COBRA noise tests

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1 Introduction

This document analyzes noise measurements from the COBRA wideband correlator system. Figure 1 shows a photo of the 4GHz COBRA Wideband System, while Figure 2 shows block diagrams of the COBRA boards and board layout within a crate.

The 4GHz COBRA Wideband System in Figure 1 consists of eight 500MHz processing bands. From top down, the crates are numbered 1 to 4, and within each crate there are two COBRA bands, with the bands numbered left to right as 1, 2 (crate 1), 3, 4 (crate 2), 5, 6 (crate 3), and 7, 8 (crate 4). Within each band, there are three digitizer boards followed by three correlator boards. The digitizer boards are numbered 1, 2, and 3, while the correlator boards are 4, 5, and 6.

The noise tests were performed with uncorrelated and correlated noise sources. The purpose of the uncorrelated noises tests was to check that the correlator integrates down with the correct statistics. This test also shows what kind of interference the system is subject to (radiated clocks etc). The integrated noise tests were performed to check that the system behaved as expected, eg. that the quadrature modulated noise source and the correlator DSPs maintained time correctly.

These tests exposed a number of interesting issues, for example, clock radiation from the timing boards in the COBRA correlator, and an unidentified correlated noise coupling into the digitizer inputs.
Figure 1: COBRA 4GHz Wideband Correlator System.
Figure 2: COBRA Wideband Correlator System. Each 500MHz bandwidth band consists of three digitizer boards and three correlator boards. A compact PCI crate can accommodate two bands. The 4GHz Wideband System requires 4 crates.
2 Lab test results

A noise source is required to exercise the digitizers in the correlator system. For system tests, both a source of correlated noise, and uncorrelated noise is desired. An uncorrelated noise source is used to test the level of correlated interfering signals, i.e., signals coupled into the analog front end.

The quadrature-modulated noise source can be used in conjunction with the digitizer board digital delay lines to generate uncorrelated noise. Its necessary to start a test with the correlated noise source so that clocks can be aligned, and phases flattened. This ensures that the measurements are not biased by FPGA setup and hold violations. By inserting appropriate delays, e.g. a 4.096$\mu$s delay for digitizer A signals, and a 2.048$\mu$s delay for digitizer B signals, and setting the correlation mode bit high (corl_mode(1) = 1) the digitizer boards will calculate the cross-correlations; A correlated with A delayed, B correlated with B delayed, and A delayed correlated with B delayed. For the delay settings mentioned, we are effectively calculating auto-correlation lags starting at lag 4096 for A, and 2048 for B, and cross-correlation lags starting at 2048 for AB. Note that in a 500MHz bandwidth COBRA system, if the three digitizer boards are setup with these delays, then on the correlator boards, odd-odd and even-even baselines will still be correlated about their zeroth lag, since the relative delays of their digitized signals will match. To decorrelate all fifteen baselines, each digitizer digital delay line needs to be set to a different delay. Having a few correlated baselines is useful as a sanity check when phase switching is used (for example, the correlated magnitudes should be near unity for the noise source). Interfering signal components that can potentially remain correlated at large delays are synchronous clocks within the system, or harmonic signals based on the clocks. The delayed correlations measured using the auto-correlators can help identify interfering components on the individual digitizers.

2.1 128MHz noise source

The lab setup typically consists of a quadrature modulated (phase switched) noise source, and no RF input signal. Without a source of uncorrelated noise, the lab setup can not be used to perform the uncorrelated noise tests that are useful for measuring RF pickup. The old 128MHz baseband noise source does have an uncorrelated source, but its still fairly correlated when the correlated component is turned off, i.e., the two uncorrelated noise components still manage to couple onto the two outputs of the noise source. Figures 3 and 4 show auto-correlations and cross-correlations measured from the 128MHz noise source. The delay lines were used to measure the correlations across a large number of lags to see how long it took before the cross-correlated component dies out. Note how when the correlated component is switched off, that the lag response extends for plus and minus 500 lags, and that the level of the correlated spectrum drops only by a factor of 10. Figures 5 and 6 show the results from 100 1s integrations using the real-time DSP software to collect the data. Clearly the uncorrelated noise source is still very correlated.

