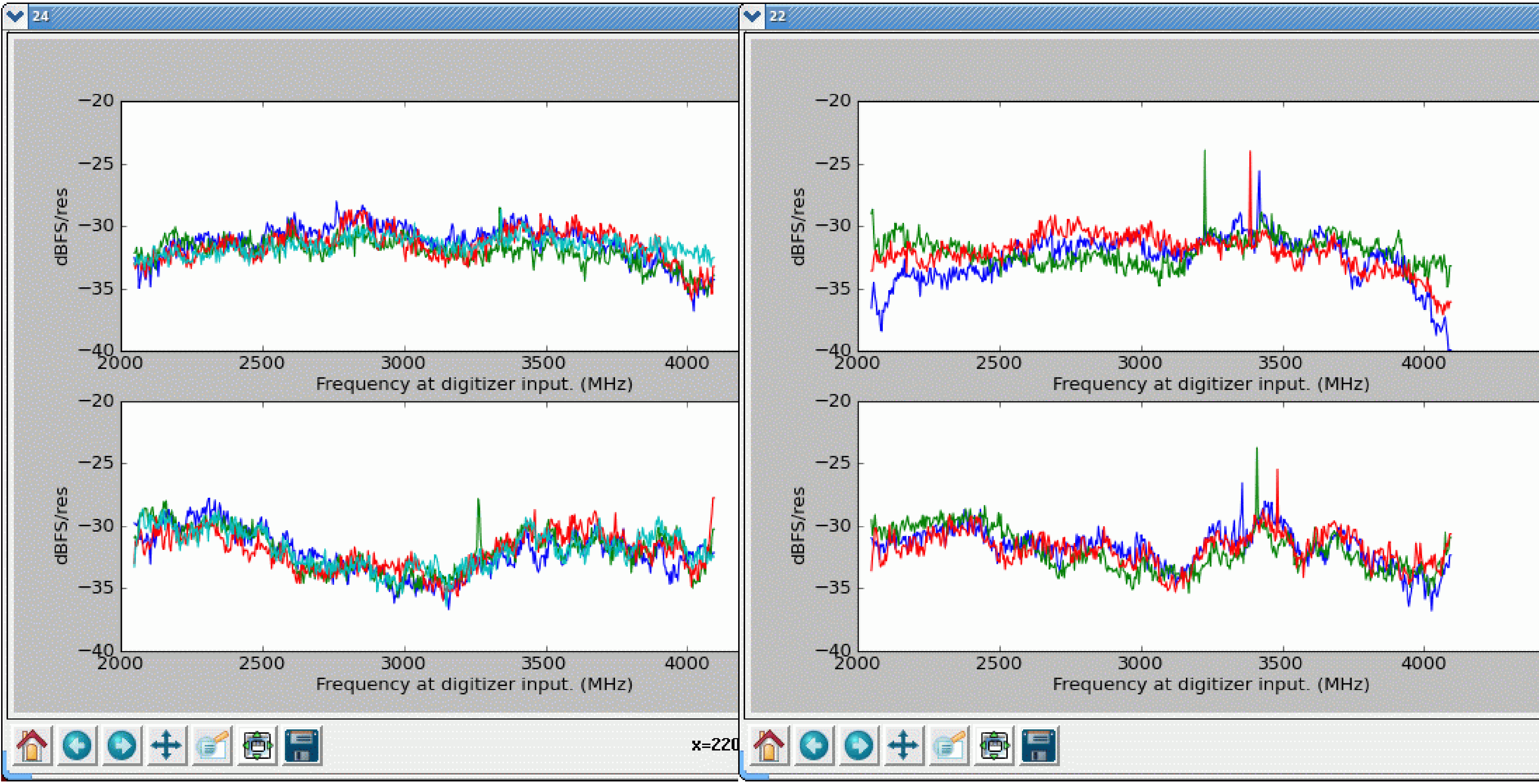
Sampler rms ratio (May 2015, new Hittite boards)