Figure 7 shows the results of 100 10s and 100s integrations using the 128MHz noise source set to its uncorrelated mode. The A delay line was set to 4096ns, while the B delay line was set to 2048ns. Both delayed auto-correlations and cross-correlations were calculated. All of the spectra in Figure 7 show correlated components at 62.5MHz and 125MHz below 500MHz. On the digitizer board, the PLL generates a 1GHz clock, but has 62.5MHz and 125MHz signals in its loop, the digitizer is fed a 1GHz clock, and produces a 500MHz output clock, the time-demultiplexing circuits are fed at 500MHz and produce both 125MHz and 62.5MHz clocks, so these harmonics could be caused by any of this logic. Most likely, the harmonics are on the 1GHz digitizer clock, and are coupling into the analog front end through the digitizer IC. Phase switching will remove these components from the cross-correlations (but not the auto-correlations, however, the signal auto-correlation will dominate in an auto-correlation).
Figure 3: 128MHz noise source. The noise source has two outputs, each with uncorrelated plus correlated noise components (1s integration, 1025-lag auto-correlations, 2048-lag cross-correlation). (a) and (b) show digitizer A auto-correlation (lags and spectral magnitude), (c) and (d) show digitizer B auto-correlation, (e), (f), and (g) show the cross-correlation (lags and spectral magnitude and phase). The correlated noise component is about half that of the uncorrelated noise. The data was recorded on a digitizer board in slot #2 of the lab crate.
Figure 4: 128MHz noise source, uncorrelated noise only (1s integration, 1025-lag auto-correlations, 2048-lag cross-correlation). (a) and (b) show digitizer A auto-correlation (lags and spectral magnitude), (c) and (d) show digitizer B auto-correlation, (e), (f), and (g) show the cross-correlation (lags and spectral magnitude and phase). The cross-correlated spectrum should ideally give no correlation, however, the peak is only down by a factor of 10 relative to the auto-correlations. The peak component in the spectrum in (f) is at 18MHz (not the reference frequency of 15.625MHz). The data was recorded on a digitizer board in slot #2 of the lab crate.
Figure 5: 128MHz noise source (correlated). (a) and (b) show the 33-lag auto-correlation results, while (c) shows the 64-lag cross-correlation results (100×1s integrations overlayed).

Figure 6: 128MHz noise source (uncorrelated). (a) and (b) show the 33-lag auto-correlation results, while (c) shows the 64-lag cross-correlation results (100×1s integrations overlayed). The plots in (c) show that there is still a significant level of correlation in the cross-correlation measurement.
Figure 7: 128MHz noise source; the noise source was set to uncorrelated, and both the auto- and cross-correlations were offset using the delay line. (a) and (b) show the 33-lag auto-correlation results, while (c) shows the 64-lag cross-correlation results for $100 \times 10^3$ integrations. (d), (e), and (f) shows the results for $100 \times 10^4$ integrations. The plots are kept at the same scale to show how the variance of the signal drops with increased integration, but the level of interferers does not. All spectra show clear levels of clock harmonics at 62.5MHz and 125MHz below 500MHz, and in the 100s integrations, it looks like there are other harmonics with spacings of 62.5MHz.
2.2 500MHz quadrature modulated noise source

Since the 128MHz noise source was not useful for performing uncorrelated noise source tests, another 500MHz to 1GHz noise source was constructed from a cascade of RF amplifiers. The output of this noise source was fed into the RF inputs of antennas AN1, AN3, and AN5.

To setup the lab system using the quadrature modulated noise source and this new noise source, the quadrature modulated noise source was first enabled on all antennas and was used to align clocks in the system. Once the clocks were aligned, the quadrature modulators for AN1, AN2, and AN3 were disabled. This results in the signals from the odd telescopes being from the RF-input noise source, and the signals from the even telescopes being from the quadrature modulated noise source. This setup results in 9 uncorrelated baselines (odd-even, or even-odd baselines), and 6 correlated baselines (even-even or odd-odd).

2.3 Correlated noise tests

Before constructing the RF-input noise source, several tests were performing using just the quadrature modulated noise source. Decorrelation at the correlators was done using the delay lines. Figure 8 shows fully correlated correlations from the quadrature modulated noise source (with phase switching turned on).

Figures 9 and 10 show uncorrelated measurements from a digitizer board located in slot#1 of the crate. Coupling of the 15.625MHz reference is obvious in the figures. Figures 11 and 12 show the same measurements for a board in slot#2 (slot#3 measurements were similar). The coupling is significantly less in slots#2 and #3. The source of this RFI is investigated further in the next section. The averaged plots all show the presence of 62.5MHz harmonics below 500MHz, however, the (d) plots in the figures show that phase switching removes these components.
Figure 8: 500MHz quadrature modulated noise source (100×1s integrations overlayed). (a) and (b) show the 33-lag auto-correlation results, (c) shows the 64-lag cross-correlation results for the four phase bins, and (d) shows the in-phase and quadrature components calculated from the phase bins.
Figure 9: Delay-line uncorrelated 500MHz quadrature modulated noise source for a slot#1 digitizer (100×1s integrations overlayed). (a) and (b) show the 33-lag auto-correlation results (cross-correlations really), (c) shows the 64-lag cross-correlation results for the four phase bins, and (d) shows the in-phase and quadrature components.
Figure 10: Delay-line uncorrelated 500MHz quadrature modulated noise source for a slot#1 digitizer (100×1s integrations averaged). (a) and (b) show the 33-lag auto-correlation results (cross-correlations really), (c) shows the 64-lag cross-correlation results for the four phase bins, and (d) shows the in-phase and quadrature components.
Figure 11: Delay-line uncorrelated 500MHz quadrature modulated noise source for a slot#2 digitizer (100×1s integrations overlayed). (a) and (b) show the 33-lag auto-correlation results (cross-correlations really), (c) shows the 64-lag cross-correlation results for the four phase bins, and (d) shows the in-phase and quadrature components.
Figure 12: Delay-line uncorrelated 500MHz quadrature modulated noise source for a slot #2 digitizer (100×1s integrations averaged). (a) and (b) show the 33-lag auto-correlation results (cross-correlations really), (c) shows the 64-lag cross-correlation results for the four phase bins, and (d) shows the in-phase and quadrature components.
2.4 15.625MHz reference pickup on slot#1

Figure 13 shows measurements from the lab setup using noise source input to the RFs of AN1, 3, and 5 and the quadrature modulated noise source on AN2, 4, and 6. The number of lags in this figure was increased to 512-lags for these tests so that the response of the 15.625MHz interference would dominate the spectrum. The uncorrelated noise tests show two main features; pickup of the 15.625MHz by the digitizer board in slot#1 of the crate, and an undetermined source of noise over the band 150MHz to 250MHz (the phase has an obvious linear slope over that region).

The tests in Figure 13 were made to try to understand the path of the coupling of the 15.625MHz reference into the first board. None of the tests showed any increase in the coupling to slots #2 and #3. Basement tests also only showed significant coupling to the digitizer board in slot#1. One interesting observation was that terminating the reference output increased the coupling of the 15.625MHz onto the board in slot#1, pointing to the buffer as the source of this radiation. Covering both the buffer and the crystal with an RF absorbing material did not change the measured coupling (though perhaps this material was not effective, and a proper grounded shield would be required).

Further investigation of the timing board is required to isolate and correct for this problem.
Figure 13: Slot#1 digitizer board 15.625MHz pickup from the timing card. (a) correlated noise, (b) uncorrelated noise (similar plots were obtained when the timing card crystal was covered, and when the buffer was covered with RF absorbing material). (c) shows uncorrelated noise with the reference out port terminated—the 15.625MHz coupling increases (no increase occurred on slots#2 and #3). Removing the source termination at the buffer results in (d) (a slight decrease relative to (b)), and the addition of output port termination then has no effect. (e) is an uncorrelated noise measurement from slot#2 (slot#3 was similar). Slots#2 and #3 do not show significant pickup of the 15.625MHz reference. (The plots are 512-lag, 2s, correlations).
2.5 Unidentified wideband noise coupling

The tests in Figure 13, and the tests shown in this section, show the coupling of a wideband correlated noise component into the digitizer inputs. Since this noise appears to be coupling into the digitizer inputs directly, phase switching will get rid of it. However, where is this noise source coming from, and does phase switching successfully remove it?