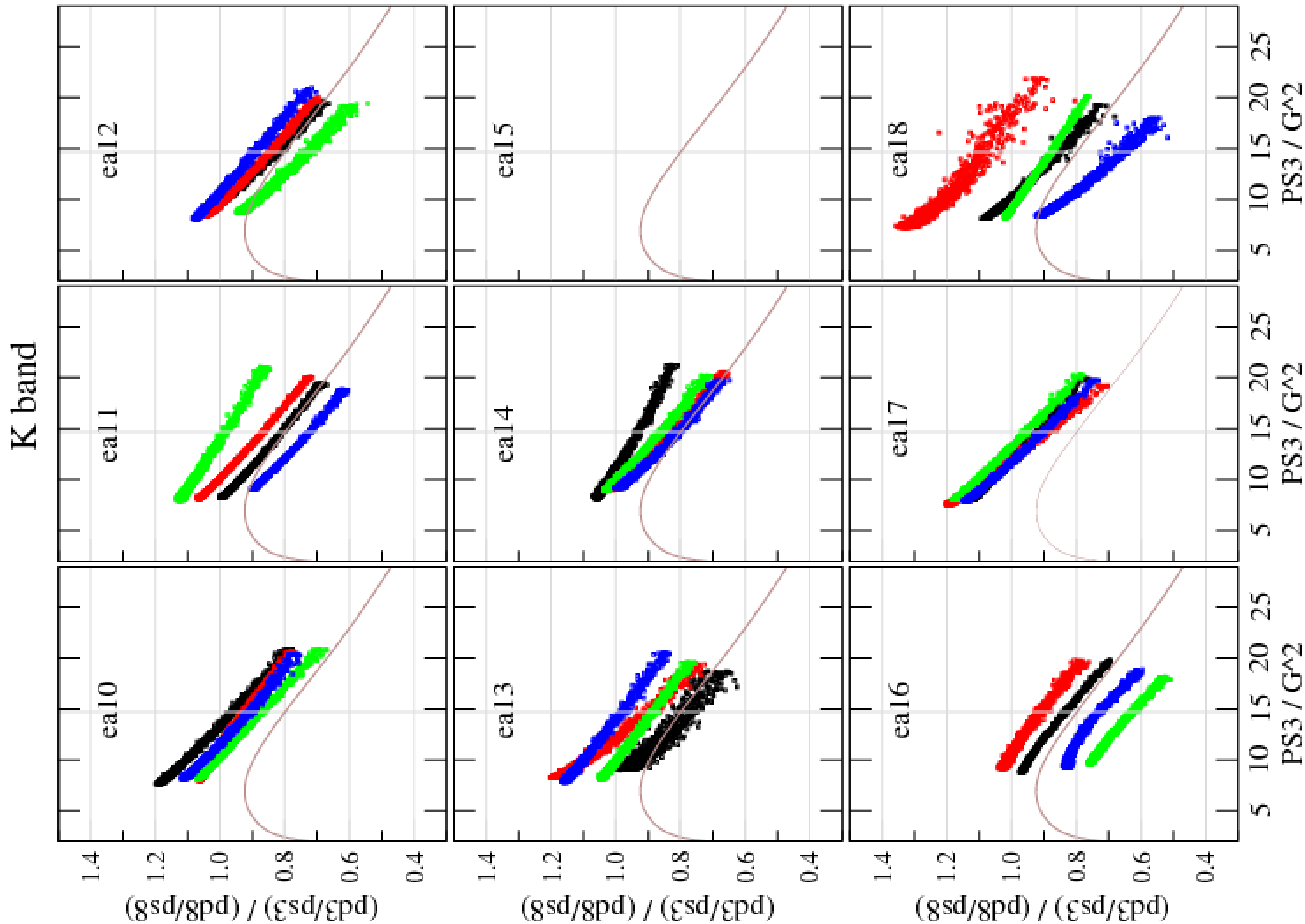
Cross-pol. bandpass (crosstalk): 3-bit vs. 8-bit