Figure 14 shows 128-lag, 5s, cross-correlations of uncorrelated noise obtained from digitizer boards located in slots#1 to #3 in the lab crate (correlator boards were also in the crate, but the LVDS cables were removed to eliminate them as the source of radiation pickup). The number of lags was increased to 64-lags per cross-correlation to capture the response of the interference. A physical delay (length of cable) was sequentially inserted at different downconverter outputs to see if the correlation response would change. Since no change was detected, the correlated noise must be coupling into the digitizer inputs directly. Changing the cables at the inputs to the digitizers did have an effect, the reponse shape was changed somewhat; again, implying that the noise is coupling at the digitizer inputs, and is in some way related to the front panel RF cable layout.

To see if the wideband noise component was associated with a particular digitizer board, tests were repeated with the digitizer boards moved to different slots. The coupling changed for both boards and slots, so the tests were somewhat inconclusive. This could suggest that the source of the noise is not the boards, since the coupling changed.

Figures 15 through 30 show the lab results from uncorrelated noise tests (AN1, 3, and 5 were fed by a noise source via the RF in input, while AN2, 4, and 6 were fed by the quadrature modulated noise source). The real-time DSP software was used to dump 100 1s, 10s, and 100s records of data. Figures 15 through 20 show the data recorded from correlator board#1 for the 0-degree phase bins (the other bins looked similar), and the in-phase components (the difference between the 0-degree and 180-degree phase bins, the quadrature bins looked similar). Phase switching was off during this test, but calculating the in-phase component is still representative of what phase-switching will eliminate. For the 100s integrations, the data recorded off correlator boards #2 and #3 are also shown in Figures 21 through 24. Averages of the 100×100s (2hrs 47mins) data sets are shown in Figures 25 through 30. Several observations from these plots are;

- For the uncorrelated baselines (the odd-even or even-odd baselines), there is a clear noise coupling, however, the phase switching removes it.
- The wideband noise coupling does not wash-out with increasing integration time, indicating that it is fairly stable.
- For the correlated baselines (the odd-odd or even-even baselines), there is a residual peak in the lag response of the phase switch demodulated data (since the data is not phase switched, phase switch demodulating it should result in no response). The source of this residual peak is most likely instability in the noise source; i.e., slight amplitude change with time.

The next section performs a similar set of tests using the 4GHz COBRA Wideband correlator system.
Figure 14: Wideband noise pickup in slots (a) #1 (BL12), (b) #2 (BL34), and (c) #3 (BL56). (128-lag, 5s, correlations). The noise pickup is also visible in Fig. 13, the number of lags was reduced here to just encompass the wideband noise lag response. (d) and (e) show the response of slot #1 BL12 for delays inserted at the downconverter output for AN1 and then AN2, since the lag response does not shift, the correlated noise must be coupling into the digitizer inputs directly.
Figure 15: Lab crate (CPU9) correlator board #1 uncorrelated noise results for 100×1s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 16: Lab crate (CPU9) correlator board #1 uncorrelated noise results for 100×1s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).
Figure 17: Lab crate (CPU9) correlator board #1 uncorrelated noise results for 100×10s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 18: Lab crate (CPU9) correlator board #1 uncorrelated noise results for 100×10s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).
Figure 19: Lab crate (CPU9) correlator board #1 uncorrelated noise results for 100×100s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 20: Lab crate (CPU9) correlator board #1 uncorrelated noise results for 100×100s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).
Figure 21: Lab crate (CPU9) correlator board #2 uncorrelated noise results for 100×100s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 22: Lab crate (CPU9) correlator board #2 uncorrelated noise results for 100×100s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).
Figure 23: Lab crate (CPU9) correlator board #3 uncorrelated noise results for 100×100s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 24: Lab crate (CPU9) correlator board #3 uncorrelated noise results for 100×100s integrations overlaid, in-phase component (0-degree minus 180-degree phase bins).
Figure 25: Lab crate (CPU9) correlator board #1 uncorrelated noise results for $100 \times 100s$ integrations averaged, 0-degree phase bin (other bins were similar).
Figure 26: Lab crate (CPU9) correlator board #1 uncorrelated noise results for 100×100s integrations averaged, in-phase component (0-degree minus 180-degree phase bins).
Figure 27: Lab crate (CPU9) correlator board #2 uncorrelated noise results for 100×100s integrations averaged, 0-degree phase bin (other bins were similar).
Figure 28: Lab crate (CPU9) correlator board #2 uncorrelated noise results for $100 \times 100$s integrations averaged, in-phase component (0-degree minus 180-degree phase bins).
Figure 29: Lab crate (CPU9) correlator board #3 uncorrelated noise results for 100×100s integrations averaged, 0-degree phase bin (other bins were similar).
Figure 30: Lab crate (CPU9) correlator board #3 uncorrelated noise results for 100×100s integrations averaged, in-phase component (0-degree minus 180-degree phase bins).
2.6 Basement uncorrelated noise tests