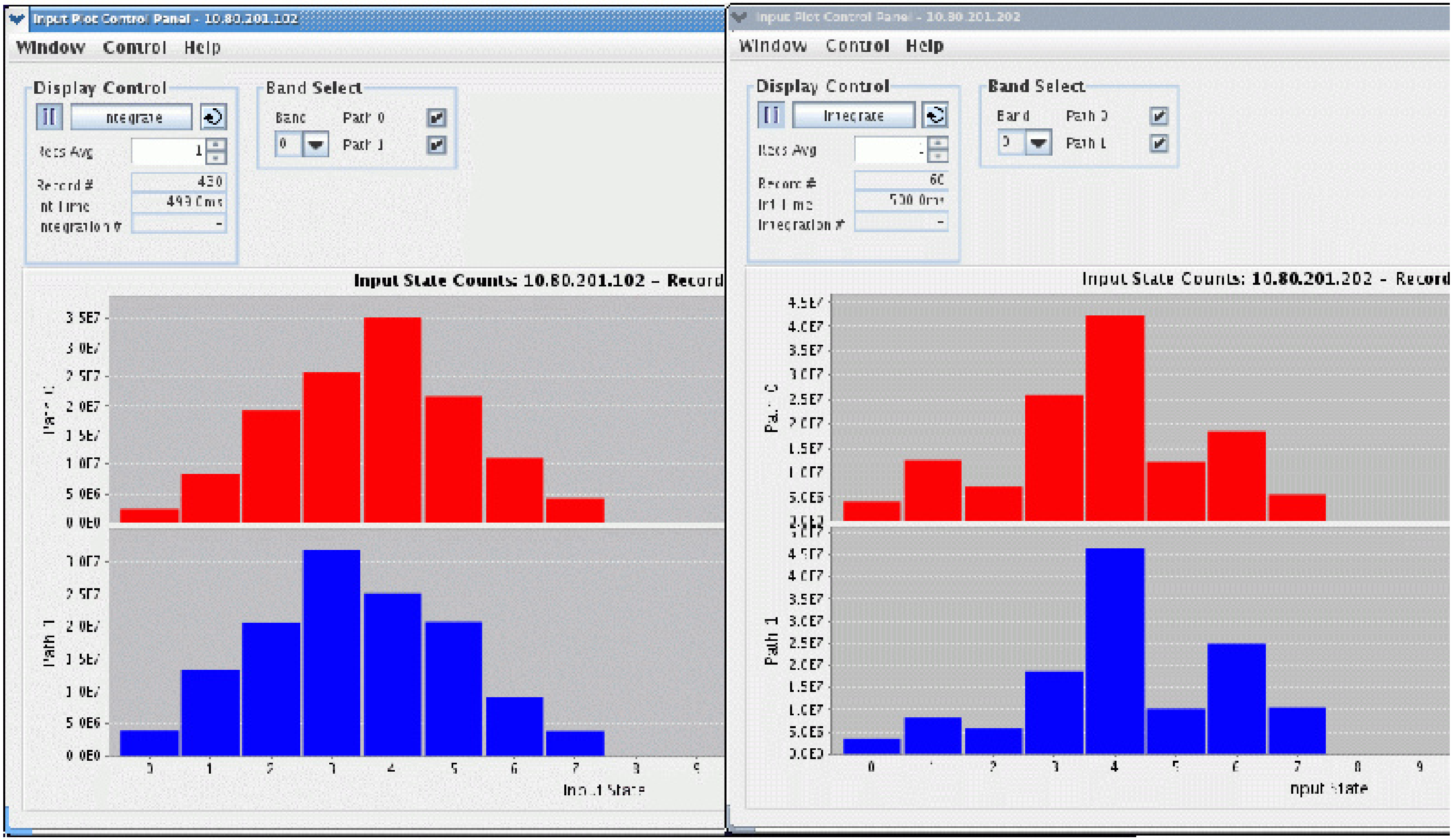
Wideband 2GHz spectra Hittites at top left - no birdies



Sampler rms ratio (Oct 2012 - old Hittite boards)



State-Count Histogram, Hittites at left.



Sampler rms ratio (Oct 2012 - old Hittite boards)