This section contains measurements from the COBRA Wideband Correlator system. The data was taken with the telescopes tracking a source, but the ambient load was switched into the beam, i.e., the telescopes acted as uncorrelated noise. Similar tests to these first exposed the fact that there was a wideband noise pickup being observed. Those tests led to the construction of an additional lab noise source to see whether the problem could be reproduced there—which the last section shows.

The 4GHz COBRA Wideband system consists of 8 parallel 500MHz bands. The correlator hardware acts identically within each band, so obtaining data on all bands gives a reasonable statistical sampling of data (and problems).

Figures 31 through 42 show the results from observing the ambient load for COBRA CPUs 1 and 2, for all three correlator boards. The 0-degree phase bin and in-phase components are shown. From these plots several observations are:

- Phase switching removes the noise coupling.
- There is an unexplained residual around the zeroth lags of some baselines. This could be an artifact of the passband of the noise. Note that the spectral plots do not show any obvious problems, as the effect of a changing delta function at the zeroth lag corresponds to a changing offset in the spectral domain.

2.7 Testing TODO list

The following are some tests that I’d like to perform at some point:

- Test a digitizer board on the benchtop and see if I get the coupling. I’m suspicious that the coupling is via the chassis ground. An alternative would be that there is coupling within the chassis, either way, an isolated benchtop test should confirm/deny this idea.
- Benchtop test using the 128MHz noise source and the ZFL-cascaded noise source. This takes the downconverters and quadrature modulated noise source out of the test setup.
- Remove the chassis-to-logic ground coupling caps - does this make any difference?
- Short chassis and logic grounds. Any difference?

3 Conclusions

There are two noise coupling problems in the COBRA correlator system; clock radiation from the timing board, and an undetermined source of wideband noise. Both problems are removed by phase switching, however, further testing is required to determine the corrections (and causes) of these problems.
Figure 31: COBRA CPU1 correlator board #1 uncorrelated noise results for 100×100s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 32: COBRA CPU1 correlator board #1 uncorrelated noise results for 100×100s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).
Figure 33: COBRA CPU1 correlator board #2 uncorrelated noise results for 100×100s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 34: COBRA CPU1 correlator board #2 uncorrelated noise results for 100×100s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).
Figure 35: COBRA CPU1 correlator board #3 uncorrelated noise results for 100×100s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 36: COBRA CPU1 correlator board #3 uncorrelated noise results for 100×100s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).
Figure 37: COBRA CPU2 correlator board #1 uncorrelated noise results for 100×100s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 38: COBRA CPU2 correlator board #1 uncorrelated noise results for 100×100s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).
Figure 39: COBRA CPU2 correlator board #2 uncorrelated noise results for 100×100s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 40: COBRA CPU2 correlator board #2 uncorrelated noise results for 100×100s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).
Figure 41: COBRA CPU2 correlator board #3 uncorrelated noise results for 100×100s integrations overlayed, 0-degree phase bin (other bins were similar).
Figure 42: COBRA CPU2 correlator board #3 uncorrelated noise results for 100×100s integrations overlayed, in-phase component (0-degree minus 180-degree phase bins).